The Glaciolacustrine Sediment Record of Cariboo Lake: Implications for Holocene Fluvial and Glacial Watershed Dynamics in Eastern British Columbia, Canada

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Abstract:

Keywords: Lake, Sediment, Holocene, Acoustic records, Varve, Climate proxy, British Columbia

Alexander Cebulski[1], Joseph Desloges[2] (ORCID ID - 0000-0001-8446-3034)

[1]Department of Geography, University of Saskatchewan, Canada

[1]Department of Geography and Department of Earth Sciences, University of Toronto, Canada

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Contents

1 Introduction

Environmental proxies that extend back beyond the modern observable record are crucial to understanding earth system processes (Huber & Knutti, 2012; Nelson et al., 2016; Turney et al., 2019). Proxy reconstructions at the sub-annual scale (e.g. ice cores, tree rings, and corals), to multi-decadal scales (e.g.sediments, pollen, boreholes) have proven useful in describing past environmental conditions across the globe (Masson-Delmotte et al., 2013). Sedimentary sequences collected from glaciated watersheds have been important in contributing to regional understanding of climate and hydrologic variability over the late Holocene. Research by Neukom et al. (2019) have utilized sedimentary sequences as part of larger paleolimnological collections to provide a reconstruction of temperature variability over the last 2000 years. In western Canada, recovered sedimentary sequences have been collected in the Coastal Mountains (Menounos & Clague, 2008), St.Elias Mountains (Crookshanks & Gilbert, 2008), Monashee Mountains (Hodder et al., 2006), and Rocky Mountains (Desloges, 1999). A study by Gilbert & Desloges (2012) looked at late glacial and Holocene infill of Quesnel Lake (272 km^2) in east-central BC but this lake and watershed represented a much larger and less climate sensitive sedimentary system. To fill in a gap for higher resolution sedimentary records from the Carbioo Mountains the study here was undertaken at the smaller Cariboo Lake (11 km^2).

This study aims to presents a new record of Holocene hydroclimatic variability over the past 10 k years using lake bottom sediment records recovered by using sub-bottom acoustic methods (coarse resolution), and long sediments cores (fine resolution covering the last 2 k years). To determine if the Cariboo Lake contains a record of regional temperature and precipitation variability, the relative role of sediment input from the upstream Cariboo River, controlled by watershed wide trends in temperature and precipitation, compared to smaller unglaciated watersheds that border the lake is assessed.

The purpose of this research is to 1) Establish an understanding of the mechanisms that control the production, connection, and transport of sediment into and within the Cariboo Lake basin. 2) determine whether sediment archives collected from Cariboo Lake contain a record of late Holocene glacier and sediment activity. 3) Compare the Cariboo Lake sediment record to other regional climate proxies. Previous studies have had success relating sediment archives with high resolution depositional sequences (e.g. varves) to changes in regional temperature, precipitation patterns, and glacier extent. However, these studies have primarily been located further east in the Rocky Mountains [Desloges (1999); Hodder2006].

2 Study Area

Cariboo Lake is located in the northern foothills of the Columbia Mountains, 85 km northeast of Williams Lake, British Columbia Figure 1. The lake receives runoff from an area of 3244 km^2, and the watershed relief ranges from 2600 m asl in the headwaters to 600 m asl at the Cariboo Lake outlet. The area of Cariboo Lake including the Kiethley Creek sub-basin of 2 km^2, is 10 km^2 which results in a lake to watershed area ratio of 0.3%. The Cariboo Lake watershed has 64 km 2 of permanent ice cover which covers 2% of the total watershed (Bolch & Bolch, 2008). The most extensive glaciated terrain is proximal to Mt. Lunn roughly 60 km upstream of Cariboo Lake.

The Cariboo River, located on the east end of the lake provides the main source of sediment into the lake. The lake is separated into two main basins, by the Keithley Creek fan delta (Figure 2). Here, the upstream basin is called the main Cariboo Lake basin, and the downstream basin is called the Keithley Creek basin. The bathymetry of the lake reaches a maximum depth of over 50 m in two scour holes within the central part of the main Cariboo Lake basin. These deep scour holes provide evidence of past glacial scouring.

Sediment connectivity to headwater glaciers along the Cariboo River is limited due to lake filtering by Lanezi and Sandy lake. Lanezi Lake is a deep fjord lake with a bathymetry reaching a maximum depth of 170 m. Sandy Lake is much shallower reaching a maximum depth of 6 m. The Matthews River, which meets the Cariboo River just below Lanezi Lake provides less filtered connection to meltwater from several alpine glaciers including the largest chunk of ice in the Cariboo Lake watershed, the Roberts Peak Glacier (10 km^2).

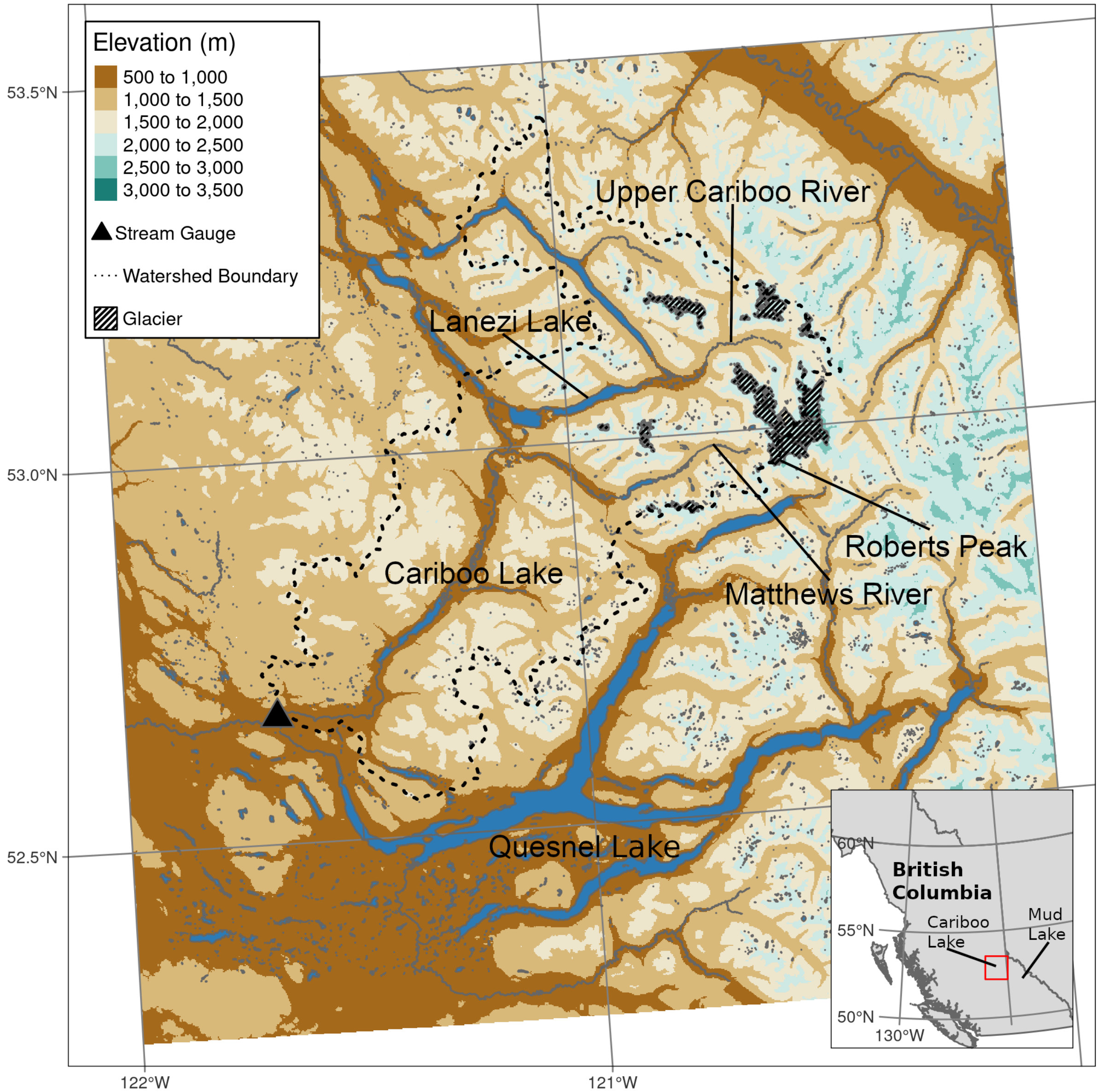

Figure 1: Map of the Cariboo Lake basin.

