

Glacier fluctuations during the past millennium in Garibaldi Provincial Park, southern Coast Mountains, British Columbia

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Abstract: The Little Ice Age glacier history in Garibaldi Provincial Park (southern Coast Mountains, British Columbia) was reconstructed using geomorphic mapping, radiocarbon ages on fossil wood in glacier forefields, dendrochronology, and lichenometry. The Little Ice Age began in the 11th century. Glaciers reached their first maximum of the past millennium in the 12th century. They were only slightly more extensive than today in the 13th century, but advanced at least twice in the 14th and 15th centuries to near their maximum Little Ice Age positions. Glaciers probably fluctuated around these advanced positions from the 15th century to the beginning of the 18th century. They achieved their greatest extent between A.D. 1690 and 1720. Moraines were deposited at positions beyond present-day ice limits throughout the 19th and early 20th centuries. Glacier fluctuations appear to be synchronous throughout Garibaldi Park. This chronology agrees well with similar records from other mountain ranges and with reconstructed Northern Hemisphere temperature series, indicating global forcing of glacier fluctuations in the past millennium. It also corresponds with sunspot minima, indicating that solar irradiance plays an important role in late Holocene climate change.

Résumé : L'histoire du Petit Âge Glaciaire dans le Parc provincial Garibaldi (sud de la chaîne Côtière, Colombie-Britannique) a été reconstruit en utilisant de la cartographie géomorphologique, des âges radiocarbone sur du bois fossile dans les avant-fronts, de la dendrochronologie et de la lichénométrie. Le Petit Âge Glaciaire a débuté au 11^e siècle. Les glaciers ont atteint leur premier maximum du dernier millénaire au 12^e siècle. Au 13^e siècle, ils étaient légèrement plus extensifs que de nos jours, mais ils ont avancé au moins deux fois aux 14^e et 15^e siècles à leur position maximale du Petit Âge Glaciaire. Les glaciers ont probablement fluctué autour de ces positions avancées entre le 15^e siècle et le début du 18^e siècle, atteignant leur maximum entre les années 1690 et 1720. Les moraines ont été déposées au-delà des limites actuelles de la glace tout au cours du 19^e siècle et au début du 20^e siècle. Les fluctuations des glaciers semblent être synchrones à travers tout le parc Garibaldi. Cette chronologie concorde bien avec des données provenant d'autres chaînes de montagnes et avec la série de températures reconstituées pour l'hémisphère Nord, indiquant un forçage global des fluctuations de glaciers au cours du dernier millénaire. Il correspond aussi à un minimum de taches solaires, indiquant que l'irradiation solaire jouait un rôle important dans les changements climatiques à l'Holocène tardif.

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Introduction

The Little Ice Age, which spans much of the past millennium, was a period of variable but generally cool climate, when glaciers were more extensive than at other times in the Holocene (Grove 1988). The event is recorded in all glacierized mountains of the world (Holzhauser 1985; Grove 1988; Wiles et al. 1999; Luckman 2000; Luckman and Villalba 2001; Koch and Kilian 2005). The Little Ice Age comprises early advances between A.D. 1100 and 1300 and

a series of late advances from 1700 to 1900 (Grove 1988, 2001). The latter were generally more extensive and commonly obliterated older deposits. Many studies of Northern Hemisphere glaciers thus provide great detail on late Little Ice Age and 20th century glacier behaviour but little information on earlier events.

Climate variability during the Little Ice Age (Moberg et al. 2005) was probably caused by interactions among several forcing mechanisms (Mann et al. 1998). Explosive volcanism contributed to Northern Hemisphere temperature changes during the past 600 years (Bradley and Jones 1993; Briffa et al. 1998), and some glacier advances coincided with intervals of elevated volcanic aerosols in the atmosphere (Porter 1986). Others have argued that solar activity influenced the climate of the past millennium (Lean et al. 1995; Crowley and Kim 1996; Crowley 2000); periods of late Little Ice Age moraine formation are associated with solar minima (Lawrence 1950; Wiles et al. 2004; Luckman and Wilson 2005). In addition, ocean-atmosphere interactions influenced atmospheric circulation and therefore glacier behaviour during the past millennium (Hendy et al. 2002;

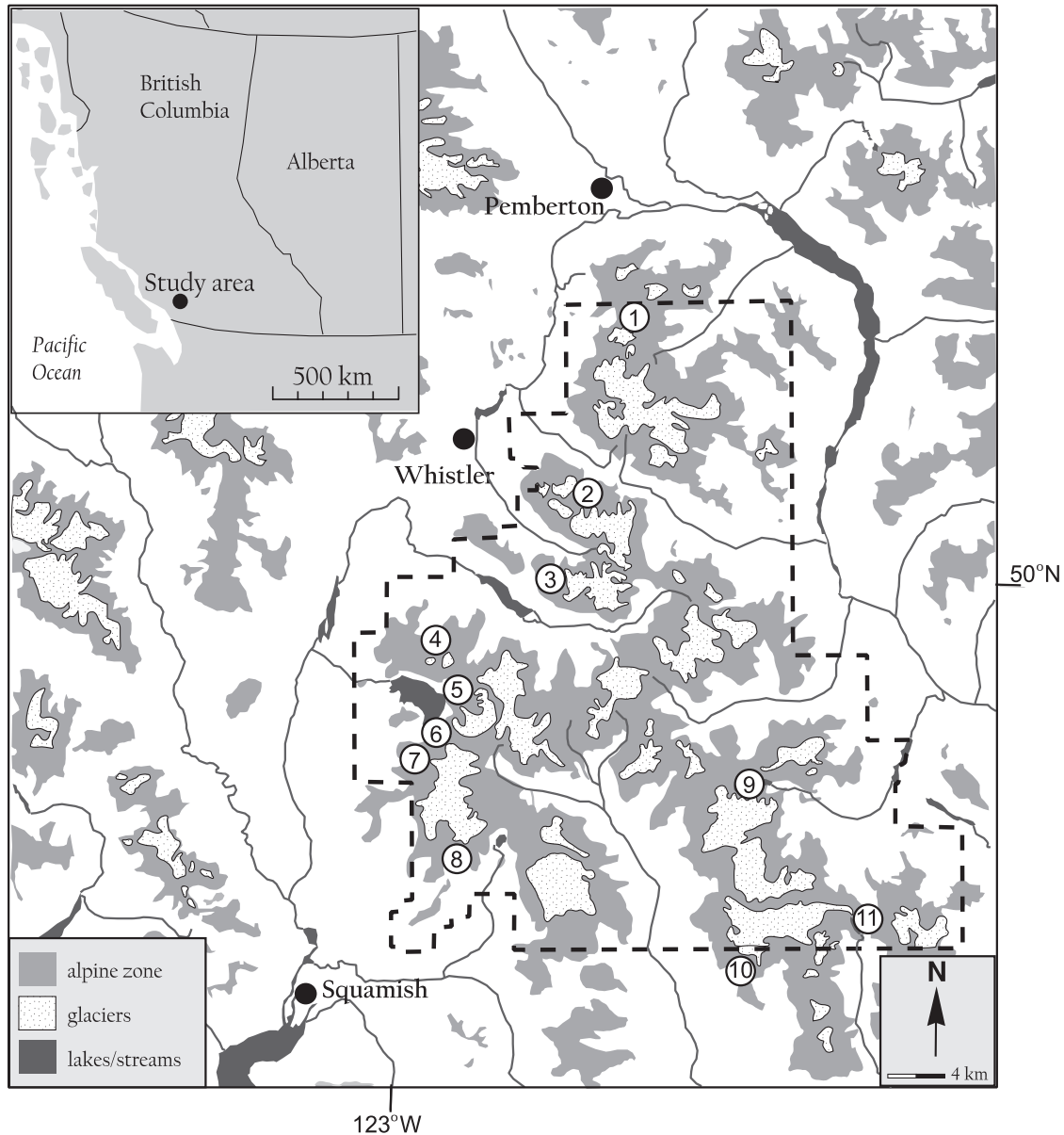
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Fig. 1. Map showing location of Garibaldi Provincial Park and its glaciers. 1, Mystery Glacier; 2, Trorey Glacier; 3, Overlord Glacier; 4, Helm Glacier; 5, Sphinx Glacier; 6, Sentinel Glacier; 7, Warren Glacier; 8, Garibaldi and Lava glaciers; 9, Snowcap Lakes; 10, West Stave Glacier; 11, Stave Glacier.



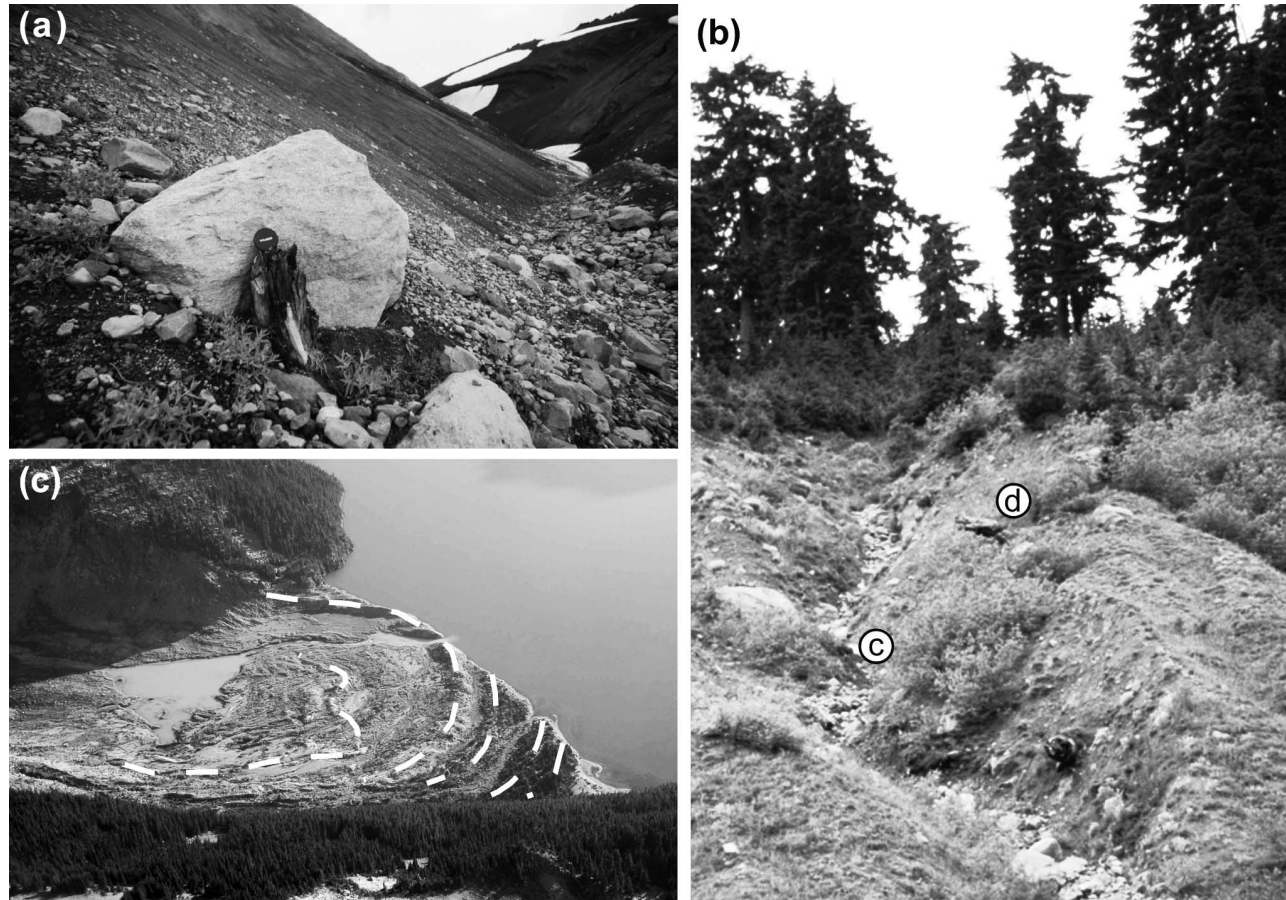
Nesje and Dahl 2003; Lewis and Smith 2004*b*; Mann et al. 2005). Ruddiman (2003) suggested that widespread farm abandonment during Black Death plagues and attendant reforestation may explain the cool phases of the Little Ice Age by changing concentrations of atmospheric carbon dioxide and methane.

