Quaternary Science Reviews 51 (2012) 71–80

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

Late Holocene glacier expansion in the Cariboo and northern Rocky Mountains, British Columbia, Canada

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ARTICLE INFO

Article history:
Received 12 June 2012
Received in revised form
20 July 2012
Accepted 24 July 2012
Available online

Keywords:
Holocene
Glacier advance
Environmental reconstruction

ABSTRACT

Castle Creek Glacier in the Cariboo Mountains of British Columbia remained close to its Little Ice Age limit for most of the past 1500 years, without significant recession until the 20th century. This conclusion is based on radiocarbon-dated detrital and in-situ plant material overrun by the glacier, and the sedimentary record from informally named On–off Lake, which received clastic sediments only when Castle Creek Glacier crossed a hydrologic divide 330 m upvalley of the Little Ice Age limit. Plant macrofossils recovered from the transition between basal inorganic silt and overlying organic silty clay in a sediment core from the lake indicate that the glacier first retreated behind the divide ca. 10.92–9.70 ka. Ages of 8.97–8.61 and 5.58–5.53 ka on detrital wood from the glacier's forefield may record earlier advances, but the first unequivocal evidence of glacier expansion is from an overridden stump with an age of 4.96–4.45 ka. Continuous accumulation of gyttja within On–off Lake, however, indicates that Castle Creek Glacier did not cross the hydrologic divide at any time during the first half of the Holocene. Glacigenic sediments began to accumulate in the lake between 2.73 and 2.49 ka, indicating that Castle Creek Glacier expanded beyond the hydrologic divide at that time. A coincident advance is also recorded in the northern Rocky Mountains of British Columbia at Kwadacha Glacier, which overran a vegetated surface at 2.69–2.36 ka. Clastic sedimentation in On–off Lake ceased soon after the Bridge River volcanic eruption (2.70–2.35 ka), indicating that Castle Creek glacier retreat to a position upvalley of the divide at that time. Sedimentation resumed before 1.87–1.72 ka when the glacier advanced again past the hydrologic divide. Following a second retreat, Castle Creek Glacier advanced across the divide a final time at ca. 1.54–1.42 ka. The snout of the glacier remained less than 330 m upvalley of the Little Ice Age moraine until the early twentieth century when annual moraines indicate rapid frontal recession to a position upvalley of the hydrologic divide. These data collectively indicate that glaciers in the Cariboo Mountains of British Columbia nearly achieved their all-time Holocene limits as early as 2.73–2.49 ka and climatic conditions in the early 20th century abruptly ended a 1500-year period favoring glacier expansion.

1. Introduction

Reconstructing the history of past glacier margins remains a key method to infer the timing, magnitude, and duration of past climatic change in mountain environments. However, several problems limit the use of conventional methods for documenting glacier activity. In the Northern Hemisphere, glacier advances of the seventeenth, eighteenth, and nineteenth centuries were generally the most extensive of the Holocene (Davis et al., 2009), and terminal moraines that demarcate the position of glaciers during earlier advances are obscured or absent. Sheared tree stumps preserved in growth position in a glacier forefield may provide calendar ages for intervals when the trees were overridden by glaciers (Luckman, 1995), but they do not indicate the spatial or temporal extent of

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http://dx.doi.org/10.1016/j.quascirev.2012.07.023

glacier advance downvalley of the site where the trees were killed. Sediment cores from proglacial lakes can provide continuous proxy records of upvalley glacier activity (Leonard and Reasoner, 1999), but the lakes may also receive sediment from non-glacial sources, which can confound the interpretation of their records.

Attempts to date pre-Little Ice Age (LIA) advances illustrate the problems posed by the fragmentary nature of the geologic record of glacier activity. Although several LIA and pre-LIA advances are recognized in the past 2000 (Reyes et al., 2006; Barclay et al., 2009; Koch and Clague, 2011), it is uncertain whether glaciers remained in extensive positions between these events. However, Castle Creek Glacier in the Cariboo Mountains of British Columbia (Fig. 1) has a relatively unusual topographic setting that provides insights into its recent history. As the glacier advanced downvalley and thickened during the Holocene, its northern margin overtopped a hydrological divide and extended northward into a different drainage basin containing a small lake that we have informally named On–off Lake. Recent studies describe the value of such 'proglacial-threshold' lakes in constraining the history of Holocene glacier fluctuations (e.g. Kaplan et al., 2002; Miller et al., 2005; Bakke et al., 2010; Briner et al., 2010). The sediment record from On–off Lake provides critical information about the relative extent and timing of advances of Castle Creek Glacier. We combine the sediment record from this proglacial-threshold lake with data from overridden plant material in the forefields of Castle Creek Glacier and two adjacent glaciers, plus data from Kwadacha Glacier in the northern Rocky Mountains, to develop a detailed record of Holocene glacier activity in western Canada.

2. Study area

Castle Creek Glacier (informal name) is a small (9.4 km^2) glacier in the Cariboo Mountains of east-central British Columbia (Fig. 1). The glacier flows 5.9 km northward from a cirque through an elevation range of 2750–1850 m above sea level (asl). Meltwater presently drains southeast via Castle Creek. On–off Lake is located in a small valley that drains north from the Castle Creek Glacier forefield. During the Late Holocene the northern lobe of the glacier flowed over a bedrock-controlled hydrological divide at 1780 m asl, 1.39 km downvalley of the 2008 glacier margin, and contributed meltwater to On–off Lake (Figs. 1 and 2). Part of the outermost Holocene moraine of Castle Creek Glacier descends to 1770 m asl and terminates at the southern end of On–off Lake, 330 m downvalley of the hydrologic divide. No other glaciers feed meltwater to On–off Lake, and there is little glacial sediment on the gentle terrain between the hydrologic divide and the lake. Thus, we interpret clastic sediments deposited in the lake to indicate that the glacier extended across the hydrologic divide.

Informally named Chiqui Glacier is a small glacier located about 4 km west of Castle Creek Glacier (Fig. 1). It flows 4.5 km northward from an elevation of 2500 m asl to 1900 m asl. Informally named Chap Glacier is located 20 km south-west of Castle Creek Glacier

