Late Holocene glacial activity at Bromley Glacier, Cambria Icefield, northern British Columbia Coast Mountains, Canada

Article *in* Canadian Journal of Earth Sciences · June 2013

DOI: 10.1139/cjes-2012-0151

2 authors:

Kira M. Hoffman
University of Victoria

Dan J. Smith
University of Victoria

NRC Research Press

ARTICLE

Late Holocene glacial activity at Bromley Glacier, Cambria Icefield, northern British Columbia Coast Mountains, Canada

Kira M. Hoffman and Dan J. Smith

Abstract: Retreating and downwasting glaciers in the British Columbia Coast Mountains are exposing the remains of forests buried during Holocene-age glacial advances. Despite recent progress in discerning the extent of these advances in the Pacific and Kitimat ranges of the southern and central Coast Mountains, comparatively little is known about the character of these advances in the Boundary Ranges of northwestern British Columbia. This research uses dendroglaciologic and radiocarbon analyses to describe late Holocene glacial advances at Bromley Glacier in the Cambria Icefield area. Four intervals of glacial expansion were identified at ca. 2470–2410, 1850, 1450, and 830 ^{14}C years BP. Absent were wood remains associated with mid-Holocene episodes of glacier expansion recorded at nearby sites. The late Holocene deposits described at Bromley Glacier are contemporaneous with those found at other glaciers in the southern Boundary Ranges and contribute to a growing understanding of the synchronous response of glaciers in this region to mass balance fluctuations during the Holocene.

Résumé : Le retrait des glaciers et leur fonte sur place dans les montagnes côtières de la Colombie-Britannique exposent des vestiges de forêts enfouies durant les avancées glaciaires de l'ère Holocène. Malgré de récents progrès dans la compréhension de ces avancées dans les chaînes Pacifique et Kitimat du sud et du centre de la Chaîne côtière, relativement peu de choses sont connues quant au caractère de ces avancées dans les chaînons Boundary du nord-ouest de la Colombie-Britannique. La présente recherche utilise des analyses dendroglaciologiques et radiocarbones pour décrire les avancées glaciaires, à l'Holocène tardif, du glacier Bromley dans le champ de glace Cambria. Quatre intervalles d'expansion glaciaire ont été identifiés à environ 2470–2410, 1850, 1450 et 830 années ^{14}C avant le présent. Il manquait toutefois des vestiges de bois associés aux épisodes d'expansion glaciaire du milieu de l'Holocène comme ceux qui avaient été trouvés à des sites avoisinants. Les dépôts de l'Holocène tardif décrits au glacier Bromley sont contemporains de ceux trouvés à d'autres glaciers dans le sud des chaînons Boundary et ils contribuent à mieux comprendre la réponse synchrone des glaciers de cette région aux fluctuations du bilan massique durant l'Holocène. [Traduit par la Rédaction]

Introduction

The rapid melting and retreat of glaciers in the British Columbia Coast Mountains is revealing land surfaces and features that were, until very recently, covered by ice for several thousand years (Koch et al. 2008). Detrital and in situ subfossil remains of forests overwhelmed during Holocene-age glacial advances are exposed in many settings (Reyes et al. 2006; Allen and Smith 2007). Dendroglaciological and radiocarbon dating of these remains has established that, following a period of early Holocene warming (Walker and Pellat 2003), glaciers located throughout the western Canadian Cordillera advanced and retreated numerous times in the mid- and late Holocene (Menounos et al. 2009). In the Coast Mountains, the rapid colonization of recently deglaciated surfaces and landforms by vegetation (ie. Larocque and Smith 2003; Koch 2009) means that each succeeding advance resulted in glaciers expanding to overwhelm and bury mature standing forests (Allen and Smith 2007; Koehler and Smith 2011).

Despite recent progress in discerning the extent of these advances in the Pacific and Kitimat ranges of the southern and central Coast Mountains (Koehler and Smith 2011; Harvey et al. 2012; Coulthard et al. 2013), comparatively little is known about the character of Holocene glacier activity in the Boundary Ranges of the northern Coast Mountains. The intrusive granitic rocks of the heavily glaciated Boundary Ranges extend northwestward from the Nass River along the Alaska – British Columbia boundary to the southern Yukon, and are flanked along their eastern margin by sedimentary and volcanic rocks of Paleozoic and Mesozoic age (Holland 1976). At its southern extent, the Boundary Ranges are distinguished by rugged, steep, mountainous terrain with extensive areas covered by high-elevation icefields and valley glaciers (Hickin et al. 2001).

Harvey et al. (2012) report that outlet glaciers from the Frank Mackie Icefield in the southern Boundary Ranges were advancing downvalley in 5450–5050 ^{14}C years BP. Following this, glacier fronts receded before periods of cooling and increased snowfall (Ryder 1987), resulted in glacier expansion in ca. 4220–3470, 3000, 2500–2300, and 1640–1390 ^{14}C years BP (Clague and Mathews 1992; Jackson et al. 2008; Harvey et al. 2012; Johnson and Smith 2012). Little Ice Age (LIA) advances were underway in the Boundary Ranges by ca. 1000 ^{14}C years BP (Clague and Mathews 1992; Osborn et al. 2013), with evidence for distinct early and late LIA events (Clague and Mathewes 1996; Jackson et al. 2008; Johnson and Smith 2012).

By the beginning of the twentieth century, the majority of glaciers in the Boundary Ranges had receded upvalley from their maximum LIA positions (McConnell 1913; Kerr 1936). Persistent negative mass balance conditions throughout the twentieth century (Moore and Demuth 2001; Wood et al. 2011) have led to substantial volumetric losses of glacier ice throughout the Coast Mountains (Vanlooy and Forster 2008; Bolch et al. 2010). Accelerated rates of melting within the last three decades follow a shift to warmer ablation season temperatures and decreased winter

Received 2 October 2012. Accepted 18 January 2013.