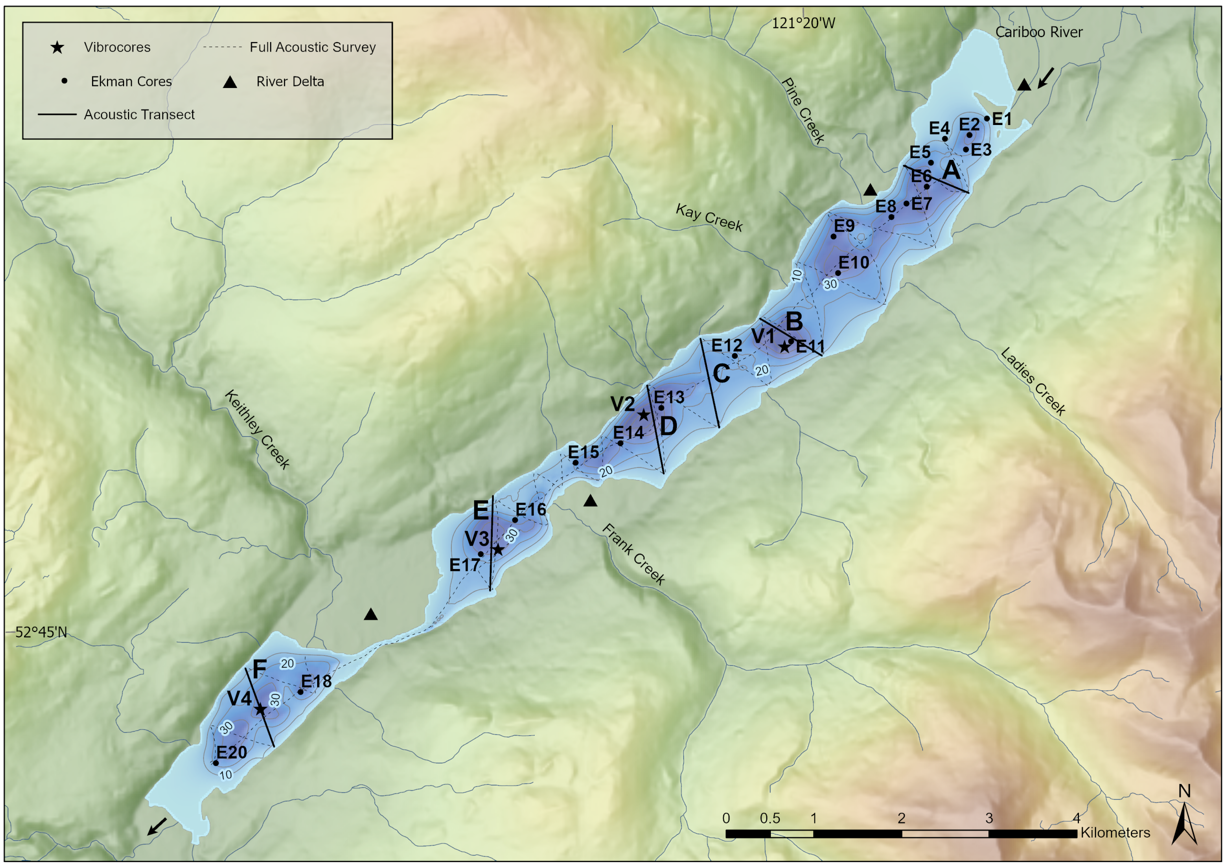

Figure 2: Map of the Cariboo Lake bathymetry and coring locations. Acoustic transects selected for analysis are shown with a black solid line and labeled A, B, C, D, E and F. River deletas mentioned in the text are represented by black triangles and are referenced to by the upstream creek (i.e. Frank Creek Delta is the triangle below Frank Creek).

3 Methods

Field Methods

A field campaign was conducted during the summer of 2017 to collect sub-bottom acoustic soundings, dredge samples, and sediment cores. Thirty-four km of sub-bottom acoustic soundings were collected across Cariboo Lake using a 10 kHz StrataBox 3510 HD. An Ekman dredge was used to collect 20 ~10 cm^3 samples of sediment from the lake bottom. The dredge samples were subsampled in the field using an 80 mm diameter PVC cylinder pushed into the block of sediment. The remaining sediment was kept as a bulk sediment sample. Four sediment cores (V1-V4) were collected using a Rossfelder submersible vibracorer with a 6 m long 70 mm diameter aluminum pipe. The Ekman subsample cores and the vibracores were split longitudinally with one half preserved as an archive and the other as a workging half. The working half samples were prepared for imaging by scraping the core parallel to the sediment laminae to create a flat surface which showed the sediment stratigraphy. The stratigraphy of cores V1 and V2 were best preserved and were selected for detailed analysis.

Laboratory Methods

Cores V1 and V2 were subsampled with 2 cm^3 of sediment extracted at a 5 cm interval, with additional samples taken within stratigraphic breaks. The Ekman bulk samples and vibracores were analyzed for laminae thickness, organic content, and particle size. Laminae couplets were digitally counted and measured for thickness using the ImageJ Rasband (n.d.) software. Organic content was determined by loss-on-ignition analysis (550 °C) following methods in Smith (2003). Samples were first weighed to provide an initial wet weight, then dried at 60 °C and weighed again after oven drying. The samples were then placed in a furnace at 550 °C for 2.5 hours and weighed a third time. Grain size analysis was conducted using a Mastersizer Particle Size Analyzer 3000. Samples were prepared following methods by Gray et al. (2010) to remove the fine fraction of particles from organic material. This involved a removal of organic material using three sequential alloquots of 20% H202 until the sample stopped reacting. To prevent flocculation of sediment grains the samples were dispersed in 0.05% solution of Calgon for 24 hours. Grain size was measured three times for each sample, resulting in an average instrument error of +/- 0.01 µm. The chronology of both cores was provided by AMS ^{14}C dating of wood fragments at the André E. Lalonde AMS Laboratory at the University of Ottawa and varve chronology from laminae counting on images.

4 Results

4.1 Sub-bottom Acoustics

Acoustic stratigraphy from six selected transects conducted across Cariboo Lake reveal the range of morphologies and character of sedimentary deposits in Cariboo Lake (Figure 2). Acoustic penetration is limited in transects A and E by coarser sediments proximal to river fan-deltas across Cariboo Lake (see triangle symbols in Figure 2 for fan-delta locations). Acoustic signal penetration, resolution and distinctive acoustic layering improves significantly along the thalweg of the lake bottom away from the main Cariboo River delta and in cross-lake transects more distal from the valley-side fan-deltas. Cross-hatching is observed over most of the acoustic record due to errant electrical interference from the research vessel. However, the interference does not affect the overall quality of the results in the six selected transects (Figure 2, A-F).

Transect A, one kilometer southwest of the headwater Cariboo River delta, has a strong acoustic reflector at the sediment-water interface indicating the presence of coarser-grained material on the lakebed (Figure 3, A). Grab samples on this transect show a high fraction of sandy materials which act as an acoustic mask limiting the penetration of the acoustic signal to a depth of 1-2 m. An acoustic multiple (echo) is observed 45 m below the sediment surface caused by the limited penetration at the surface (Figure 3, A - i).

Acoustically penetrable, well-layered sediment is observed 3.5 km from the Cariboo River delta in transect B (Figure 3, B) proximal to the long core core V1. Acoustic reflectors with 1-2 m separation lies conformably over a hummocky basement which is observed on the south side of the transect (Figure 3, B - i). The acoustic basement drops off below the observable record near the south channel-like depression. Well structured layering extends across the south side of the transect but pinches out towards the north shore (Figure 3, B, C & D). On the south side of the transect, the thickness of the well structured layering ranges from 10 to 20 m. Underlying the layered sediments is a more massively layered facies which ranges from 12 to 25 m thick before the record is cut off.

Acoustic penetration increases in locations about 4.5 km from the Cariboo River delta at transect C (Figure 3, C). The acoustic record along this transect reaches a maximum sediment thickness of 35 m in two troughs - the maximum thickness of surficial sediments observed across Cariboo Lake in this study. The acoustic basement is considered to be either bedrock or coarse-grained glacial sediment from the Last Glacial Maximum (Figure 3, C – i). Two sediment facies are observed across this transect based on geometry and the strength and continuity of reflectors. Some disruption of these facies is caused by slumping of side slopes (e.g. north end of transect C). The lower unit, facies A, has a thickness of ~ 12 m along undisturbed sections (Figure 3, C) and is more massive to weakly acoustically layered. The contact with overlying sediment above facies A appears to be conformable at the south end and middle of the transect but unconformable in other places. The unconformities are most apparent in the two sharp crested v-notch channels at the middle of the transect. These channels are a continuation of those noted in transect B. These are inferred to be scour channels formed by erosive, higher energy, turbidity currents that probably date to deglaciation of the lake basin. The lack of numerous layers and generally lighter grey tone in facies A indicates a somewhat higher energy and more rapid deposition of coarser lacustrine sediment.

Facies B begins with high-amplitude parallel reflectors with 2-3 m separation and conforms well with facies A below (Figure 3, C). Facies B has a thickness of ~ 10 m along undisturbed sections and deepens to a maximum of 13 m within the scour channels (Figure 3, C - ii & iii). The strength of reflectors in facies B are stronger and more numerous than those in facies A indicating more frequent events of lower overall magnitude during this time period. The strength of reflectors gradually decreases moving upwards and spacing thins to sub metre near the surface. The gradual decrease in reflectance is interrupted by a strong reflector at the top of facies B along the sediment-water interface.

The two buried troughs in transect C (Figure 3, C - ii, iii) are significant and best expressed in this area of the lake. The north trough (ii) appears to be a depression that was continuously infilled by facies A and then B. Hence it most likely represents an older pre-existing feature. The sediments in the southern trough (iii) are interesting in that a wedge of sediment infill seems to be an unconformable deposit with both facies B below and facies A above. It is likely that an erosional channel developed after or in the later stages of facies A deposition which infilled the wedge. Sedimentation of the wedge was then truncated by the onset of the facies B sediment. While the two troughs might have been active at the same time during deglaciation, only the southern trough was reactivated at a later time and infilled with sediment prior to the onset of facies B deposition.

Transect D, to the northeast of the Frank Creek delta has well-layered sediments in the top 5-10 m and transitions to poor acoustic penetration below this (Figure 3, D). The parallel reflectors observed in the uppermost sediment layers of transect D have a thickness of 2-3 m and have a higher amplitude compared to facies B in transect C. Some slumping of sidewall sediments is observed on the south sidewall (Figure 3, D).

Southwest of the Frank Creek fan-delta, acoustic reflectors along transect E show a decline in reflectance and a decrease in layer thickness to < 1 m. Acoustic masking from course grained sediment occurs at depths of 2-4 m along the south margin (Figure 3, E). Total sediment thickness of finer, acoustically well-layered material along the north bench is significant approaching 10 m. The sedimentary environment southwest of the Frank Creek delta is different to transects northeast of the delta. The profile suggests that much of the suspended sediment transported from the upper lake does not make it past the shallow lake depths (< 20 m) of the sill at the Frank Creek fan-delta apart from the northern most part of the transect. So, coarser sediment from the Frank Creek fan-delta dominates the south side of the transect and fine sediment deposition is restricted, or forced, to the north side. The Coriolis effect may enhance this as suspended sediments are deflected to the right as they enter Cariboo Lake from Frank Creek.

