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Geomorphology 61 (2004) 209–224
GEOMORPHOLOGY
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Spatial and temporal variability of sediment delivery from alpine lake basins, Cathedral Provincial Park, southern British Columbia

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Received 17 January 2003; received in revised form 17 December 2003; accepted 27 December 2003

Available online 14 March 2004

Abstract

This paper presents reconstructions of Holocene sediment yield from four alpine lakes in southern British Columbia. Sediment yield is reconstructed on the basis of suites of dated and correlated cores from each lake. Facies analysis of the complete set of cores suggests that significant changes in sediment delivery have occurred during the Holocene, specifically a shift to a higher energy sedimentary environment in cooler wetter conditions in the late Holocene. Estimated sediment yields range between 2.3 and 11.2 t km^{-2} a^{-1}. Maximum Holocene variability is a 115% increase at one site. Highest variability is observed at sites just above treeline suggesting that reduced vegetation cover under cooler conditions is a key control on temporal variability of sediment yield at these sites. The temporal variability observed at Holocene timescales is within the range of natural spatial variability observed between the four closely spaced lakes. Overall, the results suggest that the response of small catchments to climate change is highly contingent upon local catchment conditions, and that at all but the most sensitive sites sediment yield changes associated with moderate climate warming are likely to be of a lesser magnitude than the natural spatial variability.

Keywords: Spatial variability; Temporal variability; Sediment yield; Southern British Columbia

1. Introduction

Many mountain regions are highly active geomorphically (e.g. Caine, 1974) but perhaps the most universal characteristic is the high spatial variability in terms of climate and geomorphic activity. As such, we might expect mountain regions to provide an excellent laboratory for investigation of the complex links between climate change and landform change. However, to date, understanding of the nature of these relations is limited (Slaymaker, 1990, 2000). One of the reasons for lack of understanding is that some modest climate change may produce no dynamic geomorphic process change; some larger climate change produces dynamic geomorphic process

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doi:10.1016/j.geomorph.2003.12.007

change but no discernible landform change, and only climate changes that exceed a critical threshold lead to both process and landform change. What these threshold values are is, in general, not known, but it is proposed that the high spatial variability of climate over short distances in mountain regions offers the opportunity to investigate these threshold values. Anthropogenic changes in contemporary time are further compounding this complexity and it seems logical to try to investigate the natural variability of the system before assessing anthropogenic change. This paper aims to assess the nature of this natural variability by assessing spatial and temporal variability in sediment delivery over Holocene timescales to a set of alpine lake basins in the Cascade Mountains of southern British Columbia. We are conscious of the variations in trapping efficiency of alpine lakes and of the difficulty of determining the representativeness of lake sediment stratigraphy as an indicator of basin wide processes (Foster et al., 1990) and have some suggestions for overcoming these problems.

2. Study site

On the west coast of Canada the snowline rises rapidly inland as precipitation levels decline (Ostrem, 1966, 1972). Consequently, in the drier mountains of the interior, contemporary glaciation is absent from many high mountain catchments. This study is based on lake sediment sequences recovered from a series of cirque basins in Cathedral Provincial Park (49°03 N′ 120°12′ W) in the Okanagan Ranges of the North Cascade Mountains in southern British Columbia (Fig. 1). The core area of Cathedral Park contains five main lakes, all between 2000 and 2200 m elevation. Three of these lakes, Quiniscoe, Glacier and Ladyslipper, are headwater lakes lying in a series of adjacent easterly facing cirques. Pyramid Lake and Lake of the Woods lie down valley of Glacier Lake. The lakes are underlain by granodiorite intruded during the Jurassic period into the Nicola Group volcanics (Rice, 1947). The headward ends of the Glacier and Quiniscoe basins are underlain by inter-

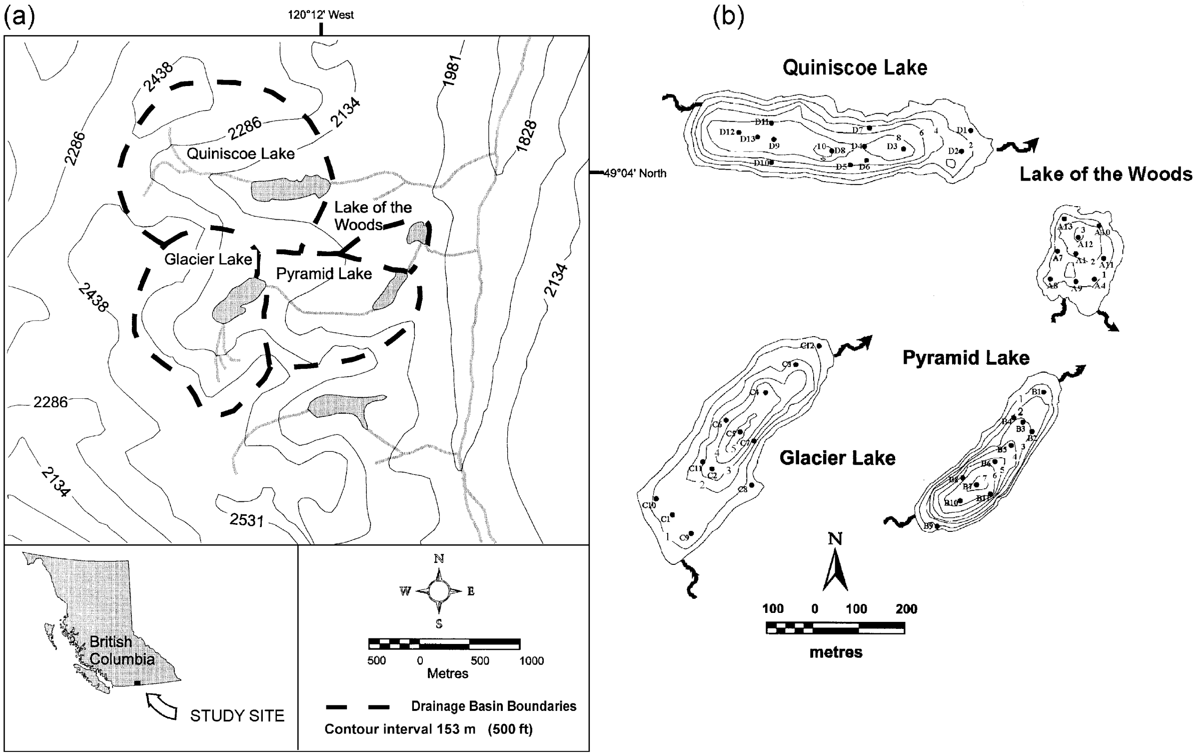

Fig. 1. Location of the Cathedral Lakes (a) and Bathymetric maps of the four lakes showing coring locations (b).

bedded Miocene basalts and sandstones of the Princeton Group, and Triassic andesites of the Nicola Group (Rice, 1947).

The most extensive surficial materials in the Cathedral basins are colluvial. Large talus cones flank the cliffs at the head of the cirques, and many of the lower angled slopes are debris mantled. Some coarse till is present forming a possible degraded lateral moraine on the northern slopes of the Glacier basin, and between the Glacier and Pyramid basins. Major till deposits are not observed in the basins.

