Late Holocene glacial activity in Manatee Valley, southern Coast Mountains, British Columbia, Canada

Lindsey Koehler and Dan J. Smith

Abstract: The dendroglaciologic and lichenometric research methodologies employed in this study provide a perspective of glaciological conditions from 5 ka to present in a remote headwater area of the British Columbia Coast Mountains. Since Holocene ice fronts of four glaciers at this site periodically extended below treeline, previous glacier advances overrode and buried forests beneath till deposits. This study suggests that glaciers were expanding into standing forests for long enough for the development of deep pedogenic surfaces and the growth of trees exceeding 300 years. Investigations at Beluga and Manatee glaciers benchmark a subsequent episode of significant glacial expansion at 2.42 ka referred to as the “Manatee Advance”. This advance has regional corollatives and is distinguished from the Tiedemann Advance at Manatee Glacier by documentation of substantive ice front retreat between the two episodes. Examination of Little Ice Age (LIA) deposits in the study area allowed for presentation and application of a revised Rhizocarpon spp. lichen growth curve. Lichenometric surveys of lateral moraines associated with Beluga, Manatee, and Oluk glaciers provided limited insight into their early LIA behaviour but record advances during the 15th and 16th centuries. Locally, glaciers achieved their maximum LIA size prior to an early to mid 18th century moraine-building event. This reconstruction of Holocene glacial history offers insights consistent with the emerging record of glacier activity described for other southern British Columbia Coast Mountain glaciers.

Introduction

The mountainous regions of southwestern British Columbia have experienced significant volumetric losses in glacial ice over the last century (Schiefer et al. 2007; Bolch et al. 2008; Vanlooy and Forster 2008). While the melt of these glaciers has been related to changing climate (Letréguilly 1988; Bitz and Battisti 1999), the brevity of historical mass balance records in the Coast Mountains prevents a reliable characterization of alpine glacierization on longer time scales. By offering direct evidence for glacial activity, dendroglaciological research has contributed greatly to developing an understanding of the response of glaciers in this region to changing climates over the last 10 ka (Ryder and Thomson 1986; Allen and Smith 2007; Koch et al. 2007a). Complimentary geobotanical studies demonstrate the ability of lichenometry to detail shorter-term glacier responses to climate variability during the Little Ice Age (LIA).
This paper presents the results of field investigations at four glacier forefields in the Manatee Valley area of the southern Coast Mountains. Reconnaissance investigations in 2006 led to the discovery of buried subfossil stumps and forest detritus. In 2007, additional wood samples were collected and fieldwork focused on determining the age of LIA moraines at the study site.

Research background

The renewal of alpine glaciation in Pacific North America during the Neoglacial follows a well-defined period of early Holocene warming (Porter and Denton 1967). Although classically the Neoglacial is defined as the initial expansion of glaciers in the mid-Holocene (Ryder and Thomson 1986), there is limited evidence for a short-lived advance at 8.30 ka (Menounos et al. 2004). The onset of regional glacial conditions corresponds to an interval of glacier expansion at 6.80–6.00 ka during the Garibaldi Phase (Ryder and Thomson 1986). This advance was followed by a shift to wetter and cooler conditions at 5.80 ka (Spooner et al. 2002; Walker and Pellatt 2003) prior to a glacial advance at ca. 4.17 ka (Menounos et al. 2008). Following this, glaciers throughout the region retreated before readvancing during the Tiedemann Advance from 3.50 to 1.85 ka (Fulton 1971; Ryder and Thomson 1986). Recent exposures of buried forests in several Coast Mountain forefields suggest, however, that the interval originally described as the Tiedemann Advance may in fact have been interrupted by distinct advances dating to ca. 3.01 and 2.30 ka (Reyes and Clague 2004; Jackson et al. 2008).

Following the Tiedemann Advance, glaciers in the region receded before readvancing into standing forests from 1.60 to 1.30 ka during the First Millennium Advance (FMA;
Reyes et al. 2006). The onset of LIA glacier expansion dates to the 11th century in southwestern British Columbia (Allen and Smith 2007; Koch et al. 2007a), with a period of moraine construction reported in the late 12th to mid 13th centuries (Larocque and Smith 2003; Allen and Smith 2007). This early period of LIA expansion was followed by an interval of ice front retreat before a significant episode of expansion and moraine construction in the early 1700s AD. Many Coast Mountain glaciers maintained extended downvalley positions until the early 20th century (Larocque and Smith 2003; Lewis and Smith 2004; Allen and Smith 2007; Koch et al. 2007b).