Similar to the Frank Creek fan-delta, the very shallow sill of less than 2 m opposite the Keithley Creek

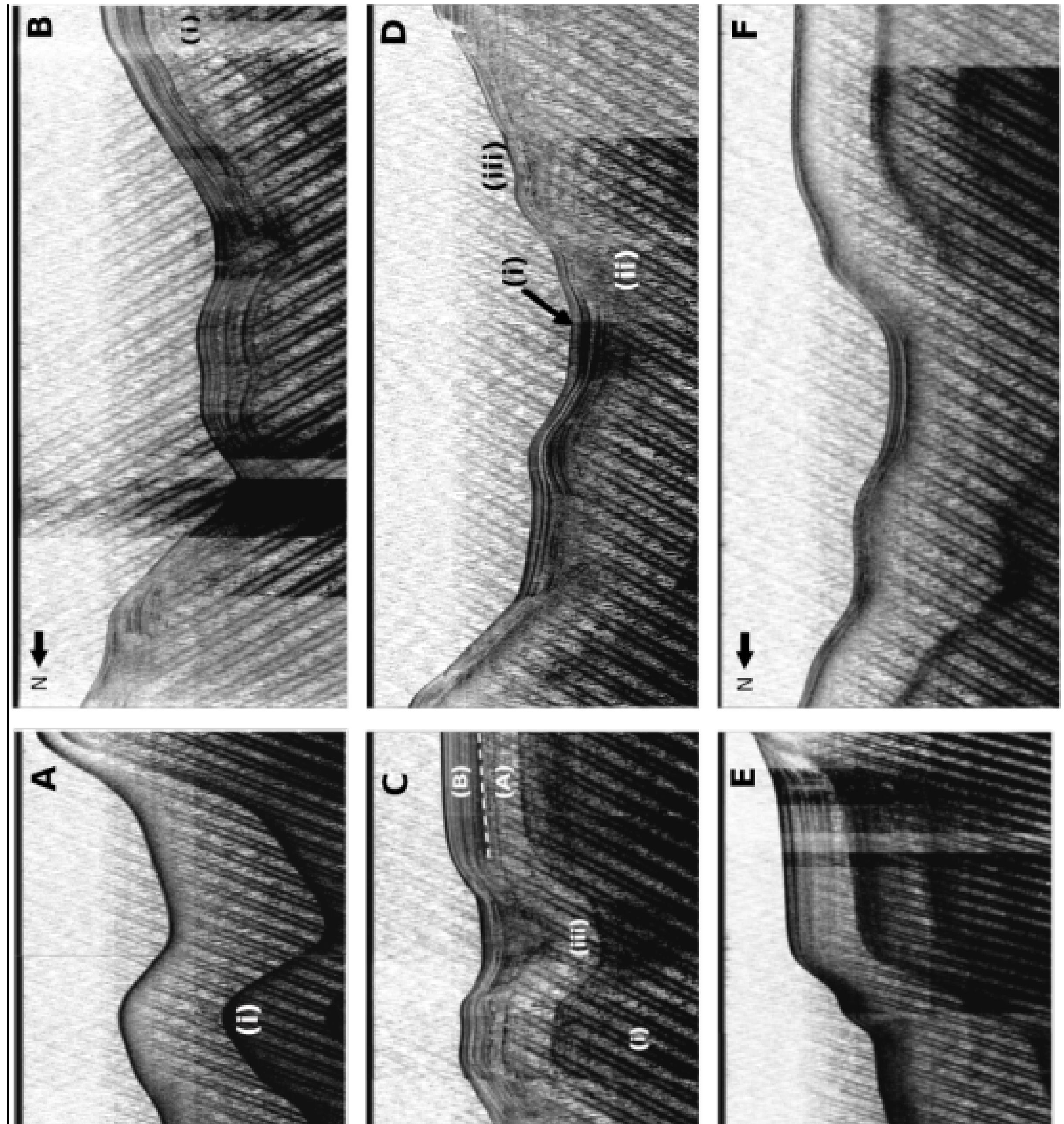

Figure 3: Panel of six selected sub-bottom acoustic transects A, B, C, D, E, and F. All transects are looking up-lake, see Figure 2 for location. Transect A and B: Acoustic echo (multiple) is denoted by (i). Transect C: (i) denotes inferred bedrock or late-glacial material. (ii) and (iii) are v-notch scour channels. (A) and (B) are sediment facies. Transect D: Scour channels are denoted by (i) and (ii). Slumping is observed at (iii).

prograding fan-delta significantly reduces sediment connectivity to the main Cariboo Lake basin (see triangle proximal to Kiethley Creek in Figure 2). Transect F, located close to the centre of the Keithley Creek sub-basin shows a maximum observable sediment thickness of 4 m concentrated in the basin thalweg (Figure 3). Below this there is acoustic masking by coarser grained sediment. The acoustic reflectors within the top 4 m of transect F are acoustically penetrable, well layered and are conformable to the basin morphology. These reflectors are of higher amplitude compared to those in transect E and are thicker at 1-2 m. This suggests that significant amounts of coarse-grained sediments are found in this part of the lake, likely originating from the high energy Keithley Creek drainage basin. Fine faction sediments from the main Cariboo Lake are expected to make up a small percentage as transport into this sub-basin is limited by up-lake storage and filtering and hypopycnal overpassing.

4.2 Spatial Trends in Surficial Sediment

Twenty surficial sediment cores ranging from 6-12 cm thick were analyzed for grain size, laminae thickness, and organic content. These samples were collected following a longitudinal transect down Cariboo Lake and indicate how sediment flux varies with distance from the Cariboo River delta (see Figure 2, for sampling locations, n = 20). Proximal to the Cariboo River delta (< 500 m) the structure of the surficial sediments exhibits massive layering, erosive contacts and the fraction of sand grains in these samples is greater than 60%. A sand bed with a thickness of 1 cm is observed in the bulk sample closest to the Cariboo River delta (Figure 5, A). The D50 grain size follows a steep decline from 89.9 µm 300 m from the delta to 31.3 µm 550 m from the Cariboo River delta (Figure 4). The decrease in grain size generally continues further down-lake with the exception to samples proximal to valley-side fan-deltas. A small increase in D50 is observed proximal to the Pine Creek fan-delta from a low of 21.5 µm at 1.1 km, up to 28.2 µm 1.83 km from the main Cariboo River delta (Figure 4). At distances greater than 2 km from the Cariboo River delta the fraction of silt-sized sediments remains over 80 %, aside from core E16 which is near the Frank Creek fan-delta. Proximal to the Frank Creek fan-delta the D50 grain size nearly doubles in size from 7.92 µm at 6.4 km to 15.1 µm at 7.35 km from the Cariboo River delta. In the main Cariboo River sub-basin, the most well-preserved core was taken 5.24 km from the Cariboo River delta in the deepest part of the sub-basin at a depth of 40 m and shows rhythmically laminated sediments (Fig 5, B). In the Keithley Creek basin the D50 grain size has an average of 15.9 µm (n = 3) and the composition of sediment 4.0% clay, 85.8% silt, and 10.2% sand (Figure 4).

Sediment cores E9-E15 and E18-E20, retrieved from areas in Cariboo Lake that are distal from river deltas and have lake depths of 30-50 m, have a high fraction of silt and clay sediment and exhibit a sequence of fine-grained dark layers followed by coarse-grained light layers (Figure 5, B & C). The thickness of sediment laminae within these surface cores demonstrate a gradual decreasing trend with distance down-lake from the Cariboo River delta (Figure 4). Maximum laminae thickness has an average of 4.7 mm (n = 6) in the Cariboo River basin and 7.9 mm (n = 3) in the Keithley Creek basin. In the Cariboo River basin, maximum varve thickness decreases by 0.62 mm/km and by 2.17 mm/km in the Keithley Creek basin with distance down-lake (Figure 4). This decrease in laminae thickness with distance from the main contributing delta's is attributed to the Cariboo River being the main source of sediment into Cariboo Lake as sediment flux typically declines with distance from the primary sediment source. The decline in thickness is steeper in the Keithley Creek Basin is likely due to additional local inputs of coarser grained sediment coming from the Keithley Creek tributary which are not transported as far as suspended sediments.

Trends in percent organic content of surficial sediment cores where not found to exhibit systematic patterns with distance down-lake (Figure 4). However, higher %LOI values were observed close to the main Cariboo River delta, likely due to the relatively low levels of erosion and high levels of allochthonous organic matter entering the lake. The lowest %LOI values were observed in the Keithley Creek basin which suggest higher levels of clastic sediment yield in this basin.

The results from particle size, laminae thickness, and percent organics suggest that sediment delivered from the main Cariboo River is the primary source of sediment to Cariboo Lake. Massive layering of sediment and coarse-grained particle sizes are limited to areas proximal to Pine Creek, Frank Creek and Keithley Creek deltas where localized turbidity currents are active. Outside of these areas, where turbidity currents and

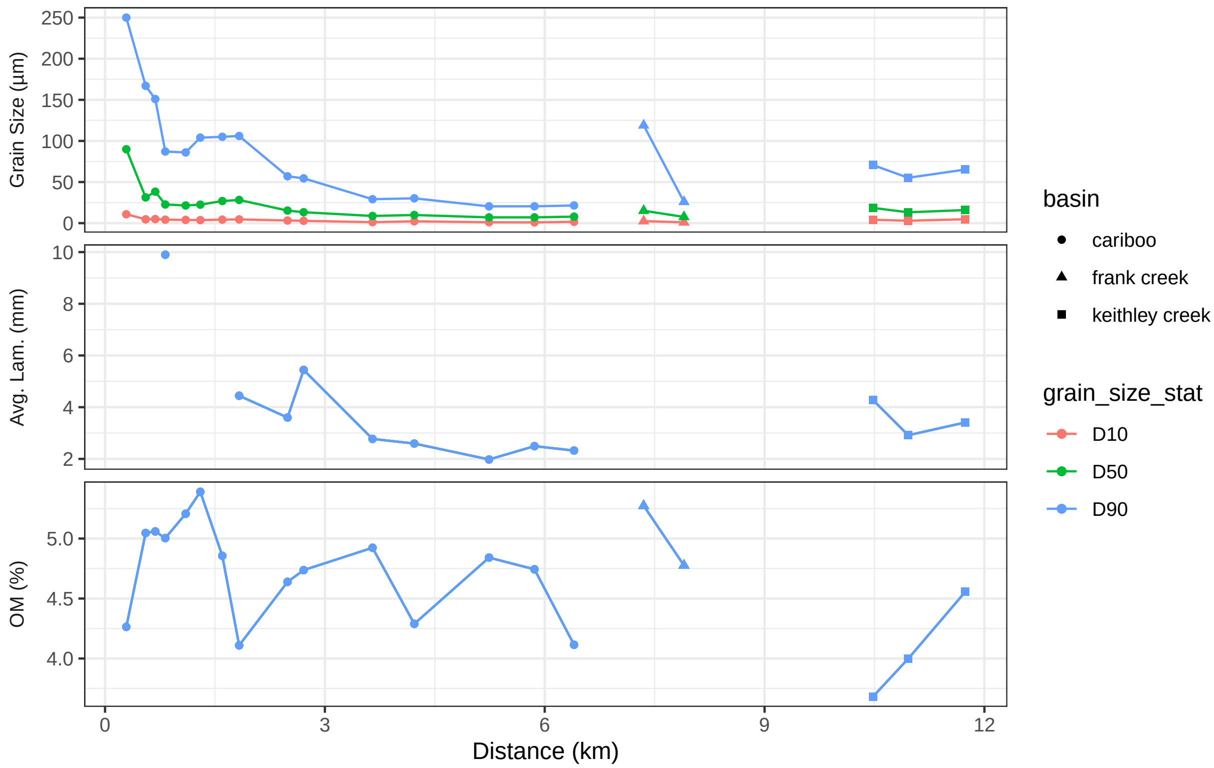

Figure 4: Sediment characteristics from the Ekman surficial bulk samples. Top panel is the D50 (µm) grain size, middle panel is the mean laminae thickness (mm), and the bottom pannel is organic matter content (LOI (%)).

bedload transport processes are reduced, the sediment in Cariboo Lake is largely comprised of rhythmically laminated silt and clay sediments likely transported primarily through suspended sediment processes from the main Cariboo River. In the Keithley Creek sub-basin grain size and laminae structures are larger in size than those observed in the main Cariboo River basin suggesting local sediment inputs from the Keithley Creek are significant (Figure 5, C).