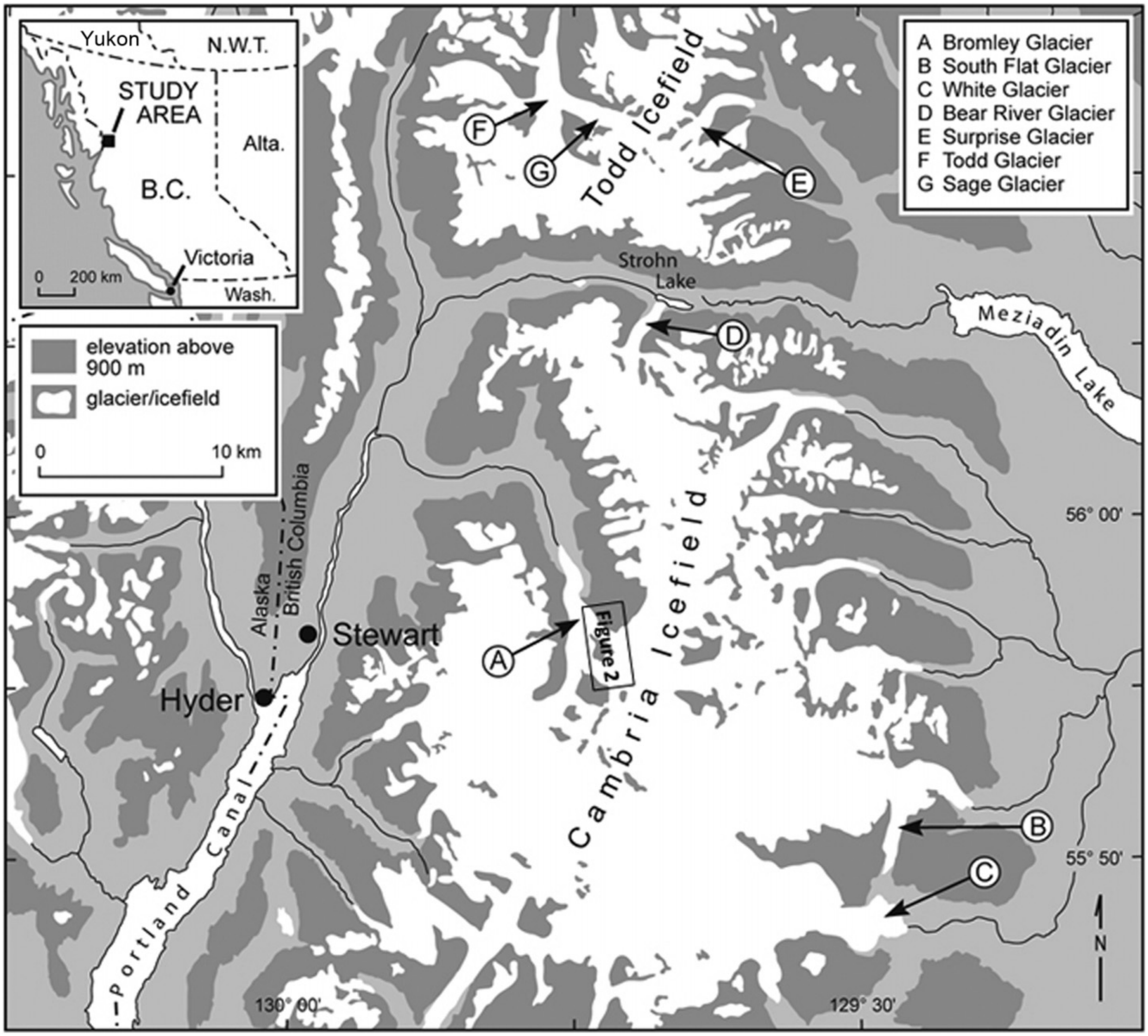
Paper handled by Associate Editor Timothy Fisher.

K.M. Hoffman and D.J. Smith. University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, P.O. Box 3060 Stn CSC, Victoria, BC V8W 3R4, Canada.
Corresponding author: D.J. Smith (e-mail: smith@uvic.ca).

Can. J. Earth Sci. **50**: 599–606 (2013) dx.doi.org/10.1139/cjes-2012-0151

Published at www.nrcresearchpress.com/cjes on 22 January 2013.

Fig. 1. Location of Cambria Icefield and the Bromley Glacier. Shown is the location of Fig. 2, the Todd Icefield, and other glaciers referred to in text.



snowfall totals at many glacier sites in the Coast Mountains (Schiefer et al. 2007; Arendt et al. 2009; Shea et al. 2009).

This paper highlights investigations at Bromley Glacier in the Cambria Icefield area, British Columbia (Fig. 1). Outlet glaciers flowing from the Cambria Icefield have receded 2.5–6 km upvalley from terminal moraines constructed during the LIA (Johnson and Smith 2012). Continuous retreat of the snout of Bromley Glacier over the last 100 years suggests the glacier has been in a prolonged negative mass balance state. Retreat rates since 1910 average 86 m/year, with the most pronounced rates occurring from 1936 to 1955 when the ice front retreated at an average rate of 213 m/year (Table 1). Unlike many Coast Mountain glaciers that experienced minor advances during the mid- to late twentieth century (ie. Vanlooy and Forster 2008), the retreat of Bromley Glacier appears only to have slowed in the 1970s and 1980s (Table 1).

Until the 1970's, five tributary glaciers merged with the Bromley Glacier close to where it spills from the Cambria Icefield (Fig. 1). Since that time all have receded and become detached, leaving only Bromley Glacier within Bitter Creek valley. Over the last 30 years, retreat and downwasting of Bromley Glacier and its tributaries has exposed a glacial forefield composed primarily of bare bedrock and glaciofluvial deposits surrounded by prominent lateral moraines, whose crests are located >100 m above the current ice level.

At Bromley Glacier, attendant lowering of the glacier surface has exposed multiple till units within the proximal face of prominent west-facing lateral moraines. In 2011, stratigraphic surveys were undertaken to describe evidence for the Holocene behaviour of Bromley Glacier. These findings are summarized in the context of expansion records at nearby glaciers and are used to refine the chronology of late Holocene glacier activity in the Cambria Icefield area.

Study area

The Cambria Icefield is situated in the Boundary Ranges ~35 km east of Stewart, British Columbia (Fig. 1). The icefield covers an area of 715 km^2, feeding several large outlet glaciers that flow into lower elevation valleys where montane forests are dominated by mixed stands of subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*) trees (MacKinnon et al. 2005). Air temperatures at Stewart (7 m above sea level (asl)) average 6 °C annually,

Table 1. Historical terminus retreat of Bromley Glacier (1910–2010).