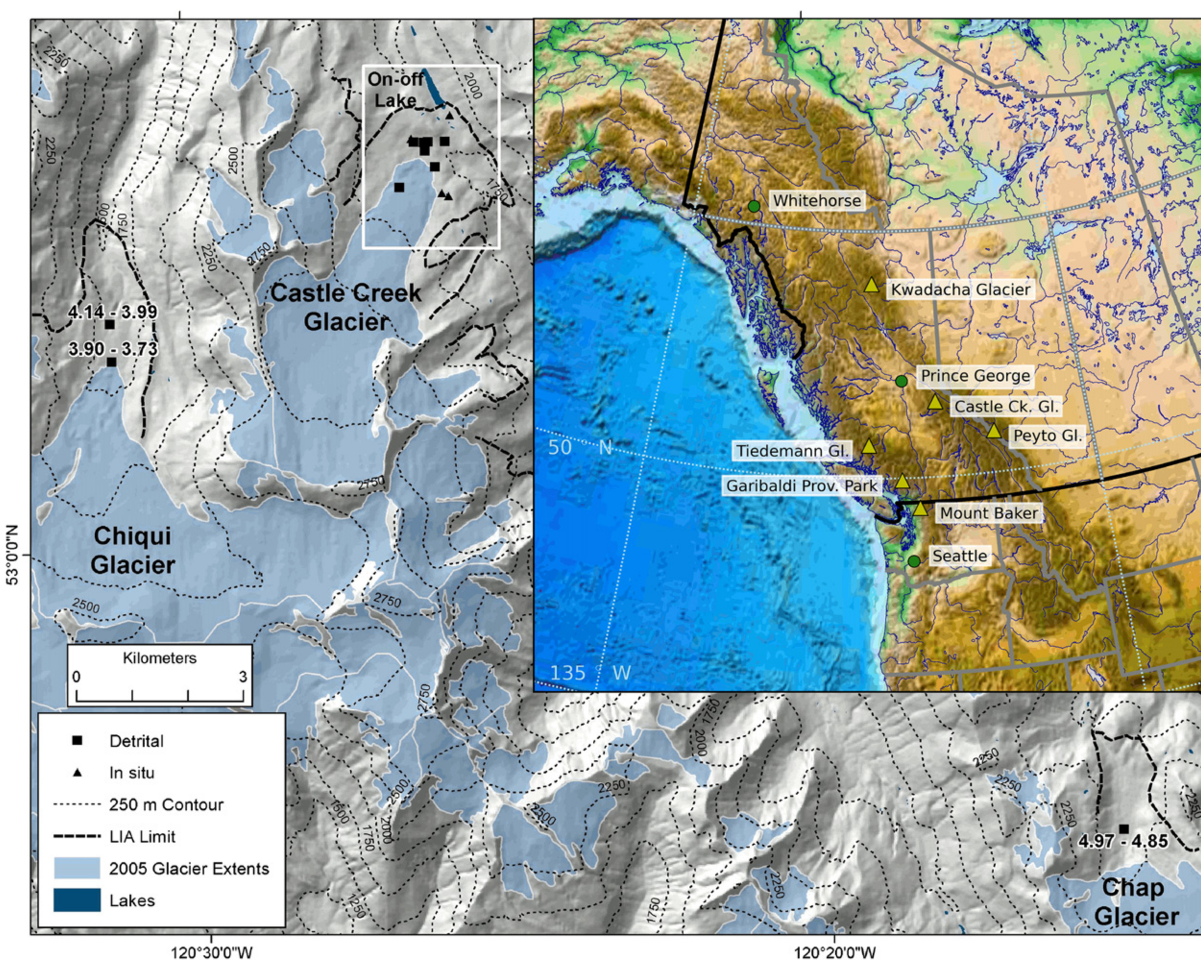

Fig. 1. Study area showing the locations of Castle Creek Glacier, Chiqui Glacier, Chap Glacier, and On–off Lake (informal names) in the Cariboo Mountains, British Columbia. Triangles and squares represent in-situ and detrital radiocarbon samples, respectively with calibrated age ranges in kilo calendar years BP (ka). White box is the area shown in Fig. 2

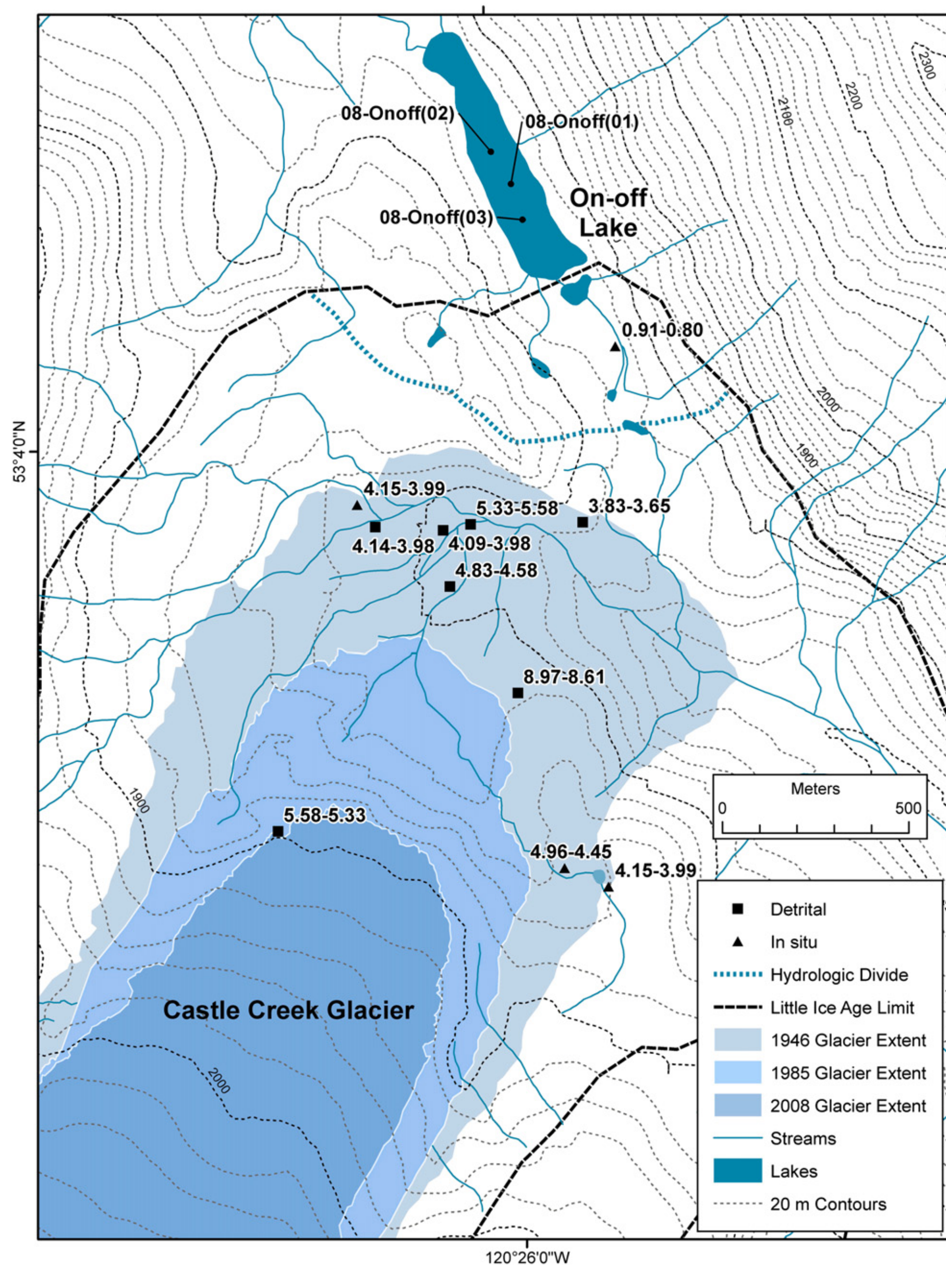

Fig. 2. Castle Creek Glacier forefield and On–off Lake. Triangles and squares demarcate in-situ and detrital radiocarbon samples, respectively with calibrated age ranges in kilo calendar years BP (ka). Circles within On–off Lake are sediment core locations.

and flows 2.6 km northward, through an elevation range of 2600–2000 m asl.

Kwadacha Glacier (12.6 km^2) is an outlet glacier of the Lloyd George Icefield in the northern Rocky Mountains (Figs. 1 and 3). It flows 6.4 km south-southeast from 2500 m asl to its 2009 terminus at 1615 m asl. A prominent end moraine and trimline 3.0 km downvalley from the 2009 snout clearly demarcate the recent maximum extent of the glacier (Figs. 3 and 4). Based on its downvalley position and unvegetated state, this moraine is assumed to date to the end of the LIA.