4.3 Sediment Accumulation Chronology

Four glaciolacustrine sediment cores, ranging from 2 – 4 m in length, were retrieved from the deepest basins of Cariboo Lake (Figure 2). Cores V1 and V2 were selected for detailed analysis as these two cores had sufficient organic material for AMS radiocarbon dating, and their sedimentary record was well preserved. The chronology of the two cores is provided by AMS radiocarbon dating and laminae counting. No evidence of volcanic tephra was found within either of the two cores. Westgate (1977) reports the most recent major volcanic ash event to reach central BC occurred 2100 yr BP, predating the basal age of the four sediment cores. This combined with the dark colour of the clastic core sediments prevented finding smaller volcanic ash events within the cores. Records of grain size, varve thickness, and organic content from these two cores demonstrate patterns in sediment delivery to Cariboo Lake over the past 2000 years.

Chronology

AMS radiocarbon dates obtained for cores V1 and V2 provide temporal control and evidence of sediment accumulation rates. A small twig from V1 at 347 cm yielded a date of 1899-1819 cal BP. Two separate samples were analyzed from V2, one comprised of a large twig at 222 cm yielding a date of 490-316 cal BP (V2a), and a combination of two separate organic pieces which were combined into one sample, a twig at 286 cm and a pine needle at 294 cm and provided a date of 2045-1895 cal BP (V2b). Figure 6, shows the dating calibration curves derived for the three AMS radiocarbon dates. The dates from samples V1 and V2b yield

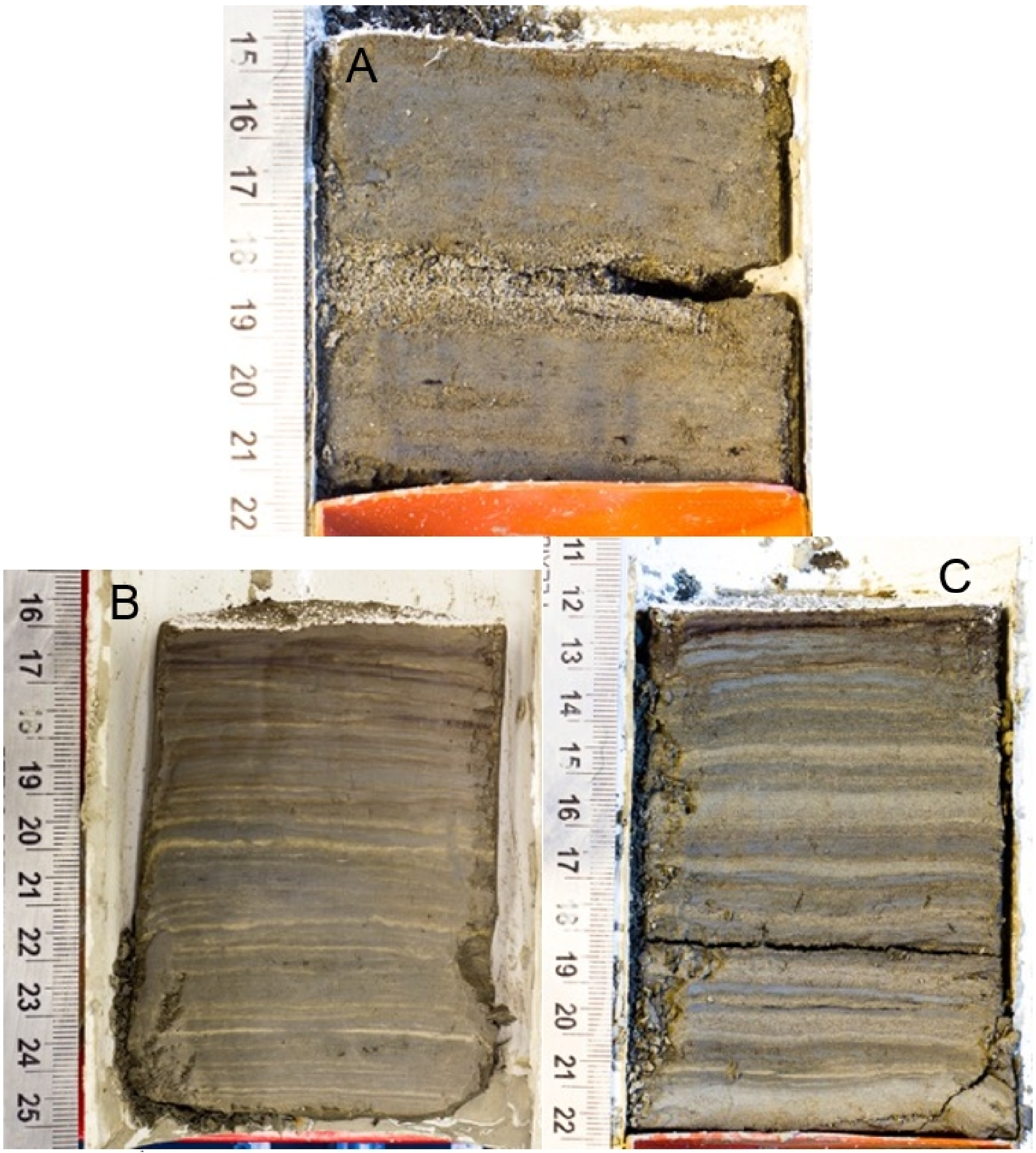

Figure 5: Selected surficial Ekman sediment core photographs. A (E1) is proximal to the Cariboo River delta (0.3 km down lake). B (E13) was retrieved from the second deepest basin in the lake in the Cariboo River basin (5.24 km down lake). C (E18) was retrieved from the Keithley Creek basin (29.53 km down lake).

consistent accumulation rates of of 1.87 +/- 0.04 mm/yr and 1.47 +/- 0.11 mm/yr respectively. Sample V2a, yields an accumulation rate of 5.51 mm/yr, inconsistent with the rates provided for V1 and V2b.

Accumulation rates derived from Ekman surficial cores 13-15 are shown in Figure 7. These are proximal to the V2 long core (see Figure 2). The light-dark couplets in the short cores are identical to annual deposits noted in dozens of other lakes throughout BC (e.g. Hodder et. al, 2007) so it is assumed that they closely approximate varves, in which case they exhibit accumulation rates of 2.24, 2.52, and 2.31 mm/yr respectively. Higher accumulation rates are expected for the Ekman samples as they are not subjected to the same level of compaction as the long cores. The consistency of the E13-E15 inferred accumulation rates when compared with two of the AMS dates from the V1 and V2b cores (Figure 7) are additional compelling evidence of the varved nature of the sediment record. This consistency also suggests that the V2a AMS sample is suspect for temporal control. In viewing the V2a sample orientation and position along the outer core it is speculated that the sample may have been pulled down during the coring process due to the large twig size at about 4 cm. This probably results in an erroneously high accumulation rate for V2a. Accumulation rates in areas proximal to river inputs in nearby Quesnel Lake were measured to be about 0.72 mm/a (see Figure 9 in Gilbert and Desloges, 2012). While this is lower than Cariboo Lake, inputs are expected to be lower in Quesenl Lake with more arid and less glaciated portions of the Quesnel Lake watershed contributing to that lower rate. Accumulation rates of 1.47 to 1.87 mm are consistent for a smaller and more glaciated Cariboo Lake watershed. Laminae couplet thickness in Ekmans and two of the three vibra core AMS dates do not support the V2a accumulation rate of 5.51 mm/yr and therefore it was not included in subsequent analysis. The AMS radiocarbon dates from samples V1 and V2b provide an important control when interpreting the inferred temporal pattern of sediment inputs to Cariboo Lake. The top section of cores V1 and V2 were disturbed - 110 mm for V1 and 70 mm at V2. While the Ekman cores were too short to overlap with the undisturbed sections of the vibra cores, laminae thickness similarities allow anchoring the top of core dates and 0/0 (depth/date) (Figure 7).

The similarity in couplet structure and thickness in cores V1 and V2 strongly suggested these are varves. This interpretation is supported by the two valid AMS radiocarbon dated samples from cores V1 and V2 which corresponded reasonably well with the varve count chronology at the same depth. A small difference between the two chronologies is present due to some isolated disturbed sections of core, core compaction, undercounting, and subjectivity in classifying the occassional-thicker (4-47 mm) graded to massive laminae/beds. The absence of laminae couplets in the disturbed-massive units makes interpreting the time elapsed over these units difficult. To compensate for the depth intervals associated with the disturbed sections, a 30-year moving average of sediment accumulation rates from immediately above and below the disturbed sections were used to interpolate accumulation rates (see method described in Menounos et al., 2008).

Laminae with thicknesses and grain size greater than 3 standard deviations from the mean thickness were classified as event-based turbidite beds. Figure 8 shows the difference in regular laminae compared to an example event-based turbidite bed. Turbidite beds observed in V1 and V2 had defined beds and were well graded (see Figure 8, d). Where possible the thickness, grain size statistics, and LOI were analyzed for each event layer. The turbidite bed grain size, LOI, and thickness shown in Table 1 illustrates the high sediment flux during these events compared to the regular, annually occurring couplets. The composition of sediment grains within the event-based layers were all characterized by a single mode with less than 0.01% clay, over 98% silt and less than 1% sand. The grain size distribution for the regular couplet sediments is characterized by a bi-modal distribution with an average composition of 16% clay, 83% silt, and less than 1% sand. Figure 9, shows that event layers do not appear to be coincident in time between V1 and V2 and are thus more locally derived. Since each of the event-based layers contain sediment deposited over a single localized event, they were removed from subsequent trend analyses of varve thickness, grain size, and percent organics. After removal, the long core sediment records were more representative of watershed wide trends in climate and precipitation rather than isolated hillslope scale events.