	Terminus position		Terminus retreat			
Date (year)	Co-ordinates (latitude N, longitude W)	Elevation (m asl)	Interval (years)	Total (m)	Average rate (m/year)	Source (image number/identifier)
1910	56°01′21.33" 129°47′24.79"	305	—	—	—	McConnell 1913 (Map-50 A)
1911	56°01′18.94" 129°47′18.86"	307	1910–1911	90	90	McConnell 1913 (Map-50 A)
1936	56°00′48.83" 129°46′40.17"	314	1911–1936	610	24	Aerial photograph (BC440-44)
1947	55°59′27.47" 129°46′17.17"	377	1936–1947	2340	213	Aerial photograph (BC2183-63, -64)
1955	55°58′39.50" 129°45′36.93"	457	1947–1955	1106	138	Aerial photograph (BC5504-29, -30)
1974	55°58′25.40" 129°45′12.58"	487	1955–1974	1111	58	Aerial photograph (74V1F109)
1982	55°58′13.57" 129°44′57.23"	559	1974–1982	510	64	Aerial photograph TRIM data
1994	55°57′59.37" 129°45′06.17"	701	1982–1994	527	44	Aerial photograph (BC94030-177, -178, -179, -208)
2010	55°57′25.67" 129°44′58.56"	821	1994–2010	1024	60	GoogleEarth
			1910–2010	7318	86	

with total yearly precipitation exceeding 1840 mm (Environment Canada 2011).

Prior descriptions of the Holocene behaviour of glaciers sourced in the Cambria Icefield are few. Johnson and Smith (2012) report that White and South Flat glaciers, flowing eastward from the Cambria Icefield (Fig. 1), expanded into mature valley-bottom forests in ca. 1550–1400 and 800–600 ^{14}C years BP (Table 2). Osborn et al. (2013) report that Bear River Glacier, a large, north-facing outlet glacier (Fig. 1), advanced into valley-side forests several times between ca. 3700 to 3300 ^{14}C years BP, and again in ca. 1040 ^{14}C years BP (Table 2). Investigations by Jackson et al. (2008) at glaciers flowing from the Todd Icefield immediately north of the Cambria Icefield (Fig. 1) led to the recognition of advances in ca. 2960, 2300, 1690, 1540–1440, and 730–160 ^{14}C years BP (Table 2).

Bromley Glacier is the largest outlet glacier sourced from the Cambria Icefield (Fig. 1). The present-day snout of Bromley Glacier is located at 821 m asl (55°56′N, 129°43′W) and is the primary source of water for northwest-flowing Bitter Creek, a tributary of Bear River that enters Portland Canal at Stewart. Field surveys were completed at sites ca. 2 km upvalley from the glacier snout (55°56′23″N, 129°43′59″W). Site investigations focused on laterally extensive wood mats separating multiple till units found within nearby segments of a prominent west-facing moraine, located close to the location where tributary glaciers historically spilled from the Cambria Icefield (Fig. 2).

Methods

Reconnaissance surveys of proximal lateral moraine exposures led to the discovery of in situ wood mats and detrital wood remains (Fig. 2). Transects were established vertically up prominent gullies and the local stratigraphy described. Where the transects intercepted wood mats, the coordinates were noted and elevations recorded with a hand-held WAAS (Wide Area Augmentation System) enabled Garmin GPSmap 76CSx (manufacturer reported global positioning system (GPS) accuracy <10 m, WAAS accuracy of 3–5 m). Observed survey accuracy was ±6–10 m vertical and ±15–20 m horizontal.

Remains of large diameter stumps and boles with bark and (or) intact perimeter wood were selectively sampled to maximize the number of annual tree rings present to assist with subsequent cross-dating (Smith and Lewis 2007). Tree disks were cut with a chainsaw and duct tape was used to secure the samples in the field. Following return to the University of Victoria Tree-Ring Laboratory, the samples were allowed to air dry before perimeter wood from selected samples was submitted to Beta Analytic Inc., Miami, Florida, for radiocarbon dating. Radiocarbon dates are presented as ^{14}C years BP and were calibrated with CALIB 6.0 (Stuiver et al. 2012) to identify their age in calibrated radiocarbon years before A.D. 1950 (ka).

To assign ages to undated samples, all the disks collected were sanded to a fine polish and a flatbed scanner was employed to provide high-resolution pith-to-perimeter digital images. The width of each tree ring was measured to 0.01 mm with a WinDENDRO measuring system (Guay et al. 1992). Attempts were made to visually cross-date undated ring-width series to radiocarbon-dated series (Stokes and Smiley 1968). Where common pointer years (narrow rings) were detected (Schweingruber 1988), the software program COFECHA was used to quality check the accuracy of cross-dating (Grissino-Meyer 2001). COFECHA correlations were calculated using a 50 year segment length, lagged successively by 25 years at a one-tailed 99% confidence level (Grissino-Meyer 2001).

Observations

Field investigations at moraine sites adjacent to the Bromley Glacier led to the discovery of tree remains overwhelmed and buried in situ beneath till units as laterally contiguous wood mats. Detrital wood fragments were found within gullies eroded into the proximal face of the lateral moraines and washed to the surface of modern alluvial fans positioned below the gullies.

Section description

Site A

Site A (55°57′80″N, 129°43′40″W) was located within the near-vertical proximal face of a lateral moraine where general collapse and focused gully erosion exposed sandy to gravelly till units horizontally separated at intervals by laterally contiguous buried wood mats (Fig. 2). A 5 m thick mat of large logs and detrital wood exposed at A1 was overlain by 15 m of unconsolidated and orange-stained till, above which rested a second wood mat (A2). A small section of perimeter wood from a large log (11BGA1, Table 3) was collected from A1. Safety constraints precluded the recovery of samples from A2.

Site B

Site B (55°56′57″N, 129°43′47″W) was located 300 m upvalley from Site A within an extension of the same lateral moraine (Fig. 2). Erosion of the proximal moraine slope exposed four distinct sandy to gravelly till units separated by laterally contiguous wood mats (Fig. 2). The lowest mat (B1) consisted of a 2 m thick admixture of large boles and minor quantities of woody detritus. No paleosol or organic horizons were present, although orange-stained, sandy sediments surrounded the wood mat. Disk samples were collected from a large diameter subalpine fir bole (11BGB1) and a mountain hemlock log (11BGB8) found in situ within the buried wood mat (Table 3).