3. Methods

We collected three sediment cores from On–off Lake with a percussion coring device in May 2008. The bathymetry of the lake was not determined, but all cores were retrieved along the centerline of the lake in water depths of 6–7 m (Fig. 2). In the laboratory we split, logged, and photographed the sediment cores and sampled every 1 cm for magnetic susceptibility, water content, wet and dry density, and organic matter content. Organic matter content determined by loss-on-ignition (Heiri et al., 2001) was compared to total carbon determined with a Carlo Erba CN Analyzer (Verardo et al., 1990). The data are linearly related ($r^2 = 0.98$; $n = 20$) over the range of measured LOI values (1.27–20.54%). Twenty samples from core 08-Onoff(02) were selected for particle-size analysis by laser diffraction using a Mastersizer 2000™ (Sperazza et al., 2004).

We mapped discontinuous moraines and well-defined trimlines below treeline using stereo photogrammetric equipment. This mapping allowed us to demarcate former glacier positions and confirm our field-based GPS mapping of the hydrologic divide (Figs. 1 and 2).

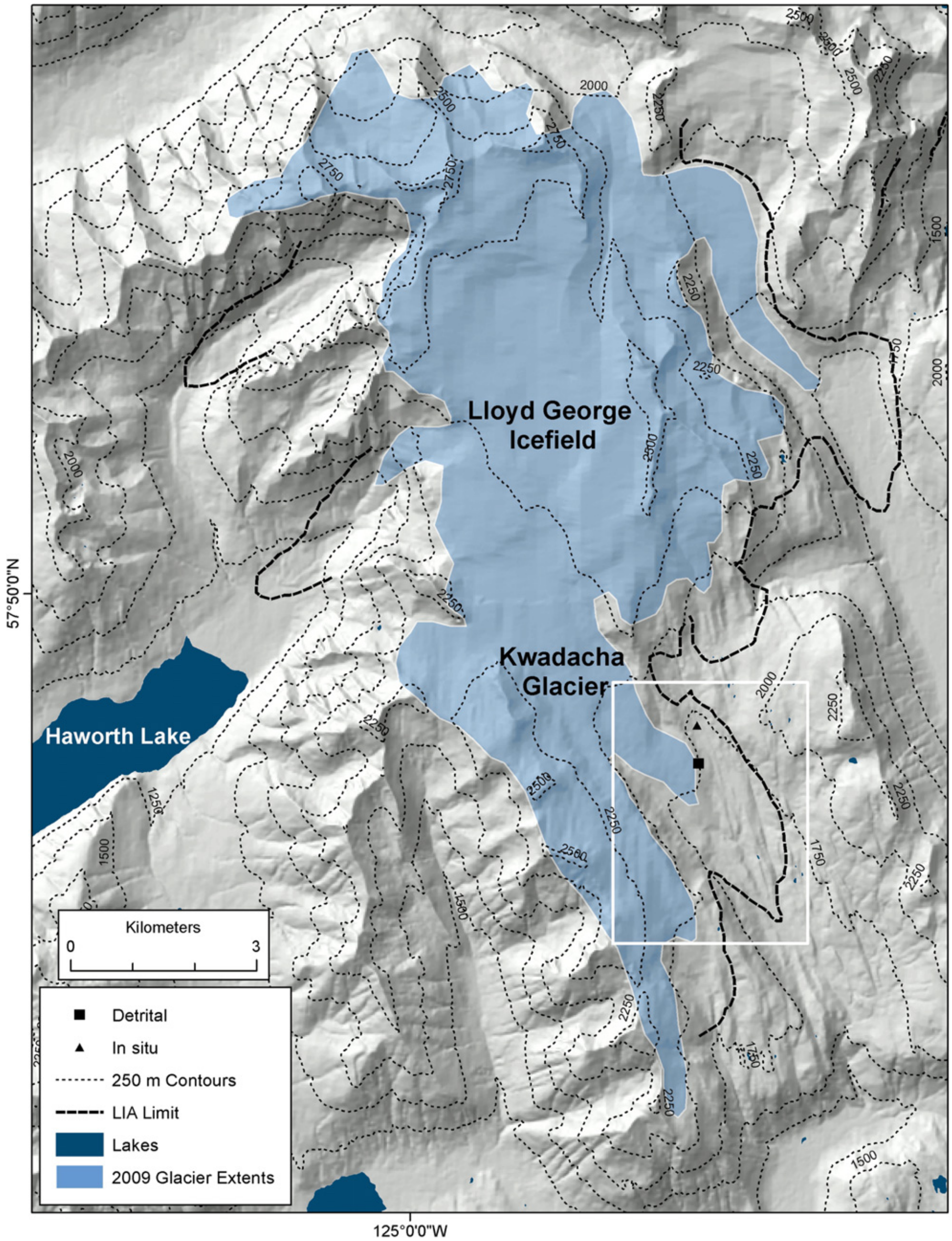

Fig. 3. Locations of Kwadacha Glacier and Lloyd George Icefield in the northern Rocky Mountains, British Columbia. Triangles and squares represent in-situ and detrital radiocarbon samples, respectively with calibrated age ranges in kilo calendar years BP (ka). White box is the area shown in Fig. 4.

Ecesis at the Castle Creek Glacier forefield was estimated in 2002 by sampling seedlings located mid-way between the ice front limit defined by 1946 and 1959 aerial photography. Tree cores taken from the oldest living trees growing on the moraines located at the south end of On–off Lake provide a minimum age for the moraine.

Samples from the outer rings of sheared in-situ tree stumps and large woody debris in the forefields of Castle Creek, Chiqui, Chap, and Kwadacha glaciers provide estimates of the time of glacier advance (Figs. 1–4). Wood samples from the glacier forefields and terrestrial macrofossils from the lake sediment cores were radiocarbon dated at the Keck Carbon Cycle accelerator mass spectrometry (AMS) Facility at the University of California Irvine. Calibrated age ranges of samples (2σ) in kilo calendar years BP (ka) were determined using CALIB 5.02 (Stuiver et al., 2005).

The study area in the Cariboo Mountains is near the limits of reported air-fall tephra plumes of both the Mazama and Bridge River eruptions (Mathewes and Westgate, 1980; Clague, 1981). No discernible tephra layers were seen in deposits within the glacier forefields or in the sediment cores, but we located two zones with non-visible concentrations of glass shards within each lake sediment core using sequential smear slide analysis. The shards were isolated from the lake sediments and analyzed for major elements using the wavelength-dispersive spectrometer JEOL JXA-8200 electron microprobe at the University of Calgary.

4. Results

4.1. Sedimentology and bulk physical properties of the sediment cores

The three sediment cores from On–off Lake range in length from 1.7 m to 2.1 m. The sediments consist of gyttja and rhythmically laminated to massive inorganic silt and clay that we subdivided into seven lithostratigraphic units (Fig. 5). A 1.5 mm interval of