Little Ice Age glacier fluctuations appear to be synchronous on a centennial timescale along the Pole–Equator–Pole I transect in the Americas (Luckman and Villalba 2001). However, most glaciers in the American Cordillera have not been studied and well-dated records of Little Ice Age glacier fluctuations are still needed (Luckman and Villalba 2001). Most research on Little Ice Age glacier fluctuations in western Canada has been conducted in the Rocky Mountains (Luckman 2000, and references therein). Less is known about glaciers in the Coast Mountains (Mathews 1951;

Ryder and Thomson 1986; Desloges and Ryder 1990), although there are now well-dated records from Vancouver Island and the adjacent British Columbia mainland (Smith and Desloges 2000; Larocque and Smith 2003; Lewis and Smith 2004*a*).

This paper describes the Little Ice Age histories of glaciers in Garibaldi Provincial Park, southern Coast Mountains, British Columbia (Fig. 1). Many glacier forefields in Garibaldi Park contain a rich record of Little Ice Age events that can be reconstructed using dendrochronology, lichenometry, and radiocarbon dating. This record allows us to reconstruct advance rates of some glaciers in the park during the Little Ice Age. We compare the Garibaldi dataset with (1) other glacial chronologies from western Canada and elsewhere, (2) climate reconstructions for the extratropical Northern Hemisphere, and (3) reconstructions of solar output.

Fig. 2. Examples of fossil wood and Little Ice Age moraines in Garibaldi Park. (a) In situ stump at Helm Glacier (site k, Fig. 4). The boulder rests against the stump. (b) Two wood layers in lateral moraine of Lava Glacier (sites c and d, Fig. 9). (c) Little Ice Age moraines of Sphinx Glacier. Photographs by J. Koch.



Study area

Garibaldi Provincial Park, located in the southern Coast Mountains about 70 km north of Vancouver, British Columbia (Fig. 1), contains over 150 glaciers. Climate is humid and cool, with very wet winters and dry summers. The northwest-trending Coast Mountains are an orographic barrier to air moving eastward from the Pacific Ocean, creating a strong west–east environmental gradient across the park. Moist maritime air controls the climate of the southwestern part of the park, and climate becomes increasingly continental to the north and east. Average annual precipitation at Squamish is 2370 mm, but declines to 1230 mm at Whistler, 60 km to the north. Trees adapted to wet conditions and large snowpacks, notably mountain hemlock (*Tsuga mertensiana*), are common in subalpine forests in the southern and western parts of the park. Species adapted to colder and drier conditions, including Engelmann spruce (*Picea engelmannii*) and whitebark pine (*Pinus albicaulis*), dominate in northern and eastern areas. Subalpine fir (*Abies lasiocarpa*) is important in glacier forefields throughout the park.

Methods

Fieldwork was conducted between 2002 and 2004. Moraines at nine glaciers were mapped and dated by dendrochronology, lichenometry, or, where possible, both. Detrital

and in situ (growth position) wood in glacier forefields was radiocarbon dated, and trees damaged by moraine construction were dated by dendrochronology.

Dendrochronology and radiocarbon dating

The oldest tree on a moraine provides a minimum age for moraine stabilization (Lawrence 1946; Sigafos and Hendricks 1969; Luckman 1998). Most moraines in Garibaldi Park have sparse tree cover (Fig. 2c), facilitating the dating of the oldest living trees. Corrections must be made for (1) ecesis (the time from surface stabilization to seedling germination; Sigafos and Hendricks 1969; McCarthy and Luckman 1993) and (2) the time for trees to grow to coring height (McCarthy et al. 1991; Winchester and Harrison 2000). Ecesis and age–height relations have been studied in detail in Garibaldi Park and corrections have been added to ring counts of the oldest tree on each moraine (Koch 2006). In this study, a local age–height correction factor was applied, based on the width of pith rings. Ecesis was established at several sites in each glacier forefield, taking into account elevation, aspect, snow depth, and other relevant environmental factors. Corrections were applied to individual trees based on their environmental setting.

Two cores from each of 10 to 15 trees on each moraine were extracted using a 4.3 mm diameter increment borer.

Two cores provide replication and minimize the possibility of missing and false rings (Stokes and Smiley 1996). Cores were air-dried, mounted, and sanded with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Rings were measured on a Velmex stage with a precision of ± 0.001 mm using the software MeasureJ2X. Tree-ring chronologies were compiled from all trees growing on a moraine. Series were visually examined to identify marker rings and checked with the International Tree-Ring Data Bank software COFECHA (Holmes 1983). The verified series were crossdated (50 year dated segments lagged by 25 years, with a critical level of correlation (99%) set at 0.32) to create master ring-width chronologies (Holmes 1983).

Discs were cut from detrital and in situ fossil wood in glacier forefields and from trees killed during moraine construction (Figs. 2a, 2b). Sample preparation was the same as for the cores, except up to four radii were measured. Floating chronologies were developed at sites where two or more samples were collected using the same procedure as for the living trees.

Series too old to crossdate with the living ring series were radiocarbon dated. Outer ring samples were dated by Beta Analytic Inc. (Miami, Florida). The radiocarbon ages were calibrated using the program CALIB 5.0 (Stuiver et al. 2005). Calibrated age ranges reported here are 1σ .

Interpretation of radiocarbon ages requires consideration of the provenance and location of the dated material (Osborn 1986; R othlisberger 1986; Ryder and Thomson 1986; Luckman 1998). Samples in growth position precisely date glacier overriding. Detrital plant fossils in stratigraphic context, such as lateral moraines, provide maximum ages for glacier overriding. Some detrital wood may have been emplaced by snow avalanches, or may have died of old age or fire; such samples provide little chronological information on glacier advances.

Lichenometry

Of the nine studied glaciers, only Overlord, Sphinx, Sentinel, and Griffin glaciers have lichen-covered moraines. We assume that the largest *Rhizocarpon geographicum* thallus provides a minimum age for the surface (Innes 1985). The long and short axes of 60 thalli of *Rhizocarpon geographicum* spp. were measured on each moraine to the nearest ± 0.1 mm using a dial caliper. Sampling was limited to near-circular lichens to avoid anomalously large or coalesced thalli (Innes 1985).

We were unable to construct a local calibration curve and so instead used published curves from nearby areas: (1) Vancouver Island, ca. 200 km to the west (Lewis 2001; Lewis and Smith 2004a); (2) the Bella Coola and Mount Waddington area, ca. 200–350 km to the northwest (Smith and Desloges 2000; Larocque and Smith 2004); and (3) the Cascade Range in Washington, ca. 100–350 km to the south (Porter 1981; O'Neal and Schoenenberger 2003). All three curves are based on the maximum diameter of the single largest lichen on independently dated surfaces. The largest single lichen on moraines in Garibaldi Park is not anomalous because it correlates closely with the mean of the maximum diameters of the five largest thalli.

Table 1. Living and floating tree-ring chronologies from glacier forefields in Garibaldi Provincial Park.

Glacier	Chronology	Period (A.D. or years)	Correlation	No. of radii/trees
Overlord	living	1649–2001	0.531	102/55
Helm	living	1763–2003	0.419	93/52
	site a	146	0.674	5/2
	site d	105	0.432	6/4
	site g	222	0.398	13/7
	site h	89	0.417	3/2
	sites e, f	246	0.497	18/8
	sites c, i	223	0.403	12/6
	sites j, k, l	307	0.485	13/7
Sphinx	living	1718–2001	0.587	128/69
	site a	346	0.384	9/5
Sentinel	living	1743–2001	0.603	129/71
Warren	living	1637–2003	0.497	78/43
Garibaldi	living	1757–2002	0.419	109/60
	site a	141	0.393	4/2
	site b	201	0.498	6/3
	sites c, d, e	227	0.597	8/4
Lava	living	1749–2003	0.553	125/75
	site b	266	0.437	3/2
Snowcap	living	1777–2003	0.431	17/9
Stave	living	1737–2001	0.498	86/45

Results

Overlord Glacier

Table 1 summarizes living tree-ring chronologies, including that for Overlord Glacier. A floating chronology based on four radii for a tree killed during construction of moraine B (Fig. 3) was crossdated with the living chronology using COFECHA. The highest correlation ($r = 0.485$) was obtained for the period 1649–1702, indicating that the tree died in 1702.

