The record of extreme hydrological and geomorphological events inferred from glaciolacustrine sediments

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Abstract Sediments in eight glacier-fed lakes of the southern Canadian cordillera have been investigated using surface coring and subbottom acoustical surveys. Laminated or varved sediments are used to construct accumulation chronologies which reflect both average and extreme depositional regimes. Average departures in varve thickness are associated with variations in spring runoff controlled by winter precipitation, summer temperature and glacier melting. Extreme departures reflect a broader range of controls such as outburst floods, autumn storms and slumps or slides directly into the lake. Discrimination between extreme and average regimes is possible using sedimentary evidence, which includes grain size, structure and spatial continuity of the deposits, allowing for inferences about the origin of events in the pre-instrument record. An average of 4-6 extreme events per 100 years appears to be common in these lakes; however, their low frequency suggests sediment delivery is dominated by the average regime. Reconstructions of specific sediment yield are in the range of 30-450 t km^{-2} $year^{-1}$ averaged over the last 140 years. Long-term declines are related to increased storage and sediment exhaustion in the upper basins.

INTRODUCTION

In the mountainous regions of western Canada it is especially difficult to assess sediment yield because of great variation in process and form, and the paucity of data. Of particular concern is determining the impact of modern land uses such as agriculture and forest extraction on the production of surface sediment relative to natural and long-term variations. An ongoing program of water and sediment sampling by the Water Survey of Canada provides essential evidence of recent sediment yield variations but there remains limited information about early and pre-twentieth century conditions over a larger area (Meade *et al.*, 1990). A partial solution to this problem is accessing the record of sediment movement and deposition found in the many, diverse lakes of the region. Deep lakes are ideal for this purpose because of their high trap efficiency, a lack of appreciable physical or biological post-depositional disturbance, and the potential for detailing the uninterrupted supply of sediment spanning the interval from late glacial to Holocene sedimentary environments. In addition, long sequences of laminated sediments contain vital information on recurrence rates of events (average and extreme) and are a key to understanding forcing factors in the earth system (Glenn & Kelts, 1991). The long-term objective of this study is to sample, measure and interpret the depositional sequences preserved in a variety of glacier-fed lakes in order to assess the varying climatic, glaciological and lithological influences on sediment yield.

CONTROLS ON LACUSTRINE DEPOSITION

Lacustrine deposits reflect a range of environmental controls that include external and internal forcing and a set of specific boundary conditions that affect both the contributing basin and receiving basin (Fig. 1). Variations in temperature and precipitation at the seasonal scale or longer control the timing and duration of runoff and the capacity for sediment movement within the drainage network. Extreme departures in external forcing (e.g. heavy rainfall, rapid increases in temperature and melting snow) may produce extreme runoff and concomitant increases in sediment concentration of the receiving basin. Normally, this is reflected in higher sediment flux rates to the lake bottom and above average deposition for a significant period following the event. However, sediment routing may not be direct and the response to extreme forcing may be severely filtered by storage effects in the intervening flood plain (Fig. 1). Dearing & Foster (1993) suggest this mechanism is most important where the drainage basin area to lake area ratio is high, resulting in deposits that are more closely coupled to exchanges in the fluvial system. As this ratio decreases, the availability of storage sites declines and there is direct coupling between the receiving and contributing basins, leading to more direct exchanges with the glacier and hillslope systems.

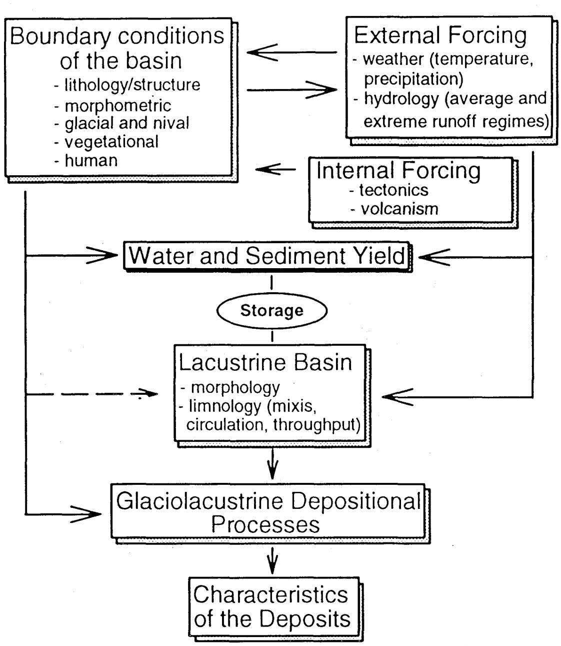

Fig. 1 Linkages between external/internal forcing and preserved sedimentary sequences of glacial lakes.