Soil development in the basins is limited, reflecting the coarse nature of the parent materials. The upper slopes are covered by poorly developed regosols. On the valley floors, particularly close to stream courses and on the distal edges of the deltas gleysolic profiles have developed. Below treeline the dominant soils are humo-ferric podzols. Podzolic profiles are also found in patches in the alpine parkland zone, but most of the soils above treeline have weakly developed horizons presumably due to frost churning.

Treeline at the study site is well defined. Opening of the forest canopy occurs above around 2130 m and the tree limit is ca. 2290 m. Below treeline the study site falls within the Engelmann Spruce-Subalpine Fir (ESSF) biogeoclimatic zone (Krajina et al., 1982). The major tree species of the continuous forest are *Abies lasiocarpa* and *Picea engelmannii*, although *Pinus contorta* and *Pinus albicaulis* are also present.

Table 1
Summary statistics for the study basins

	Glacier	Pyramid	Lake of the Woods	Quiniscoe
Lake elevation (m)	2200	2070	2050	2060
Lake area (m^2)	87,685	44,650	30,620	91,330
Lake volume m^3	171,500	137,640	38,570	452,565
Maximum depth (m)	5.1	7.2	3.6	12
Max. basin elevation (m)	2550	2500	2160	2550
Catchment area (km^2)	1.123	0.914	0.178	1.721
Catchment/Lake ratio	12.8:1	20.5:1	5.8:1	18.8:1

In the parkland zone *Larix lyallii* is common, particularly around Glacier Lake. Ground cover in the lower subalpine zone consists of ericaceous shrubs, grasses, sedges and alpine herbs. Above the tree limit rocky tundra communities of grass, sedges, and lichens are found.

An overview of the relative locations of the sites can be seen in Fig. 1. Statistics relating to the lakes and their basins are given in Table 1.

3. Methods

Sediment cores were extracted from the four lakes using a Livingstone corer deployed from a portable raft. Twelve to 15 cores were taken at a grid of points within each lake. The core stratigraphy was described visually and with reference to X-radiographs taken on chest film (instrument settings 60 kV, 2 Ma, 115 cm). The whole cores were scanned using a Sapphire Instruments susceptibility loop to measure volume magnetic susceptibility. Density measurements (dry weight (105 °C)/wet volume) were made on 10-cm sections of core at 10-cm intervals down each core. Loss on ignition at 550 °C for 1 h was measured on the same samples. These samples were subsequently heated for a further 4 h at 950 °C and re-weighed to give an estimate of carbonate content (Bengtsson and Ennel, 1986).

3.1. Core correlation

Correlations between sedimentary horizons in cores from the same lakes were derived using magnetic susceptibility traces and by reference to visual and X-ray stratigraphy. This resulted in recognition of between three and five correlated horizons in each suite of lake cores. Fig. 2 identifies correlated horizons for each lake and the basis of the correlations is identified in Table 2.

3.2. Chronology

Core chronology was established in two ways. Two tephra layers were present in all the cores; these were identified as Mazama (6845 ± 50 BP; Bacon, 1983) and St Helens Yn (3390 ± 130 BP; Fulton, 1971) on the basis of stratigraphic position and chemical analysis (Evans, 1997). They therefore provide two secure chronostratigraphic markers. Further dates were obtained as close as possible to correlated horizons by radiocarbon dating of organic inclusions in the sediments. Radiocarbon dating results are summarized in Table 3.

4. Facies classification of the Cathedral Lakes sediments

In order to simplify the stratigraphic information contained in detailed logging of almost 200 m of lake sediment core a facies classification of the sequences was developed. Fig. 3 provides a key to the principal sedimentary facies recognised in the Cathedral Lakes cores. The facies descriptions are based on five major variables, organic matter content, presence of iron sulphides, texture, lamination, and the importance of distinct minerogenic horizons. The first two parameters were based on visual inspection of the cores and testing for sulphides with HCl. Texture was estimated by examination of the split core. Particle size determinations on selected cores indicate that the dominant particle size of the sediments is in the silt range as indicated in the facies descriptions. High proportions of clay size material previously reported in Evans (1997) appear on re-analysis to be an artefact of sample preparation procedures. The mineral horizons and degree of lamination were visible in the split cores but were often more clearly identified on the X-radiographs. Fig. 2a–d presents the facies sequences from the complete set of cores from each of the four lakes together with magnetic susceptibility profiles used for correlation. The facies may be broken down into three principal associations.

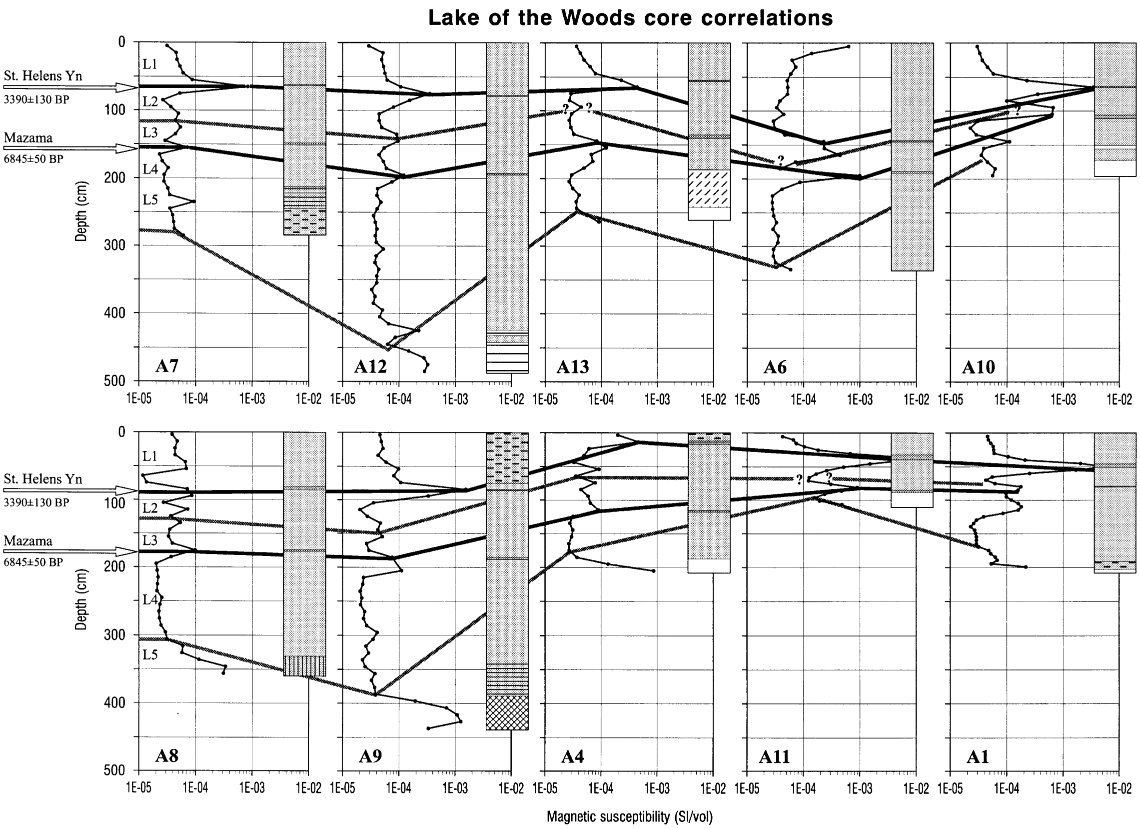

Fig. 2. Facies classification of sediment cores from the Cathedral Lakes and location of correlation horizons.