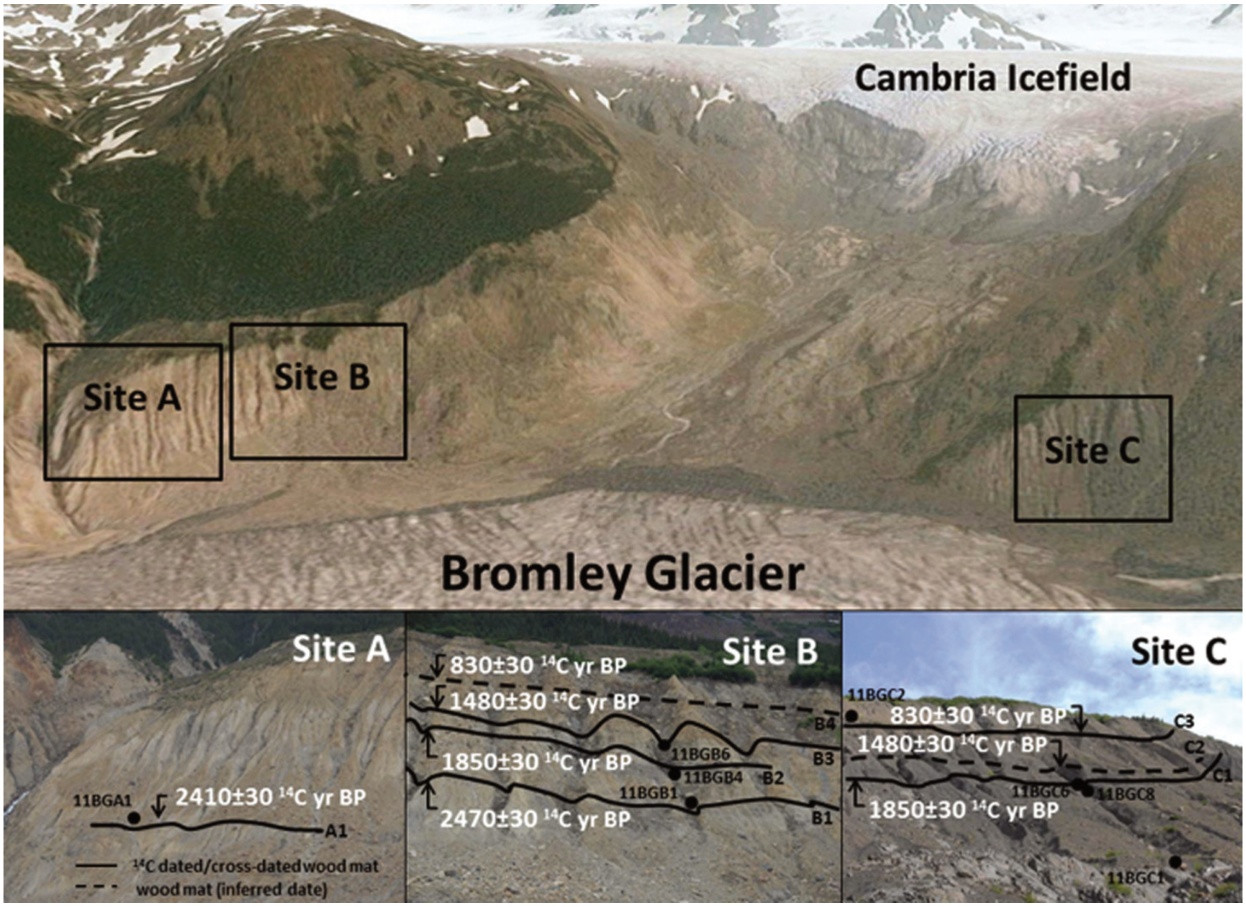
A second wood mat (B2) was found 10 m upslope where a 4 m thick assemblage of large broken boles and smaller wood fragments was surrounded by a gravelly matrix-supported till unit (Fig. 2). This wood mat rests on 10 cm organic-rich horizon underlain by a well-developed podzolic horizon formed in till (Fig. 3). A loosely packed till containing rounded, orange-stained pebbles immediately

Table 2. Summary of radiocarbon dates describing Holocene glacier activity in the Cambria and Todd icefields area.

Location	Sample Identification	Lab No.[a]	Location	No. of rings dated	^{14}C age years BP	2σ calibrated date (ka)	Source
Cambria Icefield							
Bromley Glacier	11BGB1	310681	Wood in moraine	30	2470±30	2711–2630, 2621–2433, 2414–2365	This study
	11BGA1	310684	Wood in moraine	—	2410±30	2689–2683, 2612–2597, 2498–2348	This study
	11BGC6	310685	Wood in moraine	115	1850±30	1865–1715	This study
	11BGB6	310682	Wood in moraine	76	1480±30	1409–1308	This study
	11BGC2	310683	Wood in moraine	120	830±30	789–686	This study
Bear River Glacier	B3-03	180666	Wood in moraine	—	3790±70	4408–4058, 4054–3984	Osborn et al. 2013
	B4B-04	193482	Wood in moraine	—	3710±70	428–14276, 4248–3849	Osborn et al. 2013
	B1-03	180666	Wood in moraine	—	3680±60	4221–4207, 4156–3845	Osborn et al. 2013
	BR03-801	181857	Wood in moraine	—	3680±60	4221–4207, 4156–3845	Jackson et al. 2008
	B7-04	193483	Wood in moraine	—	3540±60	3980–3686, 3660–3644	Osborn et al. 2013
	B9-04	195167	Wood in moraine	—	3410±60	3832–3554, 3532–3484	Osborn et al. 2013
	B3B-04	193481	Wood in moraine	—	3380±60	3825–3790, 3771–3745, 3730–3469	Osborn et al. 2013
	BR03-806	185808	Wood detritus	—	3340±60	3718–3442, 3423–3411	Jackson et al. 2008
	B5-03	181861	Wood in moraine	—	3330±60	3699–3441, 3427–3407	Osborn et al. 2013
	B8-04	193484	Wood in moraine	—	3310±70	3694–3387	Osborn et al. 2013
	B10B-04	193485	Wood in moraine	—	1040±50	1062–900, 867–825, 814–798	Osborn et al. 2013
South Flat and White glaciers	WG02_03	262877	Wood in moraine	—	1550±40	1524–1350	Johnson and Smith 2012
	WG03_14	262878	Wood detritus	—	1530±40	1523–1342	Johnson and Smith 2012
	WG01_01	262876	Wood in moraine	—	1460±40	1410–1296	Johnson and Smith 2012
	WG06_04	250505	Wood in moraine	—	1400±40	1378–1272	Johnson and Smith 2012
	WG02_03	262877	Wood in moraine	—	1360±40	1344–1233, 1207–1181	Johnson and Smith 2012
	WG05_02	262879	Wood in detritus	—	1360±50	1344–1233, 1207–1181	Johnson and Smith 2012
	WG07_01	250501	Lake sediments	—	1280±50	1294–1118, 1114–1081	Johnson and Smith 2012
	WG08_12	273508	Lake sediments	—	960±40	954–944, 938–784	Johnson and Smith 2012
	WG09_16	250503	Lake sediments	—	810±40	790–673	Johnson and Smith 2012
	WG09_18	250504	Lake sediments	—	610±60	669–530	Johnson and Smith 2012
Todd Icefield							
Surprise Glacier	SG03-801	181858	Wood in moraine	—	2960±70	3342–2945, 293–12930	Jackson et al. 2008
	SG04-828	197984	Wood in moraine	—	1690±60	1726–1416	Jackson et al. 2008
	SG04-829	197986	Wood in moraine	—	1440±60	1514–1461, 1439–1434, 1420–1268	Jackson et al. 2008
	SG04-804	197983	Wood in moraine	—	610±50	664–537	Jackson et al. 2008
Todd Glacier	TG03-806	181859	Wood in moraine	—	2300±60	2486–2478, 2473–2146	Jackson et al. 2008
	TG04-874	199708	Wood detritus	—	1690±60	1726–1416	Jackson et al. 2008
	TG03-815	181560	Wood in moraine	—	1540±60	1540–1313	Jackson et al. 2008
	TG04-805	197989	Wood in moraine	—	730±60	774–626, 605–557	Jackson et al. 2008
	TG04-838	197990	Wood in moraine	—	660±60	689–539	Jackson et al. 2008
	TG04-871	197991	Wood in moraine	—	660±60	689–539	Jackson et al. 2008
	TG04-801	197986	Wood detritus	—	450±60	625–606, 557–422, 399–316	Jackson et al. 2008
	TG04-872	208442	Wood detritus	—	410±60	531–417, 414–315	Jackson et al. 2008
	TG04-879	208443	Wood in moraine	—	360±60	507–305	Jackson et al. 2008
	TG04-802	197987	Glacier-killed tree	—	160±60	295–56, 46–0	Jackson et al. 2008