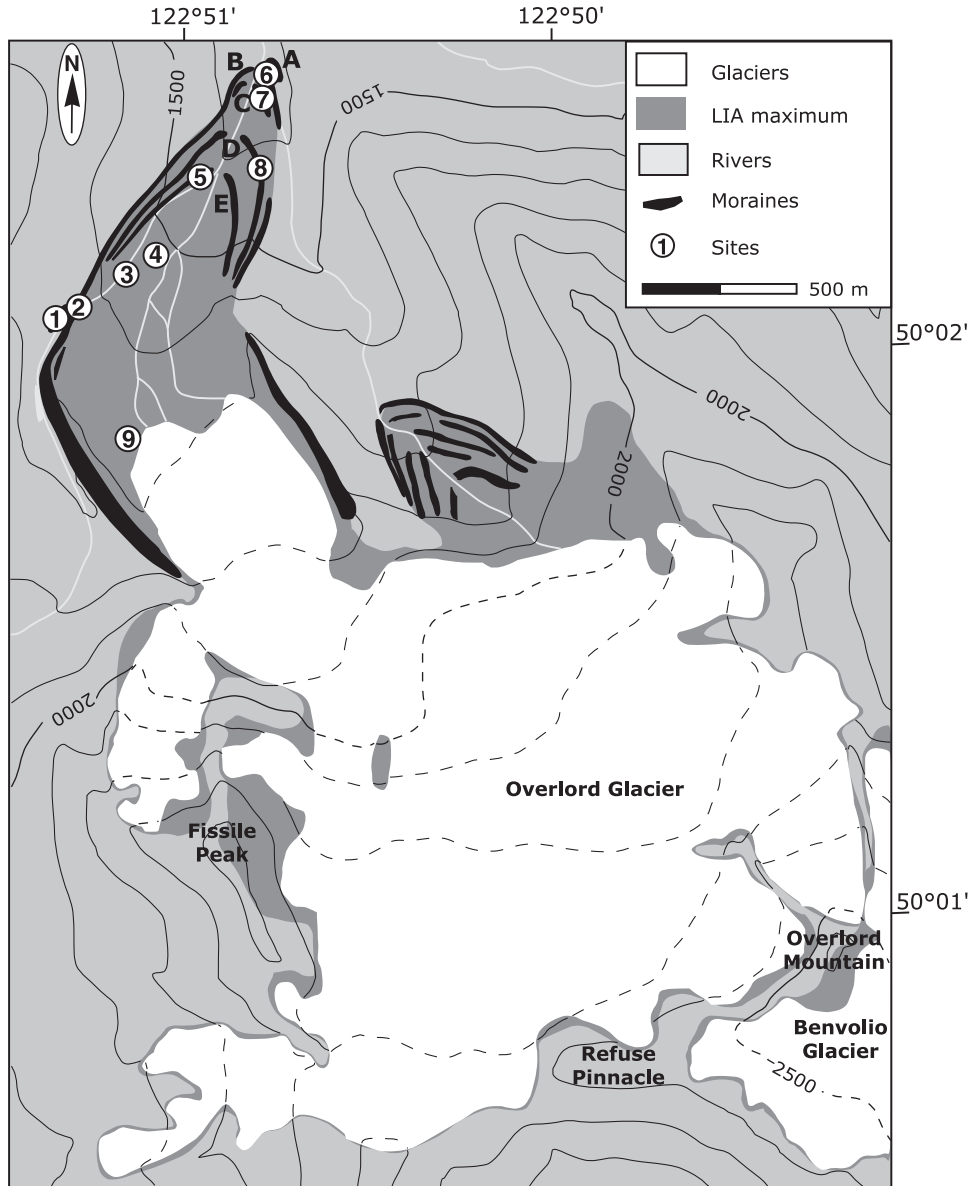
Average height growth rates of young subalpine fir at three sites in the forefield of Overlord Glacier (Fig. 3) range from 0.93 to 4.9 cm/year. Ecesis was estimated to be 6–39 years, based on the difference between the age of the oldest living tree on the second outermost moraine and the age of the tree killed during construction of that moraine, and by comparing repeat ground and aerial photographs.

The measured and corrected ages of the oldest trees on each moraine are summarized in Table 2. Lichenometric ages of the inner three moraines are consistent with the tree-ring ages when the Vancouver Island lichen growth curve is used (Table 3). Moraine A could not be dated by lichenometry or dendrochronology because the forest growing on the moraine is not first-generation.

Helm Glacier

A living tree-ring chronology and seven floating chronologies (sites a, c–i, d, e–f, g, h, and j–k–l, Figs. 4, 5) were constructed at Helm Glacier (Table 1). Floating chronologies from sites a, c–i, d, e–f, h, and j–k–l crossdate with each

Fig. 3. Map of Overlord Glacier showing moraines and maximum Little Ice Age (LIA) glacier extents. Trees were sampled and lichens measured at sites 1, 2, 5, 6, 7, and 8. Trees were sampled for ecesis and age–height growth determination at sites 3, 4, 7, and 9. Glacier margins on this and subsequent maps date to 1996.



other; they were combined into a composite floating chronology spanning about 400 years. Ecesis at Helm Glacier is 46–51 years, and the correction for sampling height is 0.65–3.04 cm/year. Mathews (1951) estimated ecesis at Helm Glacier to be 20–40 years.

Fossil wood was recovered from 13 sites at Helm Glacier. A small branch at site b (Figs. 4, 5) yielded a radiocarbon age of 810 ± 60 ^{14}C years BP (A.D. 1180–1270) (Table 4). The outer ring of the sample is intact, thus the transport distance was probably short. A radiocarbon age of 690 ± 60 ^{14}C years BP (A.D. 1260–1310) dates the outer rings of an in situ stump at site g, where several other stumps and logs were found. All these samples crossdate and indicate that Helm Glacier advanced into a forest with trees at least 222 years old. A small log on the surface in the westernmost cirque (site m) gave an age of 500 ± 40 ^{14}C years BP (A.D.

1410–1440). Two in situ stumps, one with bark and both with intact outer rings, were found at site a; one of these was dated to 490 ± 60 ^{14}C years BP (A.D. 1390–1460). Crossdating shows that the two trees died in the same year and that Helm Glacier advanced into a forest at least 146 years old. An in situ stump with an intact outer ring and seven branches and small logs (sites e and f) all died within a 12 year period. The stump yielded a radiocarbon age of 430 ± 50 ^{14}C years BP (A.D. 1420–1490). The combined ring series at sites e and f was successfully crossdated with that from site a ($r = 0.531$). Trees at site a died 17 years before the single stump at site e. The correlation between the ring series for sites j, k, and l and that for sites e and f is low (0.365), but a radiocarbon age of 380 ± 40 ^{14}C years BP (A.D. 1450–1520) on an in situ stump at site k seems to confirm the crossdating results.

Table 2. Ages of oldest trees (subalpine fir) and respective stabilization dates of moraines in Garibaldi Provincial Park.

Moraine	Tree age (years)	Age–height correction (years)	Eccesis (years)	Stabilization date (A.D.)
Overlord Glacier (sampled in 2002)				
A	nd	nd	nd	nd
B	294	n/a	6	1700s
C	146	n/a	22	1830s
D	84	n/a	25	1890s
E	52	n/a	31	1920s
Helm Glacier (sampled in 2004)				
A	241	n/a	51	1710s
B	129	4	46	1820s
C	83	n/a	49	1870s
D	43	n/a	49	1910s
Sphinx Glacier (sampled in 2002)				
A	284	n/a	24	1690s
B	171	n/a	26	1800s
C	115	n/a	24	1860s
D	68	n/a	28	1900s
E	56	3	26	1910s
Sentinel Glacier (sampled in 2002)				
A	259	2	28	1710s
B	134	9	22	1830s
C	96	n/a	28	1870s
D	77	n/a	25	1900s
E	64	n/a	25	1910s
Warren Glacier (sampled in 2004)				
A	268	14	11	1700s
B	94	n/a	24	1880s
C	72	9	16	1900s
Garibaldi Glacier (sampled in 2003)				
A	246	n/a	35	1720s
B	139	n/a	40	1820s
C	111	n/a	37	1850s
D	96	n/a	35	1870s
E	73	n/a	35	1890s
F	49	5	35	1910s
Lava Glacier (sampled in 2004)				
A	255	n/a	37	1710s
B	164	n/a	35	1800s
C	141	3	35	1820s
D	113	5	35	1850s
E	82	n/a	40	1880s
F	51	n/a	40	1910s
Griffin Glacier (sampled in 2004)				
A	227	n/a	49	1720s
B	115	n/a	56	1830s
C	nd	nd	nd	nd
D	nd	nd	nd	nd
E	nd	nd	nd	nd
F	nd	nd	nd	nd
G	nd	nd	nd	nd
Stave Glacier (sampled in 2002)				
A	265	n/a	13	1720s
B	141	n/a	16	1840s
C	102	n/a	7	1890s
D	82	8	7	1900s

Note: nd, no data; n/a, not applicable.

Table 3. Lichenometric data for moraines at Overlord, Sphinx, Sentinel, and Griffin glaciers.

Moraine	Largest lichen (mm)		Date A.D. using growth curves from		
	Single	Mean of five	Vancouver Island ^a	Cascades ^b	Central Coast Mountains ^c
Overlord Glacier					
A	nd	nd	nd	nd	nd
B	nd	nd	nd	nd	nd
C	59.7	58.4	1830s	1870s	1600s
D	47.5	46.8	1890s	1900s	1730s
E	35.6	34.9	1920s	1920s	1870s
Sphinx Glacier					
A	73.2	72.4	1790s	—	1450s
B	62.4	62.0	1820s	1860s	1570s
C	53.5	52.6	1870s	1880s	1660s
D	43.1	42.8	1890s	1900s	1780s
E	35.1	34.5	1920s	1920s	1870s
Sentinel Glacier					
A	92.1	90.9	1720s	—	—
B	57.5	57.1	1840s	1870s	1620s
C	52.1	51.7	1870s	1880s	1680s
D	41.1	40.8	1900s	1910s	1800s
E	34.7	34.3	1920s	1930s	1870s
Griffin Glacier					
A	93.2	92.1	1710s	—	—
B	61.4	60.6	1820s	1860s	1580s
C	54.7	54.1	1850s	1880s	1650s
D	50.8	50.3	1870s	1890s	1700s
E	44.3	43.5	1890s	1900s	1770s
F	40.5	39.9	1900s	1910s	1810s
G	36.3	35.8	1910s	1920s	1860s

Note: Bold dates are in closest agreement with tree-ring ages; —, beyond range of lichen growth curve; nd, no data.

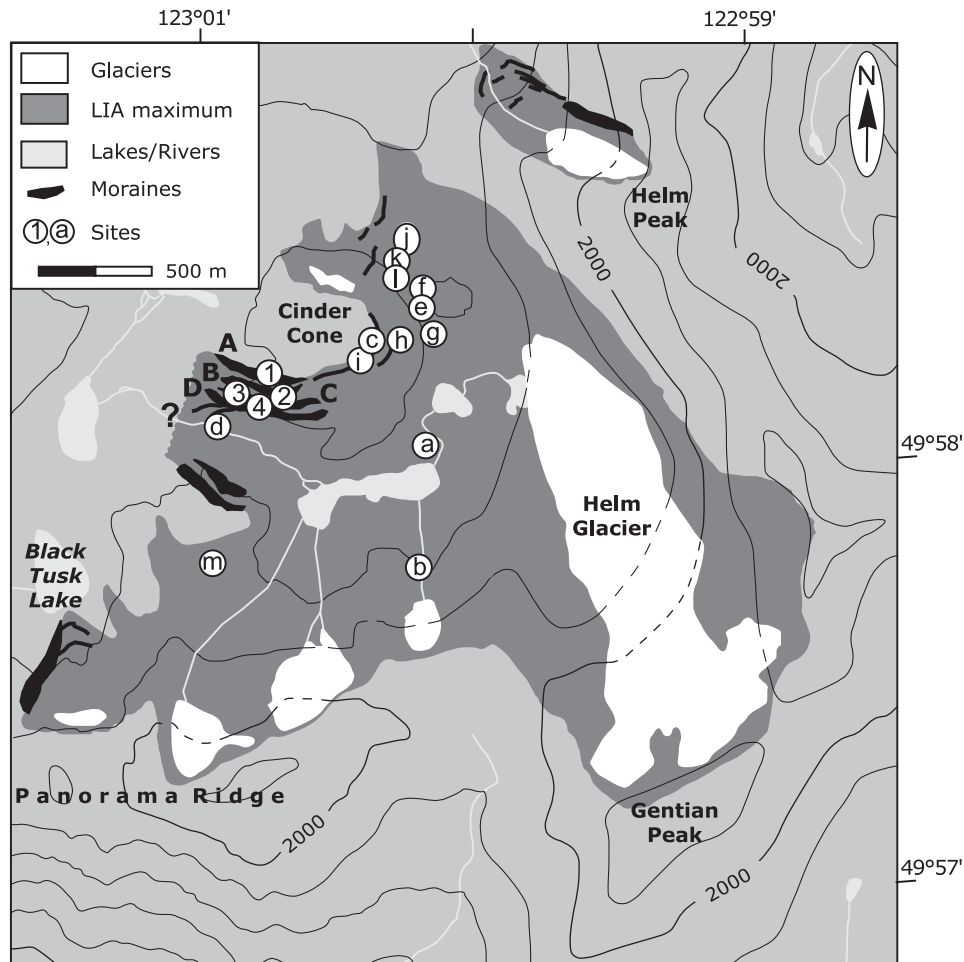
^aLewis (2001); Lewis and Smith (2004a).