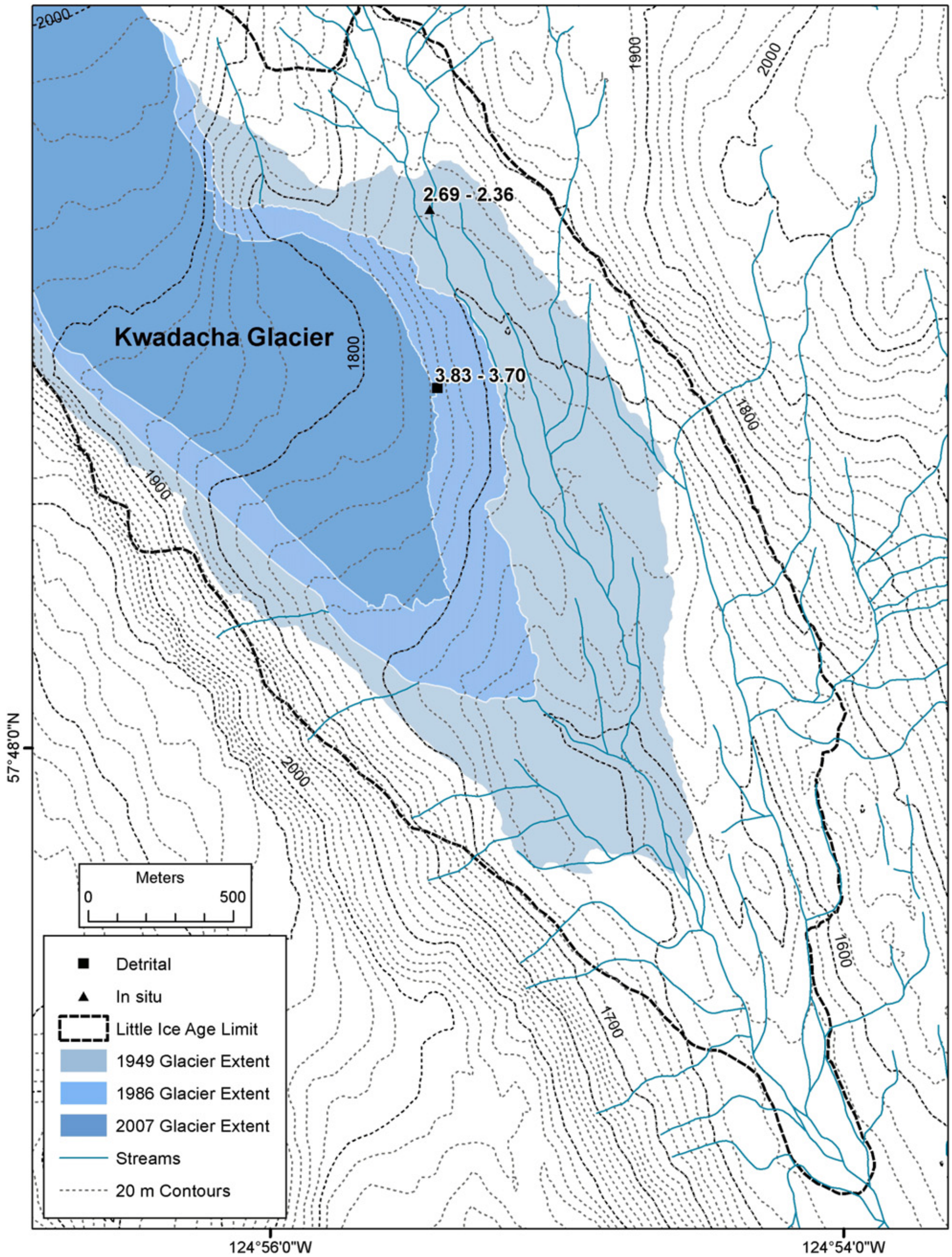

Fig. 4. Kwadacha Glacier forefield. The triangle and square demarcate in-situ and detrital radiocarbon samples, respectively with calibrated age ranges in kilo calendar years BP (ka).

gyttja was preserved at the tops of the cores, but was too thin to sample for analysis. Cores 08-Onoff(02) and 08-Onoff(03) contain all seven units, whereas core 08-Onoff(01) contains only the upper six units.

Units 1, 3, 5, and 7 are light gray silt and clay (Fig. 5). Unit 7 is rhythmically laminated, whereas units 1, 3, and 5 are massive. Units 2, 4, and 6 are gyttja. A 3-cm-thick bed of gyttja occurs in the middle of unit 3 in core 08-Onoff(03), the core with the highest sedimentation rate. The bulk physical properties of this bed are similar to those of the other gyttja units. Boundaries between units are sharp, with the exception of the boundary between units 5 and 6, which is gradational. Units 1, 3, 5, and 7 contain little organic matter and have low water contents and low carbon–nitrogen ratios. They are denser, coarser, and have higher magnetic susceptibilities than the units 2, 4, and 6 (Fig. 5).

4.2. Radiocarbon ages and tephras

Tephras and eight radiocarbon ages on terrestrial macrofossils provide chronologic control for the sediment cores (Fig. 5, Table 1). Plant fragments 0.5 cm above the boundary between units 1and 2 in core 08-Onoff(02) yielded a calibrated radiocarbon age of 10.92–9.70 ka. Glass shards at 141 cm in unit 2 in core 08-Onoff(02) are similar in character to those of Mazama tephra (Hallet et al., 1997), which dates to 7.67–7.51 ka (Zdanowicz et al., 1999). We recovered insufficient glass for conclusive microprobe fingerprinting, but the geochemistry of the shard we did collect is consistent with a Mazama source (Fig. 6). A conifer needle 0.5 cm below the contact between units 2 and 3 in core 08-Onoff(03) returned an age of 2.73–2.49 ka, and another conifer needle at the top of the organic bed in unit 3 from the same core yielded an age of 2.70–2.36 ka. Glass shards recovered from within 1 cm of the top of