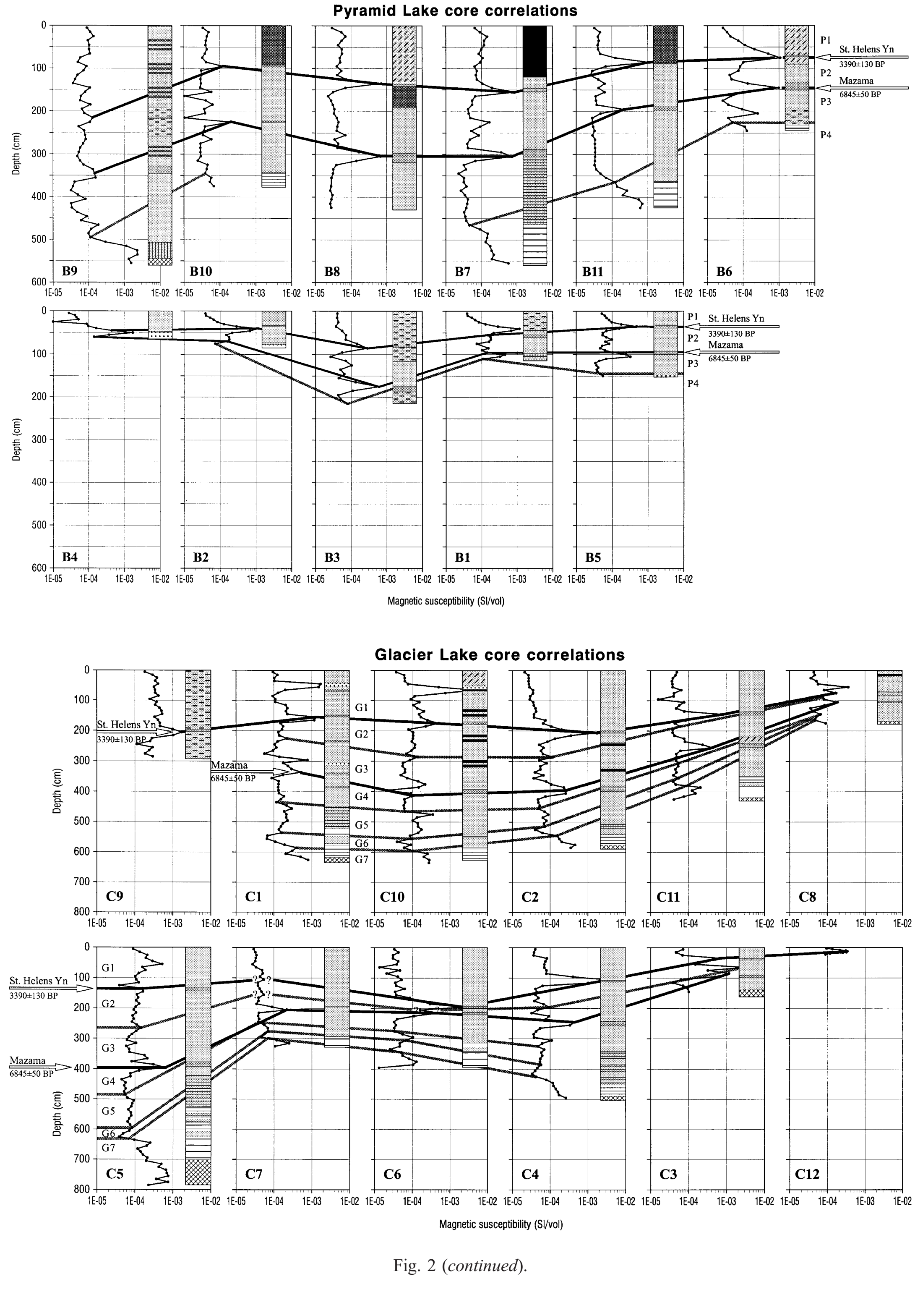

Fig. 2 (*continued*).

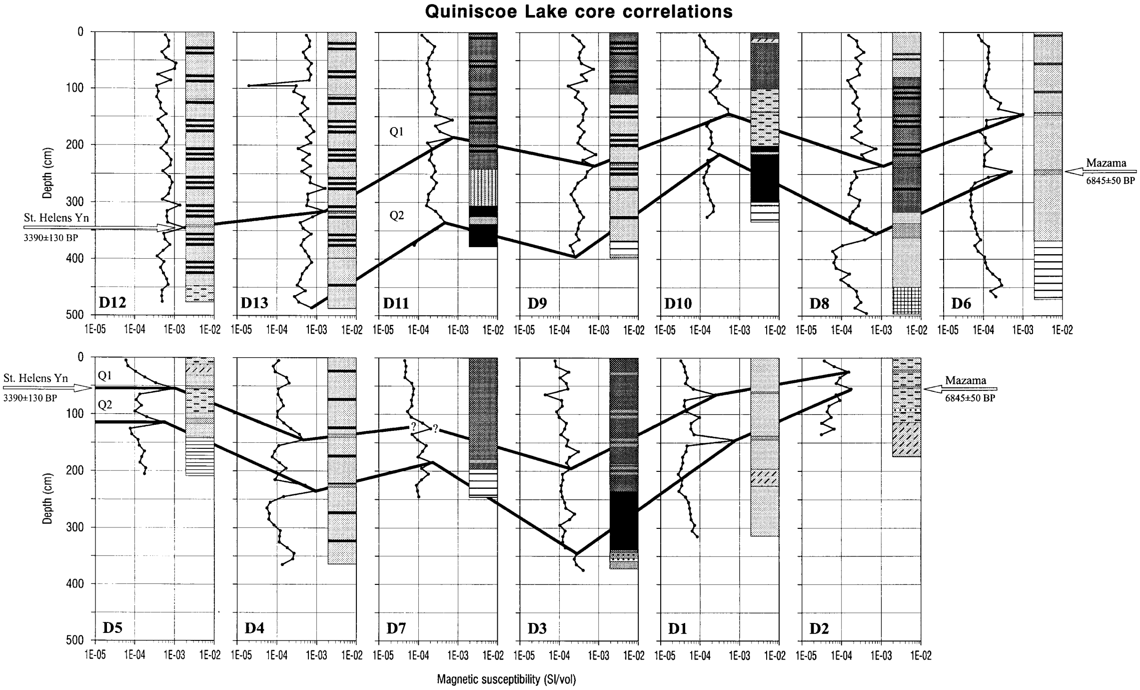

Fig. 2 (*continued*).