[a]Laboratory: Beta Analytic Inc., Miami, Florida.

Fig. 2. GoogleEarth image (6 July 2010) showing location of sample sites along the eastern perimeter of Bromley Glacier. Illustrated are the laterally contiguous wood mats, the locations where dated samples were recovered, and the radiocarbon age assigned to each wood mat. yr, years.



overlies the wood mat. Cross-sections were collected at the base of the wood mat from two mountain hemlock logs (11BGB3, 1BGB4) and two subalpine fir logs (11BGB2, 11BGB5; Table 3).

A third wood mat (B3), located ca. 50 m vertically upslope from the lower contact of B2, was exposed in an incised gully cutbank (Figs. 2, 4). Disk samples were recovered from protruding in situ mountain hemlock (11BGB6) and subalpine fir (11BGB7) logs (Table 3).

A fourth wood mat (B4) was visible ca. 20 m above B3, but was inaccessible (Fig. 2). The mat was located immediately below the lateral moraine crest and ~50 m below the present-day forest.

Site C

Site C (55°56′16″N, 129° 43′76" W) was located on a northwest-facing lateral moraine slope 1.5 km upvalley from Site B (Fig. 2). Aerial photographs show the site covered by glacier ice as recently as 1994 (BC94030-177). The proximal moraine face was eroded by deeply incised gullies, exposing tills that ranged from units characterized by fine sands to others largely composed of unconsolidated cobbles and boulders.

Detrital wood littered the apex of small debris fans emerging from gullies positioned 40 m above the ice surface at Site C (Fig. 2). Cross-sections were collected from two large trunk fragments (11BGC1, 11BGC7, Table 3) found partially buried in gravels and sands on one fan surface.

Gully traverses above the fan led to the discovery of wood mats extending across the section face at three elevations (Fig. 2). At C1 a wood mat composed of detrital wood fragments was positioned on the surface of matrix-supported till characterized by coarse, black-coloured gravels. Three mountain hemlock samples were collected, one located midway through the vertical extent of the till unit (11BGC5) and two emplaced at the contact of the till with a compacted overlying till (11BGC6, 11BGC8; Table 3).

Twenty vertical metres above C1 at C2, a 1 m thick assemblage of small diameter bole fragments and alder (*Alnus*) branches was located buried below till (Fig. 2). Disk samples were collected from fragments of two mountain hemlock trees (11BGC3, 11BGC4; Table 3). Close to the moraine crest at Site C3 (Fig. 2), a solitary mountain hemlock log (11BGC2; Table 3) with 121 rings was exposed within a matrix of dense till.

Radiocarbon dating

The oldest wood sample was recovered at B1 where 121 perimeter rings from a subalpine fir bole (11BGB1) date to 2470 ± 30 ^{14}C years BP (2.71–2.37 ka). A contemporaneous age of 2410 ± 30 ^{14}C years BP (2.69–2.35 ka) was assigned 30 perimeter rings from a bole (11BGA1) found at A1 (Table 2), suggesting the two wood mats were buried at the same time.

At Site C1, perimeter wood (115 rings) from a large mountain hemlock log (11BGC6) found on the surface of alluvial fan at C1 dates to 1850 ± 30 ^{14}C years BP [1.87–1.72 ka]. Perimeter wood (76 rings) from an in situ log (11BGB6) located at B3 dates to 1480 ± 30 ^{14}C years BP [1.41–1.31 ka]. Approximately 125 m above C1 perimeter wood (120 rings) from a partially buried log dated to 830 ± 30 ^{14}C years BP [0.79–0.69 ka] at C3 (Table 2).

Dendroglaciological dating

Cross-dating of tree ring series was used to assign radiocarbon ages to three samples from Sites B and C. Undated samples from

Table 3. Dendroglaciological samples collected from wood mats at Bromley Glacier showing (A) total number of annual rings and radiocarbon age assigned to perimeter wood and (B) cross-dating used to establish radiocarbon age of glacier-killed trees.

(A) Dendroglaciological samples.