Internal forcing may also be important in glaciolacustrine environments. Volcanic eruptions in the drainage basin contribute to the fluvial system new material, some of which (ash and pumice) may be highly erodible (Slaymaker, 1993; Desloges & Gilbert, in press), and disrupt glacial and nival regimes, creating large volumes of additional meltwater. In addition to normal, slow and rapid colluvial processes, seismic events destabilize both subareal slopes in the basin and subaqueous slopes of the lakes (Shilts & Clague, 1992). Discrimination between catastrophic inputs and more normal deposition must be made by looking for (a) disturbed, truncated or severely eroded sedimentary sequences, (b) discontinuous deposits that are only locally significant, (c) abnormal indicators of sediment sources (e.g. changing direction of sediment thickening) and (d) unique sedimentary structures in the deposits which reflect alternative depositional processes to the average depositional regime.

SITE SELECTION AND METHODS

Establishing variations in the rate of erosion and the relative importance of extreme events requires high-resolution of the depositional sequence. Thus, the primary criteria for selecting lake sites are the possibility of an undisturbed sedimentary sequence that details annual to sub-annual sediment inputs and a contributing basin which is sensitive to atmospheric forcing. Lakes occurring in partly glacierized basins meet both these requirements because of the high and variable annual sediment load and the responsiveness of glacier melting to changing temperature and snow (precipitation) conditions (Chikita, 1993). To date, eight lake basins have been investigated in the southern Canadian Cordillera (see Fig. 2 for locations) which were thought to meet these requirements. Table 1 is a summary of some key features at each site.

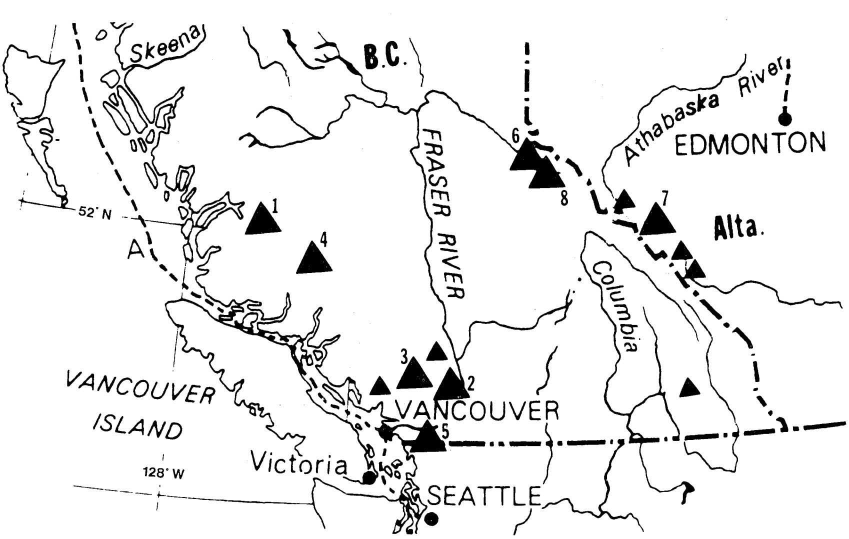

Fig. 2 Map showing locations of lakes used in this study (large triangles). Numbers refer to names given in Table 1. Small triangles show locations of other lakes where rhythmically laminated sediments have been identified.

Table 1 Characteristics of lakes studied in the southern Canadian Cordillera.

Lake[a]	Drainage area (km^2)	Lake area (km^2)	Percent glacier cover	Sediment structure	Dating control	Extreme event mechanisms	Sediment yield (t km^{-2} $year^{-1}$)
SW B.C.							
1 Ape	43	2.5	53	varved	^{137}Cs	outburst floods	265
2 Harrison	7870	269	8	laminated/ massive	^{14}C	slope failures	35
3 Lillooet	3850	21	14	varved	^{137}Cs	autumn floods	205
4 Nostetuko	12	0.5	85	varved	^{137}Cs	glacier melt floods	220
5 Stave[b]	727	27	3	laminated	known marker	autumn floods	450
SE B.C./Alta							
6 Berg	56	2.1	34	varved	^{137}Cs	glacier melt floods	310
7 Chephren	11	1.4	9	laminated/ massive	^{14}C	avalanche, slope failures	65
8 Moose	1640	12	3	varved	^{14}C	avalanche, spring floods	30

[a] see Fig. 2 for numbered locations; [b] data are for pre-dam configurations.