**Study area**

The Manatee Valley study area (Fig. 1) is located within the eastern Pacific Ranges, a belt of heavily glaciated mountains separated from the Cascade Range to the south by the Fraser River, and bordered by the Kitimat Ranges to the north. Locally the bedrock is composed primarily of granodiorite with outcroppings of metasedimentary and volcanic rocks belonging to the Gambier Group (Monger and Journeay 1994). Drainage networks carved during the Tertiary (Paleogene and Neogene) were broadened by a succession of Pleistocene glaciers (Tribe 2002).

During the Late Wisconsinan an ice sheet covered the area, reaching its maximum extent by 18.25–16.68 ka (Clague et al. 1988). By 11.50 ka, following downwasting and stagnation, glacier cover in the region was likely similar to the present (Clague and James 2002). Evidence for Quaternary volcanism is present in the region (Reyes and Clague 2004), with an eruption of Plinth Peak ca. 2.35 ka known to have blanketed the slopes of Polychrome Ridge (Read 1990).

The hydroclimatic regime of the area is characterized by orographic lifting of weather systems originating over the Pacific Ocean that regularly deliver moisture-laden air
masses. During the winter snowfall totals at the nearest climate station (Whistler, British Columbia; Lat 50° 8' 7.800" N, Long 122° 8' 57.000" W; 658 m above sea level (asl)) exceed 4 m per year (Environment Canada 2008). Air temperatures at the same station average –2.7°C in January and 16.2°C in July (Environment Canada 2008).

The study area lies within the Engelmann Spruce Subalpine Fir (ESSF) and Alpine Tundra (AT) biogeoclimatic zones (Klinka et al. 1991). Tree cover is restricted to elevations below ca. 1740 m asl. Subalpine parklands above the glacier trimline are characterized by subalpine fir (Abies lasiocarpa) tree islands, interspersed with scattered mountain hemlock (Tsuga mertensiana) and whitebark pine (Pinus albicaulis). Recently deglaciated valley bottoms and slopes are colonized by river beauty (Epilobium latifolium, also known as dwarf fireweed), alder (Alnus crispa), and willow (Salix sp.).

Five glaciers presently occupy headwater areas of Manatee Creek: Beluga (unofficial name), Dolphin, Manatee, Oluk (unofficial name), and Orca (unofficial name) glaciers (Fig. 1). The glaciers extend from a maximum altitude of 2475 m asl to terminal positions at a minimum around ca. 1625 m asl in 2006 (Fig. 1).

**Methods**

During field surveys detrital wood fragments were observed washing out from beneath Orca Glacier, glacially sheared stumps were located in two glacier forefields, and detrital wood was discovered below till at two additional sites. A late Holocene chronology of ice margin fluctuations was developed by employing dendroglaciology and radiocarbon analysis to date wood samples. Lichenometric dating techniques of prominent lateral moraine complexes were used to assign relative ages and to develop a chronology of local LIA glacier activity.

**Dendroglaciology**

At sites where glaciers advanced into forested areas, dendrochronology offers the opportunity to annually resolve glacier events (Luckman 1988, 1998; Schweingruber 1988). In dendroglaciologic applications tree rings are used either to provide a minimum age for the underlying surface (Lawrence 1946; Heusser 1956) or to cross-date glacially killed samples to identify the year the tree died (Luckman 1995;
Where cross-dating fails, radiocarbon dating of the outermost tree rings provides an approximate kill date (Wood and Smith 2004; Allen and Smith 2007).

All glacier forefields and lateral moraine slopes were systematically surveyed for subfossil wood samples. Trimlines were examined to locate trees directly impacted by glacier ice, resulting in their death, scarring, or suppression of cambial growth (Schroder 1980; Wiles et al. 1996). Cross sections were taken with a chainsaw and the resulting tree cookies secured with duct tape for transport.

At selected lateral moraine sites, survey transects were established and morphological profiles mapped with a tape measure and Abney level (Fig. 2). Moraine crests were numbered so that the most distal moraine was labeled “M1”, with the more proximal inner moraines numbered sequentially higher. Where trees were found growing on moraine crests, basal tree ring samples were removed with an increment borer to provide a minimum date of surface stabilization (Larocque and Smith 2003). Where saplings represented the oldest vegetative cohort, their minimum age was determined by counting the number of annual branch whorls of all individuals found at a site and comparing these estimates to those aged by destructive sampling (Palmer and Miller 1961). A local ecesis interval was established by documenting the difference in age between the oldest cohort of trees at individual sites and the date when that location was exposed by ice front retreat (Sigafoos and Hendricks 1969; McCarthy and Luckman 1993).

To facilitate cross-dating of glacially killed trees, a living tree ring chronology was developed from mature trees found on the forested ridge separating Beluga and Manatee glaciers. Mature subalpine fir trees were sampled with an increment borer, with two cores extracted at right angles to each other at breast height. To increase the cross-dating potential, the tree ring record was extended by collecting additional increment cores from standing snags and coarse woody debris found on the forest floor.

