Geomorphology 121 (2010) 197–205

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Dendrogeomorphic reconstruction of Little Ice Age paraglacial activity in the vicinity of the Homathko Icefield, British Columbia Coast Mountains, Canada

Sarah J. Hart [a], John J. Clague [b], Dan J. Smith [a,*]

[a] University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, Victoria, British Columbia, Canada V8W 3R4
[b] Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

ARTICLE INFO

Article history:
Received 10 August 2009
Received in revised form 11 April 2010
Accepted 19 April 2010
Available online 29 April 2010

Keywords:
Dendrogeomorphology
Homathko Icefield
Coast Mountains
Paraglacial
Tree-rings

ABSTRACT

Moraine and glacier dams bordering the Homathko Icefield in the southern British Columbia Coast Mountains failed in the 1980s and 1990s, causing catastrophic downstream floods. The largest of the floods occurred in August 1997 and was caused by overtopping and rapid breaching of the moraine dam that impounds Queen Bess Lake. The floodwaters from Queen Bess Lake eroded Holocene-age sedimentary deposits along the west fork of Nostetuko River and caused a steep rise in the hydrograph of Homathko River at the head of Bute Inlet, ~115 km downstream. A field investigation of the eroded valley fill in 2008, revealed multiple paraglacial valley-fill units, many of which are capped by *in situ* stumps and woody detritus. Dendrogeomorphological field techniques were employed to develop a chronology for the buried forests. A regional tree-ring chronology spanning the interval CE 1572–2007 was constructed from living subalpine fir (*Abies lasiocarpa*) trees at seven sites in the southern Coast Mountains. In cases where subfossil stumps and boles predated the regional chronology, relative death dates constrained by radiocarbon ages were assigned to floating chronologies. By combining these dendrogeomorphological dating methods, we identified six floodplain aggradation episodes within the past 1200 years. Comparison to local and regional glacial histories suggests that these events reflect climate-induced Little Ice Age changes in local glacier cover.

1. Introduction

Glaciers throughout the British Columbia Coast Mountains are downwasting and receding (Schiefer et al., 2007; Vanlooy and Forster, 2008). This deglacierization has been accompanied by an increase in the number and severity of floods and other catastrophic events in many mountain valleys (Evans and Clague, 1994). In the southern British Columbia Coast Mountains, failures of moraine and glacier dams during the 1980s and 1990s caused severe downstream flooding along the Homathko River and its tributaries (Fig. 1; Blown and Church, 1985; Clague and Evans, 2000; Kershaw et al., 2005). The largest of the floods, which occurred on August 12 1997, was triggered by the collapse of the lower part of Diadem Glacier into proglacial Queen Bess Lake (Clague and Evans, 2000; Kershaw et al., 2005). Waves induced by the massive ice avalanche overtopped and trenched the moraine dam, producing a flood that eroded Holocene-age sediments along the west fork of Nostetuko River. A series of sheets of silt and sand recording floodplain aggradation, separated by organic horizons containing tree stems and stumps in growth position, were exposed by the flood (Wilkie, 2006; Wilkie and Clague, 2009).

Streams can aggrade or incise their floodplains in response to changes in discharge, sediment load, and valley form (Leopold and Bull, 1979). In glacierized watersheds, changes in glacier cover can trigger floodplain aggradation or incision (Church and Ryder, 1972; Church and Slaymaker, 1989). Retreat of glaciers exposes a landscape that is susceptible to rapid change, due principally to transfers of large amounts of sediment from valley slopes to rivers. Church and Ryder (1972) coined the term “paraglacial” to define such a period of landscape adjustment and sediment transfer. Thirty years later, the paraglacial concept was extended by Ballantyne (2002a,b), who framed it in a context of sediment sources and sinks. He theorized that sediment transfers occur on different timescales (10^1 to 10^4 years), but at exponentially decreasing rates through time.

In glacierized basins, dendrogeomorphological research may provide insights into the activity of upstream glaciers on decadal to centennial timescales. Most prior dendroglaciological reconstructions in the Coast Mountains have relied on dating trees directly damaged or killed by glaciers (Smith and Laroque, 1996; Allen and Smith, 2007; Jackson et al., 2008). This approach, however, provides an incomplete record of past glacier activity because glacial advances of the past several hundred years destroyed or buried much of the evidence of earlier events (e.g. Koch et al., 2007). Dendrochronological dating of

* Corresponding author. Tel.: +1 250 472 4733; fax: +1 250 721 6216.
E-mail address: smith@uvic.ca (D.J. Smith).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.04.011

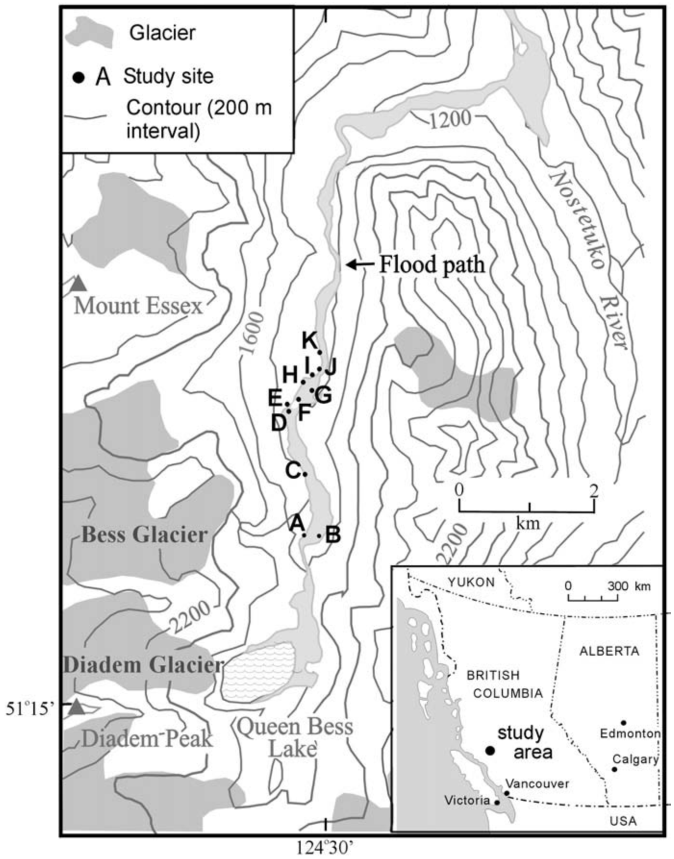

Fig. 1. Locations of study sites within the west fork of the Nostetuko River valley (modified from Clague and Evans, 2000).

paraglacial sedimentary sequences outside glacier forefields offers an opportunity to supplement and extend the direct glacial record — it provides a more complete, albeit less direct, record of climate and glacial activity (Wilkie, 2006).