A range of lake sizes has been explored with contributing basins that vary in glacier cover between 3 and 85%. Rhythmically laminated sediments – some continuously, others not – were sampled in every case. The annual nature of the rhythmic laminae (varves) could be confirmed at five sites using isot ic dating of organic and inorganic components (Table 1). It is apparent that the formation of high-resolution sedimentary sequences is dependent on the amount of glacier cover and the size of the lake relative to the contributing basin. Figure 3 is a plot of percent glacier cover against the ratio of basin area to lake area for our eight study sites. As this ratio declines the percent glacier cover required to produce distinct varves increases. Although the database is limited, the downward sloping line of discrimination can be justified on theoretical grounds. As

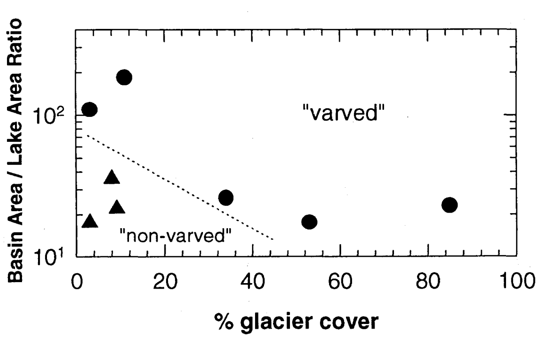

Fig. 3 Relationship between percent glacier cover and basin area/lake area ratio (see text for discussion).

lake size increases relative to the area of the contributing basin, a larger sediment load is required to form distinct laminae in the lake bottom deposits. Increased glacier coverage in the basin can lead to greater sub-glacial erosion, larger sediment loads and a greater range in seasonal runoff all of which promote the formation of varves. The simple discrimination in Fig. 3 provides a first order approximation of the potential for a high-resolution lake sediment record and thus is a useful index for site selection.

Resolution also depends on the ability to effectively sample a sequence without disturbance (Kidd & Hailwood, 1993). In lakes, where water depth and sediment thickness are low, conventional piston, percussion or gravity coring methods may be adequate. These methods have been used to establish the accumulation chronologies presented in Table 1. However, most of the lakes in this study remain unfrozen year round, some are deep ($>$250 m), others occur in remote locations and all receive large sediment loads so conventional methods provide evidence of only recent variations. These results are supplemented with indirect evidence of changing sediment composition using a 3.5 kHz subbottom profiler. Although the acoustic signal is unable to penetrate thick deposits of sand-sized materials or larger, results give a high resolution picture ($<$1 m) of changing sediment composition to depths that approach 100 m below the sediment surface. The resolution is less than that required to discriminate between events with decadal frequencies, but provides an indication of higher magnitude inputs over the entire post-glacial interval.

AVERAGE AND EXTREME DEPOSITIONAL REGIMES

An average depositional regime can be associated with a specific property of the lacustrine sediments, such as sediment thickness, grain size, mineral content etc., which show limited variance about some stationary or gradually-varying mean. An extreme depositional regime can be defined in terms of the same sedimentary properties but for which values are well above or below the mean. No simple threshold can be identified, but for practical purposes if the property (e.g. varve thickness) is greater or less than 2 standard deviations from the mean, then extreme forcing could be inferred. The advantage of adopting such a threshold is that for normally distributed properties, the frequency of such events is less than 5% of the time and thus they might be considered rare.

The subbottom record from Stave Lake illustrates this point (Fig. 4). Each acoustic reflector which shows a dark band in the record corresponds to a change in the characteristics of the sediment column. The acoustic structure of the lacustrine sediments shows a regular pattern to depths of about 30 m below the sediment surface. The average thickness of the stratified "acoustic" beds is 1.7 $\pm$ 0.9 m and the sequence can be divided into two subunits. Unit 3 beds have an average thickness of 1.4 $\pm$ 0.5 m and unit 2 beds are 2.1 $\pm$ 0.7 m thick. The upward thinning has been interpreted as a reduction in sediment supply from late-glacial to Holocene time following the reorganization of glacier ice in adjacent mountain valleys (Gilbert & Desloges, 1992). While thickness changes significantly between the two units (p = 0.95) the degree of change is not considered extreme by the definition given above and thus the lake has been subjected to "normal" glaciolacustrine processes during the last 11 000 years.