^bPorter (1981); O'Neal and Schoenenberger (2003).

^cSmith and Desloges (2000); Laroque and Smith (2004).

These data indicate that Helm Glacier advanced 380 m from sites e and f to site j in 62 years. Advance rates average 10 m/year between sites e–f and l, 4 m/year between sites l and k, and 7 m/year between sites k and j. The ring series derived from sites j, k, and l crossdate with that of an in situ stump from site h ($r = 0.492$), indicating that Helm Glacier thickened over the next 58 years and overran a forest at site h around 330 ± 60 ¹⁴C years BP (A.D. 1490–1600). The ring series from site h crossdates with the series from sites c and i ($r = 0.534$) near the lateral moraine on the east side of Cinder Cone (Figs. 4, 5). Trees at these sites died within 15 years of one another. All of the samples retain their outer rings, indicating that post-mortem transport was minor. Therefore, Helm Glacier continued to thicken for at least another 28 years, killing trees 300 ± 60 ¹⁴C years ago (A.D. 1510–1600) and depositing them at sites c and i shortly thereafter. Four pieces of eroded detrital wood were sampled from a wood layer between two tills at site d. A radiocarbon age of 270 ± 60 ¹⁴C years BP (A.D. 1510–1670) was obtained on one of the samples. The samples at site d were successfully crossdated with samples at

Fig. 4. Map of Helm Glacier showing moraines and maximum Little Ice Age (LIA) glacier extents. Trees were sampled at sites 1–4. Fossil wood was sampled at sites a–m.



sites c and i ($r = 0.494$), suggesting that the trees from which the samples were derived were overridden by the glacier at either the same site or at different sites at about the same time.

In summary, Helm Glacier advanced in the 12th century (site b), reaching site g late in the century. It probably deposited the lower till at site d before the mid-13th century, when trees started growing at sites a and k. Helm Glacier remained upvalley of sites a and k until the 15th century, when it advanced into forest at site a and, shortly thereafter, at sites e, f, l, k, and j. It continued to thicken and finally advanced into a forest at site h in the late 16th and early 17th century. At about this time, Helm Glacier deposited detrital wood near its Little Ice Age maximum position (sites c, d, and i). It probably remained close to this maximum position until the early 18th century. Recessional moraines were built throughout the 19th and early 20th centuries.

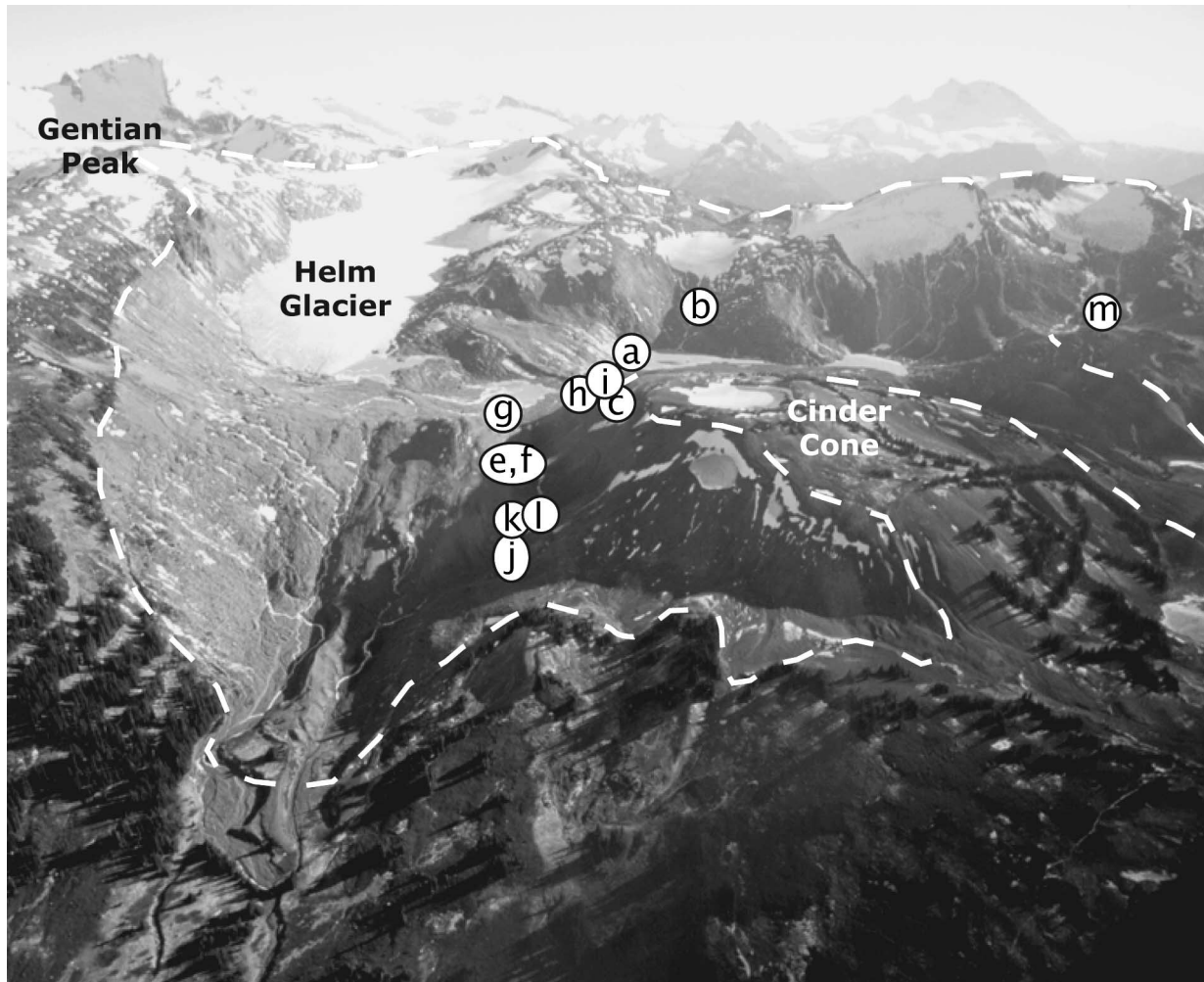
Sphinx Glacier

Average annual growth rates for young subalpine fir at two sites at Sphinx Glacier (Fig. 6) range from 0.78 to 3.59 cm/year. Ecesis was determined to be 24–31 years from repeat ground and aerial photographs. These values are similar to previous ecesis estimates for Sphinx Glacier: 20–40 years (Mathews 1951) and about 20 years (Fraser 1970).

Stabilization dates of moraines A to E were determined by dendrochronology (Table 2). The dates for moraines B to E were corroborated by lichenometry, using the Vancouver Island lichen growth curve (Table 3). Lichenometry underestimates the age of moraine A by about 100 years. This moraine is heavily vegetated, which likely retards lichen growth.

Subfossil wood was found at two sites in the forefield of Sphinx Glacier. Wood at one site (a, Fig. 6) was collected by Mathews (1951) and radiocarbon dated to 460 ± 40 ^{14}C years BP (A.D. 1420–1450, Barendsen et al. 1957) (Table 4). Several in situ and detrital stumps were found here in 2002 at the foot of a bedrock knob. One of the in situ stumps dated to 580 ± 70 ^{14}C years BP (A.D. 1300–1360). The two radiocarbon ages do not overlap at the 1σ limits and barely overlap at the 2σ limits, either because Mathews' site was farther downvalley and thus the glacier arrived there later, or because of a dating error. Five stumps were sampled at this site and successfully crossdated (Table 1). Outer rings of all five stumps were eroded after death, but the outermost intact rings of all trees date to within three years of each other. Thus in the 14th century, Sphinx Glacier advanced into forest containing trees older than 346 years midway between the present glacier snout and the Little Ice Age maximum limit. The site had been ice-free at least since the 11th century. A log in the outermost moraine (site b) yielded an age of 370 ± 70 ^{14}C

Fig. 5. Forefield of Helm Glacier showing locations of sites mentioned in the text. Maximum Little Ice Age extent of Helm Glacier is indicated by white stippled line. Photograph by J. Koch.



years BP (A.D. 1450–1630), but it was too decayed to extract a core. The radiocarbon age provides a maximum age for the moraine and confirms the dendrochronological age (Table 2).

Sentinel Glacier

Tree age below core height was determined at two sites at Sentinel Glacier (Fig. 7), and ecesis was estimated from ground and aerial photographs. Average annual growth rates range from 0.79 to 3.71 cm/year, and ecesis is 22–30 years, similar to the value of 20 years reported by Fraser (1970).

Moraine stabilization, as determined by dendrochronology, occurred in the 1710s, 1830s, 1870s, 1900s, and 1910s (Table 2). The dates were corroborated by lichenometry (Table 3).

Warren Glacier

An in situ rootstock in the tributary cirque of Warren Glacier (site a, Fig. 8) yielded an age of 920 ± 70 ^{14}C years BP (A.D. 1030–1170) (Table 4), indicating that this glacier was advancing through forest early in the Little Ice Age. The living tree-ring chronology (Table 1) includes a tree damaged during construction of the outermost moraine. Damage, indicated by reaction wood and missing rings, dates from

A.D. 1705 to 1711. The earlier date records the arrival of Warren Glacier at its Little Ice Age maximum position. A floating chronology (4 samples, 6 radii) of trees killed during moraine construction was crossdated with the living chronology. The highest correlation (0.459) with the living chronology is for the period A.D. 1637–1701, suggesting that the trees were killed shortly after A.D. 1701. All of the dead trees are missing their outer rings, consistent with the A.D. 1705 date obtained from the damaged tree.

Average annual growth rates at two sites (Fig. 8) range from 1.01 to 3.54 cm/year. Ecesis is estimated to be 11–31 years, consistent with previous estimates of 20–40 years (Mathews 1951) and about 20 years (Fraser 1970). Moraine stabilization was dated by dendrochronology (Table 2).

Garibaldi Glacier

Average annual growth rates and ecesis were determined at a site adjacent to Lava Glacier (Fig. 9), at a similar elevation and setting to Garibaldi Glacier. Growth rates range from 0.37 to 2.65 cm/year and ecesis is 32–40 years. Stabilization of lateral moraines A to F was dated by dendrochronology to the 1720s, 1820s, 1850s, 1870s, 1890s, and 1910s (Table 2).