In this paper, we identify sources and sinks of paraglacial sediment along the west fork of the Nostetuko River valley and develop an annually resolved chronology of late Holocene paraglacial aggradation events. These events are compared to independently documented periods of glacier activity in the northwestern North America Cordillera. Based on this comparison, we argue that aggradational events in the west fork of Nostetuko valley coincided with periods of glacial activity.

2. Study area

Our study area is the middle reach of the west fork of Nostetuko River valley (51° 17′ N., 124° 30′ W., ca. 1400 m asl) in the southern Coast Mountains of British Columbia (Fig. 1). The west fork of Nostetuko River originates at Diadem Glacier, an outlet glacier of the Homathko Icefield, and joins the main stem of Nostetuko River 8 km below Queen Bess Lake. Nostetuko River is a tributary of the Homathko River, which flows through the southern Coast Mountains to tidewater at the head of Bute Inlet (Fig. 1).

The west fork of Nostetuko River occupies a U-shaped valley in an area with more than 2000 m of relief. The river flows through two rock canyons and across several alluvial reaches between Queen Bess Lake and the main stem of Nostetuko River. The gradient of the west fork averages 3.8°, but ranges from 14° in the rock canyons to 0.5° in broad alluvial reaches (Kershaw, 2002). Lateral migration of the river is constrained by the steep valley slopes, rock canyons, and colluvial aprons and fans (Kershaw, 2002; Wilkie and Clague, 2009).

The study area has cold wet winters and warm dry summers. Climate normals (1961–1990) indicate that the valley has an average annual temperature of about 0.7 °C; mean monthly temperatures range from −8.8 to 9.7 °C (Wang et al., 2006). Average annual precipitation is about 1180 mm/year, of which approximately 70–75% falls as snow from October through May.

The valley lies within the Engelmann Spruce–Subalpine Fir (ESSF) biogeoclimatic zone (Meidinger and Pojar, 1991) and contains mixed stands of Engelmann spruce (*Picea engelmanni*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). Stands of mature trees are restricted to the valley floor and to the surface of several large alluvial fans and colluvial aprons. Tree growth on steep valley walls is limited by episodic snow avalanches and debris flows. The upper limit of tree growth in the valley is ca. 1750 m asl.

3. Previous research

Kershaw (2002) and Wilkie (2006) described late Holocene valley-bottom sediments eroded by floodwaters from Queen Bess Lake in 1997. Their investigations provide insights into the paraglacial history archived within the valley-fill sediments, upon which our research builds.

The west fork of Nostetuko River emerges from a rock canyon 1.25 km below Queen Bess Lake and truncates a large terminal moraine constructed by the south lobe of Bess Glacier (unofficial name; Fig. 2). The glacier probably advanced many times during the Holocene to this position, creating this moraine. A branch collected from the base of the moraine yielded a radiocarbon age of 2790 ± 60 ^{14}C year BP (Table 1; Wilkie and Clague, 2009), coincident with the regional Tiedemann Glacier advance reported by Ryder and Thomson (1986). A tree stem, exposed about 10 m below the surface of the moraine returned a radiocarbon age of 150 ± 50 ^{14}C year BP (TO-8932; Table 1).

River bank exposures downvalley of the moraine contain *in situ* stumps and boles rooted in a series of buried soil horizons and peat layers up to about 4 m above present river level. Many peat layers are not continuous or differ in thickness, but they record periods of floodplain stability and soil development that are separated by units of valley-wide silt and sand up to 1 m thick deposited during aggradational episodes (Wilkie and Clague, 2009).

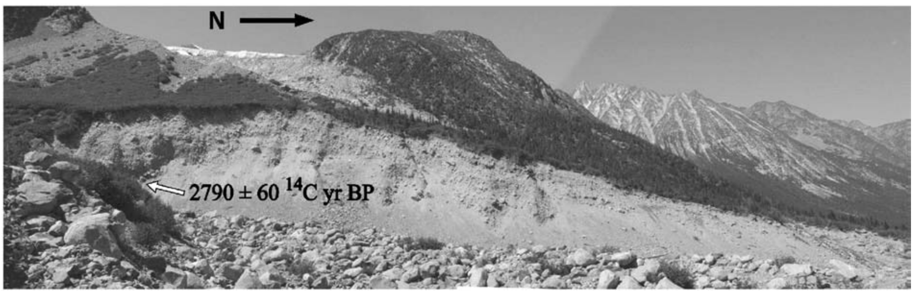

Fig. 2. The eroded terminal moraine at site A. Note the south lobe of Bess Glacier, just visible above the moraine (modified from Wilkie and Clague, 2009).

Table 1
Radiocarbon ages from the west fork of the Nostetuko River valley.

Site no.	Radiocarbon laboratory no.[a]	Radiocarbon age (^{14}C year BP)[b]	Calibrated age range (cal y CE)[c]	Material[d]
A	TO-8932	150 ± 60	1663–1895, 1903–1953	Outer rings of *in situ* stump
B	TO-8923	370 ± 50	1445–1637	*In situ* root (Kershaw et al., 2005)
D	Beta-200727	520 ± 50	1303–1365, 1383–1453	Outer rings of *in situ* stump
D	Beta-200728	940 ± 50	1018–1209	Outer rings of *in situ* stump
F	Beta-200733	600 ± 60	1284–1424	Outer rings of *in situ* stump
G	Beta-200725	620 ± 50	1284–1410	*In situ* root
I	TO-8935	110 ± 60	1669–1780, 1789–1944, 1950–1954	*In situ* root
I	Beta-200731	1030 ± 50	892–1052, 1080–1153	Outer rings of *in situ* stump
K	Beta-200732	1160 ± 50	718–743, 769–990	Outer rings of *in situ* stump

[a] Laboratories: Beta — Beta Analytic Inc.; TO — IsoTrace Laboratory (University of Toronto).
[b] Ages have been corrected for natural and sputtering fractionation to a base of $\delta^{13}C = -25.0‰$.
[c] Determined from atmospheric decadal set of Reimer et al. (2004) using the online program Calib 5.0. The range represents the 95.4% confidence limits.
[d] All samples were collected by Wilkie (2006) unless otherwise noted.

Radiocarbon dating of the exhumed stumps suggests that valley-floor forests were repeatedly buried over the past 6000 years. Wilkie and Clague (2009) interpreted these burial events as responses to upvalley glacier advances associated with the Garibaldi phase (mid-Holocene), Tiedemann advance (ca. 3000 years ago), the First Millennium CE advance (ca. 1500 years ago), and the Little Ice Age of the past 1000 years.

4. Methods

Kershaw (2002) mapped landforms in the west fork Nostetuko Valley using large-scale (1:5000 and 1:10,000), aerial photographs and topographic maps prepared from those photos. We checked Kershaw's mapping while in the field in the summer of 2008. Deposits and erosional forms of the 1997 outburst flood were readily identifiable from their lack of vegetation and coarse bouldery character. Alluvial fans were discriminated from more-common colluvial cones and aprons on the basis of their slopes: fans slope less than 15°, whereas colluvial cones and aprons are steeper (15–25°). We used the distribution of these and other landforms to assess sources and sinks of sediment in the west fork Nostetuko Valley.