Less regular patterns of acoustic structures can be interpreted differently. On the west basin wall two thick and transparent acoustic units are present, the lowest one traceable for up to 7 km and the younger overlying deposit for up to 3 km. The chaotic

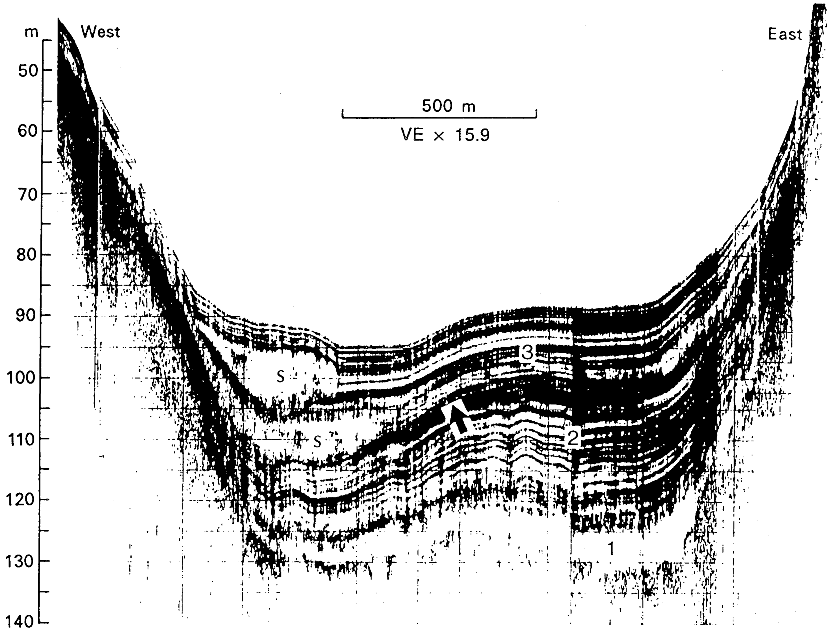

Fig. 4 Subbottom acoustic record (3.5 kHz) from a cross-lake transect of Stave Lake. Depths are plotted for a sound velocity of 1460 m s^{-1}; distances are from the shore at the beginning of the run.

acoustic character of these reflectors suggests that they are slump deposits. The degree of penetration, similar to other fine-grained materials on the lake floor, suggests that the slumped materials themselves are fine-grained. Thus they probably result from slope failure on the sides of the lake of sediments deposited from suspension in the water, just as more recent acoustically stratified sediments have been deposited since (Fig. 4). Thickness of each "event-based" deposit is an order of magnitude larger than the normal processes of lacustrine sediment deposition.

Unit 1 at the base of the sequence in Fig. 4 is characterized by acoustically unstratified fine-grained sediments. Our interpretation is that they were deposited in a quiet "fjord-like" setting with possible connections to marine waters of the Pacific during initial deglaciation of the region. The anomalously thick (massive) beds represent an extreme departure (in a sense a negative one) from the "normal" regime which dominated the majority of the Holocene (units 2 and 3).

At increasing temporal resolution, varves sampled in the surface sediments of at least five of the lakes provide an indication of normal and extreme events and some of their possible controlling mechanisms. At the annual scale, single varves exhibit inputs related to different hydrological and climatological forcing. Figure 5(a) is a simplified model of a typical varve unit with features that exhibit the range of observed structures, probable depositional processes and most likely forcing. Initial deposition of massive silts and clays occurs during winter under quiet water conditions. If large storm(s) runoff occurs in the autumn preceding the winter – a situation typical of the coastal lakes influenced by maritime air masses – then high concentrations of suspended sediment in the lake lead to anomalously thick winter varves. In the spring, snowmelt generated runoff produces peak flows of some duration which transport fine sand into an