Table 4. Radiocarbon ages pertaining to the Little Ice Age in Garibaldi Provincial Park.

Glacier	Site	Laboratory No.	¹⁴ C age (years BP)	Calender age (years A.D.)	Comment
Mystery		Beta-170664	710±50	1260–1300	stick on surface
Torey	trgl-a	Beta-157271	70±50	1690–1920	log on surface
	trgl-b	Beta-157272	60±50	1690–1920	log on surface
Helm	hegl-b	Beta-208681	810±60	1180–1270	branch on surface
	hegl-g	Beta-208682	690±60	1260–1310	in situ stump
	hegl-m	Beta-168428	500±40	1410–1440	log on surface
	hegl-a	Beta-186522	490±60	1390–1460	in situ stump
	hegl-f	Beta-186526	430±50	1420–1490	in situ stump
	hegl-k	Beta-208684	380±40	1450–1520	in situ stump
	hegl-h	Beta-208683	330±60	1490–1600	in situ stump
	hegl-c	Beta-186524	300±60	1510–1600	log on surface
Sphinx	spgl-a	Beta-186512	580±70	1300–1370	in situ stump
		Y-347 ^a	460±40	1420–1450	in situ stump; same as spgl-a
	spgl-b	Beta-186513	370±70	1450–1630	log in outermost moraine
Warren	wagl-a	Beta-148791	920±70	1030–1170	in situ rootstock
Garibaldi	gagl-c	Beta-186515	670±70	1270–1390	in situ stump
	gagl-b	Beta-208680	490±60	1390–1460	log in lateral moraine
	gagl-a	Beta-186514	290±70	1490–1600	log in till
Lava	lagl-c	Beta-186518	860±70	1150–1260	log in lower wood layer in lateral moraine
	lagl-a	Beta-157266	640±50	1290–1390	log in lateral moraine S of Opal Cone
	lagl-d	Beta-186519	640±40	1290–1390	log in upper wood layer in lateral moraine
	lagl-b	Beta-186516	530±30	1400–1430	in situ stump
Stave	stgl-b	Beta-171095	830±50	1170–1260	log in lateral moraine
	stgl-a	Beta-171094	310±50	1510–1600	branch on surface
West Stave	wsgl-a	Beta-170669	250±50	1520–1680	log in lateral moraine

Note: Dated samples were outer-perimeter wood comprising <25 rings.

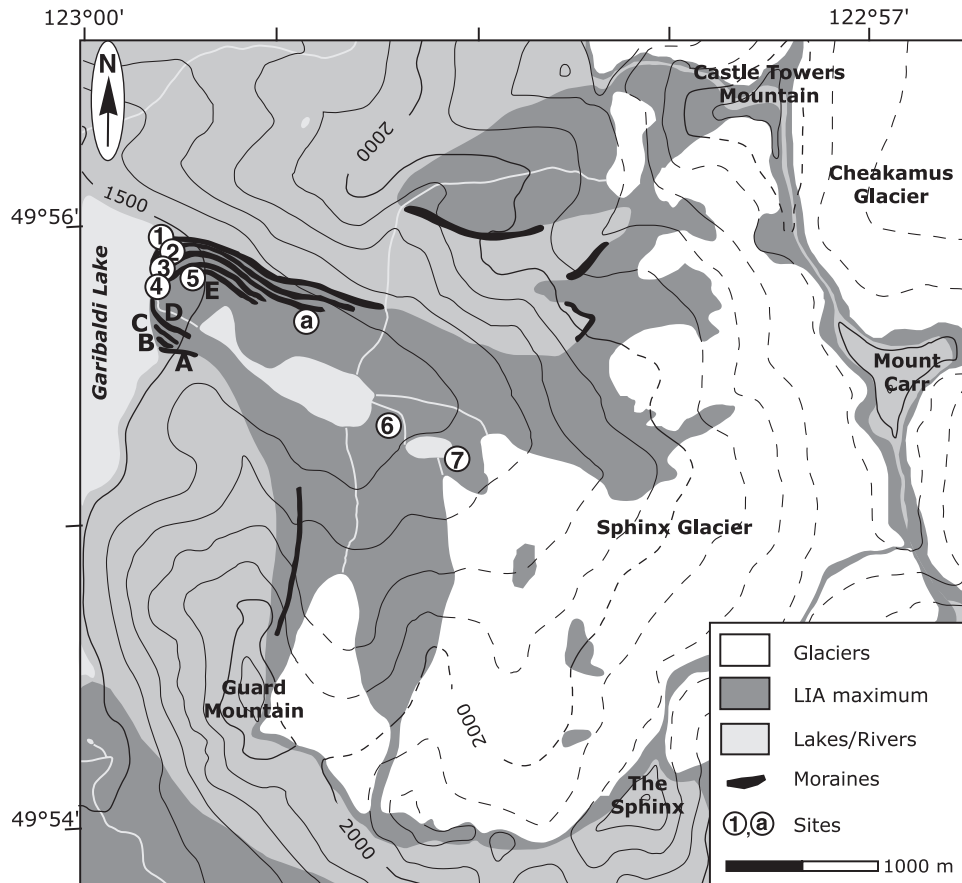
^aBarendsen et al. (1957).

Fossil wood was found at five sites at Garibaldi Glacier. An in situ stump (site c) gave an age of 670 ± 70 ¹⁴C years BP (A.D. 1270–1390) (Table 4) and crossdated with a detrital log and a detrital stump at site e and with a detrital log at site d (Fig. 9). The detrital stump was possibly eroded from a bedrock outcrop located above site e and about 80 m upvalley of site c. It came from a tree that died at least 17 years before the death of the tree represented by the in situ stump at site c. Neither stump retains bark and outer rings, but the difference in tree-ring ages indicates that Garibaldi Glacier advanced 80 m over a period of more than 17 years in the 14th century. Several detrital logs were found in a gully in the east lateral moraine of Garibaldi Glacier (site b). One log yielded an age of 490 ± 60 ¹⁴C years BP (A.D. 1390–1460), indicating that either Garibaldi Glacier receded after its 14th century advance to positions upvalley of site b or the glacier thickened between the 14th and the 15th centuries. Till near the Little Ice Age maximum limit of Garibaldi Glacier (site a) contains detrital logs and branches. One log yielded an age of 290 ± 70 ¹⁴C years BP (A.D. 1490–1600), and this log was successfully crossdated with another log (Table 1). Although neither log retains outer rings, they date to within 12 years of one another and possibly derive from trees killed when Garibaldi Glacier was advancing to its Little Ice Age limit.

Lava Glacier

Dendrochronology shows that Lava Glacier moraines A to F were stabilized in the 1710s, 1800s, 1820s, 1850s, 1880s, and the 1910s (Table 2). Fossil wood was recovered at four sites in the glacier forefield. Two distinct wood layers, including logs to branches, are separated by a layer of till in the west lateral moraine (sites c and d, Figs. 2b, 9). The wood layers can be traced over a distance of 110 m across several gullies. A sample from the lower wood layer gave a radiocarbon age of 860 ± 70 ¹⁴C years BP (A.D. 1150–1250), and a sample from the upper wood layer dated to 640 ± 40 ¹⁴C years BP (A.D. 1290–1390) (Table 4). The intervening till unit, about 25–35 m above the valley floor, was probably deposited in the 13th century, at which time Lava Glacier reached a position within 200 m of its Little Ice Age maximum. The till overlying the younger wood layer was deposited by Lava Glacier as it advanced towards its Little Ice Age maximum. This advance was underway in the 14th century. Sites a and b provide additional evidence that this advance started at that time. A log 4 m below the crest of the lateral moraine at site a, on the south side of Opal Cone, dates to 640 ± 50 ¹⁴C years BP (A.D. 1290–1390). In situ stumps and detrital logs occur at site b; one stump yielded an age of 530 ± 30 ¹⁴C years BP (A.D. 1400–1430). Two of the in situ stumps were successfully crossdated (Table 1).

Fig. 6. Map of Sphinx Glacier showing moraines and maximum Little Ice Age (LIA) glacier extents. Trees were sampled and lichens measured at sites 1–5. Trees were sampled for ecesis and age–height growth determination at sites 3, 6, and 7. Fossil wood was sampled at site a. Site b is the same as site 1.



The outermost ring of one tree was intact; the other tree died no more than 3 years earlier.

In summary, Lava Glacier advanced in the late 12th century. The glacier approached its Little Ice Age limit in the 13th century, then receded an unknown distance before re-advancing in the late 14th century. In the early 15th century, Lava Glacier overtopped the west side of the main valley where it overrode a forest with trees older than 266 years. This site had previously been ice-free since at least the 12th century. The outermost Little Ice Age moraines were built in the late 17th or early 18th century.

Snowcap Lakes area

Average annual tree growth rates and ecesis values at Snowcap Lakes (Fig. 10) are 0.75–3.18 cm/year and 42–56 years, respectively. The latter are larger than the ecesis values of 13–51 years reported by Ricker (1979).

The two outermost moraines at Snowcap Lakes stabilized in the 1720s and the 1830s based on dendrochronology, or in the 1710s and 1820s based on lichenometry (Tables 2, 3). Lichen-based ages for moraines C to G are the 1850s, 1870s, 1890s, 1900s, and 1910s (Table 3).

Stave Glacier

Average annual tree growth rates were determined at one site at Stave Glacier (Fig. 11) and range from 1.12 to

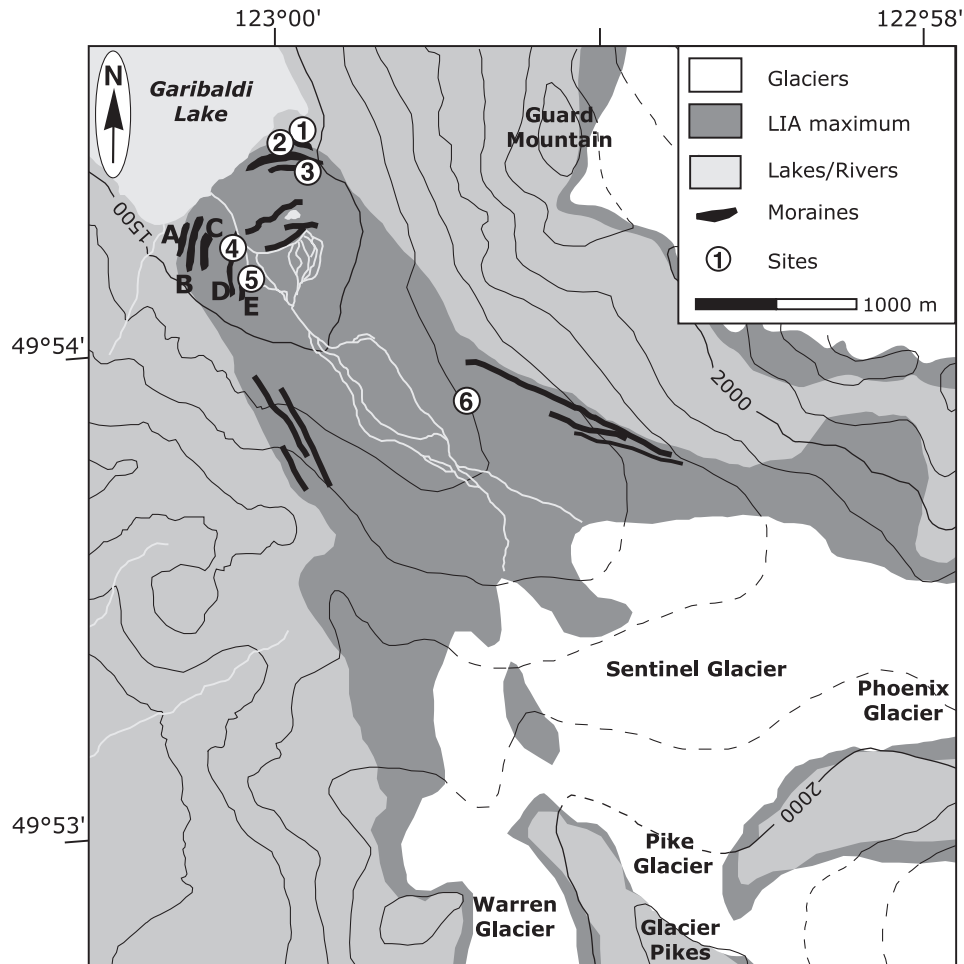
5.27 cm/year. Ecesis ranges from 7 to 16 years. Moraines A to D were dendrochronologically dated to the 1720s, 1840s, 1890s, and 1900s (Table 2).