We conducted fieldwork in July 2008 at nine sites where subfossil tree stumps and stems were exposed along a 3-km reach of the river (Fig. 1). Wilkie (2006) and Wilkie and Clague (2009) previously described six of the study sites; the other three sites have not been previously reported (Table 2).

We used a chain saw to collect cross-sections of subfossil trees exposed in the riverbanks. The stratigraphic position of each sample was noted and its height above river level was determined using a tape measure. A perimeter age was assigned to each sample by either cross-dating to a living chronology or by linking a floating tree-ring chronology to a radiocarbon age assigned to a perimeter wood sample.

Table 2
Locations of study sites.

Site no. This study	Site no. Wilkie and Clague (2009)	Latitude (N)	Longitude (W)	Elevation (m asl)
A	1	51° 16.30′	124° 30.28′	1473
B	2	51° 16.19′	124° 30.31′	1493
C		51° 16.46′	124° 30.27′	1448
D	3	51° 17.18′	124° 30.53′	1390
E	4	51° 17.19′	124° 30.56′	1389
F	5	51° 17.22′	124° 30.48′	1389
G	6	51° 17.38′	124° 30.37′	1408
H		51° 17.26′	124° 30.50′	1387
I	7	51° 17.41′	124° 30.26′	1380
J		51° 17.43′	124° 30.21′	1383
K	9	51° 17.65′	124° 30.17′	1381

4.1. Living chronology

We established a living tree-ring chronology from 40 increment core samples (20 trees, 2 cores each) collected from a mature stand of subalpine fir trees (> 300 years in age) growing adjacent to the river on a valley-bottom alluvial fan. The cores were transported to the University of Victoria Tree-Ring Lab (UVTRL), where they were air-dried and then glued into slotted mounting boards. The cores were subsequently sanded to a 600-grit polish to enhance annual rings (Stokes and Smiley, 1964). The ring widths of each sample were measured to the nearest 0.01 mm along a single radius using WinDendro software and a high resolution flatbed scanner (Guay et al., 1992). A Velmex stage equipped with a microscope and video display was used with the computer program MeasureJ2X (VoorTech Consulting, 2008) to measure widths of exceptionally narrow rings.

We constructed a chronology by cross-dating the series using common marker years (Stokes and Smiley, 1964). The International Tree Ring Database (ITRDB) computer program COFECHA was subsequently used to verify block correlations between each tree-ring series and the master chronology to ensure absolute dating accuracy (Holmes et al., 1986). We removed those cores from the data set that exhibited aberrant growth patterns and were not significantly correlated to the group.

We strengthened and extended back in time the living tree-ring chronology by supplementing it with six cross-dated subalpine fir chronologies previously collected by UVTRL researchers in the region (Table 3). The regional chronology incorporates only tree-ring data collected within 95 km of the study site on the relatively dry leeward slopes of the Coast Mountains. We constructed the regional chronology using all series from the pooled tree-ring data and removing only those series that were not significantly correlated to the group.

Table 3
Locations of chronologies used to develop a regional subalpine fir chronology for the southern British Columbia Coast Mountains.

Site	Latitude (N)	Longitude (W)	Elevation (m asl)	Source
Hope Glacier	51° 31′	124° 52′	1920	Larocque (2003)
Escape Glacier	51° 37′	125° 07′	1760	Larocque (2003)
Liberty Glacier	51° 35′	124° 49′	1525	Larocque (2003)
Cathedral Glacier	51° 14′	124° 51′	1600	Larocque (2003)
Homathko Icefield	51° 17′	124° 30′	1390	This study
Bridge Glacier	50° 48′	123° 29′	1544	Allen (2007)
Manatee Glacier	50° 36′	123° 38′	1600	Koehler (2009)

4.2. Subfossil dendrogeomorphology

We constructed floating tree-ring series from the subfossil cross-sectional samples by measuring ring widths along at least two radii. Care was taken to use paths with the maximum number of rings and to avoid areas with reaction wood. Companion series from each subfossil sample were cross-dated using CDendro 7.1 (Larsson, 2003).

We built species-specific floating chronologies from subfossil samples rooted in the same organic layer. The species of each sample was determined using a simple visual identification key and a light microscope (Hoadley, 1990). We calculated correlation coefficients for the floating chronologies as an average linear correlation between each series and every other series. We used this method because it provides conservative estimates of the year-to-year agreement between members of the chronologies.

Attempts were made to cross-date individual floating chronologies to the local and regional living chronologies using CDendro 7.1 (Larsson, 2003). Cross-dating was deemed successful based on high correlation coefficients, *t*-statistics, and visual similarity between the floating chronology and a dated chronology. Where successful, cross-dating provided absolute death dates. Where this approach was unsuccessful, radiocarbon ages of samples included in the floating chronology or located on the same organic horizon provided approximate age constraints for the burial event (Koch et al., 2007). We assume an ecesis interval of 5 years (Wilkie, 2006).

When flooded, conifers characteristically undergo changes in ring width (Sigafoos, 1964; SigafoFriedman et al., 2005; Mizugaki et al., 2006) or produce adventitious roots (Kozlowski et al., 1991). The absence of adventitious roots and suppression of growth at the end of the trees' lives indicate that most aggradation events were fatal, a less common but still documented response (Strunk, 1988). We interpret periods of abnormal outer ring growth to represent the beginning of the aggradation period.

5. Results

5.1. Sediment sources and sinks

Primary sediment sources in the west fork Nostetuko valley include rockwalls and glacigenic sediments (Fig. 3). Pleistocene and modern glaciers have steepened rock slopes, which have increased tensile stresses within the slopes and facilitated slope failure and downslope transfers of sediment. The glacier forefields are areas of abundant unconsolidated glacigenic sediment that have only incipient soil and scanty vegetation. During periods when glaciers are advancing or retreating, some of this sediment is mobilized by a variety of processes – debris flows, snow avalanches, fluvial erosion, and periglacial processes – and carried downvalley by the west fork of Nostetuko River. The forefields of glaciers, including Diadem and Bess glaciers, are important sources of sediment to the fluvial system. In particular, the Nostetuko west fork flows past the Little Ice Age terminal moraines of Diadem and Bess glaciers, eroding both at times of high discharge (Fig. 3; Kershaw, 2002).

The major sediment sinks in the west fork of the Nostetuko River valley are debris cones, composite alluvial–colluvial fans, and the alluvial fill on the valley floor (Fig. 3). Wilkie and Clague (2009) document aggradation units over 1 m thick covering the floor of the valley. Other important sediment sink are five composite fans and one debris cone on the valley sides within the study area. The largest fans are on the western, more glacierized side of the valley. These features are largely depositional, but may also represent important secondary sources of sediment for later paraglacial events (Fig. 3).