(1) Facies 1 through 7 comprise massive silt/clay gyttja with inclusions of sand, organics, and sulphide. Also included in this association are finely laminated (individual laminae < 1 mm) gyttjas characteristic of the early Holocene sections of some cores. These laminae appear to be composed of a gyttja layer and a paler mineral layer that is very rich in diatoms. The details of these individual facies may be interpreted in environmental terms with regard to both the in-lake environment and conditions in the catchment. For example, sulphide deposition is associated with strong reducing conditions in surficial lake sediments (Jones and Bowser, 1978; Saarnisto, 1986). Sulphide in the sediments therefore suggests the development of meromixis in the lake coupled with an adequate supply of organic matter to the lake floor. Similarly, the diatom-rich laminae are probably formed annually by summer diatom blooms (Saarnisto, 1986) and are likely to be associated with warmer lake waters in the early Holocene. Inclusions of sand and coarse organic material in the gyttja suggest the operation of higher energy catchment processes delivering material to the lake.

The massive fine-grained nature of the gyttja facies association is regarded as representing periods of continuously operating low energy processes. Sediment inputs in these periods were most likely to have been fluvial, aeolian or due to sheetwash erosion of surface materials. The absence of sequences of coarse minerogenic beds in this association suggests that major mass movement events and large floods were not significant contributors to the sediment body.

(2) Facies 14–18 comprise facies association 2, which is characterised by sequences of coarse, often graded, minerogenic laminae. The character of individual laminae is variable. Thickness ranges from 1 to 40 mm with most between 5 and 10 mm. Texture ranges from sand through clay with thicker beds fining upwards through this range. The laminae typically have sharp contacts with the gyttja. These laminae are interpreted as representing large, discrete episodes of sediment input. Kotarba et al. (1990) and Jonasson (1991) have ascribed similar minerogenic laminae in alpine lakes to debris flow activity in the basin. This interpretation is largely based on the

Table 2
Basis for core correlations of sediments of the Cathedral Lakes

Correlation zone boundary	Criterion (Downcore change)	Date, and dating method
Glacier Lake		
G1/G2	St. Helens ash	3390 ± 130 BP (tephra)
G2/G3	Susceptibility peak between the two ashes	5080 ± 70 (^{14}C)
G3/G4	Mazama ash	6845 ± 50 BP (tephra)
G4/G5	Step increase in susceptibility and stratigraphic change to clays and minor sulphide	8330 ± 80 BP (^{14}C)
G5/G6	Susceptibility minima, and change to more organic sediment	10,310 ± 110 (^{14}C)
G6/G7	Dramatic rise in susceptibility and decreased organic content	Undated
Pyramid Lake		
P1/P2	St. Helens ash	3390 ± 130 BP (tephra)
P2/P3	Mazama ash	6845 ± 50 BP (tephra)
P3/P4	Increased susceptibility, decreased organic content, or organic sediments deposited on bedrock	9070 ± 110 BP (^{14}C)
Lake of the Woods		
L1/L2	St. Helens ash	3390 ± 130 BP (tephra)
L2/L3	Susceptibility peak between the two ashes	5450 ± 90 BP (^{14}C)
L3/L4	Mazama ash	6845 ± 50 BP (tephra)
L4/L5	Increased susceptibility and stratigraphic shift to more minerogenic material, or organic sediment/bedrock interface	10,650 ± 140 BP[a]
Quiniscoe Lake		
Q1/Q2	St. Helens ash	3390 ± 130 BP (tephra)
Q2/Q3	Mazama ash	6845 ± 50 BP (tephra)
Late glacial/ Holocene	Transition to minerogenic sediments and rise in susceptibility	Undated

[a] The basal AMS date for Lake of the Woods conflicts with the series of conventional radiocarbon dates obtained for the early Holocene sediment by Heinrichs et al. (in prep.). The normal superposition of these dates suggests that the AMS date may be in error. Consequently, the date for this correlation horizon is obtained by extrapolation from the date of 10,200 ± 70 BP measured 29 cm above the correlation horizon.

geomorphic context of the lakes. In the Cathedral basins there is evidence of mass movement on the talus adjacent to Pyramid, Quiniscoe and Glacier Lakes. Several avalanche tracks also run into Quiniscoe Lake, and debris flow tracks run across the Glacier fan-delta. However, these three lakes all have deltaic deposits at their inflow. Therefore, there is no gross contextual basis for identifying the coarse clastic deposits as mass movement rather than flood deposits. However, at a finer scale, differentiation may be possible. The physics of sediment deposition in lakes dictates that the coarse component of fluvial sediment load is deposited on the delta, whilst distal deposition is finer. Similarly, mass movement events may be recorded as coarse deposition only in marginal deposits adjacent to the event site. Therefore the spatial distribution of facies associations 1 and 2 contains useful information about the relative importance of these two sediment transfer processes at a given time.

Facies associations 1 and 2 are restricted to Holocene deposits in the Cathedral basins, since fine organic material is a necessary component of the gyttja matrix.

(3) Facies association 3 (facies 8–13) is characterised by inorganic blue-grey or green-grey clays. The clays are massive or variously laminated. Coarse clastic laminae are common especially in the basal sediments. Fine (< 1 mm) black sulphide lamina are also characteristic of many of these deposits. On the basis of their inorganic nature, and basal position, the deposits of facies association 3 are interpreted as late-glacial sediments derived from a sparsely vegetated, unstable (paraglacial) landscape.

5. Temporal patterns of geomorphic activity interpreted from facies classification

Facies association 3 is an important indicator of late-glacial conditions within the catchment and the coarse clastic laminae of the facies indicate active sediment redistribution within the catchments. Temporal variability of these facies is limited to the phasing of the onset of ice free conditions in the lake catchments. Consequently, subsequent discussion focuses on the spatial and temporal variability of facies associations 1 and 2 which are indicative of temporal variability of geomorphic activity within the Holocene.