Both the increment cores and subfossil tree cookies were polished, measured, and cross-dated according to standard dendrochronological protocols (Stokes and Smiley 1968; Fritts 1976; Schweingruber 1988). A flatbed scanner was used to obtain high-resolution digital images of the samples and the annual ring-width increments measured to the nearest 0.001 mm with a WinDENDRO (version 2006b) tree ring measuring system (Guay et al. 1992). Visual cross-dating was verified using the software program COFECHA (Holmes 1999; Grissino-Mayer 2001). Standardized ring-width indices were constructed by fitting the tree ring series to a negative exponential curve using the software program.
ARSTAN (Cook and Holmes 1999). Where a negative exponential curve was not appropriate, for example, in the case of a very long series, then a negatively sloped line was fit to the data. The expressed population signal (EPS) cut-off year was calculated for 25 year moving periods to quantify signal strength through time; the cut-off year was defined as the central year within the last 25 year segment when the EPS value was greater than the 0.85 cut-off value (Wilson and Luckman 2002).

Ring-widths in subfossil wood samples were measured with WinDendro™ along a minimum of two radii. An attempt was first made to cross-date individual series to the living tree ring chronology. Where cross-dating failed, site-specific floating chronologies were constructed, and the radiocarbon ages assigned to perimeter wood samples were determined by Beta Analytic, Inc. (Miami, Florida, USA). The $^{14}$C ages were calibrated using INTCAL 04 (Reimer et al. 2004) and the 2σ probability range reported in cal years BP. The midpoint of the probability range was chosen to represent the calendar age of a sample in thousands of years (ka). Where the $^{14}$C age intercepted multiple peaks, the midpoint of the dominant peak was used to represent the calendar age.

### Lichenometry

Lichenometry assigns minimum dates to glacial landforms by assuming a linear relationship between the size of lichen thallus and age of the substrate (Beschel 1973; Innes 1985). In this instance, lichen diameters of the genus *Rhizocarpon* were measured with digital calipers to the nearest 0.1 mm.

### Table 4. Summary of radiocarbon-dated wood recovered from Manatee Valley, arranged oldest to youngest.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Sample No.</th>
<th>No. of rings</th>
<th>Description</th>
<th>Beta' lab No.</th>
<th>No. of rings dated</th>
<th>$^{14}$C age (years BP)</th>
<th>Calibrated age$^b$ (ka)</th>
<th>2σ calibration$^b$ (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>MC06-03</td>
<td>146</td>
<td>Detrital wood recovered from alluvial deposits 500 m downvalley from the 2006 ice front of Orca Glacier.</td>
<td>227635</td>
<td>32</td>
<td>4270±60</td>
<td>4.76</td>
<td>4.96–4.80</td>
</tr>
<tr>
<td>1</td>
<td>MC06-27</td>
<td>120</td>
<td>Detrital wood flushed from beneath Orca Glacier by subglacial meltwater in 2006.</td>
<td>230434</td>
<td>27</td>
<td>3500±60</td>
<td>3.78</td>
<td>3.92–3.63</td>
</tr>
<tr>
<td>5</td>
<td>MC06-07</td>
<td>164</td>
<td>Bole segment found below till lying on paleosol in front of Manatee Glacier.</td>
<td>230433</td>
<td>27</td>
<td>3440±60</td>
<td>3.70</td>
<td>3.84–3.56</td>
</tr>
<tr>
<td>3</td>
<td>MC06-23</td>
<td>302</td>
<td>Glacially sheared stump rooted in a paleosol that was partially buried by Beluga Glacier till.</td>
<td>227637</td>
<td>37</td>
<td>2350±70</td>
<td>2.42</td>
<td>2.70–2.64</td>
</tr>
<tr>
<td>4</td>
<td>MC06-04</td>
<td>239</td>
<td>Standing snag located distal to Beluga Glacier lateral moraine</td>
<td>227636</td>
<td>17</td>
<td>290±70</td>
<td>0.18</td>
<td>0.21–0.14</td>
</tr>
</tbody>
</table>

$^a$Radiocarbon Laboratory: Beta Analytical Inc., Miami, Fla.

$^b$Radiocarbon dates converted to cal years BP using IntCal04 (Reimer et al. 2004). For dates with multiple peaks, the midpoint of the dominant peak was used.

**Fig. 5.** View of the westward-facing snout of Orca Glacier showing the confluent Orca and Beluga glaciers forefield. The outermost rings of two pieces of detrital wood from sites 1 and 2, respectively, were radiocarbon dated at 3.78 ka (MC06-27) and 4.76 ka (MC06-03).
at moraine crest interception points found within ±5 m of linear transects (Fig. 2). The thallus with the largest near-circular diameter was used to estimate the surface age.