5.2. Tree-ring chronologies

The local living subalpine fir chronology comprises 29 series from 18 trees and spans 279 years (CE 1729 to 2007; Table 4). The mean series intercorrelation value, calculated using 50-year segments, lagged successively by 25 years, is significant at the 99% confidence level ($r = 0.444$, Table 4).

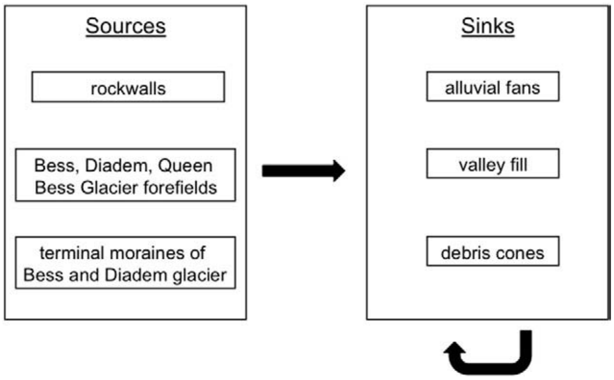

Fig. 3. The paraglacial sediment system in the west fork of the Nostetuko River valley. Sediment is transported from rockwalls, glacier forefields, and terminal moraines to form alluvial fans, valley fills and debris cones. The sediment in these depositional features is then available for subsequent paraglacial sediment movement.

The composite regional chronology consists of over 250 series and extends the tree-ring record back to CE 1572 (Table 4). COFECHA revealed a high degree of agreement between series (Table 4). The chronology, however, loses significant sample depth before CE 1725 (Fig. 4). Statistics calculated on the regional and site chronologies indicate similar sensitivities and intercorrelation values (Table 4). A strong correlation ($r = 0.53$) between the two chronologies was found using CDendro after detrending both average raw ring width series with a negative exponential curve.

5.3. Subfossil samples

We sampled 135 subfossil trees on the Nostetuko valley floor. Most of the samples were found in growth position, rooted in organic layers abruptly overlain by thick layers of silt and sand. The samples were identified as Engelmann spruce, subalpine fir, or whitebark pine. None of the 135 trees sampled showed evidence of adventitious roots. Periods of suppressed radial growth, traumatic resin canals, and reaction wood were observed in some samples, but they were restricted to the end of the ring series. We interpret the absence of adventitious roots and suppression of growth at the end of the trees' lives to mean that catastrophic aggradation caused the death of the trees.

Of the 135 samples, only 57 were suitable for dendrochronological analysis (17 whitebark pine, 32 subalpine fir, and 8 Engelmann spruce samples). Many of the samples were deemed unsuitable for analysis because they contained too few rings. Other samples could not be used because the tree-ring series were too complacent or contained too much reaction wood.

Site A is the fluvially eroded face of the large moraine fan below Bess Glacier (Fig. 2; Table 2). A laterally continuous mat of stumps, boles, and branch fragments is exposed ca. 10 m below the surface the fan. The downvalley orientation and character of the detrital wood indicate that the trees were killed and buried during an advance of

Table 4
Tree-ring chronology statistics.

Site	Interval	No. series	Average series intercorrelation[a]	Average mean sensitivity
Local	1792–2007	29	0.444	0.214
Regional	1572–2007	257	0.513	0.214

[a] Calculated using computer program COFECHA; default setting of 50-year segments with a 25-year overlap.

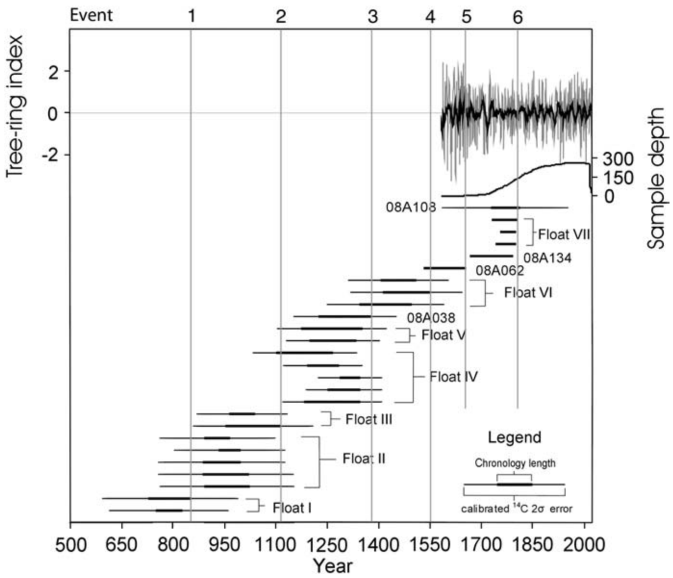

Fig. 4. Tree-ring series constructed from sites in the Nostetuko River valley. The top gray line represents the regional subalpine fir COFECHA chronology; the black line is a five-year moving average. The sample depth of the regional chronology is plotted below the COFECHA chronology. Subfossil floating chronologies are plotted below the regional chronology. Thick black lines indicate the position in time generated from either radiocarbon or dendrochronological dating. Thin lines indicate the error associated with each date. Each line represents one sample; cross-dated samples are grouped with brackets. The six aggradation events are noted across the top *x*-axis.

Table 5
Subfossil samples and floating chronologies developed in analyzing the paraglacial history of the west fork of Nostetuko River.

Subfossil series				Subfossil chronologies				
Sample no.[a]	Species[b]	Site	No. of rings	Name	Length (years)	Radiocarbon age (^{14}C year BP)	No. of samples	*r*
08G003	saf	A	46	Float VII	76	150 ± 60	3	0.48
08G007	saf	A	76					
08G009	saf	A	60					
KW21	saf	B	102	Float VI	216	370 ± 50	3	0.49
08A044	saf	F	151					
08A045	saf	F	136					
08A043	saf	F	180	Float V	180	600 ± 60	2	0.31
08A048	saf	F	136					
KW15	saf	G	165	Float IV	245	620 ± 50	5	0.31
KW18	saf	G	92					
08A090	es	H	165					
08A093	saf	H	97					
08A094	saf	H	61					
08A040	saf	E	160	Float III	160	940 ± 50	2	0.35
08A039	saf	E	76					
08A108	saf	I	76	Float II	142	1030 ± 50	5	0.34
08A119	es	I	64					
08A121	saf	I	132					
08A091	saf	H	110					
08A092	es	H	135					
08A126	es	K	126	Float I	94	1160 ± 50	2	0.41
08A132	saf	J	78					
08A062	saf	H	152					
08A134	saf	C	137					
08A038	saf	E	152			520 ± 50		
08A108	saf	H	84			110 ± 60		

[a] 08A### collected by the senior author; KW## collected by Wilkie (2006).
[b] saf = subalpine fir; es = Engelmann spruce.