Table 3
Radiocarbon dates from the Cathedral Lakes sediments

Core/depth	Material	Date ± 1 s.d.	Source	Technique
C1 541–564/C10 554–575	Bulk organic sediment	10,310 ± 110 BP	Beta-87,710	Conventional
A9 376	Plant fragments	9650 ± 110	To-6051	AMS
B7b 475–486	Conifer needles	9070 ± 110	To-6052	AMS
B9 209–218	Wood/needle fragments	3310 ± 90	Beta-100,775	Conventional
C1 225–230	Conifer needles	5080 ± 70	To-6028	AMS
C1 433–438	Conifer needles	8330 ± 80	To-6029	AMS
A9 140–150	Bulk sediment	5450 ± 90	Heinrichs et al., in prep.	Conventional
A9 241–250	Bulk sediment	8580 ± 80	Heinrichs et al., in prep.	Conventional
A9 341–350	Bulk sediment	10,200 ± 70	Heinrichs et al., in prep.	Conventional

5.1. Quiniscoe lake

Sediments of facies association 2 dominate the lithostratigraphy of the Quiniscoe Lake cores, particularly the proximal cores. Facies association 1 sediments are more frequent in the early Holocene and in the distal cores. Cores D12b and D13 from the front of the delta at the west end of Quiniscoe Lake are incomplete. The longer (D13) ends at the Mazama tephra layer. These cores record for the mid- and late Holocene a pattern of frequent silt/sand graded laminae, which are interpreted as a record of flood events

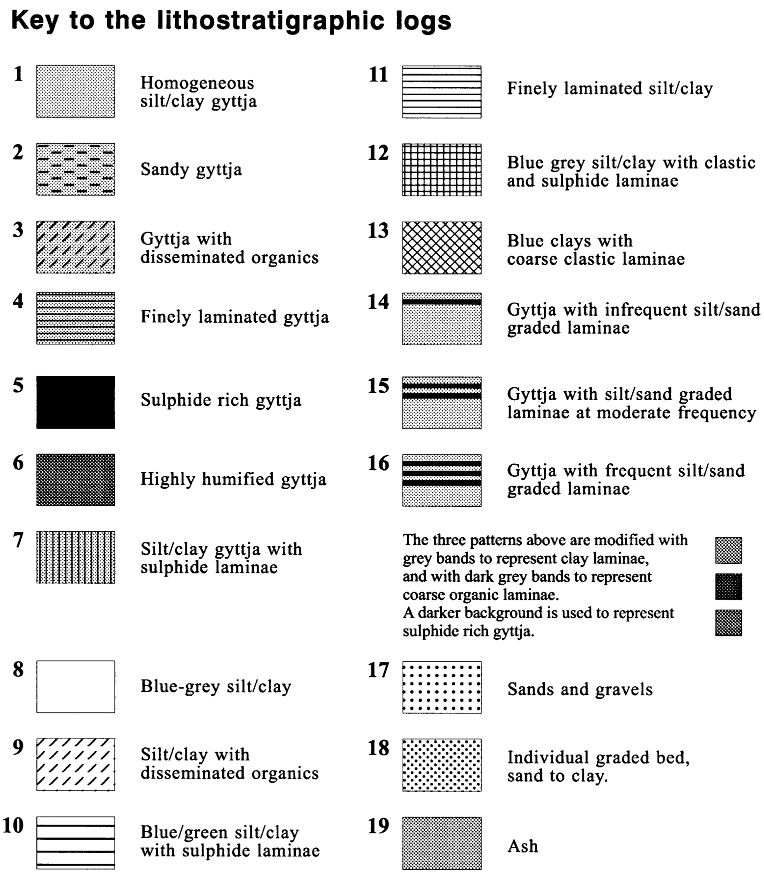

Fig. 3. Key to facies classification.

across the delta. Both cores show a pattern of thicker laminae at moderate frequency in the top metre of the core and more frequent thinner laminae below. For example, in the top metre of D13 the mean thickness of minerogenic laminae is 11.1 mm and there are 29 events. In the rest of the core an average of 56.8 events per 100 cm have a mean thickness of 6.2 mm. This pattern is repeated in more distal cores. If the frequency of "event" deposits in core D13 is calculated for correlation zones Q1 and Q2 the figures are 5.1 events per 100 years after the St. Helens ashfall and 1.42 events per 100 years between the Mazama and St. Helens tephra layers. The same change in the character of the clastic laminae in the upper metre is also identifiable in central and distal cores (D3 and D8). The frequent clastic laminae extend to just above the Mazama ash and below this the cores are composed of homogeneous gyttja. The clastic laminae in the two more distal cores are finer (silt/clay) than those at the delta front. This observation, in combination with the similarity in pattern of deposition down lake, suggests that the sediments in Quiniscoe Lake are largely a reflection of fluvial sediment input at the head of the lake. Localised variability in the sedimentation pattern is noticeable in core D5 at the foot of one of the major avalanche chutes adjacent to the lake, but it appears that mass movement is a relatively minor contributor of material to the lake.

5.2. Glacier lake

The lithostratigraphic record in Glacier Lake is quite variable in space. In the distal and mid-lake cores, sediments described by facies association 1 dominate. In the deeper water cores there is a shift from laminated gyttja in the early Holocene to unlaminated gyttja after the Mazama ashfall. The cores from the front of the Glacier fan-delta (C1, C10) are composed of gyttja (facies association 1) in the lower, pre-Mazama, part of the core, and change to laminated facies association 2 after the Mazama ashfall. However, the frequency of "event" deposits does not approach that seen in the sediments of Quiniscoe Lake. Frequencies for correlation zones C1, C2 and C3, respectively, from core C1 are 0.47, 0.30 and 0.68 events per 100 years. The fact that the post-Mazama shift to facies association 2 is not reflected in the more distal cores suggests that although there may have been an increase in debris flow/flood intensity across the fan during this period, the absolute magnitude of the events was not large. In particular, with the exception of one coarse graded bed deposited after the St. Helens ashfall, there is no sedimentological evidence of debris flow deposition directly to the lake. The fineness of proximal deltaic laminae suggests reworking of fresh debris flow material rather than direct deposition. The morphology of the fan supports this interpretation, since no coarse debris flow material is apparent on the front edge of the fan.

5.3. Lake of the Woods

The sedimentary record in Lake of the Woods is homogeneous both spatially and temporally. The Holocene sediments in the lake all fall within facies association 1, and in fact are described by just two facies, gyttja, and sandy gyttja. The sandy gyttja is mostly confined to basal sediments with the exception of the post St. Helens ash sediments in core A9, which is situated close to the inflow to the lake. The record from Lake of the Woods suggests constancy in the relative importance of sediment delivery processes throughout the Holocene and emphasises the minimal importance of mass movement events in this basin.

5.4. Pyramid lake

Like Lake of the Woods, the Holocene sedimentary record in Pyramid Lake is described by facies association 1. Within this association the sediments are, however, more variable, with differing degrees of humification, sandiness, lamination, and sulphide content in the gyttja. One consistent trend in the deepwater cores (B6–B11) is an increase in the role of organic matter after the St. Helens ashfall. This is variously manifest as more humic gyttja, the inclusion of coarse organic particles, and increased sulphide production. Core B9 after the Mazama ashfall is characterised by facies association 2. It is, however, unusual in that the "event deposits" are dominantly organic, composed largely of wood fragments and conifer needles. Core B9 penetrates the full depth of the fluvial delta deposited at the lake inflow at the eastern end of the lake, and therefore should record changes in fluvial inputs to the lake. It is clear that the site of core B9 has been a higher energy environment in the last 6800 years; however, two possible explanations of this pattern emerge. The pattern may reflect higher runoff in the mid- and late Holocene in response to cooling and wetting of the climate; however, an alternative explanation is that the delta advanced over the core site around the time of the Mazama ashfall. The increased importance of organic matter in the other Pyramid Lake cores supports the hypothesis of increased fluvial activity. However, the dominance of organic material in the flood deposits suggests that, although river flows may have increased in the cooler and wetter Neoglacial period, the fluvial erosion of clastic material has not increased significantly.