Three *Rhizocarpon geographicum* growth curves have been developed for lichenometric analysis in this region: one for Vancouver Island (Lewis and Smith 2004), one for the Bella Coola – Mount Waddington area (Smith and Desloges 2000; Larocque and Smith 2003), and another for the Cascade Range (Porter 1981; O’Neal and Schoenenberger 2003). To establish which curve was applicable to the study area, aerial photographs were examined to identify historical ice front positions (Fig. 2). Two locations were visited in 2007; the diameters of all lichen present within ±10 m of the historical ice front positions were measured.

**Results**

**Dendrochronology and tree ecesis**

A master tree ring chronology was constructed from living and dead subalpine fir trees found on a north-facing slope between Beluga and Manatee glaciers (Fig. 1). Twenty living trees were used to build a reference chronology extending from 1573 to 2007 AD. Cores from six standing snags cross-date with the living chronology, allowing a master chronology to be constructed extending back to 1299 AD. The chronology displays an interseries correlation of 0.547 and has a mean sensitivity of 0.214 (Table 1). After 1675 AD, the EPS value dropped below the 0.85 threshold (Wigley et al. 1984; Briffa and Jones 1990).

Subalpine fir seedlings found at two sites in front of Manatee Glacier were used to establish the local ecesis interval (Sigafous and Hendricks 1969; McCarthy and Luckman 1993). Seventeen trees were surveyed on bedrock surfaces exposed in 1948 and nine trees from a bedrock area exposed in 1970 (Table 2). The oldest individuals yielded minimum ages of 39 and 20 years, respectively, and define a minimum ecesis interval of 17 years (Table 2).

**Dendroglaciology results**

An eroded terminal moraine complex at ca. 1300 m asl marks the confluent downvalley LIA extension of Orca, Beluga, and Manatee glaciers down Manatee Creek (Fig. 3). Distinct LIA trimlines and nested lateral moraine sequences illustrate the position of former ice levels within the valley (Figs. 1 and 2). All four glaciers retreated upvalley over the last century at rates averaging 5–35 m/year (Table 3).

**Orca Glacier**

Until early in the 20th century the western snout of Orca Glacier was confluent with Beluga Glacier and flowed downvalley to join Manatee Glacier (Figs. 3 and 4). Following separation from Beluga Glacier after 1970, the terminus of Orca Glacier receded upvalley at an average rate of 39 m/year (Table 3).

In 2006, Orca Glacier terminated on a gentle slope of ground moraine at 1676 m asl (Fig. 4). Detrital wood fragments recently washed from a subglacial meltwater portal were collected within a channel 5 m downstream of the snout (Site 1, Fig. 4). Included was a small portion of stem with 120 annual rings (MC06-27; Table 4). The outermost 24 rings gave a radiocarbon age of 3.78 ka (Table 4). A second bole fragment (MC06-03, <30 cm length) with 146 annual rings was found partially buried in alluvial sediments ca. 590 m down valley (Site 2, Fig. 4). The outermost 32 tree rings date to 4.76 ka (Table 4).

**Beluga Glacier**

The snout of Beluga Glacier is located 800 m downvalley from Orca Glacier, where it spills from a tributary valley to terminate at 1650 m asl (Figs. 4 and 5). Ice front recession averaged 33 m/year from 1948 to 1970, but slowed to 17 m/year from 1970 to 2006 after Beluga Glacier separated from Orca Glacier (Table 3).

Partially buried subfossil wood samples were collected at two locations. One site consisted of a group of glacially sheared stumps and scattered detrital boles partially buried by till on the lee side of a prominent glacially sculpted bedrock knoll ca. 800 m downvalley from the glacier snout (Site 3, Fig. 4). Historical aerial photographs indicate the site was exposed by retreating ice in ca. 1948 (Fig. 4).

Samples were collected from eight subalpine fir stumps found rooted in a well-developed paleosol (Fig. 6). All the samples were tilted downvalley and most appeared to have been sheared ca. 1 m above the ground surface. The samples...
contained from 94 to 302 annual rings and cross-date to produce a floating chronology that indicates all the trees along a 15 m transect were killed within a 50 year period. A perimeter wood sample with 23 rings from one of the cross-dated stumps (MC06-23) has a radiocarbon age of 2350 ± 70 14C years BP (2.42 ka, Table 4).

A second site was located along the outermost lateral moraine (M1) of Beluga Glacier at 1644 m asl (Site 4, Fig. 4). The moraine contains two large trunk segments; one was found partially buried within the distal debris (Fig. 7a) and a cover of large lichen thalli (maximum diameter 55.3 mm; Table 5). A solitary snag abuts the distal slopes of the moraine (Fig. 7b).