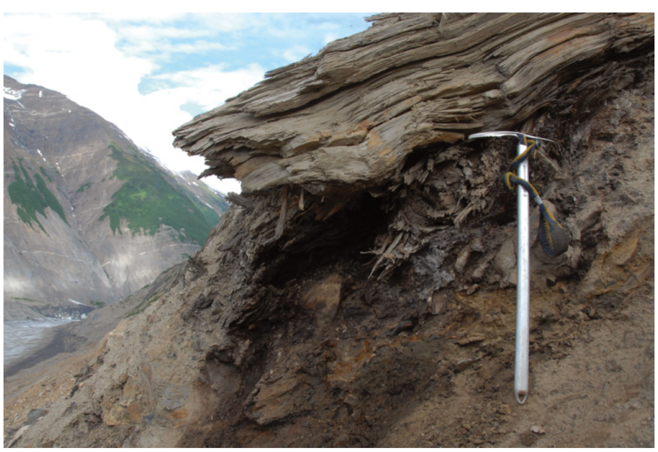
Site	Unit	Elevation (m asl)	Sample No.	Species	No. of annual rings	Lab No.[a]	^{14}C years BP	Tree-ring cross-date[b] (^{14}C years BP)	Description
Site A	A1	890	11BGA1	Unknown	>30	310681	2410±30	—	Bole in wood mat at A1
Site B	B3	970	11BGB7	SAF[c]	87	—	—	—	Bole in wood mat at B3
	B3	968	11BGB6	MH[d]	130	310682	1480±30	—	Bole in wood mat at B3
	B2	917	11BGB2	SAF	72	—	—	—	Bole eroded from wood mat at B2
	B2	917	11BGB3	MH	96	—	—	—	Bole in wood mat at B2
	B2	915	11BGB4	MH	192	—	—	1850±30	Bole in wood mat at B2
	B2	915	11BGB5	MH	123	—	—	—	Bole in wood mat at B2
	B1	897	11BGB8	MH	297	—	—	—	Bole eroded and spilled into gully above B1
	B1	895	11BGB1	SAF	121	310684	2470±30	—	Bole in wood mat at B1
Site C	C3	1075	11BGC2	MH	120	310683	830±30	—	Bole in till at C3
	C2	987	11BGC3	MH	127	—	—	—	Branch in till at C2
	C2	985	11BGC4	MH	70	—	—	—	Branch in till at C2
	C1	960	11BGC6	MH	115	310685	1850±30	—	Bole in till at C1
	C1	957	11BGC8	MH	201	—	—	1850±30	Bole in till at C1
	C1	950	11BGC5	MH	75	—	—	—	Bole in till at C1
	C	931	11BGC7	MH	140	—	—	—	Detrital wood on alluvial fan below gully
	C	930	11BGC1	MH	255	—	—	1480±30	Detrital wood on alluvial fan below gully

(B) Tree-ring cross-dating.

	Sample No.	Correlation	Duration (years)	^{14}C years BP
Chronology 1				
	11BGB6	0.470	0–130	1480±30
	11BGC1	0.418	18–129	—
Series intercorrelation[e]		0.404	0–130	
Chronology 2				
	11BGB4	0.332	189–281	—
	11BGC6	0.515	209–324	1850±30
	11BGC8	0.539	0–297	—
Series intercorrelation		0.444	0–324	

[a]Laboratory: Beta Analytic Inc.
[b]Age assigned to samples cross-dated to radiocarbon dated samples (see B).
[c]MH: mountain hemlock.
[d]SAF: subalpine fir.
[e]Series intercorrelation: strength of common signal in chronology.

Fig. 3. Buried podzolic soil horizon, with surface organics and wood detritus at Site B2 at 917 m asl preserved below sample 11BGB2 dating to 1850 ± 30 ^{14}C years BP.



Sites B2 (11BGB4) and C1 (11BGC8) cross-date to radiocarbon dated wood recovered at Site C1 (11BGC6). The resulting chronology (0.444) spans a 351 year interval (Table 3*b*). The kill date assigned to the outermost rings of samples at Site C1 suggests that trees at this location were killed and buried at least 57 years before trees located downvalley at Site B2 were killed in 1850 ± 30 ^{14}C years BP.

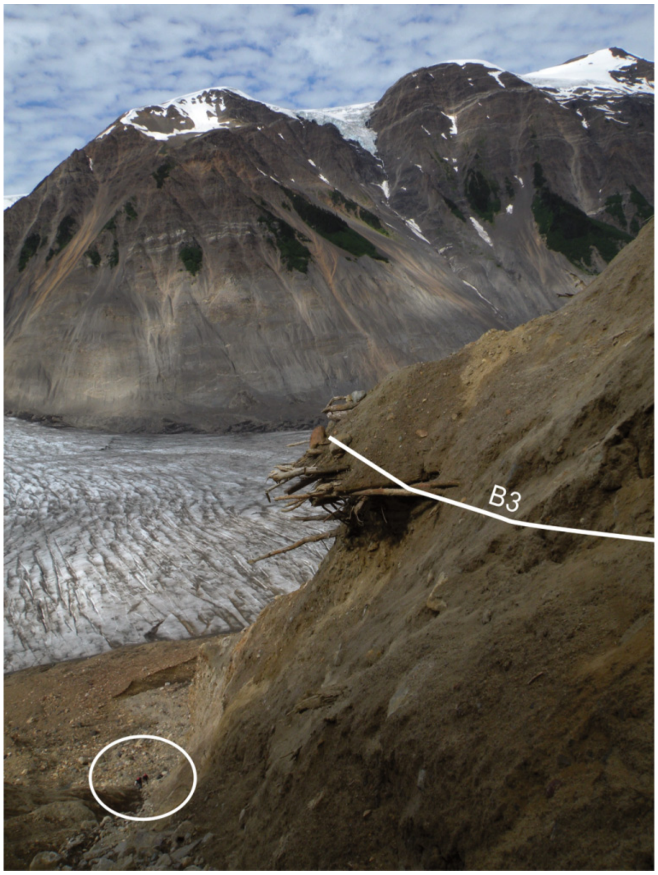
An undated sample found on the fan surface below C1 (11BGC1) cross-dates to radiocarbon dated wood recovered at Site B3 (11BGB6; Table 3). The resulting floating chronology (0.404) spans a 130 year period and is interpreted to suggest that Bromley Glacier was burying living trees at Sites B3 and C2 at 1480 ± 30 ^{14}C years BP (Table 3).

Attempts were made to cross-date the remaining undated samples to previously constructed Holocene-age dendroglaciological chronologies from other sites in the Cambria and Todd icefields area (Jackson et al. 2008; Johnson and Smith 2012). Cross-dating between sites was, however, unsuccessful due to complacent ring-widths, low mean sensitivity, and differences in tree species between the samples.

Discussion

Our investigations at Bromley Glacier did not identify wood remains associated with any of the mid-Holocene episodes of

Fig. 4. Exposed proximal face of lateral moraine at Site B3 showing location of wood mat dating to 1480 ± 30 ^{14}C years BP (B3) at 968 m asl. Shown in the background is the surface of Bromley Glacier at ca. 910 m asl. Figures are circled for scale.



glacier expansion described by Clague and Mathews (1992) and Harvey et al. (2012). There was also an absence of deposits associated with the 3790 ± 70 to 3310 ± 70 ^{14}C years BP advances preserved within the nearby Bear River Glacier moraine (Jackson et al. 2008; Osborn et al. 2013; Table 2) and the 2960 ± 60 ^{14}C years BP advance recorded at Surprise Glacier (Jackson et al. 2008; Table 2).