Bess Glacier into the valley. The perimeter rings of a bole recovered from the site in 2004 yielded a radiocarbon age of 150 ± 60 ^{14}C year BP (TO-8932; Table 1). When visited in 2008, further erosion and collapse of the face had exposed additional detrital wood.

Cross-sections were collected from nine subfossil subalpine fir samples found within the moraine face and on the talus below. The oldest sample contained 97 annual growth rings. No bark was present on the samples, and some perimeter rings were assumed missing because of weathering. Three of the nine samples cross-date to form a 76-year-long floating chronology (float VII, Table 5). This chronology cross-dates to the regional chronology and suggests that in ca. CE 1807 Bess Glacier was advancing over a moraine surface likely first colonized by trees about CE 1731 (Fig. 4). Assuming that the local ecesis interval is five years and that the oldest tree sampled was the first colonizer of a recently deglaciated surface, we infer that Bess Glacier had retreated some distance upvalley by the mid-1720s.

Site B is the eroded face of a fluvial terrace on the east side of the river across from site A (Fig. 1; Table 2). *In situ* roots and stumps are associated with a buried organic layer located about 3 m below the terrace surface. The outer rings of an *in situ* root yielded a radiocarbon age of 370 ± 50 ^{14}C year BP (TO-8923; Table 1). We examined another stump, collected in 2004 by Wilkie (2006). Accounting for ecesis, the minimum period of stability recorded by the organic layer at site B is 107 years.

Site C is located on the west side of the valley, about 295 m north of site A and adjacent to a small meltwater stream that flows from the south lobe of Bess Glacier (Fig. 1). Two rooted stumps in growth position were exposed in the bank of the stream, about 0.75 m below the surface. One of the two stumps was cross-dated to the regional tree-ring chronology and was 137 years old when it died in CE 1794 (Fig. 4). This finding suggests that the site was stable from CE 1657 to 1794, after which trees were killed and buried by sediment.

Sites D and E are located on the west side of the river, 1.3 km downvalley from site C (Fig. 1). The sites are located along the upstream edge of a large treed valley-side alluvial fan. Erosion during the 1997 outburst flood scoured an elongate depression, exposing a thick sequence of alternating facies of stratified silt, sand, and peat. Site D is located at the SE edge of the depression close to the forest. Site E is located at the NW edge of the abandoned floodway. The lowest exposed organic horizon at site D was radiocarbon-dated to 940 ± 50 C year BP (Beta-200728; Table 1). The outer rings of a stump rooted in another peat less than 1 m higher in the sequence yielded a radiocarbon age of 520 ± 50 ^{14}C year BP (Beta-200727; Table 1). This finding and the presence of several other buried forest layers higher in the sequence suggest that trees repeatedly colonized overbank sediments on the valley floor at this site.

Forty-two cross-sections of stumps were collected at sites D and E. Two *in situ* stumps of subalpine fir in the lowest organic horizon cross-date and form a 160-year-long floating chronology (float III; Table 5). The trees were killed and buried by silt and sand in 940 ± 50 ^{14}C year BP. It is inferred that this event was followed by a lengthy interval without significant aggradation, as a subalpine fir stump with 152 rings, slightly higher in the sequence, dates to 520 ± 50 ^{14}C year BP (Table 1).

Site F is located 100 m downvalley from sites D and E at the north side of a forested bedrock knob (Fig. 1). Sand separates two laterally extensive organic horizons, each of which contains subalpine fir stumps in growth position. The lower organic horizon is at river level, about 3 m below the surface. Two cross-sections of these stumps cross-date to form a 180-year-long floating chronology (float V, Table 5) with an outer perimeter wood age of 600 ± 60 ^{14}C year BP (Table 1).

The upper organic horizon is buried by ca. 1 m of fine sand (Fig. 5). Two cross-sections of stumps from this layer cross-date to form a 202-year-long floating chronology (float VI; Table 5). This floating chronology cross-dates with the sample from site B; thus a perimeter date of 370 ± 50 ^{14}C year BP was assigned to both (Table 5).

Site G is an exposure of silt and sand eroded by the 1997 outburst flood and located 315 m downvalley from site F (Fig. 1). A buried peat layer >2 m below the surface contains *in situ* stumps. Cross-sections of two stumps radiocarbon-dated by Wilkie (2006; KW15 and KW18)

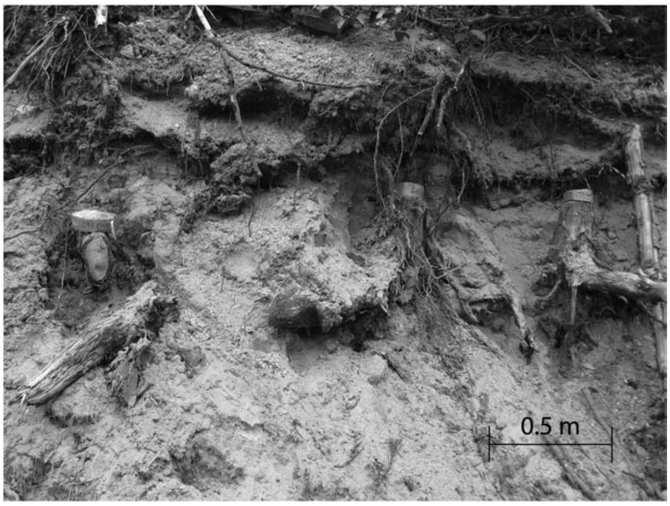

Fig. 5. The top woody mat sampled at site F. Note the three *in situ* subfossil tree stumps and the massive layer of fine sand and silt that overlies them. These trees were killed following burial in aggradation event 4 in 1445–1637 CE (Table 6).

cross-date with samples from site H (float IV; Table 5). This result indicates that the trees at site G were killed in ca. 620 ± 50 ^{14}C year BP (Table 1), after a period of floodplain stability lasting at least 165 years.

Site H is a riverbank exposure 50 m downstream from site G (Fig. 1; Table 2), along a side channel. Exhumed stumps are exposed in the side of the riverbank (Fig. 6). Two cross-sections of *in situ* stumps collected from the lowest organic horizon ca. 3.5 m below the surface cross-date to form a floating chronology. They also cross-date with samples from site I to form a 142-year-long floating chronology (float II, Table 5) with a perimeter radiocarbon age of 1030 ± 50 ^{14}C year BP (Beta-200731; Table 1). These results suggest that the trees growing at site H were killed and buried in 1030 ± 50 ^{14}C year BP following a period of floodplain stability that lasted at least 142 years (Table 5).

Six samples were collected from stumps rooted in a second woody layer about 2.5 m below the surface. Three samples (two subalpine fir and one Engelmann spruce) cross-date with samples from site G (float IV, Table 5). This finding suggests that these trees were killed 620 ± 50 ^{14}C year BP after a period of floodplain stability lasting at least 245 years (Table 5).