Ring-width measurements from the two trunks and a snag cross-date with the master tree ring chronology constructed from trees found within the adjacent subalpine forest (Fig. 8). Although no bark remained and some perimeter wood loss was evident, the two trunks found in the lateral moraine are the remains of trees that died in ca. 1733 (MC06-04) and 1736 (MC06-05; Fig. 7b) AD. The standing snag died a short time later in 1738 AD (Table 4). A sample of perimeter wood with 17 rings from the latter sample (MC06-06) has a radiocarbon age of 0.18 ka (Table 4).

**Manatee Glacier**

Prior to 1948, Manatee Glacier merged with the confluent flow of Beluga and Orca glaciers (Fig. 3). Nested and partially vegetation-covered lateral moraines flank the valley perimeter. Historical downwasting exceeding 150 m and terminus retreat averaging 14.8 m/year since 1948 (Table 3) have exposed subfossil wood deposits at two locations downvalley of the present ice front (Fig. 9).
A mat of woody detritus was located below till on the distal slope of a bedrock shelf at 1606 m asl (Site 5, Fig. 9). Broken fragments of four boles and numerous large branches were found pressed into an underlying paleosol. The outermost 27 perimeter rings of MC06-07 have a radiocarbon age of 3430 ± 6014C years BP (3.7 ka, Table 4).

At the second site (Site 6, Fig. 10), sixteen subalpine fir bole fragments were found partially exposed below a veneer of till along the lower proximal slopes of a north-facing lateral moraine 900 m downvalley of Manatee Glacier. Aerial photographs indicate this area was free of ice by 1948 (Fig. 10), at a time when the terminus of Manatee Glacier extended to the northeastern end of the adjacent proglacial lake. The boles were found lying oriented downvalley on the surface of a buried paleosol that extended for more than 100 m along the western shore of the lake. Their size and condition (no bark and limited surface mastication) suggest they were not transported far from their growth position after being overridden by Manatee Glacier.

Counts of the annual growth rings within samples collected at the site indicate the trees ranged in age up to 200 years. Thirteen of the samples cross-date to the radiocarbon-dated Beluga Glacier floating chronology (Table 1). Assuming limited perimeter wood loss, the trees at this site died ca. 123 years after Beluga Glacier killed those in the adjacent valley at 2.55 ka (Table 4).

### Table 5. Lichenometric dates derived for lateral moraine stabilization at Manatee Glacier and Oluk Glacier.

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation above sea level (m)</th>
<th>Maximum thallus (mm)</th>
<th>Average of five largest thallus (mm)</th>
<th>Surface age (years)</th>
<th>Moraine date (year AD)</th>
<th>95% CI (year AD)</th>
</tr>
</thead>
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<tr>
<td><strong>Transect A–a</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>1640</td>
<td>78.6</td>
<td>64.3</td>
<td>590</td>
<td>1417</td>
<td>1348–1506</td>
</tr>
<tr>
<td>M2</td>
<td>1625</td>
<td>41.8</td>
<td>35.7</td>
<td>184</td>
<td>1823</td>
<td>1784–1867</td>
</tr>
<tr>
<td>M3</td>
<td>1620</td>
<td>41.0</td>
<td>35.4</td>
<td>175</td>
<td>1832</td>
<td>1793–1875</td>
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<td>M4</td>
<td>1616</td>
<td>36.0</td>
<td>32.9</td>
<td>125</td>
<td>1882</td>
<td>1847–1920</td>
</tr>
<tr>
<td>M5</td>
<td>1615</td>
<td>32.5</td>
<td>30.7</td>
<td>97</td>
<td>1910</td>
<td>1908–1912</td>
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<tr>
<td>M6</td>
<td>1615</td>
<td>25.2</td>
<td>24.3</td>
<td>57</td>
<td>1950</td>
<td>1948–1952</td>
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<td><strong>Transect B–b</strong></td>
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<tr>
<td>M1</td>
<td>1805</td>
<td>50.1</td>
<td>47.1</td>
<td>276</td>
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<td>1685–1786</td>
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<td>1807</td>
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<td>132</td>
<td>1875</td>
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<tr>
<td>M3</td>
<td>1808</td>
<td>34.8</td>
<td>32.1</td>
<td>115</td>
<td>1892</td>
<td>1859–1929</td>
</tr>
<tr>
<td>M4</td>
<td>1803</td>
<td>33.9</td>
<td>29.1</td>
<td>107</td>
<td>1900</td>
<td>1898–1902</td>
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<tr>
<td>M1</td>
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<td>61.2</td>
<td>57.1</td>
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<td>51.9</td>
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<td>1711</td>
<td>1664–1768</td>
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<tr>
<td>M1</td>
<td>1735</td>
<td>66.8</td>
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<td>460</td>
<td>1547</td>
<td>1488–1622</td>
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<td>M2</td>
<td>1737</td>
<td>66.3</td>
<td>46.9</td>
<td>455</td>
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<td>1722</td>
<td>33.0</td>
<td>29.2</td>
<td>101</td>
<td>1906</td>
<td>1904–1908</td>
</tr>
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</table>

**Note:** Transect locations and orientations are displayed in Fig. 3. Minimum dates for moraine stabilization incorporate systematic errors associated with the *Rhizocarpon* spp. growth curve from the central Coast Mountains (Larocque and Smith 2004; Smith and Desloges 2000).