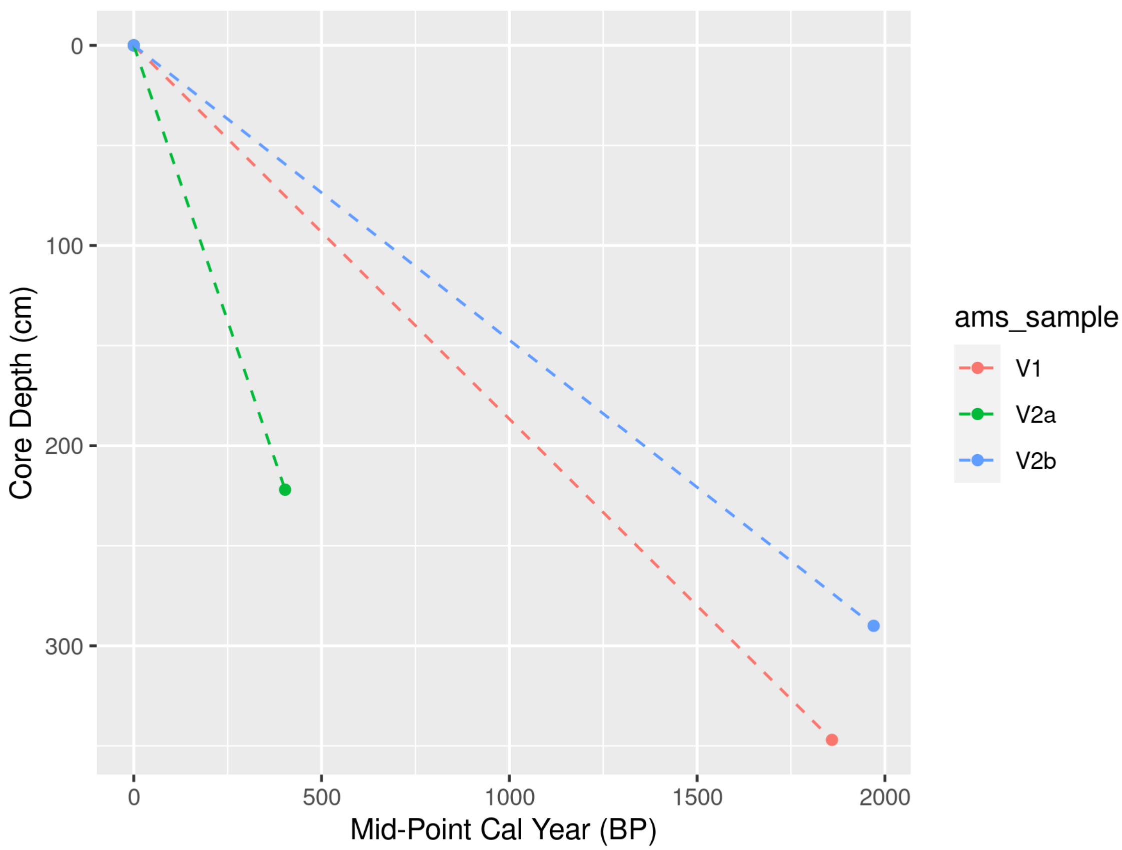

Figure 6: Sediment accumulation rates derived from the three C14 dates for Cores V1 (Red), and V2 (Green and Blue)

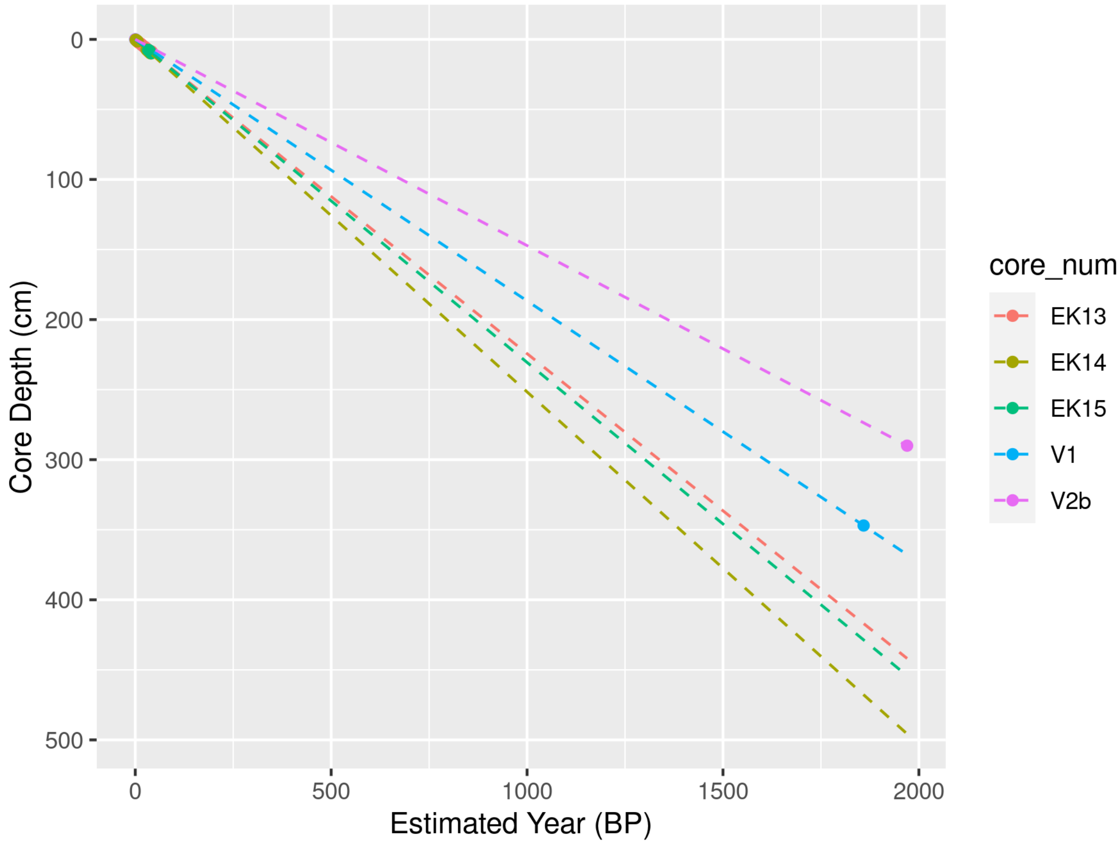

Figure 7: Cumulative accumulation rates for cores V1 and V2 and Ekman surficial cores E13, E14, and E15 proximal to V2.

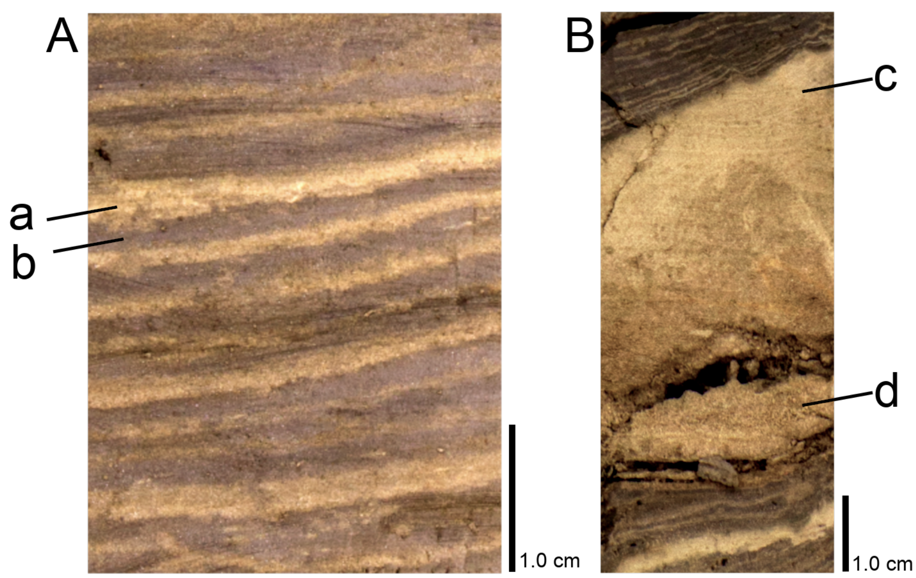

Figure 8: Example of regular laminae from V1 (A) and an event-based turbidite bed from V2 (B). Features labelled within this figure include: 'a' is the high flow spring/summer freshed laminae, 'b' is the low flow winter laminae, 'c' is the top of the turbidite bed, and 'd' is the bottom of the turbidite bed.

Table 1: Sediment characteristics of regular laminae 'Couplet (varve)' compared to turbidite beds (events) for V1 and V2. The 'Event mean' is the mean sediment characteristic, 'Event sd' is the standard deviation, and 'Event n' is the number of turbidite beds

core	metric	Couplet (varve) mean	Event mean	Event sd	Event n
V1		7.642364			
V2		6.348587			
V1		4.751140			
V2		4.713630			
V1		2.397969			
V2		1.514953			

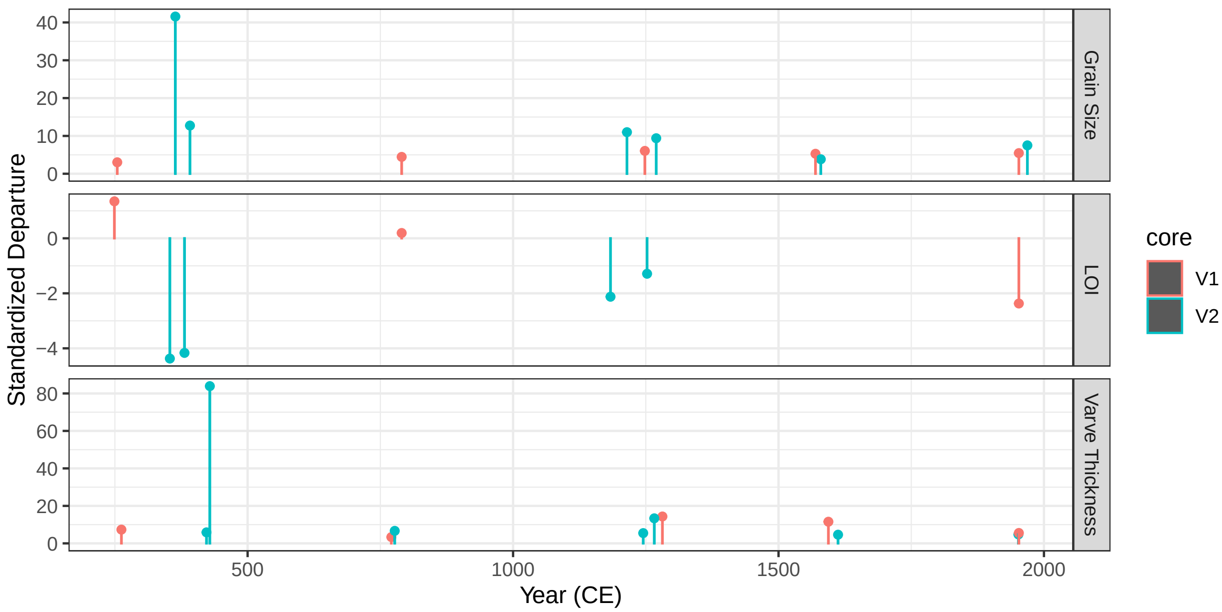

Figure 9: Timing and Standardized Departures of turbidite thickness, grain size, and LOI for V1 and V2. Year (CE) is the estimated year using linear interpolation from the AMS radiocarbon dates.