Fossil wood was found at two sites at Stave Glacier. A small log embedded in till in the north lateral moraine (site b, Fig. 11) gave a radiocarbon age of 830 ± 50 ^{14}C years BP (A.D. 1170–1260) (Table 4). The sample was found 500 m from the present snout and 150 m above the valley floor, suggesting that Stave Glacier was more extensive at the onset of the Little Ice Age than in 2002. Detrital wood found at site a, 650 m downvalley from the present terminus, yielded an age of 310 ± 50 ^{14}C years BP (A.D. 1510–1600), suggesting that Stave Glacier retreated to near its present margin after its early Little Ice Age advance.

Other glaciers

Fossil wood from three other glacier forefields was radiocarbon dated. A small stick at Mystery Glacier gave an age of 710 ± 50 ^{14}C years BP (A.D. 1260–1300) (Table 4). Its location suggests a fairly extensive advance at this time. A weathered log buried in till below the crest of the lateral moraine of West Stave Glacier yielded an age of 250 ± 50 ^{14}C years BP (A.D. 1520–1680). The maximum Little Ice Age advance of the glacier occurred after this time. Two detrital logs, about 500 m apart near the Little Ice Age limit of Trorey Glacier, gave ages of 70 ± 50 ^{14}C years BP (A.D.

Fig. 7. Map of Sentinel Glacier showing moraines and maximum Little Ice Age (LIA) glacier extents. Trees were sampled and lichens measured at sites 1–5. Trees were sampled for ecesis and age–height growth determination at site 6.



1690–1920) and 60 ± 50 ^{14}C years BP (A.D. 1690–1920), which are maximum ages for the climatic Little Ice Age advance of this glacier.

Discussion

Lichenometry in the southern Coast Mountains

Rhizocarpon thalli were found in only four glacier forefields in Garibaldi Park. Their absence elsewhere is attributed to widespread Plio-Pleistocene volcanic rocks, which inhibit lichen colonization.

Lichen ages assigned to moraines were checked using independently determined tree-ring ages. The lichen growth curve from Vancouver Island (Lewis 2001; Lewis and Smith 2004a) fits closely with tree-ring ages in Garibaldi Park (Fig. 12). Other curves yield deposit ages inconsistent with the tree-ring ages. The Cascades curve (Porter 1981; O'Neal and Schoenenberger 2003) seems to work for the youngest moraines, but gives inconsistent ages for moraines predating the late 19th century. A curve from the central Coast Mountains (Smith and Desloges 2000; Larocque and Smith 2004) consistently overestimates the ages of moraines in Garibaldi Park. Growth rates may be higher on Vancouver Island, the Cascade Range, and Garibaldi Park than in the mountains of central British Columbia because of more fa-

vourable ecological conditions (Larocque and Smith 2004). It remains unclear whether these differences are because of latitude, continentality, or other factors.

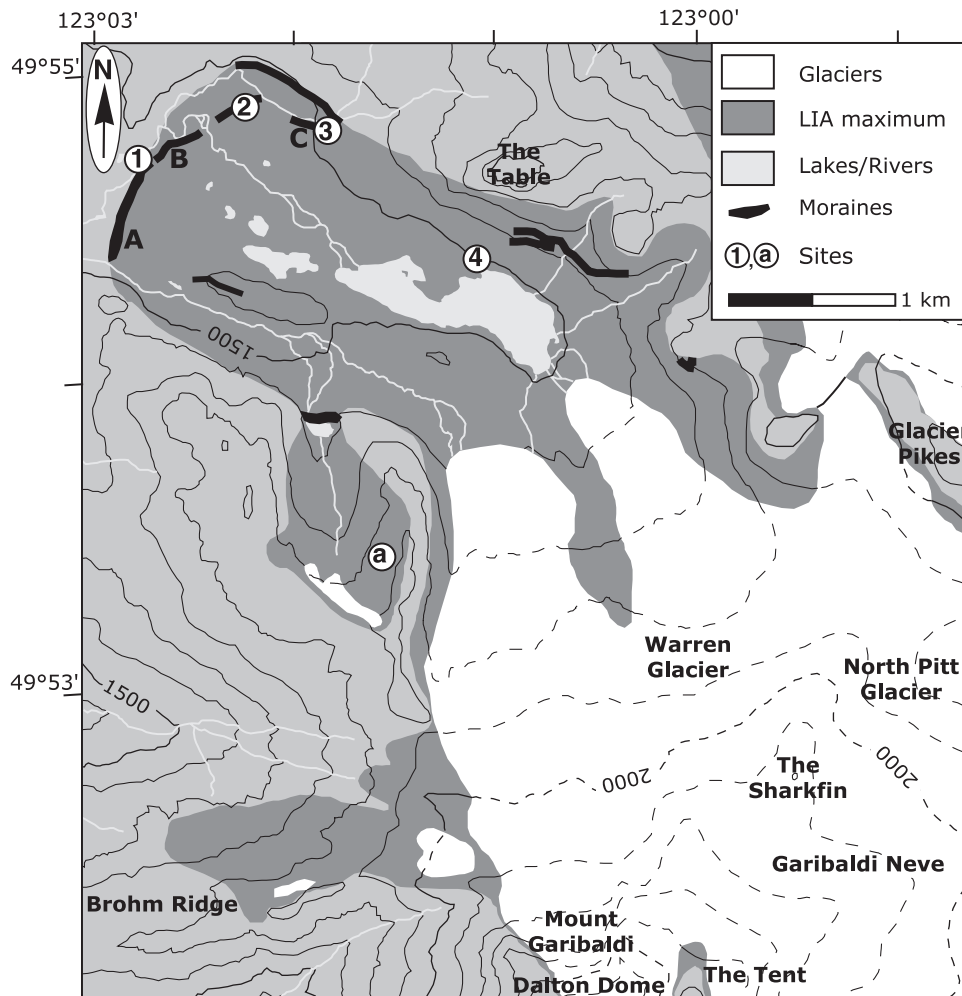
Little Ice Age chronology

The Little Ice Age began in Garibaldi Park before 920 ± 70 ^{14}C years BP (A.D. 1030–1170, tributary of Warren Glacier). At least three glaciers advanced in the 12th or 13th century: Lava Glacier about 860 ± 70 ^{14}C years BP (A.D. 1150–1250), Stave Glacier 830 ± 50 ^{14}C years BP (A.D. 1170–1260), and Helm Glacier 810 ± 60 ^{14}C years BP (A.D. 1180–1270). The outermost moraine at Overlord Glacier also may have been constructed at this time.

This first advance was followed by recession, possibly back to near-present glacier margins. Evidence for recession comes from the forefield of Stave Glacier, where detrital wood 650 m downvalley from the present glacier snout dates to 310 ± 50 ^{14}C years BP (A.D. 1510–1600). Helm, Lava, Sphinx, and Garibaldi glaciers remained behind their 12th century advance limits for at least a century.

These four glaciers advanced into mature forests in the 14th and 15th centuries. Evidence from Lava Glacier indicates at least two middle Little Ice Age advances separated by short-lived recession. Helm Glacier affords the most detailed reconstruction of events during this period. It ad-

Fig. 8. Map of Warren Glacier showing moraines and maximum Little Ice Age (LIA) glacier extents. Trees were sampled at sites 1–3. Trees were sampled for ecesis and age–height growth determination at sites 1 and 4. Fossil wood was sampled at site a.



vanced one or more times during the middle Little Ice Age, culminating in construction of the outermost Little Ice Age moraine. This outermost moraine stabilized sometime between A.D. 1690 and 1720 when Helm Glacier began to retreat. Subsequent advances in the 19th and early 20th centuries were less extensive, forming up to five moraines close to the outermost Little Ice Age moraine.

Regional comparisons

Little Ice Age glacier activity in Garibaldi Park is similar to that in other areas of western North America (Heikkinen 1984; Luckman 2000; Larocque and Smith 2003; Lewis and Smith 2004a). The beginning of the Little Ice Age in western Canada dates to between 1000 ± 80 and 810 ± 70 ^{14}C years BP, similar to its onset in Garibaldi Park (Luckman 1986, 2006; Osborn 1986; Ryder and Thomson 1986; Luckman et al. 1993; Osborn et al. 2001; Reyes and Clague 2004).