### Lichenometry results

To describe the LIA history of Manatee and Oluk glaciers, lichenometric surveys were completed along four transects on the lateral moraine complexes (Fig. 2). The findings of the surveys were interpreted using a modified version of the lichen growth curve presented by Larocque and Smith (2004).

### Lichen growth curve

The lichen growth curve presented by Larocque and Smith (2004) was derived from 18 independently dated control points in the central Coast Mountain region (Smith and Desloges 2000; Larocque and Smith 2003). Our investigations provide additional points that further calibrate the curve.

At Manatee Glacier, aerial photographs dating from 1948 (BC686:7) and 1970 (A2204:012) were used to map the position of the receding ice front (Fig. 2). Measurement of the maximum diameter of >20 thalli in 2007 at each location was used to document the age–size relationship of the first (largest) lichen colonizers. The two locations provide reliable control points (59 years: 26.3 mm, 37 years: 22.4 mm; Table 2) consistent with those previously documented for thalli of this size (Table 2 in Larocque and Smith 2004).

At Beluga Glacier >20 thalli were measured in 2006 on the surface of the lateral moraine constructed in ca. 1736 AD (Table 1). The maximum lichen diameter (55.3 mm)
Fig. 8. Summary of dendroglaciological studies at Site 4 along the outermost lateral moraine (M1) of Beluga Glacier. The upper portion of the figure illustrates the duration of the three cross-dated subfossil samples (grey lines). Whereas the youngest portion of each record indicates the pith date of the sample, the oldest portion does not necessarily represent the absolute age of the sampled wood due to surface abrasion and rot. The lower portion of the graph illustrates the *Abies lasiocarpa* chronology (black line) derived from living trees, standing snags and coarse woody debris found in the adjacent forest. Dates and dashed lines refer to common pointer years.

Fig. 9. The buried remains of a subalpine fir tree located along the proximal slope of the eastern lateral moraine of Manatee Glacier. The tree (MC06-07) was killed ca. 3.70 ka when the glacier thickened to late LIA proportions.
measured on the moraine surface provides a reliable control point at 270 years (Table 2).

Figure 11 presents a revised *Rhizocarpon* spp. lichen growth curve that includes the control points used in the curve presented by Larocque and Smith (2004), three new points from the Manatee Valley area, and a previously excluded control point from Whitesaddle Glacier in the Mount Waddington area (Larocque and Smith 2004: 409–410). These control points were translated into line equations defining statistical lichen growth relationships and 95% confidence intervals were established to allow for age-specific error estimates (O’Neal and Schoenenber 2003; Larocque and Smith 2004).

**Little Ice Age (LIA) lichenometry: Manatee Glacier lateral moraine complex**

Three lichenometric transects were completed on lateral moraines lining the upper limit of Holocene glaciation in the valley below Manatee Glacier (Figs. 2 and 4). One transect (A–a', Fig. 12) extends across a nested sequence of six distinct lateral moraine crests at ca. 1640 m asl on the east side of the valley (Fig. 2). Moraine M1 consisted of a discontinuous line of large boulders located within the adjacent subalpine fir parkland. Coalesced *R. geographicum* thalli blanket most boulders, making it difficult to distinguish individual thalli. The largest thallus measured 78.6 mm in diameter and provides a minimum moraine stabilization date.
of ca. 1417 AD (Table 5). Large boulders with diameters ranging from 0.3–0.5 m form the crests of M2 and M3 (Fig. 12). The largest lichen found on these moraines indicates that they were deposited in ca. 1823 AD and 1832 AD, respectively (Table 5). The more proximal crests of M4 and M5 demarcate moraine positions occupied in the late 19th and early 20th centuries. The most recently deposited moraine (M6) records a minor interval of glacier expansion in the mid 20th century (Table 5).