The presence of large boles and logs entombed in the wood mats at Sites A1 and B1 suggest Bromley Glacier was expanding downvalley 2470 ± 30 to 2410 ± 30 ^{14}C years BP to overwhelm a mature valley-side forest (297 years old, 11BGB8). Following this advance, the glacier downwasted and retreated upvalley sufficiently long for soils and a valley-side forest exceeding 192 years in age (11BGB4) to develop on the proximal face of the lateral moraine at B2 (Fig. 2).

Renewed expansion in 1850 ± 30 ^{14}C years BP saw Bromley Glacier killing mature mountain hemlock stands at Sites B2 and C1. Following this advance, the glacier surface either downwasted or stabilized before a second phase of expansion at 1480 ± 30 ^{14}C years BP buried mature trees at B3 (130 years, 11BGB6) and C2 (255 years, 11BGC1) (Fig. 2).

Bromley Glacier downwasted following the 1480 ± 30 ^{14}C years BP advance before expanding to kill a 121 year old mountain hemlock tree (11BGC2) at C3 at 830 ± 30 ^{14}C years BP. Positioned close to the moraine crest at 1075 m asl, the location of this sample indicates that Bromley Glacier was of sufficient size to merge with the glacier tongue spilling from the Cambria Icefield between Sites B and C (Fig. 2), and likely filled the trunk valley to an elevation close to the present-day tree line.

The dendroglaciological evidence recovered at Bromley Glacier describes episodes of late Holocene expansion that have regional correlatives. Episodes of glacier expansion at 2470 ± 30 to 2410 ± 30 ^{14}C years BP are presumed equivalent to an advance of Sage Glacier, a tributary to Todd Glacier, into standing forests at 2300 ± 60 ^{14}C years BP (Jackson et al. 2008; Table 2) and regional advances also occurring at this time (Koehler and Smith 2011).

Expansion of Bromley Glacier at 1850 ± 30 and 1480 ± 30 ^{14}C years BP are expressions of the two-phase First Millennium Advance (FMA) described by Reyes et al. (2006). The synchronicity of early and late FMA activity in the Boundary Ranges is demonstrated by similarly dated advances of Forrest Kerr (Lewis and Smith 2005), Frank Mackie (Clague and Mathews 1992), South More (Craig et al. 2011), Surprise (Jackson et al. 2008), and White (Johnson and Smith 2012) glaciers. Contemporaneous intervals of early and late FMA glacier expansion are reported from sites located in southern Alaska (Barclay et al. 2009).

Expansion of Bromley Glacier at 830 ± 30 ^{14}C years BP is presumed synchronous with the early LIA advance of Bear River Glacier at 1040 ± 50 ^{14}C years BP (Osborn et al. 2013), and White and South Flat glaciers at 900–810 ± 40 ^{14}C years BP (Johnson and Smith 2012). Although no dated evidence of late LIA activity was collected at Bromley Glacier, nearby Surprise Glacier was expanding at 240 and 100 calendar years BP (Jackson et al. 2008). It seems likely that the sparsely forested terminal moraines found downvalley of the snout of Bromley Glacier in Bitter Creek valley in 1910 (McConnell 1913) describe the maximum extent of the glacier in the eighteenth and nineteenth centuries.

Conclusions

Reconstruction of the late Holocene behaviour of Bromley Glacier contributes to our understanding of the synchronous response of glaciers in the Boundary Ranges to persistent episodes of positive mass balance. At Bromley Glacier, four intervals of glacial expansion were recorded by glacially killed and glacially buried trees: (1) an advance at 2470 ± 30 to 2410 ± 30 ^{14}C years BP; (2) a two-stage advance corresponding to the FMA at 1850 ± 30 and 1480 ± 30 ^{14}C years BP; and (3) an early LIA advance at 830 ± 30 ^{14}C years BP. These findings reveal substantial changes in the size and thickness of Bromley Glacier over the past 2500 years and facilitate a broader understanding of glacier behaviour in the northern British Columbia Coast Mountains.

Acknowledgements

We are grateful for the field assistance of Bethany Coulthard and Jessica Craig. Research funding was provided by grant to D.J. Smith from the Natural Sciences and Engineering Research Council of Canada (NSERC). Our field research was partially supported by grants to K.M. Hoffman from the Northern Scientific Training Program (NSTP) and the Royal Canadian Geographic Society (RCGS).

References

Allen, S.M., and Smith, D.J. 2007. Late Holocene glacial activity of Bridge Glacier, British Columbia Coast Mountains. Canadian Journal of Earth Sciences, **44**(12): 1753–1773. doi:10.1139/E07-059.

Arendt, A., Walsh, J., and Harrison, W. 2009. Changes of glaciers and climate in northwestern North America during the late twentieth century. Journal of Climate, **22**: 4117–4134. doi:10.1175/2009JCLI2784.1.

Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Tree-ring cross-dates for a First Millennium Advance of Tebenkof Glacier, southern Alaska. Quaternary Research, **71**: 22–26. doi:10.1016/j.yqres.2008.09.005.

Bolch, T., Menounos, B., and Wheate, R. 2010. Landsat-based inventory of glaciers in western Canada, 1985–2005. Remote Sensing of Environment, **114**: 127–137. doi:10.1016/j.rse.2009.08.015.

Clague, J.J., and Mathewes, R.W. 1996. Neoglaciation, glacier-dammed lakes, and vegetation change in northwestern British Columbia, Canada. Arctic and Alpine Research, **28**: 10–24. doi:10.2307/1552081.

Clague, J.J., and Mathews, W.H. 1992. The sedimentary record and Neoglacial history of Tide Lake, northwestern British Columbia. Canadian Journal of Earth Sciences, **29**(11): 2383–2396. doi:10.1139/e92-186.

Coulthard, B., Smith, D.J., and Lacourse, T. 2013. Dendroglaciological investigations of mid- to late-Holocene glacial activity in the Mt. Waddington area, British Columbia Coast Mountains, Canada. The Holocene, **23**(1): 93–103. doi: 10.1177/0959683612455537.

Craig, J. Smith, D.J., and Lewis, D. 2011. Dendroglaciological exploration at South More Glacier, Northern British Columbia Coast Mountains. Canadian Association of Geographers Annual Meeting and Conference. 31 May – 4 June 2011. University of Calgary, Calgary, Alberta. Program and Abstract, Volume 70.