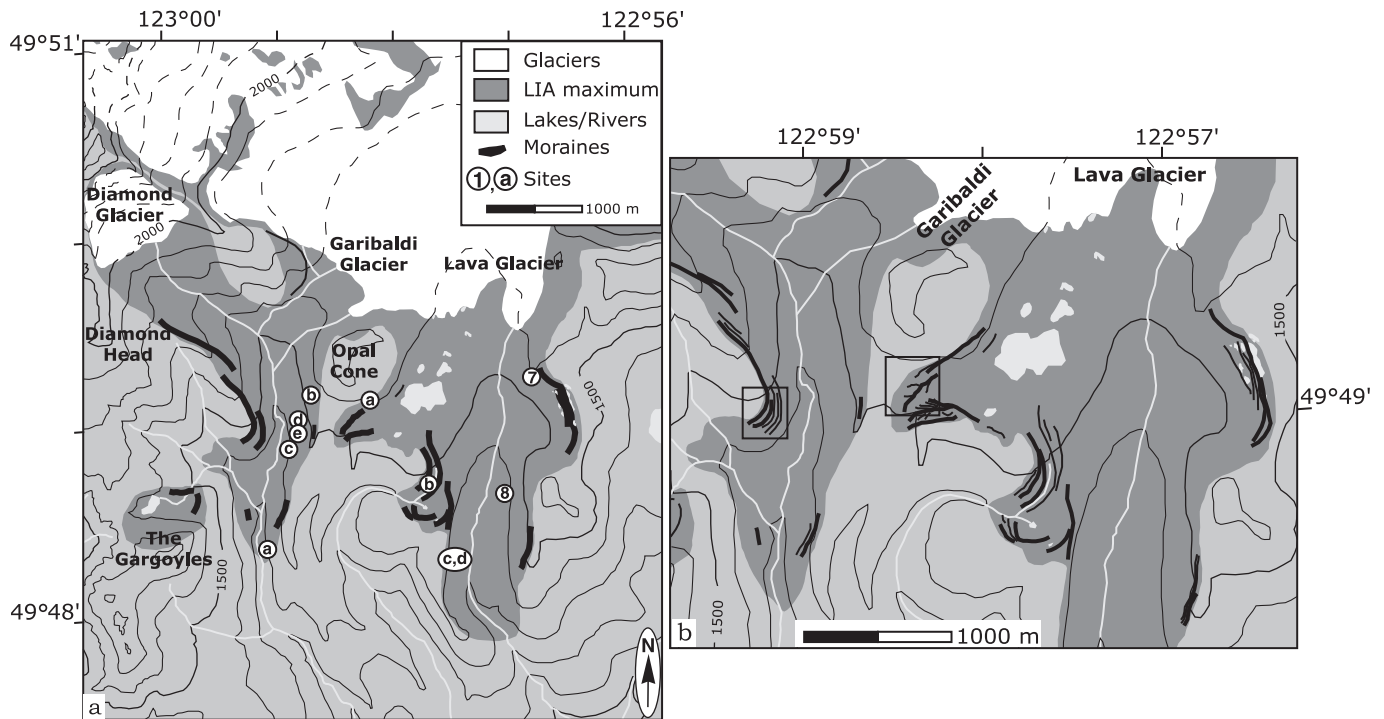
Little Ice Age moraines predating the mid-17th century were found only at Overlord Glacier. They are also uncommon elsewhere in western Canada, having been reported only at Colonel Foster Glacier on Vancouver Island (older than A.D. 1397, Lewis and Smith 2004a), at Bridge Glacier ca. 100 km northwest of Garibaldi Park (ca. A.D. 1384, Allen and Smith 2004), and at a few glaciers in the Canadian

Rocky Mountains (Luckman 2000). The outermost Overlord moraine may have been built during this event, or during any of the advances documented in the central Coast Mountains (A.D. 1200–1230, 1440–1460, 1500–1525, 1560–1575, and 1600–1620, Larocque and Smith 2003) and the Cascades (A.D. 1520–1560 and 1620, Heikkinen 1984). It could even date to the older Tiedemann Advance (ca. 2300 ^{14}C years BP, Ryder and Thomson 1986) or the recently recognized First Millennium Advance (Reyes et al. 2006).

Reconstructed early Little Ice Age advances of Helm, Garibaldi, Lava, and Sphinx glaciers coincide with advances of Robson, Peyto, and Stutfield glaciers in the Canadian Rocky Mountains between A.D. 1150 and 1375 (Luckman 1995, 2000), which reached to within 500 m of the Little Ice Age limit.

Moraines dating to A.D. 1690–1720 occur on Vancouver Island (A.D. 1690–1710, Lewis Lewis and Smith 2004a) and in the Canadian Rockies (A.D. 1700–1725, Luckman 2000). Moraines of about the same age have been identified in the Cascades (A.D. 1740, Heikkinen 1984) and the central Coast Mountains (A.D. 1660 and 1760–1785, Larocque and Smith 2003). Moraines were built in the 19th and early 20th century, not only in Garibaldi Park, but also in the Cascades (A.D. 1820–1890, A.D. 1920, Heikkinen 1984), on Vancou-

Fig. 9. Maps of Garibaldi and Lava glaciers showing (a) maximum Little Ice Age (LIA) glacier extents and (b) moraines. Living trees were sampled on each moraine within the rectangle in the Garibaldi Glacier forefield and on the northern moraines within the rectangle in the Lava Glacier forefield. Trees were sampled for ecies and age–height growth determination at sites 7 and 8. Fossil wood was sampled at sites a, b, c, and d in both forefields and site e at Garibaldi Glacier.



ver Island (A.D. 1840, 1890, and 1930, Lewis and Smith 2004a), the central Coast Mountains (A.D. 1820–1840, 1870–1900, and 1915–1930, Larocque and Smith 2003), and the Canadian Rocky Mountains (A.D. 1825–1850 and 1850–1920, Luckman 2000).

Glacier mass balance for the past 300–400 years has been reconstructed from tree rings at several sites in western Canada (Lewis and Smith 2004b; Watson and Luckman 2004; Larocque and Smith 2005). Periods of positive balance generally coincide with times of moraine formation in Garibaldi Park. Glacier fluctuations in the park also agree with a 1000 year tree-ring-based reconstruction of summer temperature from the Canadian Rocky Mountains (Fig. 13; Luckman and Wilson 2005). Relatively cold periods coincide with glacier advances and relative warmth with glacier recession.

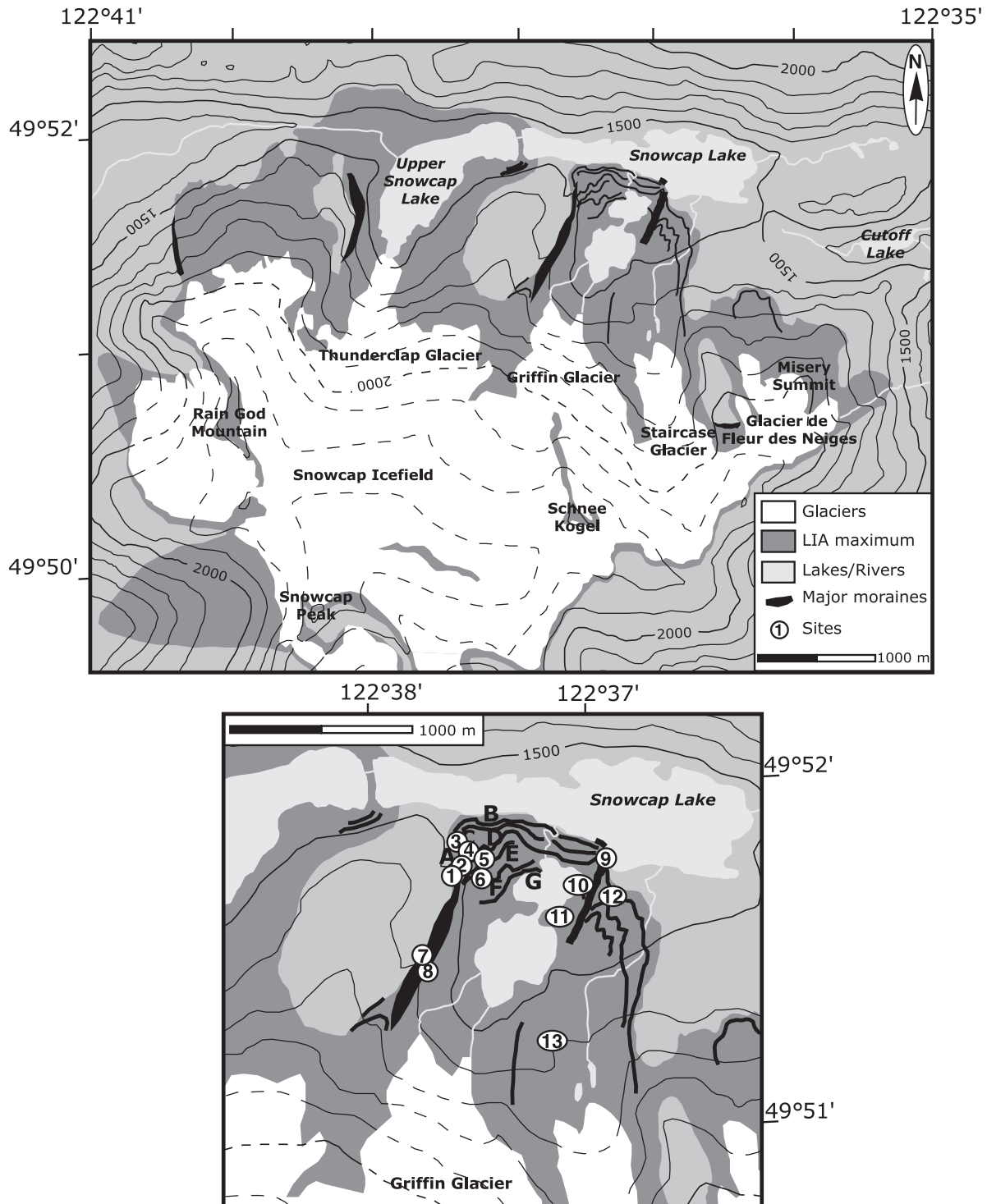
Global implications of the Garibaldi chronology

The Medieval Warm Period has been dated to the 9th through 14th centuries (Hughes and Diaz 1994), A.D. 900–1250 (Grove and Switsur 1994), A.D. 960–1050 (Cook et al. 2004), and A.D. 1100–1200 (Bradley et al. 2003). Its global significance and synchronicity have been questioned by some researchers, who have disputed claims that temperatures during parts of the Medieval Warm Period were as warm as or warmer than today (Grove and Switsur 1994; Hughes and Diaz 1994; Bradley et al. 2003; Cook et al. 2004). Temperature-sensitive tree-ring series from the extratropical Northern Hemisphere show persistently above-average temperatures from A.D. 960 to A.D. 1050 (Cook et al. 2004). However, the timing appears to be in conflict with the European “High Medieval” warm period (A.D. 1100–1200, Bradley et al.

2003). Glaciers in Garibaldi Park were relatively small at both times (Fig. 13), but more extensive than during the late 20th century. This evidence suggests that temperatures were lower during the periods A.D. 960–1050 and A.D. 1100–1200 than in the last two decades. Further, these two periods were interrupted by significant advances of Lava, Stave, and Helm glaciers (Fig. 13). We conclude that the Medieval Warm Period is an ill-defined term that allows for a large range of possibly unrelated climate anomalies to be grouped under the same name.

The similarity in the timing and extent of glacier fluctuations in western Canada and the US Pacific Northwest argues for regional or global climate forcing. Similar Little Ice Age chronologies have been reported from western Canada, Alaska, Scandinavia, Europe, South America, and New Zealand (e.g., Holzhauser 1985; Gellatly et al. 1988; Karlén 1988; Wiles et al. 1999; Luckman 2000; Nicolussi and Patzelt 2000; Koch and Kilian 2005), suggesting global forcing (Koch and Clague 2006). Figure 14 compares the history of Little Ice Age glacier fluctuations in Garibaldi Park with the histories of three glaciers in the European Alps (Holzhauser et al. 2005). The early onset of the Little Ice Age in Garibaldi Park is consistent with advances of European glaciers in the 11th to 13th centuries. During that period, the glaciers shown in Fig. 14 reached positions nearly as advanced as later during the Little Ice Age, and they remained relatively extensive until the 20th century, consistent with Grove’s (2001, p. 53) definition of the term “Little Ice Age.” These early advances are poorly recorded in both North America and Europe because subsequent advances removed or obscured most of the evidence for them.