For core V1, laminae couplets were counted down to a core depth of 347 cm, where the AMS radiocarbon organic material was retrieved. This resulted in a couplet-derived age estimated of 1450 BP compared to the AMS radiocarbon estimate of 1899 - 1819 cal BP. For core V2 a date of 1886 BP was estimated by couplet couplet counting down to a core depth of 294 cm which matches closely with the V2b AMS radiocarbon date of 2045-1895 cal BP. The better alignment between the couplet counting age and the AMS derived age in V2 can be attributed to the higher degree of core disturbance in V1 compared to V2. Disturbed sections that had indiscernible couplets may have resulted in the undercounting within core V1. Still, based on the relatively close agreement between the AMS radiocarbon dated organic material and couplet counting, laminae couplets in V1 and V2 are considered to be deposited annually. Close alignment was not expected due to the aforementioned error present in the couplet counting methodology and the limited 14C dates available.

The basal age for each core is estimated using both the varve chronology and the AMS radiocarbon accumulation rate. The basal age of V1 at a depth of 382 cm is approximately 1620 BP based on the varve chronology and 2046 cal BP, or about a 400 year difference from the extrapolated 14C date. The basal age of

V2 at a depth of 291 cm is about 1910 BP based on the varve chronology and 2007 cal BP by extrapolating the 14C. Accumulation rates estimated using varve chronology and AMS radiocarbon dates had a larger difference at V1 with 2.4 mm/yr and 1.87 +/- 0.04 mm/yr respectively. Closer agreement was observed at V2 with 1.52 mm/yr estimated using the couplet counting method and 1.47 +/- 0.11 mm/yr from the AMS radiocarbon date. While V2 is likely the better predictor of changes in accumulation rates over the last 2000 years, both cores as valid estimates of late Holocence sediment accumulation patterns.

Sediment Yield Statistics

The mean varve thickness with event-based layers removed for V1 is 2.4 mm compared to V2 which is 1.5 mm. Higher varve thickness is expected at V1 due to its closer proximity to the Cariboo River delta. Figure 10 shows the time series of varve thickness measured from V1 and V2 and illustrates trends in suspended sediment delivery to Cariboo Lake. The measured couplet thicknesses in the two cores are plotted as standardized departures to facilitate comparison between the two cores. In each plot a 30-year moving average with a 1-year time step is plotted in black to emphasize decadal to centennial patterns in accumulation rate departures. Chronologies in Figure 10 assume a linear interpolation from the single AMS radiocarbon dates.

The 30-year average varve thickness remains above average from 0 to 750 CE, for both V1 and V2, with a stronger signal observed for V1 which is closer to the main Cariboo River outlet. Below average varve thickness is observed at both V1 and V2 from 750-1600 CE. After 1600 CE, trends in varve thickness between the two cores depart, with V2 above average during the Little Ice Age and V1 remains below average. Sub-centennial trends are not reported due to the coarse temporal control for both V1 and V2.

Grain Size

The mean D50 grain size at V1 is 7.6 +/- 0.01 µm compared to 6.3 +/- 0.01 µm at V2. The larger grain size and varve thickness at V1 compared to V2 is consistent with the spatial trends in sediment delivery observed from the Ekman cores. While based on a limited number of measurements compared to the varve thickness analysis, the temporal pattern in standardized departures of D50 grain size between the two cores shoes a consistent pattern (Figure 11). Both V1 and V2 have above average grain size between 0 to 700 CE and below average from 700 to 1500 CE. After 1500 CE, grain size follows an increasing trend with average to above average grain size. V1 shows a more dramatic increase in grain size compared to V2. While couplet thickness does not increase substantially over the LIA interval, gain size does. Overall, grain size fluctuations at a temporal resolution of about 100-years shows good correspondence between the two cores over the last 2000 years.

Loss on Ignition

The average OM content at V1 and V2 is similar at 4.76% and 4.80% respectively suggesting that the flux of allochthonous organic material to the core locations is not dependent on distance from the main Cariboo River as it is easily transported through the lake due to the low density. Figure 12 shows the percent mass lost on ignition (LOI) for both V1 and V2. Higher levels of organic content are shown in V1 and V2 from from 0-1000 CE and mostly below average from 1000-2000 CE. Specific periods of above average OM for V1 occur around CE 50-500, 650-1150, around 1300 and 1750-1850. OM in V2 matches above average values in the interval CE 250-550 and 650-950. During the last 100 years both cores show a persistent decline in OM which could be attributed to a relative increase in sediment delivery to Cariboo Lake suggested by the increase in D50 and varve thickness. As glaciers declined from peak LIA extents around 1750 CE, an increase in vegetation growth is expected which may also contribute to a decline in OM as organic content is locked up as needleleaf coniferous forest.

5 Discussion

Evidence of late Pleistocene deglaciation in the Cariboo Lake region is provided by coarse resolution sub-bottom acoustic results whereas greater detail of late Holocene watershed activity comes from sediment cores which span the last 2 ka BP. Evidence of late Pleistocene deglaciation and lake sediment infill of the

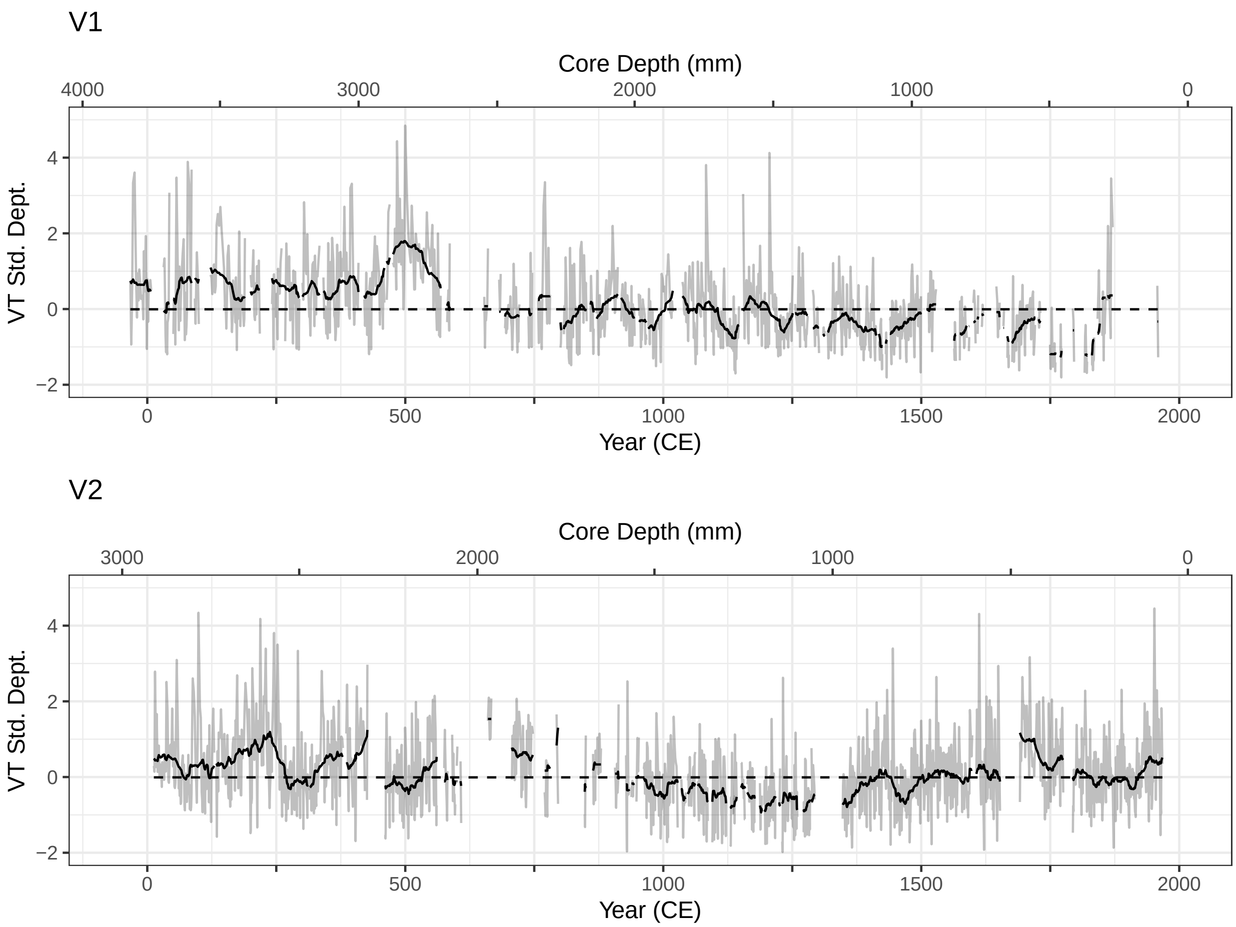

Figure 10: Standardized departure from the mean varve thickness (VT) for cores V1 and V2. The gray lines represent measured varve thickness at couplet (annual) resolution where available, the black line is a 30-year moving average, gaps correspond to portions of the core that did not have discernible varves. The bottom axes, labelelled Year (CE), was estimated using linear interpolation from the AMS radiocarbon dates. Laminae counting in V1 was not possible beyond the estimated date of 1890 CE and beyond 1970 CE in V2.