The lithostratigraphic record from the four lake basins provides clear evidence of the relative importance of large, discrete sediment input events in depositing the lake sediments. The Glacier and Quiniscoe basins are characterised by episodic delivery of mineral material, particularly in the second half of the Holocene. In the Glacier basin it is likely that material is delivered by a combination of debris flows and fluvial action across the headward fan-delta. Notably, the absolute frequency of events in the Glacier basin is much lower than in the Quiniscoe basin, where lithostratigraphy suggests that sediment delivery events are dominantly fluvial.

Stratigraphic evidence for such large sediment delivery events is lacking for the Lake of the Woods, whilst in the Pyramid basin the sediment moved in such events appears to be largely organic. Facies association 2 deposits represent the post-Mazama deposition in cores taken from the deltas of Pyramid, Glacier and Quiniscoe lakes which suggests increased runoff during this period.

The characteristics of the cores allow for an initial characterisation of the sediment delivery regimes in the four study basins. Holocene sediments from both Lake of the Woods and Pyramid Lake are described by facies association 1, suggesting deposition by relatively low energy processes. In contrast, Holocene sedimentation in Quiniscoe Lake shifts from facies association 1 in the early Holocene to facies association 2 after the Mazama ashfall (6845 BP) indicating a change to higher energy fluvial and mass movement depositional processes. Glacier Lake is in some senses intermediate, with central and distal cores revealing a pattern similar to the downstream lakes and proximal cores exhibiting the pattern seen at Quiniscoe Lake. At a coarse level this lithostratigraphic pattern indicates that the Cathedral Lake basins may perhaps be considered as two groups, Pyramid Lake and Lake of the Woods where the record appears to be relatively complacent, and Quiniscoe and Glacier lakes which provide indications of greater variability in sediment input.

6. Holocene sediment yields of the Cathedral Lakes basins

6.1. Calculation of sediment yield

Analysis of the lacustrine sedimentology has allowed a qualitative assessment of changing geomorphic activity in the study basins over the Holocene. Quantification of changing rates of sediment accumulation associated with these process changes requires calculation of rates of sediment accumulation. Conventionally, sediment accumulation rates in individual cores are converted to volume by averaging across the lake area (Foster et al., 1990). If a simple average accumulation rate is combined with the lake area to produce these estimates associated error estimates are inflated since they incorporate real spatial variability in addition to potential sampling error. An alternative approach incorporates this variability into the estimate by combining volume estimates produced from individual core accumulation rates and the area of thiessen polygons constructed around the coring locations (O'Hara et al., 1993). However, using this approach each core is a single sample wherein simple error statistics cannot be derived. In this study an alternative approach to sediment yield calculation was devised using a regression model of the accumulation surface to predict sediment accumulation and error intervals for each core site.

Point sediment mass corrected for autochthonous components (P) was calculated as

$$P = Z_i D_i \left(1 - \left(\frac{L_i}{100}\right)\right) \bullet \left[1 - \left(\frac{d+k}{100}\right)\right] \tag{1}$$

where Z_i is the depth of the unit in core i, D_i is the mean dry wt./wet volume of the unit in core i, and L_i is the mean percentage Loss on Ignition value for the unit in core i. d is the mean percentage diatom concentration in the longest central lake core, and k is mean carbonate percentage for the zone from the same core. Note the terms for the removal of autochthonous sediments are split because in this study the diatom and carbonate concentrations were calculated as a proportion of the mineral sediment.

Sediment yield (Y) for each chronostratigraphic unit was then calculated as

$$Y = \left[\frac{\sum P_i A_i \cdot \left(\frac{100}{T}\right)}{t}\right] \tag{2}$$

where P_i is the estimated point mass (t/m) for the unit in core i derived from a regression model relating measured point mass to core location, A_{i} is the area of the thiessen polygon surrounding core i (m^2), T is the trap efficiency (%) of the lake estimated from Brune curves (Brune, 1953) and t is the time interval in radiocarbon years represented by the stratigraphic unit. The error term for the estimate p_i is combined with values from the Brune envelope curves and confidence intervals from the radiocarbon dates to generate confidence intervals for the estimated sediment yield (a more detailed description of the approach is given in Evans and Church (2000)). This approach produced sediment yield estimates which were a good approximation to conventional approaches but which additionally have realistic error estimates associated with them.

Sediment yield calculated in this manner can be regarded as representative of geomorphic activity within the lake basin only in the light of some assessment of aeolian deposition of material from extra-local sources within the basin. This is particularly the case for alpine basins, since Caine (1986) has suggested that, for some alpine basins, this source of sediment may dominate lake deposition. Accordingly in the Cathedral basins dustfall was monitored at a range of sites over a 1-year period. Winter dustfall was assessed from snow cores taken early in the melt period, whilst summer dustfall was assessed directly using bulk collectors following the methods of Owens and Slaymaker (1997). Results show that monitored dustfall at sites within the study basins was log normally distributed, with modal values around 1–2 g m^{-2} a^{-1}. These values are assumed to represent the regional dustfall with higher values associated with local redistribution of material. At this level dustfall to the lake basins comprises ca. 1% of total sediment yield and is disregarded in subsequent analysis.

6.2. Spatial patterns of sediment yield

Calculated Holocene sediment yields from the Cathedral Lakes are presented in Fig. 4. In the period since the St Helens Yn ashfall (3390 ± 130 BP) the specific sediment yield to the four Cathedral Lake basins ranges from 2.3 to 11.2 t km^{-2} a^{-1}. In the Glacier–Pyramid–Lake of the Woods system, the highest sediment yield is 8.8 t km^{-2} a^{-1} to Glacier Lake. However, rather than a steady downstream decline, the lowest value of 2.3 t km^{-2} a^{-1} is recorded in Pyramid Lake. This observation is in line with the high trap efficiencies estimated for the lakes, suggesting that local sediment production dominates rather than throughput from higher up the system. The Pyramid basin is steeper, has a lower proportion of forest cover and a higher proportion of bare surfaces than Lake of the Woods, which lies downstream. It therefore seems unlikely that the lower sediment yield to this basin is a function of lower sediment production. Instead, it is suggested that the relatively low sediment yields to Pyramid Lake may be due to storage effects. Pyramid Lake lies at the distal end of the elongate Pyramid basin and has the highest catchment to lake ration of the four lakes. The low slopes of the forested valley floor provide a storage zone between the lake and the active unvegetated slopes at the head of the basin, which may explain the unusually low sediment yield to the lake. The highest recent sediment yield is recorded in Quiniscoe lake where yields are 11.2 km^{-2} a^{-1} for the period 3390 BP to present.

The pattern of spatial variability in the early Holocene contrasts with later periods. Glacier and Quiniscoe Lakes have early Holocene-specific sediment yields between 5.1 and 6.7 t km^{-2} a^{-1} (BP), whilst values in Lake of the Woods reach 8.3 t $km^{-2}a^{-1}$. Sediment yield to Pyramid Lake remains lower at 2.5 t km^{-2} a^{-1}.

