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

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A B S T R A C T
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 Oneoff 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 Oneoff 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 Onoff 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.

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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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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 km²) 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.
and flows 2.6 km northward, through an elevation range of 2600–2000 m asl.

Kwadacha Glacier (12.6 km²) 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. 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.
Eciesis 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 (2$\sigma$) in kilo calendar years BP (ka) were determined using CALIB 5.02 (Stuiver et al., 2005).

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
Gyttja was preserved at the tops of the cores, but was too thin to sample for analysis. Cores 08-0noff(02) and 08-0noff(03) contain all seven units, whereas core 08-0noff(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 08-0noff(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 tephas

Tephas 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 1 and 2 in core 08-0noff(02) yielded a calibrated radiocarbon age of 10.92±9.70 ka. Glass shards at 141 cm in unit 2 in core 08-0noff(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 finger-printing, 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 08-0noff(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
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
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 4.14–3.99 ka. This age is close to the end of the Little Ice Age when most glaciers in western Canada reached their maximum, all-time Holocene position below till.

The estimated ecies 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 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 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 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 or a continuation of the expansion at 4.96–4.45 ka.

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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 ± 0.23 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 ± 0.24 ka and 2.70 ± 0.23 ka.

After deposition of Bridge River tephra at 2.70 ± 0.23 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 ± 0.17 ka and retreated shortly thereafter, before it expanded over the hydrologic divide a final time just before 1.54 ± 0.14 ka. It overran a tree 100 m downvalley of the hydrologic divide at 0.91 ± 0.10 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 ± 0.14 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 ± 0.70 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 ± 0.45 ka coincides with an early phase of Neoglacial activity identified elsewhere in British Columbia (Fig. 7; Ryder and Thomson, 1986; Menounos et al., 2009).
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 advances 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 expanded 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 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.

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