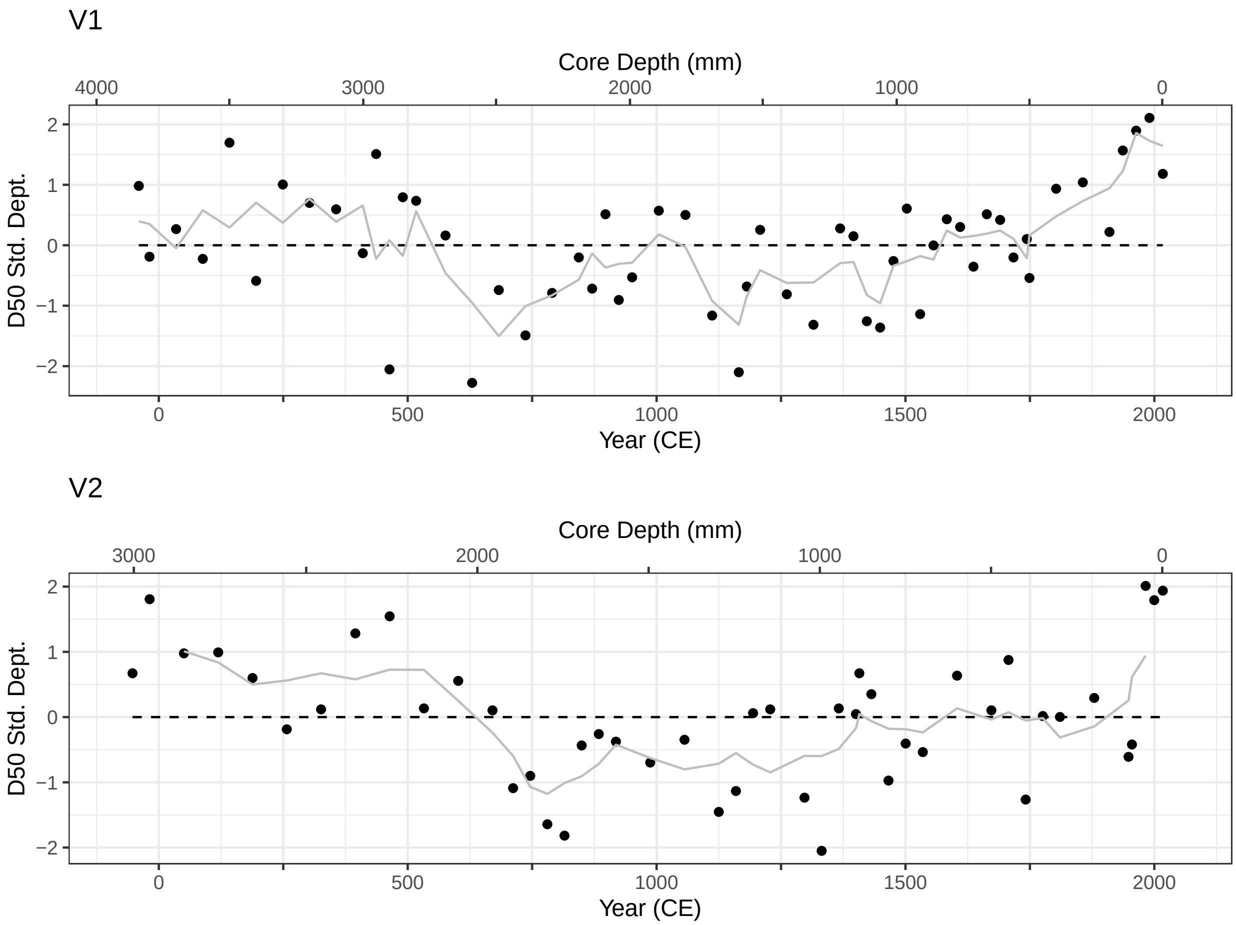

Figure 11: Standardized departure from the mean D50 grain size for cores V1 and V2. The black points represent D50 grain size at 5 - 10 cm intervals and the gray line is the 3 sample (125 year) moving average. The top axes, labelelled Year (CE), was estimated using linear interpolation from the AMS radiocarbon dates. The black X's on the bottom graph of V1 and V2 denote the AMS radiocarbon age (± dating error) and depth of the respective sample.

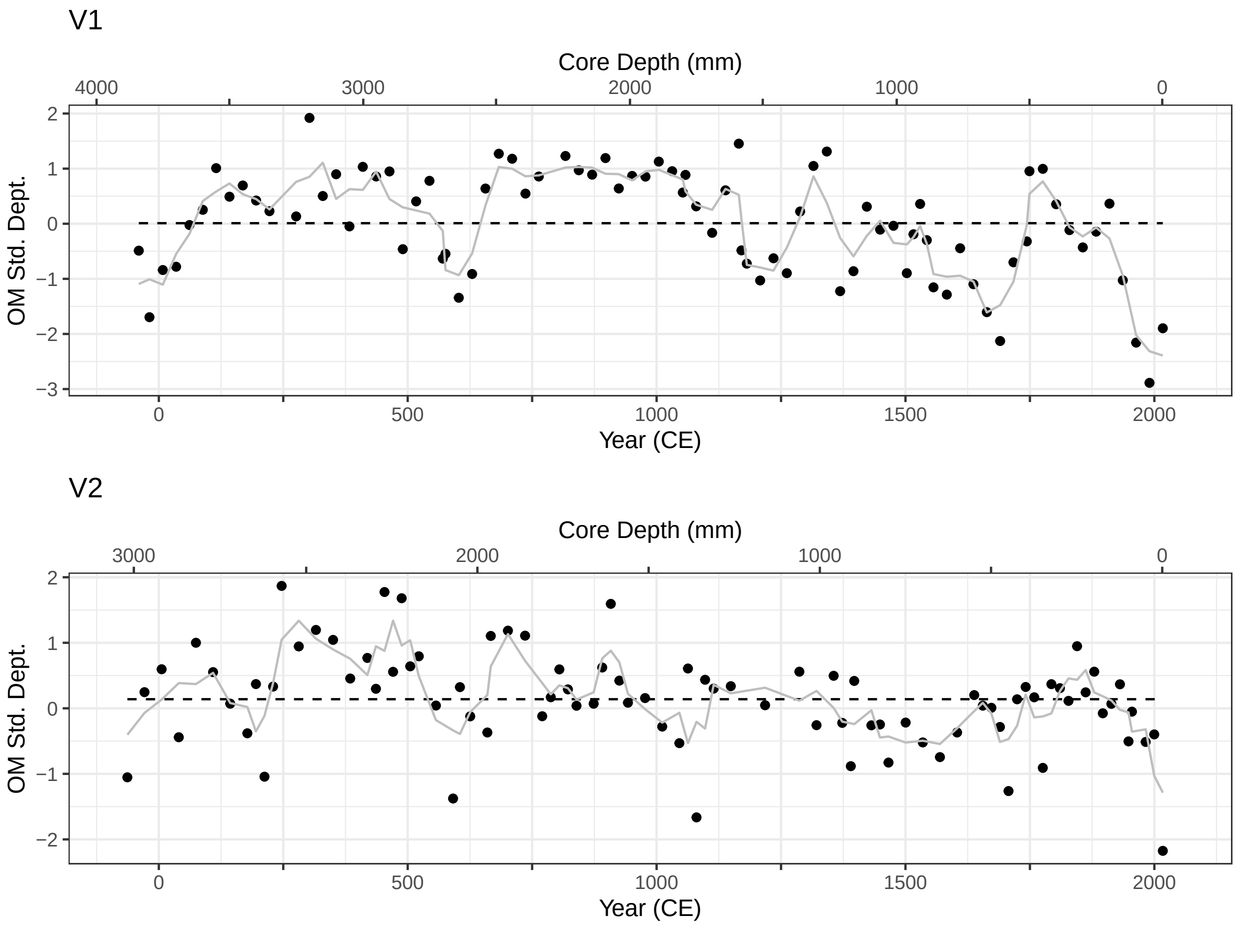

Figure 12: Standardized departure from the mean percent LOI for cores V1 and V2. The black points represent percent LOI at 2.5 - 5 cm intervals and the gray line is the 3 sample (75 year) moving average. The top axes, labelelled Year (CE), was estimated using linear interpolation from the AMS radiocarbon dates. The black X's on the bottom graph of V1 and V2 denote the AMS radiocarbon age (± dating error) and depth of the respective sample.

nearby, and similar sized watershed of Mud Lake (Figure 1 – inset) is evaluated by by Hodder et al. (2006). They found the early phases of deglaciation started just prior to 9.6 ka BP. Gilbert and Desloges (2012) indicate deglaciation of the north and west arms of the much larger Quesnel Lake was probably complete by 8.7 ka BP. Menounos et al. (2009) pointed to the deglaciation of most of the Cordilleran ice sheet before 10.5 ka BP. The Cariboo Lake acoustic results contribute to this regional record. Higher resolution AMS dated sediments from the west arm of Quesnel Lake (Gilbert & Desloges (2012)) showed a very consistent mean rate of sedimentation throughout the entire Holocene. Contrasting somewhat from this pattern are results from Menounos et al. (2009) and Desloges (1999) who note that early to mid Holocene sediment accumulation rates in the southeastern Canadian Cordillera were lower than the late Holocene neoglacial period. However, those shifts came from watersheds with much higher percentages of glacier ice cover. So, we believe using the 2 ka rates from Cariboo Lake to estimate thickness of the Holocene sediment package is valid.

Sub-bottom acoustic records from Transect B shown in Figure 4, which is proximal to the V1 core, indicate an upward transition from massive to well layered sediments occurring at a depth of about 20 m. Assuming a Holocene sediment accumulation rate of approximate 1.9 mm/yr from V1, this would put this transition at about 10.5 ka BP. Transect C, located in-between cores V1 and V2, has ~ 15 m of well layered sediment overlying a massively layered lower facies. Using a combined V1 and V2 average accumulation rate of 1.7 mm/yr in this region of the lake puts this facies transition at around 9 ka BP. The timing of this transition is similar to the onset of deglaciation and start of the Holocene sediment package within Mud Lake, BC in Hodder et al. (2006) of 9.6 ka BP, Moose Lake, BC in Desloges (1999) around 10.3 ka BP, Gilbert and Desloges (2012) in Quesnel Lake at 8.7 ka BP and the Upper Bow River, AB in Leonard & Reasoner (1999) 11.7 ka BP. The massively layered sediment package of Cariboo Lake that underlies/predates the 10.5 - 9 ka BP boundary is therefore likely a result of high energy sediment delivery when glacier ice was more proximal to the lake. Warming in the early Holocene, around 9.10-6.70 ka BP in the Rockies (Luckman (1986)) and British Columbia (Clague (1989)) would lead to a more regular seasonality of sediment inputs and lamiae formation. This is coincident with a hypsithermal depletion of glacier ice in the upper cirque basins of the Cariboo watershed.