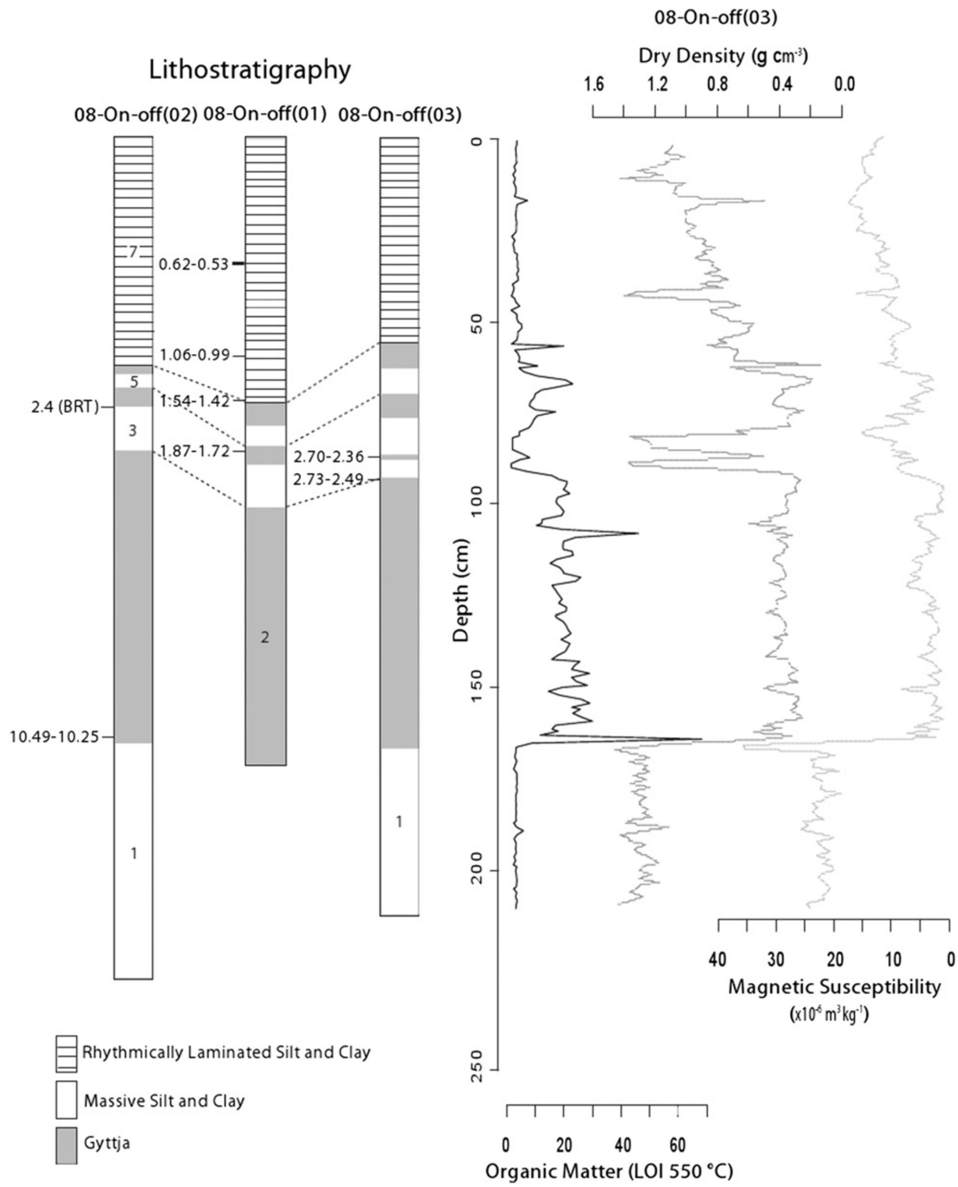

Fig. 5. Sediment core lithostratigraphy, chronologic control, and trends in bulk physical properties. Radiocarbon ages at unit contacts are in kilo calendar years BP (ka). BRT = Bridge River tephra.

unit 3 have the habit and chemistry of Bridge River tephra (Fig. 6; Reasoner and Healy, 1986), which has an age of 2.70–2.35 ka (Clague et al., 1995). A conifer needle 2 cm below the top of unit 4 in core 08-Onoff(01) gave an age of 1.87–1.72 ka, and another needle 0.5 cm above the contact between units 6 and 7 yielded an age of 1.54–1.42 ka. Two additional ages on terrestrial macrofossils from 62 cm and 38 cm within unit 7 in core 09-Onoff(01) returned ages of, respectively, 1.06–0.98 and 0.62–0.53 ka.

Eighteen additional radiocarbon ages on plant fossils constrain times of possible advances of Castle Creek, Chiqui, Chap, and Kwadacha glaciers (Figs. 1–4, Table 1). Detrital wood dated 8.97–8.61 ka was found 450 m downvalley of the 2008 Castle Creek Glacier terminus. Two pieces of detrital wood that melted out of the glacier in 2008 yielded the same age of 5.58–5.33 ka.

An age of 4.96–4.45 ka (Menounos et al., 2009) was obtained from a stump in growth position, 350 m downvalley of the 2008 terminus of Castle Creek Glacier. A thin alpine moss layer beneath till and a stump in growth position in the glacier forefield, which were, respectively, about 350 m and 1.05 km downvalley of the glacier terminus, yielded identical calibrated radiocarbon ages of 4.15–3.99 ka (Fig. 2). Two other detrital wood samples nearby returned ages of 4.14–3.98 and 4.09–3.98 ka. Collectively, the in-situ moss and detrital wood samples indicate that around 4.15–3.99 ka, Castle Creek Glacier had a similar extent as it did in AD 1946. A till-covered tilted tree trunk with intact roots 230 m inside the maximum LIA moraine of Castle Creek Glacier yielded an age of 0.91–0.80 ka (Fig. 2).

We dated four pieces of detrital wood from the forefields of Chiqui and Chap glaciers (Fig. 1, Table 1). Two pieces of wood from the forefield of Chiqui Glacier returned ages between 4.14 and 3.98 ka; another wood fragment from this forefield returned an age of 3.90–3.73 ka. A wood fragment from the forefield of Chap Glacier yielded an age of 4.97–4.85 ka.

We also recovered and dated detrital wood and organic material in growth position from the forefield of Kwadacha Glacier (Fig. 4, Table 1). We collected 5–10 cm diameter fragments of wood

Table 1
Radiocarbon ages from lake sediments and glacier forefields.

Laboratory no.[a]	Field no.	Material	^{14}C age (yr BP)	Calendar age (ka)[b]	Northing (m)[c]	Easting (m)	Elevation (m)
On–off Lake[d]							
UCIAMS-101785	08-Onoff(01); 38 cm	Conifer needles	545 ± 15[e]	0.62–0.53	5,883,525	671,934	1770
UCIAMS-101784	08-Onoff(01); 62 cm	Conifer needles	1130 ± 15	1.06–0.98	5,883,525	671,934	1770
UCIAMS-54614	08-Onoff(01); 78.5–79 cm	Conifer needles	1605 ± 20	1.54–1.42	5,883,525	671,934	1770
UCIAMS-54615	08-Onoff(01); 87–88 cm	Conifer needles	1860 ± 30	1.87–1.72	5,883,525	671,934	1770
UCIAMS-54616	08-Onoff(03); 77.5–78.5 cm	Conifer needles	2450 ± 15	2.70–2.36	5,883,518	671,939	1770
UCIAMS-54617	08-Onoff(03); 82–83 cm	Conifer needles	2510 ± 20	2.73–2.49	5,883,518	671,939	1770
UCIAMS-54618	08-Onoff(02); 163–164 cm	Plant matter	9200 ± 35	10.49–10.25	5,883,566	671,914	1770
UCIAMS-54619	08-Onoff(02); 164–165 cm	Plant matter	9160 ± 140	9.70–10.92	5,883,566	671,914	1770
Castle Creek Glacier[d]							
UCIAMS-634122	08-Castle(F)	Stump in growth position below till	930 ± 15	0.91–0.80	5,883,006	672,280	1770
UCIAMS-634124	08-Castle(O)	Detrital log	3465 ± 20	3.83–3.65	5,882,533	672,193	1790
UCIAMS-40544	07-Castle(02)	Detrital log	3690 ± 15	4.09–3.98	5,882,511	671,818	1800
GSC-6700	RS1-9	Detrital log	3710 ± 80	4.35–3.84	5,882,515	671,687	1800
UCIAMS-634123	08-Castle(G)	Detrital log	3715 ± 20	4.14–3.98	5,882,520	671,636	1810
UCIAMS-40543	07-Castle(01)	Stump in growth position	3720 ± 15	4.15–3.99	5,882,579	671,587	1820
UCIAMS-54620	08-Castle(08)	Terrestrial moss below deformed lake sediment and till	3740 ± 20	4.15–3.99	5,881,554	672,262	1860
UCIAMS-63119	08-Castle(A)	Detrital log	4160 ± 20	4.83–4.58	5,882,360	671,836	1810
GSC-6709	RS5-15,16	Stump in growth position	4210 ± 80	4.96–4.45	5,881,604	672,144	1840
UCIAMS-63121	08-Castle(D)	Detrital log	4710 ± 20	5.58–5.33	5,882,527	671,892	1800
UCIAMS-40545	07-Castle(06)	Detrital log	4715 ± 20	5.58–5.33	5,881,703	671,375	1900
UCIAMS-63125	08-Castle(P)	Detrital log	7915 ± 25	8.97–8.61	5,882,075	672,019	1820
Chiqui Glacier[d]							
UCIAMS-63127	08-Chiqui(02)	Detrital log	3555 ± 20	3.90–3.73	5,879,237	666,167	1700
UCIAMS-63129	08-Chiqui(08)	Detrital log	3700 ± 20	4.14–3.98	5,878,560	666,167	1710
UCIAMS-63128	08-Chiqui(04)	Detrital log	3720 ± 20	4.14–3.99	5,878,559	666,197	1710
Chap Glacier[d]							
UCIAMS-63126	08-BM(01)	Detrital log	4345 ± 25	4.97–4.85	5,870,150	684,421	1820
Kwadacha Glacier							
UCIAMS-54621	08-Kwad(b)	Terrestrial moss below till	2440 ± 15	2.69–2.36	385,604	6,409,975	1720
UCIAMS-54622	08-Kwad(02)	Detrital wood	3480 ± 20	3.83–3.70	385,631	6,409,355	1760