Environment Canada 2011. Stewart, B.C. Climate norms 1971–2000. Accessed 5 August 2011 from http://www.climate.weatheroffice.gc.ca/climate_normals/results_e.html.

Grissino-Meyer, H.D. 2001. Evaluating cross-dating accuracy: A manual and tutorial for the computer program COFECHA. Tree Ring Research, **57**: 205–221.

Guay, R., Gagnon, R., and Morin, H. 1992. MacDENDRO, a new automatic and iterative tree ring measurement system based on image processing. Tree Rings and Environment: Proceedings of the International Dendrochronological Symposium, Ystad, Sweden, 3–9 September 1990. Lundqua Report. Lund University. pp. 128–129.

Harvey, J.E., Smith, D.J., Laxton, S., Desloges, J., and Allen, S. 2012. Mid-Holocene glacier expansion between 7500–4000 cal. yr BP in the British Columbia Coast Mountains, Canada. The Holocene, **22**: 973–983. doi:10.1177/0959683612437868.

Hickin, A.S., Brooks, E.D., and Brobowsky P.T. 2001. North Coast LRMP aggregate potential map: accompanying notes. British Columbia Ministry of Energy, Mines and Petroleum Resources, Victoria British Columbia, Open File 2001-19, map scale 1:2 000 000.

Holland, S. 1976. Landforms of British Columbia: a Physiographic Outline. British Columbia Ministry of Energy, Dept. of Mines and Petroleum. Victoria, British Columbia. p. 136.

Jackson, S.I., Laxton, S.C., and 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**(1): 83–98. doi: 10.1139/E07-071.

Johnson, K., and Smith, D.J. 2012. Dendroglaciological reconstruction of late Holocene glacier activity at White and South Flat Glaciers, Boundary Range, northern British Columbia Coast Mountains, Canada. The Holocene, **22**: 984–992. doi:10.1177/0959683612437866.

Kerr, F.A. 1936. Quaternary glaciation in the Coast Range, northern British Columbia and Alaska. The Journal of Geology, **44**: 681–700. doi:10.1086/624470.

Koch, J. 2009. Improving age estimates for late Holocene glacial landforms using dendrochronology – Some examples from Garibaldi Provincial Park, British Columbia. Quaternary Geochronology, **4**: 130–139. doi:10.1016/j.quageo.2008.11.002.

Koch, J., Clague, J.J., and Osborn, G. 2008. Alpine glaciers in western Canada approach their smallest size of the past 7000 years. Geophysical Research Abstracts, **10**: EGU2008 A-01749.

Koehler, L., and Smith, D.J. 2011. Late Holocene glacial activity in Manatee Valley, southern Coast Mountains, British Columbia, Canada. Canadian Journal of Earth Sciences, **48**(3): 603–618. doi:10.1139/E10-087.

Larocque, S.J., and 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**(10): 1413–1436. doi:10.1139/E03-053.

Lewis, D.H., and Smith, D.J. 2005. Dendroglaciological evidence of late Holocene glacier activity at Forrest Kerr Glacier, Andrei Icefield, northern British Columbia Coast Mountains. Paper presented at Annual Meeting of the Canadian Association of Geographers. Tuesday, May 31 - Saturday, June 4, 2005. London, Ontario.

MacKinnon, A., Pojar, J., and Coupe, R. 2005. Plants of Northern B.C. (2nd ed.) Lonepine Publishers, Edmonton, Canada. p. 113.

McConnell, R.G. 1913. Portions of Portland Canal and Skeena Mining Divisions, Skeena District, BC. Geological Survey of Canada, Memoir 32. Ottawa.

Menounos, B., Osborn, G., Clague, J.J., and Luckman, B.H. 2009. Latest Pleistocene and Holocene glacier fluctuations in western Canada. Quaternary Science Reviews, **28**: 2049–2074. doi:10.1016/j.quascirev.2008.10.018.

Moore, R.D., and Demuth, M.N. 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, **15**: 3473–3486. doi:10.1002/hyp.1030.

Osborn, G., Haspel, R., and Spooner, I. 2013. Late-Holocene fluctuations of the Bear River Glacier, northern Coast Ranges of British Columbia, Canada. The Holocene, **23**: 330–338. doi:10.1177/0959683612463093.

Reyes, A.V., Wiles, G.C., Smith, D.J., Barclay, D.J., Allen, S., Jackson, S., Larocque, S., Laxton, S., Lewis, D., Calkin, P.E., and Clague, J.J. 2006. Expansion of alpine glaciers in Pacific North America in the First Millennium A.D. Geology, **34**: 57–60. doi:10.1130/G21902.1.

Ryder, J.M. 1987. Neoglacial history of the Stikine–Iskut area, northern Coast Mountains, British Columbia. Canadian Journal of Earth Sciences, **24**(7): 1294–1301. doi:10.1139/e87-125.

Schiefer, E., Menounos, B., and Wheate, R. 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, **34**: L16503. doi:10.1029/2007GL030780. doi:10.1029/2007GL030780.

Schweingruber, F.H. 1988. Tree Rings: Basics and Applications of Dendrochronology. Kluwer Academic Publishers, Dordecht, Holland. p. 292.

Shea, J.M., Moore, D.R., and Stahl, K. 2009. Derivation of melt factors from glacier mass balance records in western Canada. Journal of Glaciology, **55**: 123–130. doi:10.3189/002214309788608886.

Smith, D.J., and Lewis, D. 2007. Dendroglaciology. Encyclopedia of Quaternary Science. *Edited by* S.A. Elias. Elsevier Scientific. Volume 2. pp. 986–994.

Stokes, M.A., and Smiley, T.L. 1968. An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago. p. 73.

Stuiver, M., Reimer, P.J., and Reimer, R. 2012. CALIB 6.0. http://calib.qub.ac.uk/calib/.

Vanlooy, J.A., and Forster, R.R. 2008. Glacial changes of five southwest British Columbia Icefields, Canada, mid-1980s to 1999. Journal of Glaciology, **54**: 469–486. doi:10.3189/002214308785836931.

Walker, I., and Pellat, M. 2003. Climate change in British Columbia- a paleoenvironmental perspective. Canadian Water Resources Journal, **28**: 531–566. doi:10.4296/cwrj2804531.

Wood, L., Smith, D.J., and Demuth, M.N. 2011. Extending the Place Glacier mass balance record to AD 1585, using tree-rings and wood density. Quaternary Research, **76**: 305–313. doi:10.1016/j.yqres.2011.07.003.