The west side of the valley is distinguished by four to five nested lateral moraines whose crests gradually decline in elevation from 1740 m asl in the vicinity of Manatee Glacier, to 1400 m asl where they cross Oluk Creek 2 km downvalley (Fig. 2). In the vicinity of transect B–b’ the moraine crests are largely devoid of vegetation, with only a sparse cover of small willows (Salix spp.) in sandy areas. The largest thallus found on M1 measured 50.1 mm and dates to a period of glacier expansion ending prior to the early 18th century (Table 5). Moraines M2 and M3 extend 400 m downvalley, where they were dissected by a meltwater stream (Fig. 2). A 36.8 mm thallus found on the crest of M2 indicates moraine stabilization occurred in ca. 1875 AD (Table 5). Moraines M3 and M4 record subsequent intervals of ice expansion that terminated in ca. 1892 AD and 1900 AD, respectively (Table 5).

Transect C–c’ is located ca. 0.5 km downvalley from B–b’ (Fig. 2). Moraine M1 is colonized by mature subalpine fir, moss, lichen, and alder. While the trees (minimum 248 rings + 17 year ecesis) indicate M1 stabilized prior to 1742 AD, a lichen measuring 62.1 mm suggests it was constructed prior to 1609 AD (Table 5; Fig. 12). The crests of M2 and M3 merge at several points and appear to have been deposited within a short time of each other in ca. 1705 AD and 1711 AD, respectively (Table 5). Lichens on boulders on the crest M4 and M5 indicate their deposition occurred between ca. 1837 AD and 1875 AD. A survey of trees colonizing the surface of M4 suggests the crest of the moraine had stabilized by 1932 AD (58 rings + 17 year ecesis).

(Little Ice Age) LIA lichenometry: Oluk Glacier lateral moraine

The terminus of Oluk Glacier historically spilled into Manatee Creek valley, but has retreated at an average of 13 m/year since 1948 to a bedrock bench at ca. 1900 m asl (Table 3). Transect D–d’ crosses a prominent lateral moraine complex with five nested crests along the southern perimeter of the glacier forefield (Figs. 2 and 12). Thalli on M1 and M2 indicate the moraine crests were constructed within a short time of each other ca. 1547 AD and 1552 AD (Table 5). Moraine M3 was deposited prior to 1768 AD.
Moraines M4 and M5 record periods of glacier expansion that ended by ca. 1882 AD and 1906 AD, respectively (Table 5).

Fig. 12. Topographic cross-sections of the lateral moraines surveyed on the northern and southern margins of Manatee Glacier and the southern boundary of Oluk Glacier (see Fig. 2 for transect locations). The moraines are numbered so that M1 is always in the most distal position. Numbers from different transects are not necessarily time-synchronous. The dates in brackets are minimum estimates provided by lichenometry for moraine construction.

Synthesis and interpretation

Dendroglaciologic and lichenometric evidence from the study area records four distinct periods of late Holocene glacier expansion at 4.76, 3.78, and 2.42 ka, and during the LIA. Evidence for the earliest advance at 4.76 ka is restricted to detrital wood flushed from beneath Orca Glacier (Site 2, Fig. 4). Representing the fragmented remnants of small, possibly krummholz-scale trees, the kill date of this detrital wood may correspond to that associated with trees killed by the 5.50 ka advance of Sphinx Glacier in Garibaldi Provincial Park (Koch et al. 2007a). Alternatively, they may record the inception of a subsequent period of regional glacier expansion that Menounos et al. (2009) indicate culminated in ca. 4.17 ka.

Two sites in the Manatee drainage area record an interval of glacier expansion corresponding to the Tiedemann Advance. The discovery of glacially transported tree remains resting on a paleosol buried below till along the eastern margin of Manatee Glacier provides evidence for ice thickening to near LIA depths by 3.70 ka (Site 5, Fig. 2). Glacially killed detrital wood dating to this time found at nearby Lillooet and Bridge glaciers confirms the regional significance of this event (Reyes and Clague 2004; Allen and Smith 2007).

Dendroglaciological evidence from the forefields of Beluga and Manatee glaciers benchmarks a distinct interval of ice expansion at 2.42 ka, referred to herein as the “Manatee Advance”. Cross-dated samples confirm that both glaciers were concurrently advancing, killing and burying mature standing forests at this time. At Manatee Glacier, the valley bottom position of this forest (Site 6, Fig. 2) would have required both substantial ice retreat and downwasting (>100 m) following the 3.7 ka glacier expansion (Site 5, Fig. 2). Given that the trees were >200 years in age when killed and were found resting on a well-developed paleosol, a significant ice-free period necessarily elapsed between the downvalley expansion of Manatee Glacier at 3.70 and 2.42 ka.