6.3. Temporal patterns of sediment yield

Sediment yield to Lake of the Woods remains relatively constant throughout the Holocene although the highest values are recorded in the early Holocene

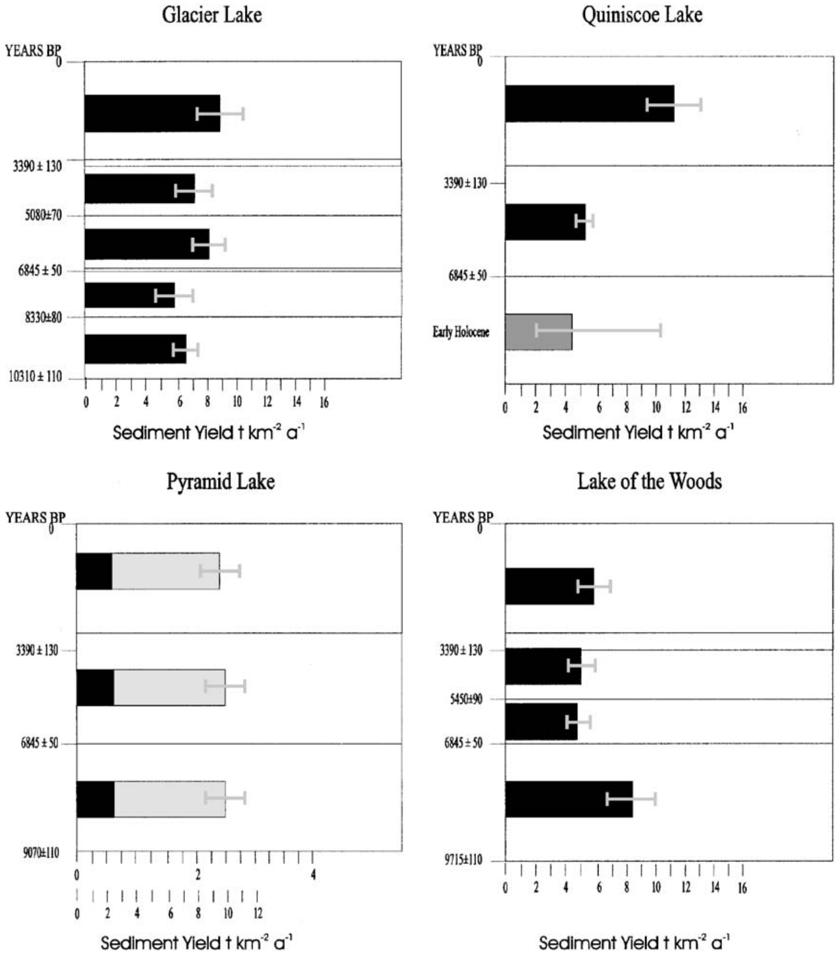

Fig. 4. Holocene sediment yields to the Cathedral Lakes. Error bars represent 95% confidence intervals. The exception is the early Holocene estimate at Quiniscoe lake. The thickness of the Mazama ash layer in this lake prevented recovery of early Holocene sediments at many sites. As an approximation of early Holocene sedimentation at these sites, the depth of early Holocene sediment as a proportion of the combined depth of post-Mazama sedimentation was calculated for each complete core. A mean, minimum and maximum value of these proportions was calculated and multiplied by the absolute post-Mazama sediment yield to produce the early Holocene estimate in Quiniscoe lake. The error bars on this estimate are the minimum and maximum proportions calculated. For Pyramid Lake black bars are to scale with other plots, grey bars are enlarged to show detail.

period. Sediment yield to Pyramid Lake is stable for the duration of the Holocene.

In contrast the two lakes with basins at least partly above treeline (Glacier and Quiniscoe) present a more variable pattern of Holocene sedimentation. In the Glacier Lake basin sediment yields were relatively low in the early Holocene, and increase from less than 6 to 7.1–8.8 t km^{-2} a^{-1} after the Mazama ashfall. There is some fluctuation in the late Holocene, in particular the period 6845–5080 BP has lower sediment yield (7.1 t km^{-2} a^{-1}), and the highest Holocene values are in the period since the St Helens ashfall. The sediment yield estimate for the recent period is significantly different at the 95% level from the period of lower sedimentation prior to the Mazama ashfall, indicative of real Holocene variability in the record. All other comparisons have lower levels of significance, although the 95% error bars for the periods immediately before and after the Mazama ashfall overlap only slightly.

Quiniscoe Lake has exhibited stable, relatively low sediment yields through the early and mid-Holocene, but after 3390 BP there is a large and significant increase in sediment yield. The sediment yield of 11.1 t km^{-2} a^{-1} during this period is more than double that of the preceding periods.

It is clear from the above that the quantitative assessment of Holocene sedimentation patterns in the Cathedral basins has revealed considerable variability in space and time and confirms the indication from the facies analysis that the two higher elevation lakes (Glacier and Quiniscoe) exhibit greater variance in sediment delivery during the Holocene.

6.4. Sediment yield in regional context

Maximum Holocene sediment yields to the Cathedral Lakes are 11.1 t km^{-2} a^{-1}. In a regional context this is relatively low but it is consistent with the scale control of sediment yield in the region identified by Church and Slaymaker (1989, see also Church et al., 1999) which suggests that sediment yield for basins of 1 km^2 area in the region will fall between .35 and 75 t km^{-2} a^{-1}. The values presented here are also consistent with the additional data on small basins presented by Owens and Slaymaker (1992). In small headwater systems in British Columbia paraglacial sediments have been largely removed from the system and sediment transport is partly weathering limited. This is likely to be particularly the case in currently unglacierised basins with limited evidence of neoglaciation, such as the Cathedral Lakes. Nevertheless, the significant sediment yield variability observed between basins indicates that sediment delivery is variable between lake basins and that the highly contingent nature of sediment transport systems in a given basin exerts an important control on overall sediment yield. This observation is consistent with work by Schiefer et al. (2001) suggesting that the relation of specific sediment yield to basin area is locally contingent at sub-regional scales. Caine (1974, 1986) has noted that low sediment yields are characteristic of unglacierised high alpine basins in Colorado. The data presented here would support the idea that low yields are more generally characteristic of unglacierised alpine basins. In the alpine zone there is a fundamental mismatch between the calibre of material produced by active frost weathering and the power of the transporting processes to transport material over low angled footslopes and into stream channels. This is particularly the case in areas of former alpine glaciation such as the Cathedral Lakes where cirques may act as effective sediment traps. Only where there is a well-developed fluvial system and efficient linkage between slopes and channels (Evans, 2000) are higher sediment yields expected.