Fig. 6. Exposed subfossil trees at site H. The three stems in the foreground grew in the peat layer at the base of the section and were killed in CE 1284–1424 following aggradation event 3 (Table 6). The stems in the background are rooted 2.5 m below the top of the section and died in CE 1445–1637 following aggradation event 4. Note the fine sand and silt that separate the two layers.

A third organic layer is about 1 m below the present-day ground surface. It contains snags that extend above ground level. One of the four stumps sampled from this horizon cross-dates with the regional subalpine fir chronology and has a death date of CE 1657. This chronology extends back 152 years, indicating the floodplain was stable from CE 1505 to 1657 (Fig. 4).

Site I is located 78 m downstream from site H along the west bank of the river (Fig. 1). The site is actively eroding and significant slumping has exposed a 3 m sequence of bedded overbank silt and sand. Two prominent wood mats, 1.5 and 3 m below the surface, contain rooted stumps, and several thin organic horizons occur between the two mats.

Three samples from the lower wood mat cross-date to form a 142-year-long floating chronology (float II, Table 5). The trees were killed and buried 1030 ± 50 ^{14}C year BP (Beta-200731; Table 1) after a period of surface stability that lasted more than 76 years. Numerous sand layers with minor organic interbeds totaling 1.45 m in thickness separate the lower horizon from the upper wood mat that was buried in 110 ± 60 ^{14}C year BP (TO-8935; Table 1).

Site J is an exposure of flood-scoured overbank sediments adjacent to site I (Fig. 1). Prominent organic layers occur at the base of the section and 1.5 m higher. Cross-sections were collected from several stumps in growth position, but only one of them was successfully cross-dated to a sample at site K with a perimeter age of 1160 ± 50 ^{14}C year BP (Beta-200732; Table 5).

Site K is located 60 m downstream from site J adjacent to the main river channel and is being actively eroded by the river (Fig. 1). A prominent noneroded peat layer which gave a radiocarbon age of 1160 ± 50 ^{14}C year BP (Table 1) occurs at water level. Five cross-sections were collected from stumps rooted in the peat layer. One sample cross-dates with a 94-year floating chronology at site J (float I; Table 5). We infer that the floodplain was stable for at least 126 years, after which an episode of sediment aggradation buried and killed the trees at sites J and K shortly after 1160 ± 50 ^{14}C year BP.

6. Synthesis

Significant geomorphic change occurred on the valley floor of the west fork of Nostetuko River during the Holocene. This change occurred within a context of the episodic advance and retreat of glaciers from upper valley positions to the edge of the trunk valley. Of greatest importance is the late Holocene delivery of sediment by Diadem and Bess glaciers. We identified and dated six aggradation events during the past 1200 years on the basis of overlapping radiocarbon ages and stratigraphic evidence (Fig. 4; Table 6). The oldest event (no. 1) occurred CE 718–990, based upon the radiocarbon age of 1160 ± 50 ^{14}C year BP and floating chronology I from an organic horizon within the valley-fill sedimentary sequence (Fig. 7). The chronology overlaps chronologies II and III in radiocarbon time, but none of the three chronologies cross-dates. The three organic layers

Table 6
Aggradation events.

Event	Calibrated age range (CE)	Radiocarbon age (^{14}C year BP)	Floating chronologies	Cross-dated chronologies
1	718–990	1160 ± 50	I	
2	892–1209	940 ± 50	II	
		1030 ± 50	III	
3	1284–1424	600 ± 60	IV	
		620 ± 50	V	
4	1445–1637	370 ± 50	VI	
5	1657			08A062
6	1669–1954	110 ± 60	08A108	
	1794			08A134

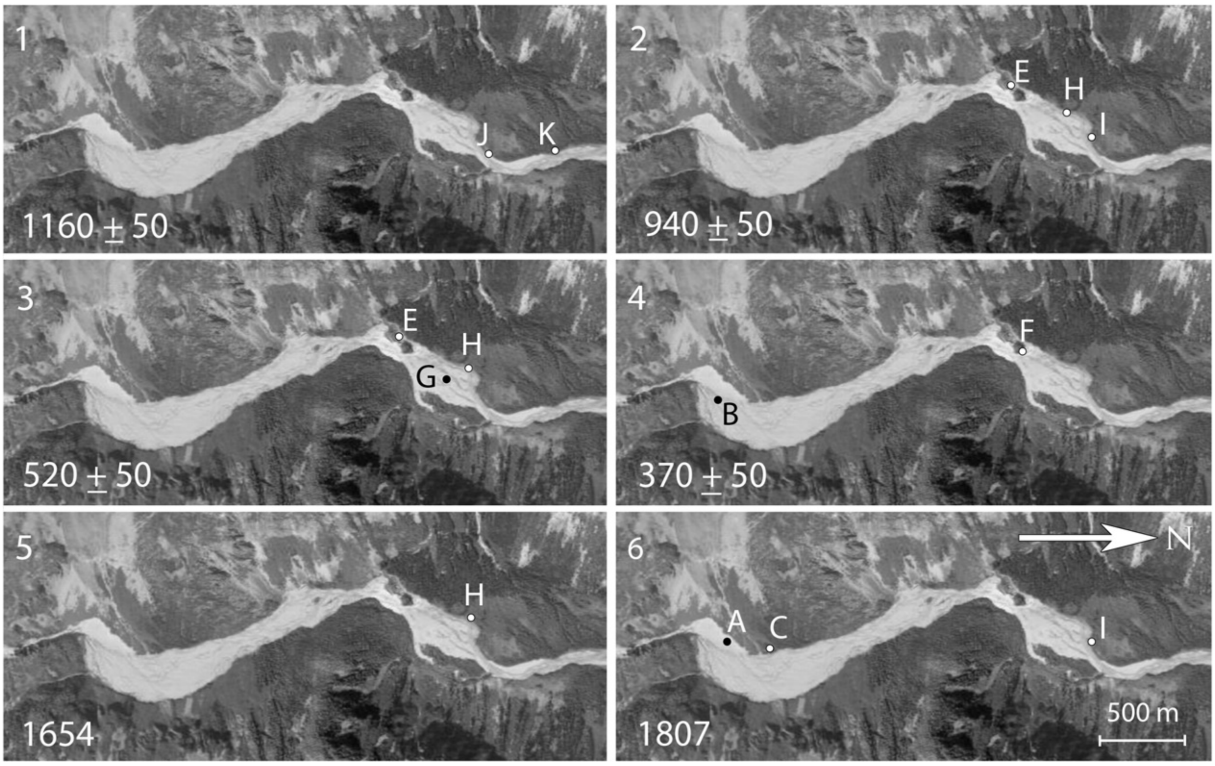

Fig. 7. Inferred spatial extent of each of the six aggradation events documented in the west fork of the Nostetuko River valley. Sites with at least one sample dated to the event (number noted at top left, year at bottom left) are marked (modified from a 2005 Spot Image from Google Earth, 2009).

differ significantly in character, suggesting that they are not of the same age. This event appears to coincide in time with a well documented advance of Bridge Glacier, 90 km to the SE, at 1190 ± 60 ^{14}C year BP (Allen and Smith, 2007).