The 2.42 ka advance of Beluga and Manatee glaciers is broadly synchronous with a distinct interval of glacier expansion increasingly recognized throughout the Coast Mountains. Similar ages were obtained on detrital wood at Lillooet Glacier (Reyes and Clague 2004), Bridge Glacier (Allen and Smith 2007) and in Garibaldi Provincial Park (Koch et al. 2007a). Farther north in the Coast Mountains, detrital wood fragments indicate glaciers were also advancing at this time in the Monarch Icefield near Bella Coola (Desloges and Ryder 1990) and in the Boundary Ranges near Stewart (Clague and Mathews 1992; Clague and Mathews 1996; Jackson et al. 2008). Unlike previous reports, however, the dendroglaciologic evidence from Manatee Valley definitively shows that glaciers advanced into and buried mature living trees at this time. Given this evidence, the 2.42 ka “Manatee Advance” should be recognized as distinct from those described as the 3.50 ka Tiedemann Advance (Ryder and Thomson 1986).

Lichenometric investigations at four sites characterize the LIA activity of Manatee and Oluk glaciers. Moraine M1 at Manatee Glacier (Transect A–a; Fig. 2) was assigned an early 15th century stabilization date. Although lichenometry has dated moraines to this time elsewhere in southwestern...
British Columbia (Lewis and Smith 2004; Allen and Smith 2007; Koch et al. 2007b), the extensive cover of lichens found on this moraine suggests it may predate the LIA. Lichens measured on M1 and M2 at Oluk Glacier record a period of moraine construction in the mid-1500s AD (D–d; Fig. 11). While moraines of corresponding age were documented at Bridge Glacier (Allen and Smith 2007), the limited number of thalli measured on the exposed Oluk Glacier moraines prevents a reliable estimate of surface age by lichenometry.

The largest lichen colonizing the outermost Beluga Glacier lateral moraine (Site 5, Fig. 4) provide a 270 year calibration point for the revised growth curve (Fig. 10). The perimeter tree rings of two logs incorporated within the moraine indicate it was constructed in ca. 1736 AD. While the trees may have died prior to being killed by the advancing glacier, there is no corresponding evidence of dead trees in the adjacent forest. Furthermore, the apparent death of the standing snag in 1738 AD following emplacement of M1 suggests the moraine was constructed as Beluga Glacier expanded into a mature valley-side forest (>239 years) during the early part of the 18th century. The discovery of similarly aged moraines at Manatee and Oluk glaciers indicates this period was a time of significant glacier expansion (Fig. 11). Comparable findings are reported from many sites in the Coast Mountains (Smith and Desloges 2000; Larocque and Smith 2003; Lewis and Smith 2004; Allen and Smith 2007; Koch et al. 2007b).

Following the 18th century advance, Manatee and Oluk glaciers downwasted before expanding in the early 19th century (Fig. 12). This episode of ice expansion was followed by another period of downwasting before a last moraine-building episode in the late 19th to early–mid 20th centuries.

Conclusion

The dendroglaciologic and lichenometric research methodologies employed in this study provide a long-term perspective of glaciological conditions from 5 ka to present in the southern British Columbia Coast Mountains. Although our insights into mid-Holocene glacial activity are limited by a lack of deposits, our findings do suggest that glaciers were expanding in 4.76 and 3.78 ka. By 3.70 ka Manatee Glacier had thickened to depths close to those reached in the LIA. Following this, glaciers in this area receded upvalley sufficiently long enough for the development of deep pedogenic surfaces and the growth of trees (exceeding 200 years) by 2.42 ka.

Our investigations in Beluga and Manatee glacier forefields benchmark a significant episode of glacial expansion at 2.42 ka. The “Manatee Advance” has regional correlates and is distinguished from the 3.70 ka Tiedemann Advance at Manatee Glacier by recognition of substantive volumetric losses in ice between the two episodes.

Examination of LIA deposits in the study area allowed for presentation and application of a revised Rhizocarpon spp. lichen growth curve. Lichenometric surveys of lateral moraines associated with Beluga, Manatee, and Oluk glaciers provided insight into their early LIA behaviour. Both Beluga and Manatee glaciers achieved their maximum LIA size in the early to mid 18th century. Subsequent oscillations in glacier size are recorded by lateral moraines constructed in the early 19th century and the late 19th to early 20th centuries. Historical ice front retreat is ongoing, albeit at a slower pace in recent decades.

Our paper chronicles the behavior of glaciers in the headwaters of Manatee Creek. Although fragmentary, the dendroglaciologic and lichenometric evidence from this area demonstrates adjustments in ice geometry that are synchronous with regional accounts of late Holocene glacier dynamics.

Acknowledgements

D. Smith was provided with project funding through a grant received from the Natural Sciences and Engineering Research Council of Canada (NSERC) and an award made by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) to the Western Canadian Cryospheric Network. The authors thank Leslie Able, Bethany Coulthard, Kelly Penrose, and Michi Main for their assistance in the field. Sonya Larocque generously recompiled the data presented in Fig. 11.

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