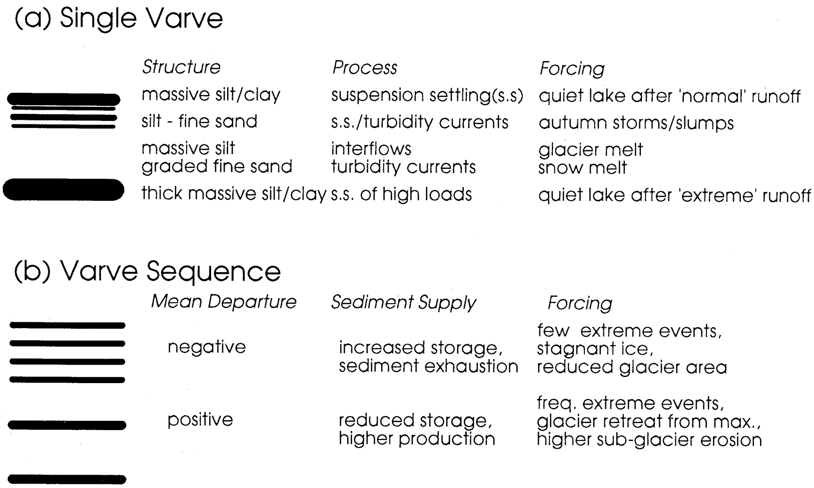

Fig. 5 Schematic diagram of (a) a single varve and (b) a varve sequence representing "extreme" events at two temporal scales.

isothermal lake forming underflows and graded laminae. As snow disappears and temperatures increase later in the summer, glacier melting yields abundant silt which enters as interflows in a warming and sometimes thermally stratified lake. Commonly, silt- and sand-rich laminae in the summer deposit represent inflow pulses associated with melt during warm periods or rain events. These pulses give rise to turbidity currents that deposit sediments as discrete graded beds. Deposition of clay-sized sediment dominates in the autumn as sediment supply declines and glacier melting ceases. Settling of the fine suspended fraction is interrupted by flood-derived bottom currents generated during autumn rain or early winter rain-on-snow storms. These hydrological events are extreme in the context of basin hydrology (Kundzewicz *et al.*, 1993). For example, the flood of 4 October 1984 in the Lillooet River basin was the largest in the 70 years of available gauging records and the resulting varve thickness was 3.9 standard deviations above the mean reconstructed for the interval 1850-1989 AD. The inference made from the varve record is that this flood event had a recurrence interval greater than 140 years.

A varve sequence contains information on extreme departures at the decadal scale or longer (Fig. 5(b)) (cf. Leonard, 1985). A sequence of below average varve thickness (negative departures) may relate directly to climate forcing (low temperatures and low precipitation, reduced runoff) or indirectly via responses in basin boundary conditions such as decreased glacier cover and reduced sub-glacial erosion rates. Sediment storage might increase as new lakes form in front of retreating ice margins. This occurred at Ape and Stave glaciers during rapid glacier retreat in the early twentieth century. In contrast, a sequence of positive departures in varve thickness represents enhanced production and/or delivery of sediment to the lake (Fig. 5(b)). A higher frequency of extreme events may contribute to thickening of the varve, although confirmation of this can only be made by detailed interpretation of the sedimentary structures within each varve unit.

INFERENCES ABOUT HYDROLOGIC AND GEOMORPHIC FORCING

To illustrate the mixed nature of the forcing signal preserved in the sediments, we present varve sediment chronologies from three of the study sites (Fig. 6). These are composite chronologies based on three or more cores from each lake and varve thickness is presented as standardized departures from a long-term mean. A simple linear regression line is fitted to each series in order to illustrate long-term persistence in thickness for each record. Dashed lines are placed 2 standard errors away from the mean and provide an estimate of the frequency of extreme positive and negative departures. The slow decline in varve thickness towards present for Ape and Moose lakes is associated with the sediment exhaustion and storage effects discussed above. Based on comparisons with known climatic and hydrologic variations in each local region after 1945, inferences about the possible origin of extreme positive departures in varve thickness before 1945 can be made. The dominant causes are listed in Table 1 and their order in time is plotted on Fig. 6.