Event 2 occurred at about CE 892-1153 (940 ± 50 ^{14}C year BP; Table 6). It is recorded at three sites in the valley (Fig. 7). An early Little Ice Age advance of this age has been identified at numerous sites in the southern Coast Mountains (Reyes and Clague, 2004; Allen and Smith, 2007; Koch et al., 2007) and in the northern Coast Mountains (Haspel et al., 2005; Spooner et al., 2005).

Event 3 occurred in the late fourteenth century (600 ± 60 ^{14}C year BP; Table 6) and is recorded by aggradation at valley-floor sites E, G, and H (Fig. 7). This time period is widely recognized as one when glaciers were advancing throughout the southern Coast Mountains (Ryder and Thomson, 1986; Larocque and Smith, 2003; Lewis and Smith, 2004; Allen and Smith, 2007; Koch et al., 2007).

Event 4 is a valley-wide aggradational episode that occurred about CE 1445–1637 (370 ± 50 ^{14}C year BP; Fig. 4, Table 6). Evidence for this event was found at sites B and F (Fig. 7). These sites are located within alluvial fan sediments spilling from the northern lobe Bess Glacier and within downstream floodplain sediments. Glacier advances in the early to mid-1500s have been reported in the Mount Waddington area, 50 km to the NW (Larocque and Smith, 2003).

A sheet of sediment deposited during event 5 dates to CE 1657 at site H (Fig. 4; Table 6). Trees growing at site C are believed to have colonized a mineral surface ca. CE 1660 (sample 08A134, Fig. 6). This observation suggests that this event may have been short lived. Moraines elsewhere in the region stabilized shortly after this time, in the mid to late 1660s (Larocque and Smith, 2003; Lewis and Smith, 2004).

Aggradation during event 6 dates to ca. 1794 at site C (Fig. 4; Table 6). A radiocarbon-dated stump from site H may have been buried during event 6 (Table 6). This event is contemporaneous with advances of other glaciers in the southern Coast Mountains during the late Little Ice Age (Larocque and Smith, 2003; Menounos et al., 2009).

7. Discussion

All six aggradation events documented in this study correspond to periods of regional glacial activity. Dated samples were recovered from peat layers separating thick silt and sand units that record valley-wide aggradation. The general coincidence between aggradation events and periods of independently documented regional glacier activity is characteristic of a paraglacial system. We infer from this synchronous behavior that sediment from glacier forefields, moraines, and valley slopes was delivered at higher-than-normal rates during times when climate was cooler and wetter, and thus glaciers more extensive, than today.

We compared tree death dates determined in this study to local dates of glacier activity to determine at what point in the glacial cycle the west fork of the Nostetuko River aggraded its valley and killed valley-bottom forests. In the mid-1720s, Bess Glacier was some distance inside its maximum Little Ice Age limit, whereas in 1806 it was advancing toward this position (Fig. 2). The aggradation events closest in time to this dated activity are events 5 (CE 1657) and 6 (CE 1794). Given that small watersheds will respond to glacier fluctuations more rapidly than large watersheds (Harbor and Warburton, 1993), we infer that aggradation event 6 occurred in response to the advance in 1806. The temporal and spatial relations between the advance and aggradation suggest that the latter may occur prior to glaciers reaching their maximum extent during any given advance. Aggradation events appear to coincide with, rather than lag, periods of regional glacial advance and moraine stabilization. We caution, however, that climate and glaciers in British Columbia have fluctuated on a range of timescales (10^1 to 10^3 years; Clague et al., 2009). This variability and inherent limitations in our ability to resolve prehistoric glacier activity on timescales of years complicate our comparison of aggradation events and glacier activity in the Nostetuko River watershed. More research at high temporal and spatial resolution is needed to understand these relationships.

8. Conclusions

We constructed a regional subalpine fir chronology for the period CE 1572-2007 from samples collected at seven sites in the southern Coast Mountains. This chronology was used to cross-date *in situ*, subfossilized trees bounded by sheets of silt and sand in the valley of the west fork of Nostetuko River. Some of the exhumed forest horizons predate the regional chronology. In these cases, floating chronologies were pinned with radiocarbon ages on outer rings of subfossil trees in the valley. Using these two methods, we documented and dated six, spatially extensive episodes of aggradation in the Nostetuko River valley during the past 1200 years. The six sedimentation events coincide with independently dated periods of glacier expansion in the Coast Mountains and reflect increased sediment delivery to the west fork of the Nostetuko River by Bess, Queen Bess, and other glaciers within the upper part of the watershed.

Most previous dendrochronological reconstructions of Holocene glacial history in the Canadian Cordillera have focused on trees that have been directly impacted by glaciers. This approach only captures some of the most recent glacier fluctuations, because the climactic advances of the late Little Ice Age buried or destroyed much of the evidence of earlier advances. Sediment supply to rivers draining glacierized catchments may change in response to an increase or decrease in ice cover. In some cases, the response is manifested in aggradation or incision of floodplains. As these environments lie outside Little Ice Age glacier limits, they may yield a more complete record of Holocene glacier activity than the evidence from glacier forefields themselves.

Acknowledgements

Kirsten Brown, Bethany Coulthard, Kate Johnson, and Kyla Patterson helped in the field. Sandy Allen, Lynn Koehler, and Sonya Larocque allowed us to use their chronologies in building our regional chronology. Kenna Wilkie provided radiocarbon ages on subfossil wood. Mike King (White Saddle Air Services) provided helicopter access to the study area. We also thank Dennis Jelinski, Terri Lacourse, and Vic Levson for their comments and scientific insight. The research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants to Clague and Smith and by a Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) grant to the Western Canadian Cryospheric Network.