Although coarser grained sediments from discrete turbidite flows are found proximal to sidewall tributary deltas, silt and clay comprise over 90% of the sediment at V1 and V2 and is inferred to have been delivered via suspension from the main Cariboo River. Therefore, the sediment stratigraphy from cores V1 and V2 provide a high-resolution physical proxy for late Holocene hydroclimatic regimes in the watershed. The Cariboo River has two main tributaries, the Upper Cariboo River and the Matthew River which are connected to high alpine peaks and glaciers which provide a significant source of sediment. Sediment connectivity between these upper tributaries is limited by several deep fjord like lakes including Lanezi Lake and Sandy Lake along the Upper Cariboo River, and Ghost Lake along the Matthew River. They act as sediment traps limiting the transfer of sediment from the glacier sediment production zones and resultthe low sedimentation rates observed in cores V1 and V2. Although connectivity is limited, there are sufficient seasonal contrasts in suspended sediment flux to produce couplets (annual varves) in the main basin of Cariboo Lake. This is unlike the west arm of Quesnel Lake where sediment rates are 2 to 3 times lower due storage in the massive upper lake regions producing non-annual layering. This difference in sediment rates is expected due to the lower lake to watershed area ratio of 0.3% for Cariboo Lake compared to the much larger Quesnel Lake which has a ratio of 4.7%.

Across the Canadian Cordillera glacial lakes have a range of Holocene accumulation rates from relatively low at millimeters per year (e.g. Quesnel Lake with 0.7 mm/yr; Gilbert & Desloges (2012)), to centimeters per year (e.g., Lillooet Lake, 2-7 cm/a; Desloges & Gilbert (1994)), to a maximum of 0.5 m/a observered in Kluane Lake (Crookshanks & Gilbert (2008)). The relative range in accumulation rates has been understood to be a result in the variability of sediment production from glacier processes and steep topography (Ballantyne, 2002), and the basin connectivity to deliver the sediment downvalley Wohl et al. (2019). The average accumulation rate for Cariboo Lake of 1.7 mm/yr over the last two millenia, based off on an average of two radiocarbon dates, fits on the lower end of the range of accumulation rates previously identified across the Canadian Cordillera. While Quesnel Lake is adjacent to the Cariboo Lake Basin and located in a similar topographic setting, the relatively low glacier coverage of 0.8% for that basin combined with the extreme lake volume and length from source areas likely limits sediment deliver to the lake bed. Moose Lake, which is fed by the steep valley glaciers of Mount Robson, and has basin glacier coverage of 3.2%, has a average sediment accumulation of 2.7 mm/yr.

Previous authors on sediment varve studies have noted the sediment signal from climatic transitions typically occur over hundreds of years due to the slow reponse of sediment availability, conveyance, and deposition. Boundary conditions may also exist which can limit the sensitivity of sediment yield to climate change (Desloges, 1999)

Higher organic content corresponds with higher rates of sediment accumulation from 0-700 CE.

Comparison to regional climate anomalies

- Thicker and coarser varves from 0-700 CE during colder wetter climate, why is there more LOI during this time.
- Smaller less coarse varves from 700-1500 CE during warmer dryer climate, LOI stays high.
- Coarser, thick varves during cold wet climate over the LIA, and LOI decreases
- Post- LIA LOI shows dramatic decline in organic content. Maybe lead lag effect? Boundry Conditions?
- One of the components of this study is the relative role of upstream sediment inputs controlled by watershed wide temp and precip trends and inputs of sediment from small watersheds that boarder the lake. The small lake deltas appears at first to be important at first but the study I think shows that they are good at delivering coarse sediment and not the fine stuff that makes up the "climate" sensitive varve sediments of the deep basin. These small, unglaciated basins do not provide a significant source of fine grained sediments. So one of the questions is are the turbidites (thicker more massive beds) resulting from major flooding off the main Cariboo delta or are they the result of local, small tributary inputs. initially suggest these are importunique features of this

6 Conclusion

- Acoustic records provide coarse resolution of sedimentation into Cariboo Lake. Facies A and B from transect C, totaling 25 m thick provide evidence of sediment accumulation rates from 15 ka BP to present (based on 1.7 mm/yr avg accumulation rate from V1 and V2 AMS dates). Higher rates of sediment delivery to Cariboo Lake is evident over Facies A, from 15 - 9 ka BP. More frequent, but lower in magnitude reflectors are observed over Facies B, from 9 ka BP to present.
- Rhythmically laminated silt and clay sediment are found in deep sub-basins (30-50 m deep) distal from river deltas.
- Above average sediment accumulation to Cariboo Lake is observed from 0 to 700 CE, above average from 700-1500 CE based on grain size and varve thickness, and average to above average from 1500 CE to present.
- Past major climate anomolies do not correlate well across all sediment characteristics

References

Ballantyne, C. K. (2002). Paraglacial geomorphology. *Quaternary Science Reviews*, *21*(18), 1935–2017.

Bolch, T. (submitter)., & Bolch, T. (analyst). (2008). *GLIMS Glacier Database*. National Snow; Ice Data Center. Boulder, CO. https://doi.org/10.7265/N5V98602

Clague, J. J. (1989). *Quaternary geology of the Canadian Cordillera* (pp. 15–96). https://doi.org/10.1130/dnag-gna-k1.15

Crookshanks, S., & Gilbert, R. (2008). Continuous, diurnally fluctuating turbidity currents in Kluane Lake, Yukon Territory. *Canadian Journal of Earth Sciences*, *45*(10), 1123–1138.

Desloges, J. R. (1999). Geomorphic and climatic interpretations of abrupt changes in glaciolacustrine deposition at Moose Lake, British Columbia, Canada. *Gff*, *121*(3), 202–207. https://doi.org/10.1080/11035899901213202

Desloges, J. R., & Gilbert, R. (1994). Sediment source and hydroclimatic inferences from glacial lake sediments: the postglacial sedimentary record of Lillooet Lake, British Columbia. *Journal of Hydrology*, *159*(1-4), 375–393. https://doi.org/10.1016/0022-1694(94)90268-2

Gilbert, R., & Desloges, J. R. (2012). Late glacial and Holocene sedimentary environments of Quesnel Lake, British Columbia. *Geomorphology*, *179*, 186–196. https://doi.org/10.1016/j.geomorph.2012.08.010

Gray, A. B., Pasternack, G. B., & Watson, E. B. (2010). Hydrogen peroxide treatment effects on the particle size distribution of alluvial and marsh sediments. *Holocene (Sevenoaks)*, *20*(2), 293–301.

Hodder, K. R., Desloges, J. R., & Gilbert, R. (2006). Pattern and timing of sediment infill at glacier-fed Mud Lake: Implications for lateglacial and Holocene environments in the Monashee Mountain region of British Columbia, Canada. *Holocene*, *16*(5), 705–716. https://doi.org/10.1191/0959683606hl965rp

Huber, M., & Knutti, R. (2012). Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geoscience*, *5*(1), 31–36.

Leonard, E. M., & Reasoner, M. A. (1999). A continuous holocene glacial record inferred from proglacial lake sediments in Banff National Park, Alberta, Canada. *Quaternary Research*, *51*(1), 1–13. https://doi.org/10.1006/qres.1998.2009

Luckman, B. H. (1986). Reconstruction of Little Ice Age Events in the Canadian Rocky Mountains. *Géographie Physique Et Quaternaire*, *40*(1), 17–28.

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, J., González Rouco, J. F., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X., & Timmermann, A. (2013). Information from paleoclimate archives. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change* (pp. 383–464). Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.013

Menounos, B. P., & Clague, J. J. (2008). Reconstructing hydro-climatic events and glacier fluctuations over the past millennium from annually laminated sediments of Cheakamus Lake, southern Coast Mountains, British Columbia, Canada. *Quaternary Science Reviews*, *27*(7-8), 701–713. https://doi.org/10.1016/j.quascirev.2008.01.007

Menounos, B. P., Osborn, G. D., Clague, J. J., & Luckman, B. H. (2009). Latest Pleistocene and Holocene glacier fluctuations in western Canada. *Quaternary Science Reviews*, *28*(21-22), 2049–2074. https://doi.org/10.1016/j.quascirev.2008.10.018

Nelson, M. C., Ingram, S. E., Dugmore, A. J., Streeter, R., Peeples, M. A., McGovern, T. H., Hegmon, M., Arneborg, J., Kintigh, K. W., Brewington, S., Spielmann, K. A., Simpson, I. A., Strawhacker, C., Comeau, L. E. L., Torvinen, A., Madsen, C. K., Hambrecht, G., & Smiarowski, K. (2016). Climate challenges, vulnerabilities, and food security. *Proceedings of the National Academy of Sciences*, *113*(2), 298–303. https://doi.org/10.1073/pnas.1506494113

Neukom, R., Barboza, L. A., Erb, M. P., Shi, F., Emile-Geay, J., Evans, M. N., Franke, J., Kaufman, D. S., Lucke, L., Rehfeld, K., Schurer, A., Zhu, F., Bronnimann, S., Hakim, G. J., Henley, B. J., Ljungqvist, F. C., McKay, N., Valler, V., & Gunten, L. von. (2019). Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. *Nature Geoscience*, *12*(8), 643–649.

Rasband, W. S. (n.d.). *ImageJ*. U. S. National Institutes of Health. https://imagej.nih.gov/ij/

Smith, J. G. (2003). Aspects of the loss-on-ignition (loi) technique in the context of clay-rich, glaciolacustrine sediments. *Geografiska Annaler: Series A, Physical Geography*, *85*(1), 91–97. https://doi.org/10.1111/1468-0459.00191

Turney, C. S. M., McGregor, H. V., Francus, P., Abram, N., Evans, M. N., Goosse, H., Von Gunten, L., Kaufman, D., Linderholm, H., Loutre, M.-F., & Neukom, R. (2019). Introduction to the special issue "climate of the past 2000 years: Regional and trans-regional syntheses". *Climate of the Past*, *15*(2), 611–615.

Westgate, J. A. (1977). Identification and Significance of Late Holocene Tephra From Otter Creek, Southern British Columbia, and Localities in West-Central Alberta. *Can J Earth Sci*, *14*(11), 2593–2600. https://doi.org/10.1139/e77-224

Wohl, E., Brierley, G., Cadol, D., Coulthard, T. J., Covino, T., Fryirs, K. A., Grant, G., Hilton, R. G., Lane, S. N., Magilligan, F. J., Meitzen, K. M., Passalacqua, P., Poeppl, R. E., Rathburn, S. L., & Sklar, L. S. (2019). Connectivity as an emergent property of geomorphic systems. *Earth Surface Processes and Landforms*, *44*(1), 4–26. https://doi.org/10.1002/esp.4434