[a] Radiocarbon laboratory: GSC – Geological Survey of Canada; UCIAMS – University of California at Irvine.
[b] Calendar ages ranges determined using Calib 5.02 (Stuiver et al., 2005).
[c] UTM Zone 10, WGS 84 datum.
[d] Informal names.
[e] Analytical uncertainty is 2σ for GSC radiocarbon ages and 1σ for all other ages.

melting out of the terminus of the glacier in 2009. No trees grow higher in the valley today. One of these samples returned an age of 3.83–3.70 ka. At a second site, about 600 m to the north (Fig. 4), a meltwater gully exposed 1–2 m of till underlain by 20–30 cm of gravel and a mixture of gravel, soil, and alpine moss. Several buds of alpine moss from an individual plant stem returned an age of 2.69–2.36 ka.

The estimated ecesis interval at Castle Creek Glacier is 20–30 years. Using this estimate, we determined that the oldest living trees on the Castle Creek Glacier moraines located at the south end of On–off Lake colonized the moraine surface about AD 1880–1890. This age is close to the end of the Little Ice Age when most glaciers in western Canada reached their maximum, all-time Holocene limits (Menounos et al., 2009).

5. Discussion

5.1. Holocene glacial record in the Cariboo and northern Rocky Mountains

The stratigraphy of the On–off Lake cores and radiocarbon ages from the lake cores and the glacier forefield allow us to determine the history of Castle Creek Glacier during the Holocene (Fig. 7). By 10.92–9.70 ka Castle Creek Glacier had retreated upvalley of the hydrologic divide and no longer discharged meltwater into On–off Lake. Detrital wood samples dating to 8.97–8.61 ka and 5.58–5.33 ka record times when the glacier was relatively restricted in extent and perhaps expanded into a forest, but the first unequivocal evidence for Holocene expansion of Castle Creek Glacier is an overridden stump dating to 4.96–4.45 ka.

In-situ radiocarbon ages of wood and plant fossils of 4.15–3.99 ka indicate either a second advance of Castle Creek Glacier or a continuation of the expansion at 4.96–4.45 ka. Detrital logs collected in the forefield of Chiqui Glacier yielded ages comparable to the age of overridden plant matter at Castle Creek Glacier and thus indicates that more than one glacier in the Cariboo Mountains advanced at that time. Castle Creek Glacier, however, failed to reach the hydrologic divide 1.39 km downvalley of its 2008 position during these advances. These data demonstrate that no Holocene advance was more extensive than those of the Late Holocene.

The sediment record from On–off Lake indicates that Castle Creek Glacier first advanced past the hydrologic divide and was within 330 m of its Holocene maximum position at 2.73–2.49 ka. Accumulation of clastic sediments within On–off Lake from 2.73 to 2.49 ka until 2.70–2.35 ka (Bridge River tephra) indicates that Castle Creek Glacier terminated downvalley of the hydrologic divide during that interval. Unit 3 lacks the rhythmic structure that

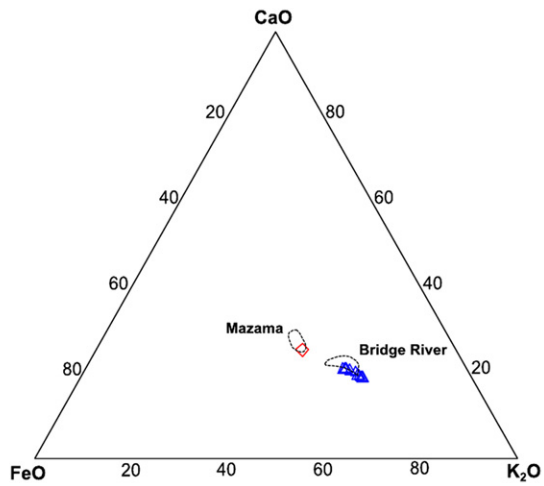

Fig. 6. FeO–CaO–K_2O ternary diagram with the compositional fields of tephra glass shards recovered from the On–off Lake cores. The diamond indicates the geochemistry of a glass shard from unit 2 in core 08-Onoff(02). Triangles indicate the chemical composition of the glass shards at the contact between units 3 and 4 in core 08-Onoff(02). The dash-line polygons are the compositional fields of Mazama and Bridge River tephras (Reasoner and Healy, 1986).

characterizes unit 7, perhaps because the glacier did not extend beyond the hydrologic divide long enough to contribute enough sediment to the lake to produce deposits with internal structure (Souch, 1994). The presence of a thin organic bed with an age of 2.70–2.36 ka in unit 3 suggests that Castle Creek Glacier retreated upvalley from the hydrologic divide for a short time during this period and is consistent with our argument that Castle Creek Glacier did not reach far beyond the hydrologic divide between 2.73–2.49 ka and 2.70–2.35 ka.

After deposition of Bridge River tephra at 2.70–2.35 ka, Castle Creek Glacier retreated an unknown distance upvalley from the hydrologic divide and the lake began to accumulate gyttja. The glacier advanced beyond the hydrologic divide again just after 1.87–1.72 ka and retreated shortly thereafter, before it expanded over the hydrologic divide a final time just before 1.54–1.42 ka. It overran a tree 100 m downvalley of the hydrologic divide at 0.91–0.80 ka (AD 1160–1049).

The earliest aerial photographs, taken in AD 1946, show that Castle Creek Glacier terminated 1.02 km downvalley of its 2008 position and 370 m upvalley of the hydrologic divide. Successive ice front positions in the vicinity of the hydrologic divide are marked by a sequence of 15–16 well-developed annual moraines (Reid, 2011) that record an average rate of recession of 14–15 m yr^{-1}. The distance between the glacier terminus in AD 1946 and the first of these annual moraines, dated to 1957, yields a similar average rate of recession of 14.2 m yr^{-1} (Beedle et al., 2009).

Based on these data we estimate that glacial meltwater last entered On–off Lake sometime in the early 1920s. This estimate is consistent with the minimum limiting age of AD 1880–1890s for the stabilization of the Holocene terminal moraine that extends across the lake near its inlet. These data imply that Castle Creek Glacier remained within 330 m of its maximum Holocene limit from 1.54–1.42 ka until the beginning of the twentieth century (Fig. 7).

5.2. Regional comparison

Most alpine glaciers in western Canada achieved their present limits by 11.0 ka (Clague, 1981; Menounos et al., 2009). The minimum limiting age of 10.92–9.70 ka from On–off Lake can only be used to constrain the time when Castle Creek Glacier was smaller than it was in the early 20th century. The limited extent of Castle Creek Glacier in the early to middle Holocene accords with regional records from western Canada and at Mt. Baker, Washington (Menounos et al., 2009; Osborn et al., 2012).