References

Allen, S.M., 2007. Late Holocene glacial activity of Bridge Glacier, British Columbia Coast Mountains. M.Sc. thesis, University of Victoria, Victoria, BC, Canada.
Allen, S.M., Smith, D.J., 2007. Late Holocene glacial activity of Bridge Glacier, British Columbia Coast Mountains. Canadian Journal of Earth Sciences 44, 1753–1773.
Ballantyne, C.K., 2002a. A general model of paraglacial landscape response. The Holocene 12, 371–376.
Ballantyne, C.K., 2002b. Paraglacial geomorphology. Quaternary Science Reviews 21, 1935–2017.
Blown, I., Church, M., 1985. Catastrophic lake drainage within the Homathko River basin, British Columbia. Canadian Geotechnical Journal 22, 551–563.
Church, M., Ryder, J.M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. Geological Society of America Bulletin 83, 3059–3072.
Church, M., Slaymaker, O., 1989. Holocene disequilibrium of sediment yield in British Columbia. Nature 327, 452–454.
Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews 19, 1763–1783.
Clague, J.J., Menounos, B., Osborn, G., Luckman, B.H., Koch, J., 2009. Nomenclature and resolution in Holocene glacial chronologies. Quaternary Science Reviews 28, 2231–2238.
Evans, S.G., Clague, J.J., 1994. Recent climatic change and catastrophic geomorphic processes in mountain environments. Geomorphology 10, 107–128.
Guay, R., Gagnon, R., Morin, H., 1992. A new automatic and interactive tree-ring measurement system based on a line scan camera. The Forestry Chronicle 38, 138–141.
Harbor, J., Warburton, J., 1993. Relative rates of glacial and nonglacial erosion in alpine environments. Arctic and Alpine Research 25, 1–7.
Haspel, R., Osborn, J., Spooner, I., 2005. Neoglacial deposits of Bear River Glacier, Northern Coast Ranges, British Columbia. Annual Meeting, Western Division, Canadian Association of Geographers. University of Lethbridge, Lethbridge, AB, Canada.
Hoadley, R.B., 1990. Identifying Wood: Accurate Results with Simple Tools. The Taunton Press, Newtown, CT.
Holmes, R.L., Adams, R.K., Fritts, H.C., 1986. Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including user manuals for computer programs COFECHA and ARSTAN. Chronology Series VI. Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ.
Jackson, S.I., Laxton, S.C., Smith, D.J., 2008. Dendroglaciological evidence for Holocene glacial advances in the Todd Icefield area, northern British Columbia Coast Mountains. Canadian Journal of Earth Sciences 45, 83–98.
Kershaw, J.A. 2002. Formation and failure of moraine-dammed Queen Bess Lake, southern Coast Mountains, British Columbia. M.Sc. thesis, Simon Fraser University, Burnaby, BC.
Kershaw, J.A., Clague, J.J., Evans, S.G., 2005. Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada. Earth Surface Processes and Landforms 30, 1–25.
Koch, J., Clague, J.J., Osborn, G.D., 2007. Glacier fluctuations during the past millennium in Garibaldi Provincial Park, southern Coast Mountains, British Columbia. Canadian Journal of Earth Sciences 44, 1215–1233.
Koehler, L., 2009. Late Holocene glacial history of Manatee Valley, upper Lillooet Provincial Park, southern Coast Mountains, British Columbia. M.Sc. thesis, University of Victoria, Victoria, BC, Canada.
Kozlowski, T., Kramer, P., Pallardy, S., 1993. Soil aeration, compaction and flooding. The Physiological Ecology of Wood Plants. Academic Press, New York, NY.
Larocque, S.J., 2003. Glacier and climate fluctuations during the Little Ice Age, Mt. Waddington area, southern Coast Mountains of British Columbia. Ph.D. thesis, University of Victoria, Victoria, BC, Canada.
Larocque, S.J., Smith, D.J., 2003. Little Ice Age glacial activity in the Mt. Waddington area, British Columbia Coast Mountains, Canada. Canadian Journal of Earth Sciences 40, 1413–1436.
Larsson, L.A., 2003. CDendro — Cybis Dendro Dating Program. Cybis Elektronik & Data AB, Saltsjöbaden, Sweden.
Leopold, L.B., Bull, W.B., 1979. Base level, aggradation, and grade. Proceedings of the American Philosophical Society 123, 168–202.
Lewis, D.H., Smith, D.J., 2004. Little Ice Age glacial activity in Strathcona Provincial Park, Vancouver Island, British Columbia, Canada. Canadian Journal of Earth Sciences 41, 285–297.
Meidinger, D., Pojar, J., 1991. Ecosystems of British Columbia. Special Report Series No. 6. B.C. Ministry of Forests, Victoria, BC, Canada. 330 pp.
Menounos, B., Osborn, G., Clague, J.J., Luckman, B.H., 2009. Latest Pleistocene and Holocene glacier fluctuations in western Canada. Quaternary Science Reviews 28, 2049–2074.
Mizugaki, S., Nakamura, F., Araya, T., 2006. Using dendrogeomorphology and 137Cs and 210Pb radiochronology to estimate recent changes in sedimentation rates in Kushiro Mire, Northern Japan, resulting from land use change and river channelization. Catena 68, 25–40.
Reimer, P.J., Baillie, M.G.L., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 026 cal kyr BP. Radiocarbon 45, 1029–1058.
Reyes, A., Clague, J.J., 2004. Stratigraphic evidence for multiple Holocene advances of Lillooet Glacier, southern Coast Mountains, British Columbia. Canadian Journal of Earth Sciences 41, 903–918.
Ryder, J.M., Thomson, B., 1986. Neoglaciation in the southern Coast Mountains of British Columbia: chronology prior to the late Neoglacial maximum. Canadian Journal of Earth Sciences 23, 273–287.
Schiefer, E., Menounos, B., Wheate, R., 2007. Recent volume loss of British Columbian glaciers, Canada. Geophysical Research Letters 34. doi:10.1029/2007GL030780, 2007.
Sigafoos, R., 1964. Botanical evidence of floods and flood-plain deposition. Geologic Survey Professional Paper, United States Government Printing Office, Washington.
SigafoFriedman, J., Vincent, K., Shafroth, P., 2005. Dating floodplain stability using tree-ring response to burial. Earth Surface Processes and Landforms 30, 1077–1091.
Smith, D.J., Laroque, C.P., 1996. Dendroglaciological dating of a Little Ice Age glacial advance at Moving Glacier, Vancouver Island, British Columbia. Géographie physique et Quaternaire 50, 47–55.
Spooner, I., Haspel, R., Osborn, G.D., 2005. Holocene history of Bear River Glacier, northern Coast Ranges, British Columbia. Water, Ice, Land, and Life: The Quaternary Interface. Canadian Quaternary Association, University of Manitoba, Winnipeg, MB, Canada, p. A87.
Stokes, M.A., Smiley, T.L., 1964. An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, IL.
Strunk, H., 1998. Dating of geomorphological processes using dendrogeomorphological methods. Catena 31, 137–152.

Vanlooy, J.A., Forster, R.R., 2008. Glacial changes of five southwest British Columbia icefields, Canada, mid-1980s to 1999. Journal of Glaciology 54, 469–486.
VoorTech Consulting, 2008. MeasureJ2X [computer program]. Version 4.1.2. Holderness, NH.
Wang, T., Hamann, A., Spittlehouse, D., Aitken, S.N., 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climatology 26, 383–397.
Wilkie, K.M.K., 2006. Fluvial response to late Holocene glacier fluctuations in the Nostetuko River Valley, southern Coast Mountains, British Columbia. M.Sc. thesis, Simon Fraser University, Burnaby, BC, Canada.
Wilkie, K.M.K., Clague, J.J., 2009. Fluvial response to Holocene glacier fluctuations in the Nostetuko River Valley, southern Coast Mountains, British Columbia. Geological Society of London Special Publication 320, 199–218.