7. Sediment yield and climate change

7.1. Regional patterns of Holocene climate

Hebda (1995) proposes a threefold division of Holocene climates in British Columbia into early Holocene “xerothermic conditions” (warmer and drier than present), mid-Holocene “mesothermic” conditions (warmer than present with close to modern precipitation levels) and late Holocene Neoglacial conditions (similar to the present climate)[1]. Dates for these transitions are approximately 7000 BP for the xerothermic/mesothermic transition and close to 4000 BP for the mesothermic/Neoglacial transition. The palaeoecological record suggests that these transitions were gradual rather than abrupt. In terms of the Cathedral sediment record these dates approximate to the Mazama and St Helens tephra layers (6845 and 3390 BP). Two lines of evidence from the Cathedral Lakes basins support the suggestion that these regional trends were reflected locally. Conifer needle records from Glacier Lake show a marked decline after 3390 BP, consistent with a retreat of treeline to lower elevations under cooler climate conditions (Evans, 1997). Secondly, pollen and chironomid data from Lake of the Woods (Heinrichs et al., in prep.) support Hebdas’ tripartite division of Holocene climates, indicating wetting around 6800 BP and cooling close to 3500 BP.

[1] Note that Hebda defines the xerothermic and mesothermal periods as divisions of the Hypsithermal. Common usage divides the Holocene in British Columbia into the Hypsithermal (before around 6500 BP) and the Neoglacial (after around 6500 BP). In this paper Hypsithermal refers to the early Holocene warmer drier period before the Mazama ashfall (6845 BP).

7.2. Correlation between periods of climatic change and changes in the sediment record

Pyramid Lake exhibits very little Holocene variability in sediment yield. There is therefore no indication that estimated bulk sediment yields are responding to climate change.

Lake of the Woods similarly exhibits considerable Holocene stability. The early Holocene sediment yield, although statistically indistinguishable from later periods, does exhibit a higher mean value. Heinrichs et al. (in prep.) show that the early Holocene forest around Lake of the Woods had an open structure and was frequently burnt. Given the conservative nature of the error estimates, some of the increased yield estimated for this period may therefore be real and result from increased surface erosion. This would indicate sensitivity of early Holocene sediment production and delivery processes to a drier climate.

Glacier Lake exhibits greater Holocene sediment yield variability than either of the downstream lakes discussed above. A significant increase in yield after the Mazama ashfall coincides with climatic evidence for wetting at that time. However, it may also represent reworking of Mazama ash, since the initial increase after 6845 BP is followed by a slight decline in sediment yield. After 3390 BP there is an increase to the highest Holocene levels of sediment yield. This increase is approximately coincident with climate cooling after 4000 BP and mirrors the decline in treeline recognised at Glacier Lake.

Quiniscoe Lake, like Glacier Lake, exhibits minimum sediment yields during the warm dry early Holocene. Maximum Holocene sediment yield occurs after 3390 BP and represents a significant increase over mid-Holocene yields. Although, in common with Glacier Lake, maximum yields occur in the late Holocene, sediment yields to Quiniscoe Lake are not significantly elevated between 6845 and 3390 BP. This may represent a real difference in response between the two lakes. However, it should be noted that averaging the sediment yield for the two mid-Holocene zones at Glacier Lake also emphasises the late Holocene sediment yield increase correlative with climate cooling.

Some more general patterns emerge. During the Holocene epoch, Glacier Lake and Quiniscoe Lake have the most variable sediment yield records, both showing maximum sediment yield in the late Holocene. These are the two basins with significant proportions of their basin above treeline. This is at least suggestive that increased late Holocene sediment yield is due to reduced vegetation cover and frost disturbance of the surface under cooler climate conditions, as indicated by the Glacier Lake macrofossil record (Evans, 1997). In contrast, the two lakes with basins below treeline show no sediment yield changes in the late Holocene, it should, however, be noted that these basins also have lower mean slopes.

What an assessment of the data reveals is that there is some correlation between the climate proxy record, sediment yield changes estimated from the sediment cores, and process change inferred from the facies analysis, in the Cathedral basins. However, the relationship is not perfect and there is a strong suggestion of differential sensitivity between basins. This differential sensitivity appears to be linked to controls on sediment yield which are intrinsic to the basins, and the resistances to change that they impart. The significance of treeline shifts suggests a role of vegetation in mediating external sensitivity to climate change at ecotonal sites. Similarly, the apparent insensitivity of Lake of the Woods and Pyramid Lake, where lower slopes adjoin the lakes, points to an apparent morphological control on sensitivity associated with the efficiency of linkage between slopes and channels. The significant differences between sediment yields to Quiniscoe and Glacier lakes during the late Holocene have been explored in more detail in a recent publication (Evans, 2000). Contrasts in Holocene sediment sources suggest that whilst cooling and treeline retreat may have led to enhanced rates of surface erosion above treeline in the two basins, it is the more extensive fluvial network in the Quiniscoe basin and consequent enhanced degree of slope-channel linkage that promotes a greater sensitivity of downstream sediment yield.

8. Conclusions

Data from the four lake basins studied in Cathedral Park indicate fourfold variability in sediment yield between four basins spanning 4 km^2. This contrasts with maximum twofold intra-lake variability over the span of the Holocene. This suggests that catchment responses to natural climate changes of the scale experienced during the Holocene are within the range of natural variability at wider spatial scales. Similarly, overall sediment yields measured for these non-glacial alpine catchments are relatively low in a regional context, particularly in comparison with contemporary glacierised basins. Increased sediment yield during the late Holocene appears to be mediated by vegetation change, notably movement of treeline to lower altitude. It therefore seems likely that the response of these systems to postulated climate warming would be a reduction in sediment yields over a timescale of 10^2–10^3 years as treeline advances. This conclusion is highly dependent upon the validity of mid-Holocene conditions as an analogue for future climate warming. For example, it assumes no significant changes in summer rainfall intensity. Menounos (1996) has shown that sediment yields to an alpine lake in Colorado increase under warmer mid-Holocene conditions, due to increased debris flow frequency associated with convectional storms. Such effects might to some extent mitigate sediment yield reductions associated with treeline advance.. The lake sediment data from this study indicate that the response is likely to be highly spatially variable contingent upon very local catchment conditions. In particular, catchment responses are heavily dependent on the nature of slope-channel linkages within the system. Consequently, landscape averaged rates of change are likely to be less than the maximum twofold variability identified here.

Overall, the data suggest that sediment yield from unglacierised alpine catchments in the region is both relatively low and relatively insensitive to climatic change. Contemporary sediment yields are in the range 2.3–11.2 t km^{-2} a^{-1} and the maximum observed Holocene variability is the 115% increase in specific sediment yield recorded for Quiniscoe Lake. Significant changes in sediment yield are associated with crossing of thresholds associated with vertical movements of treeline, and regionally, snowline.

Changes in temperature of sufficient magnitude that these vertical shifts affect large catchment areas occur at the interstadial–stadial timescale (10^4 years) rather than on Holocene timescales. It would appear that the dominant scale of natural process rate variability is on the order of at least 10^4 years.

Variability in sediment yield associated with natural spatial patterning and local human impacts are likely to exceed the impacts of moderate global warming. Future work on sediment yield sensitivity in these environments should focus on establishing the full extent of spatial variability of yield and yield sensitivity.

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