Expansion of Castle Creek Glacier at 4.96–4.45 ka coincides with an early phase of Neoglacial activity identified elsewhere in British Columbia (Fig. 7; Ryder and Thomson, 1986; Menounos et al.,

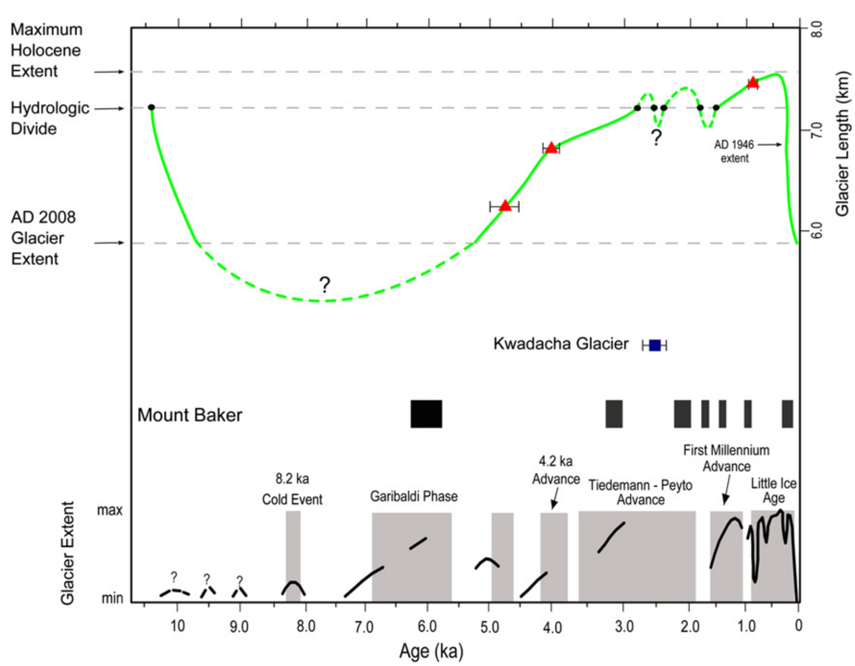

Fig. 7. Top: Time-distance diagram for Castle Creek Glacier from 10 ka to AD 2008. Triangles denote ages (±2σ uncertainties) and locations of stumps and moss in growth position that were overrun by the glacier. Circles are ages of contacts between clastic sediments and gyttja in the lake cores. Middle: Rectangles represent ages of expansion for Kwadacha Glacier and glaciers on Mount Baker. Bottom: Generalized activity of Holocene glaciers in western Canada during the Holocene (modified from Clague et al., 2009). Gray blocks are named advances.

2009). We assign slightly younger ages, ranging from 4.15–3.99 ka to 3.83–3.65 ka, to the '4.2 ka Advance', an advance of alpine glaciers recognized at many sites in western Canada (Menounos et al., 2008).

Corroborating evidence for glacier expansion near the end of the 4.2 ka Advance is provided by sediment cores recovered from a lake 100 km west of Kwadacha Glacier in the northern Rocky Mountains (Menounos et al., 2008). A dated interval of clastic sediments in the cores and the age of the detrital wood found at Kwadacha Glacier (3.83–3.70 ka) overlap the ages of detrital from Castle Creek and Chiqui glaciers.

The advance of glaciers in the Cariboo Mountains between 2.73–2.49 ka and 2.70–2.35 ka broadly correlates with glacier advances elsewhere in western Canada, the northern Rocky Mountains, Alaska, and the US Pacific Northwest. The first expansion of Castle Creek Glacier over the hydrologic divide just before 2.73–2.49 ka coincides with the Peyto–Tiedemann Advance recognized throughout western Canada (Ryder and Thomson, 1986; Luckman et al., 1993; Menounos et al., 2009; Koehler and Smith, 2011). Overridden alpine vegetation dating to 2.69–2.36 ka at Kwadacha Glacier indicates that glaciers also expanded in the northern Rocky Mountains during the Peyto–Tiedemann Advance (Fig. 7). Glaciers in Alaska (Fig. 1) advanced around 3.3–2.9 ka and 2.2–2.0 ka (Barclay et al., 2009), and glaciers in the Canadian arctic expanded to near their Little Ice Age maximum positions around 3.5 to 2.5 ka (Briner et al., 2009). Deming Glacier on Mount Baker in the Cascade Mountains of Washington (Fig. 1) advanced into a forest ca. 3.24–3.0 ka and again at 2.35–2.15 ka (Fig. 7; Easterbrook and Donnell, 2007; Osborn et al., 2012). Collectively, these data indicate that glaciers throughout North America expanded at least twice during the period 3.0–2.0 ka and that at least some of them reached downvalley almost as far as during the Little Ice Age.

The advances of Castle Creek Glacier at 1.87–1.72 ka and again at 1.54–1.42 ka coincide with an advance of Deming Glacier at 1.82–1.71 ka and possibly another at 1.53–1.42 ka (Osborn et al., 2012). These two events fall within the First Millennium Advance (1.8–1.1 ka) recognized throughout maritime British Columbia and Alaska (Fig. 7; Reyes et al., 2006). The Castle Creek Glacier record demonstrates that glacier activity during the First Millennium Advance was not limited to maritime environments. Like the interval 3.0–2.0 ka, the First Millennium Advance was not a single event, but one characterized by regionally coherent phases of expansion and retreat. These first millennium advances are also recognized outside western North America (Davis et al., 2009).

The overridden tree 100 m downvalley of the hydrologic divide at Castle Creek Glacier with an age of AD 1040–1160 is consistent with evidence for an early Little Ice Age advance at this time elsewhere in western Canada and at Mount Baker, Washington (Luckman, 2000; Koch et al., 2007; Osborn et al., 2012). Stabilization of the terminal moraine at Castle Creek Glacier around AD 1880–1890 is also close to the time that glaciers on the south side of Mount Baker achieved their maximum Holocene size (Osborn et al., 2012). Like glaciers in southern British Columbia, Castle Creek Glacier rapidly retreated in the twentieth century during a period of warm dry conditions (Menounos, 2006; Koch et al., 2007).

5.3. Significance of the Cariboo Mountains glacial record

Castle Creek Glacier was more extensive throughout the past 1500 years than it has been since the 1920s. This fact highlights the anomalous nature of twentieth century climate in relation to the previous 1500 years. Furthermore, the relative stability of Castle Creek Glacier over that 1500-year period argues against the hypothesis that substantial fluctuations in its length might result simply from stochastic weather events over periods of hundreds of years (Reichert et al., 2002; Roe, 2011). Finally, these data indicate that advances during the past three millennia in the Cariboo Mountains were comparable in extent to those of the Little Ice Age.

The detail and resolution acquired in this study would not have been possible without the use of evidence from a proglacial-threshold lake located close to the Castle Creek Glacier's Holocene maximum position. Other studies have used similar proglacial-threshold lakes to improve constraints on glacier activity during the Holocene (Mercer, 1968; Miller et al., 2005; Bakke et al., 2010; Briner et al., 2010). We found that the position of the threshold and the lake relative to the maximum Holocene extent determined the interval in which detailed information could be gathered. In our study the position of the hydrologic divide allowed sediment from On–off Lake to record information about the glacier's activity only after 2.73–2.49 ka. Targeting similar topographic situations in other regions could potentially provide the same detail for other periods of the Holocene.

6. Conclusion

An early Neoglacial expansion of glaciers in the Cariboo Mountains of east-central British Columbia commenced at about 4.96–4.45 ka. These glaciers and Kwadacha Glacier in the northern Rocky Mountains advanced again at about 4.15–4.00 ka. Castle Creek Glacier first extended across a hydrologic divide 1.39 km downvalley of its 2008 terminus after 2.73–2.49 ka. This advance is coeval with an advance of Kwadacha Glacier and with advances of other glaciers throughout British Columbia. Castle Creek Glacier subsequently advanced and retreated at least twice, at ca. 1.87–1.72 ka and 1.54–1.42 ka, reaching to within 330 m of its maximum Holocene limit. After 1.54–1.42 ka Castle Creek Glacier remained within 330 m of its Little Ice Age maximum position until the early twentieth century. Our data demonstrate that glacier advances during the past three millennia were similar in extent to the maxima achieved in the late Little Ice Age. The favorable co-location of an alpine glacier terminus, a hydrologic divide, and a sedimentary basin is not unique to our study area, thus the methodology utilized in this study could be applied elsewhere to refine the time, duration, and extent of past glacier advances.