The events that generate anomalous deposits are:(a) autumn and winter storms, particularly in the maritime lakes such as Ape and Lillooet ; (b) spring floods generated from rapid melting of a deep and dense snowpack followed by enhanced glacier melting in the summer (e.g. Moose Lake); (c) outburst floods which may affect lakes directly, by causing lake levels to drop leading to increased slumping and shoreline erosion as occurred at Ape Lake in 1984/85 (Gilbert & Desloges, 1987), or indirectly by generating a flood which mobilizes sediments in the pro-glacial zone and downstream

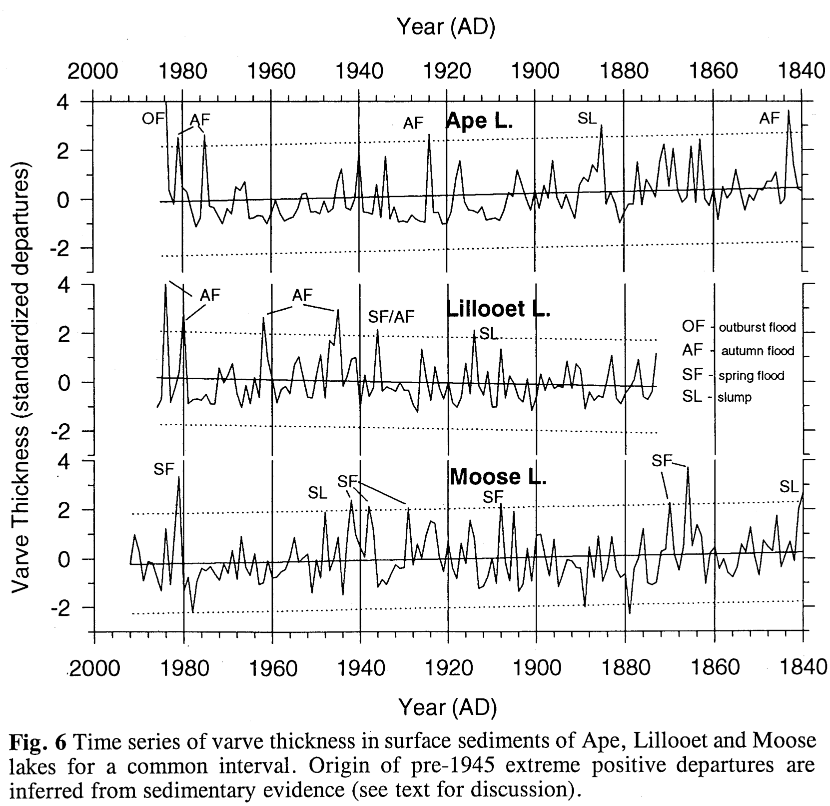

Fig. 6 Time series of varve thickness in surface sediments of Ape, Lillooet and Moose lakes for a common interval. Origin of pre-1945 extreme positive departures are inferred from sedimentary evidence (see text for discussion).

valley; and (d) mass wasting events, some of which are subaerial in origin like the avalanche activity into Moose Lake, and others which are sub-aqueous in origin (see Stave Lake example above). By way of contrast, the factors that are conservative and that lead to uniformity of deposition are moderate departures in temperature and precipitation, less variable runoff, the absence of intense storms and limited tectonic activity.

CONCLUSIONS

Although extreme events are capable of transporting large quantities of sediment, their low frequency (about 4-6 events per 100 years for the series in Fig. 6) suggests that "normal" depositional processes dominate the sediment yield record. Therefore, the sediment accumulation chronologies presented here for lakes of the southern Canadian Cordillera provide direct evidence of long-term variations in sediment yield. Table 1 summarizes the estimated specific sediment yield from each of the eight watersheds studied. The rates vary from 30 to 450 t km^{-2} $year^{-1}$ and are probably minimums because they do not include the coarser sand and gravel sediment fraction stored in deltas which are prograding into some lakes. The estimates, which are an order of magnitude lower, reflect the influence of upstream sediment traps such as flood plains (Moose Lake), proglacial zones (Chephren Lake) and intervening lakes (Harrison Lake). Estimates in the range 2-4 $\times$ 10^2 t km^{-2} $year^{-1}$ are more typical of delivery rates which have been occurring during the last 100-200 years. This corresponds to a phase of renewed glacier activity in southern British Columbia (Little Ice Age) and thus is thought to represent rates higher than those present during comparatively ice-free conditions of the middle Holocene. Confirmation of this hypothesis using delivery rates inferred from the geophysical sediment record has been made at Stave and Ape Lakes only. At these two sites average Holocene erosion rates are suspected of being less than half of those inferred for the twentieth century. Further confirmation of this requires better dating control (deep drilling and sampling) of the major acoustic reflectors identified at other sites.

Acknowledgements Research and equipment grants from the Natural Sciences and Engineering Research Council of Canada funded this work. Logistical assistance has been kindly provided by M. Church, J. Shaw, and D. Smith.

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