Acknowledgments

Our paper benefitted from valuable input from the journal referees Jason Briner and Nicolaj Krog Larsen. We thank K. Adams, H. Luckman, H. Haines, and R. Wheate for help in the field, and W. Arnott (University of Ottawa) for logistical support. Funding for our research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), and the Canadian Foundation for Innovation (CFI). This paper is ESS publication #20120159.

References

Bakke, J., Dahl, S.O., Paasche, Ø., Simonsen, J.R., Kvisvik, B., Bakke, K., Nesje, A., 2010. A complete record of Holocene glacier variability at Austre Okstindbreen, north Norway: an integrated approach. Quaternary Science Reviews 29, 1246–1262.

Barclay, D.J., Wiles, G.C., Calkin, P.E., 2009. Holocene glacier fluctuations in Alaska. Quaternary Science Reviews 28, 2034–2048.

Beedle, M.J., Menounos, B., Luckman, B.H., Wheate, R., 2009. Annual push moraines as climate proxy. Geophysical Research Letters 36, L20501. http://dx.doi.org/10.1029/2009GL039533.

Briner, J.P., Davis, P.T., Miller, G.H., 2009. Latest Pleistocene and Holocene glaciation of Baffin Island, Arctic Canada: key patterns and chronologies. Quaternary Science Reviews 28, 2075–2087.

Briner, J.P., Stewart, H.A.M., Young, N.E., Philipps, W., Losee, S., 2010. Using proglacial-threshold lakes to constrain fluctuations of Jokobshavn Isbræ ice margin, western Greenland, during the Holocene. Quaternary Science Reviews 29, 3861–3874.

Clague, J.J., 1981. Late Quaternary geology and geochronology of British Columbia, Part 2: summary and discussion of radiocarbon-dated Quaternary history. Geological Survey of Canada Paper 80-35, 41.

Clague, J.J., Evans, S.G., Rampton, V.N., Woodsworth, G.J., 1995. Improved age estimates for the White River and Bridge River tephras, western Canada. Canadian Journal of Earth Sciences 32, 1172–1179.

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.

Davis, P.T., Menounos, B., Osborn, G., 2009. Holocene and latest Pleistocene alpine glacier fluctuations: a global perspective. Quaternary Science Reviews 28, 2021–2033.

Easterbrook, D.J., Donnell, C.B., 2007. Glacial and volcanic history of the Nooksack Middle Fork, Washington. Geological Society of America Abstracts with Programs 39 (4), 12.

Hallet, D.J., Hills, L.V., Clague, J.J., 1997. New accelerator mass spectrometry radiocarbon ages for the Mazama tephra layer from Kootenay National Park, British Columbia, Canada. Canadian Journal of Earth Sciences 34, 1202–1209.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments; reproducibility and comparability of results. Journal of Paleolimnology 25, 101–110.

Kaplan, M.R., Wolfe, A.P., Miller, G.H., 2002. Holocene environmental variability in southern Greenland inferred from lake sediments. Quaternary Research 58, 149–159.

Koch, J., Clague, J.J., 2011. Extensive glaciers in northwest North America during Medieval time. Climatic Change 107, 593–613.

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, 1215–1255.

Koehler, L., Smith, D.J., 2011. Late-Holocene glacial activity in Manatee Valley, southern Coast Mountains, British Columbia, Canada. Canadian Journal of Earth Sciences 48, 603–618.

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, 1–13.

Luckman, B.H., 1995. Calendar-dated, early 'Little Ice Age' glacier advance at Robson Glacier, British Columbia, Canada. The Holocene 5, 149–159.

Luckman, B.H., 2000. The Little Ice Age in the Canadian Rockies. Geomorphology 32, 357–384.

Luckman, B.H., Holdsworth, G., Osborn, G.D., 1993. Holocene glacier fluctuations in the Canadian Rockies. Quaternary Research 39, 144–155.

Mathewes, R.W., Westgate, J.A., 1980. Bridge River tephra: revised distribution and significance for detecting old carbon errors in radiocarbon dates of limnic sediments in southern British Columbia. Canadian Journal of Earth Sciences 17, 1454–1461.

Menounos, B., 2006. Anomalous early 20th century sedimentation in proglacial Green Lake, British Columbia, Canada. Canadian Journal of Earth Sciences 43, 671–678.

Menounos, B., Clague, J., Osborn, G., Lakeman, T., Luckman, B.H., Minkus, R., 2008. Western Canadian glaciers advance in concert with climate change circa 4.2 ka. Geophysical Research Letters 35, L07501. http://dx.doi.org/10.1029/2008GL033172.

Menounos, B., Osborn, G., Clague, J.J., Luckman, B.H., 2009. Latest Pleistocene and Holocene glacier fluctuations in western Canada. Quaternary Science Reviews 26, 2049–2074.

Mercer, J.H., 1968. Variations of some Patagonian glaciers since the Late-glacial. American Journal of Science 266, 91–109.

Miller, G.H., Wolfe, A.P., Briner, J.P., Sauer, P.E., Nesje, A., 2005. Holocene glaciation and climate evolution on Baffin Island, Arctic Canada. Quaternary Science Reviews 24, 1703–1721.

Osborn, G., Menounos, B., Ryane, C., Riedel, J., Clague, J.J., Koch, J., Clark, D., Scott, K., Davis, P.T., 2012. Latest Pleistocene and Holocene glacier fluctuations on Mount Baker, Washington. Quaternary Science Reviews 49, 33–51. http://dx.doi.org/10.1016/j.quascirev.2012.06.004.

Reasoner, M., Healy, R., 1986. Identification and significance of tephra encountered in a core from Mary Lake, Yoho National Park, British Columbia. Canadian Journal of Sciences 23, 1991–1999.

Reichert, B.K., Bengtsson, L., Oerlemans, J., 2002. Recent glacier retreat exceeds internal variability. Journal of Climate 15, 3069–3081.

Reid, E.M., 2011. The Formation of Small Scale Glacial Flutes: a Case Study of the Castle Creek Forefield, Cariboo Mountains, B.C. M.Sc thesis, University of Western Ontario London, ON.

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., Clague, J.J., 2006. Expansion of alpine glaciers in Pacific North America in the first millennium A.D. Geology 34, 57–60.

Roe, G., 2011. What do glaciers tell us about climate variability and climate change? Journal of Glaciology 57, 567–578.

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.

Souch, C., 1994. A methodology to interpret downvalley lake sediments as records of Neoglacial activity: Coast Mountains, British Columbia, Canada. Geografiska Annaler 76, 169–185.

Sperazza, M., Moore, J.N., Hendrix, M.S., 2004. High-resolution particle size analysis of naturally occurring very fine-grained sediment through laser diffractometry. Journal of Sedimentary Research 74, 736–743.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.2. http://calib.qub.ac.uk/calib/.

Verardo, D.J., Froelich, P.N., McIntyre, A., 1990. Determination of organic carbon and nitrogen in marine sediments using the Carlo-Erba NA-1500 analyzer. Deep-Sea Research 37, 157–165.

Zdanowicz, C., Zielinski, G., Germani, M., 1999. Mount Mazama eruption: Calendric age verified and atmospheric impact assessed. Geology 27, 621–642.