Fig. 10. Maps of Snowcap Lakes area showing moraines, 1996 and maximum Little Ice Age (LIA) glacier extents, and sample sites. Trees were sampled and lichens measured at sites 1–11. Trees were sampled for ecesis and age–height growth determination at sites 12 and 13.



Comparison of the Garibaldi record with a recent Northern Hemisphere temperature reconstruction spanning the last millennium (Fig. 13; Cook et al. 2004) shows that the two are in broad agreement. Periods of glacier advance and recession in the park are broadly synchronous with relatively cold and warm periods, respectively.

Glacier advances and moraine formation during the late stages of the Little Ice Age have been related to sunspot num-

bers (Lawrence 1950; Wiles et al. 2004; Luckman and Wilson 2005). We compared the timing of Little Ice Age glacier fluctuations in Garibaldi Park with the record of solar activity during the past millennium (Stuiver 1961; Bond et al. 2001) and with reconstructed sunspot numbers (Solanki et al. 2004; Fig. 15). Glacier advances and times of moraine construction appear to coincide with sunspot minima, specifically the Oort (A.D. 1020–1080), Wolfe (A.D. 1290–1370), Spörer (A.D.

Fig. 11. Map of Stave Glacier showing moraines and maximum Little Ice Age (LIA) extents. Trees were sampled at sites 1–4. Trees were sampled for ecasis and age–height growth determination at site 5. Fossil wood was sampled at sites a and b.

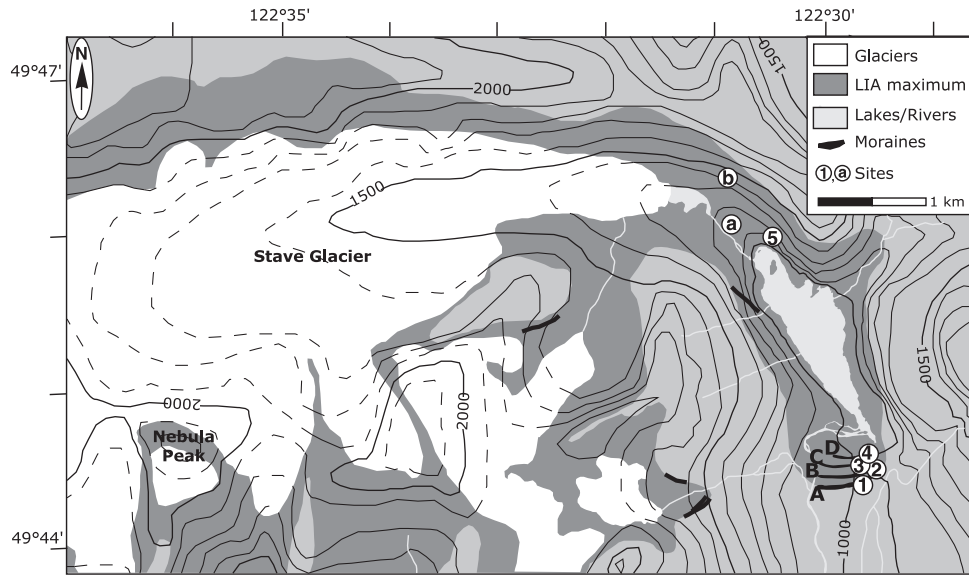


Fig. 12. Three lichen growth curves considered in this study and data points from four glacier forefields in Garibaldi Provincial Park. The Garibaldi data best fit the curve from Vancouver Island. PP, Provincial Park.

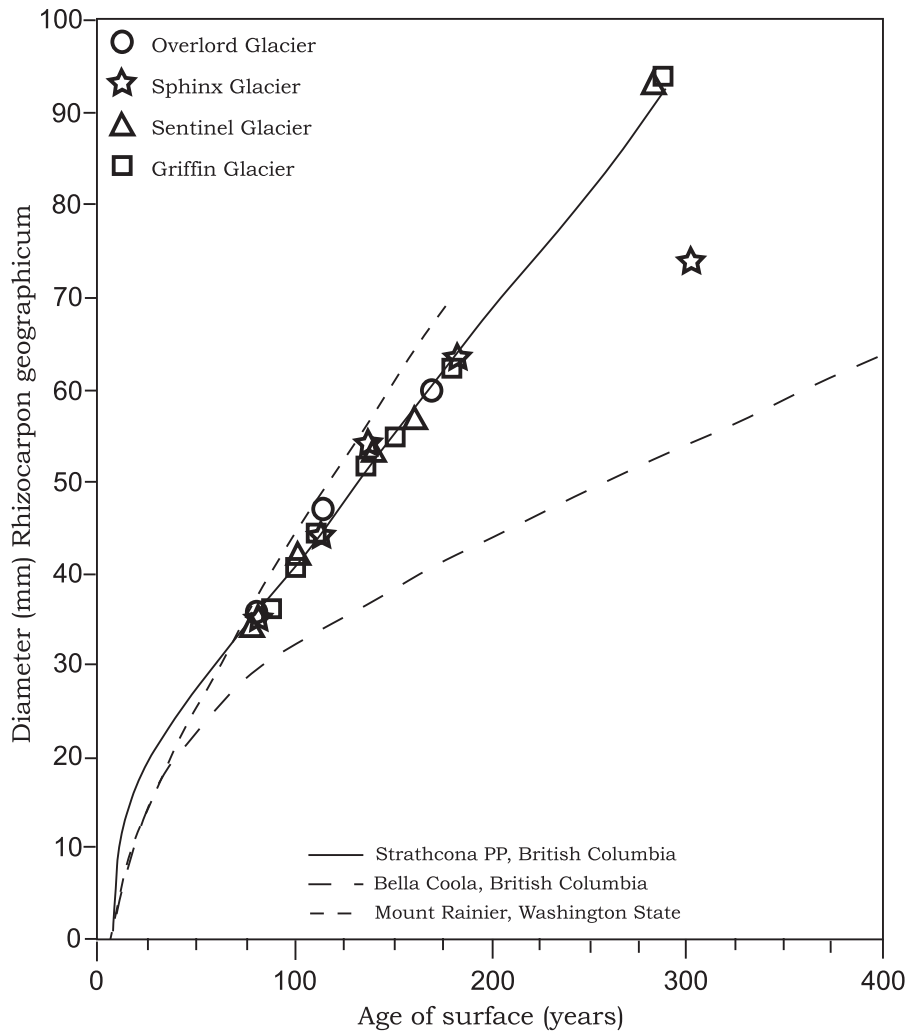


Fig. 13. (a) Northern Hemisphere temperature change based on extratropical tree ring widths; thin black lines are bootstrap 95% confidence intervals (Cook et al. 2004). (b) Canadian Rocky Mountains temperature change based on a maximum latewood density record (Luckman and Wilson 2005). (c) Generalized history of glacier extent in Garibaldi Park. (d) Ages of fossil wood overridden by glaciers in the park; each horizontal bar shows the length of a tree-ring series extending back in time from the midpoint of the calibrated radiocarbon age range. The histogram shows the number of dated moraines grouped in 50-year periods; black bars are the outermost moraines. Dark grey vertical bars indicate times of relative maximum extents.

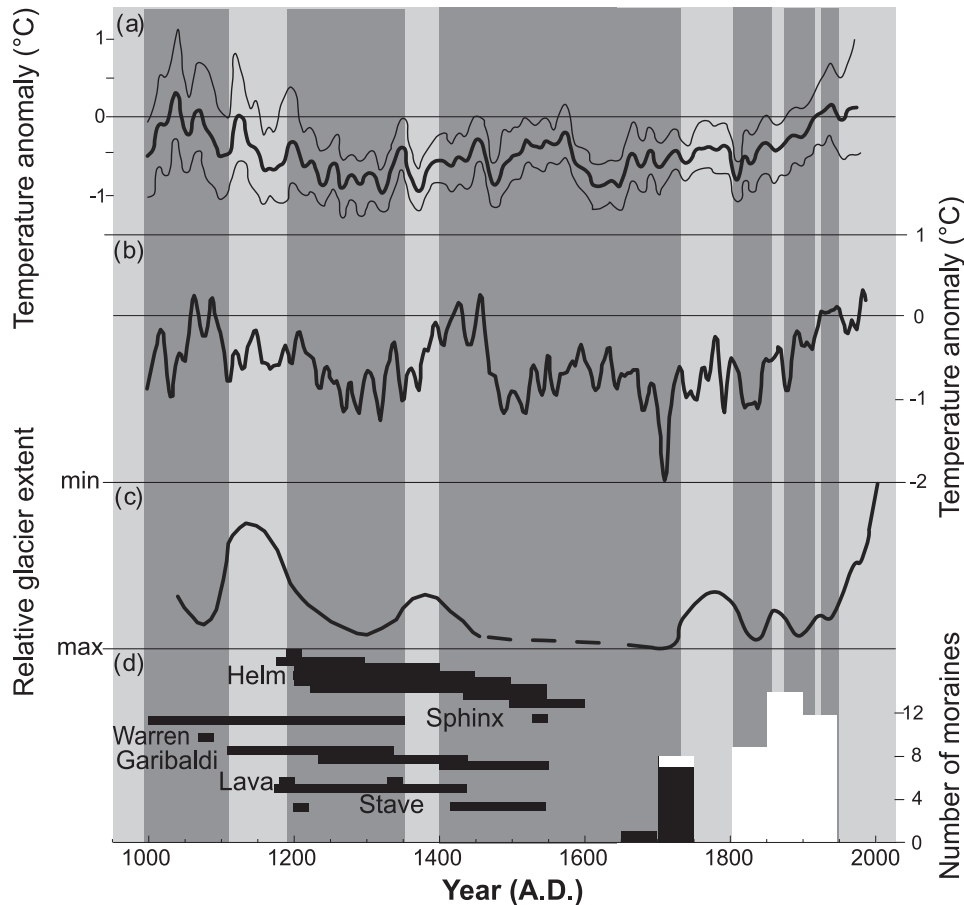
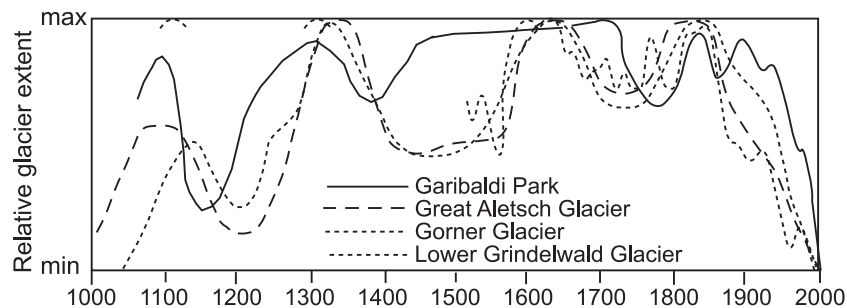


Fig. 14. Comparison of generalized Little Ice Age history of glaciers in Garibaldi Park and histories of three glaciers in the European Alps (Holzhauser et al. 2005).



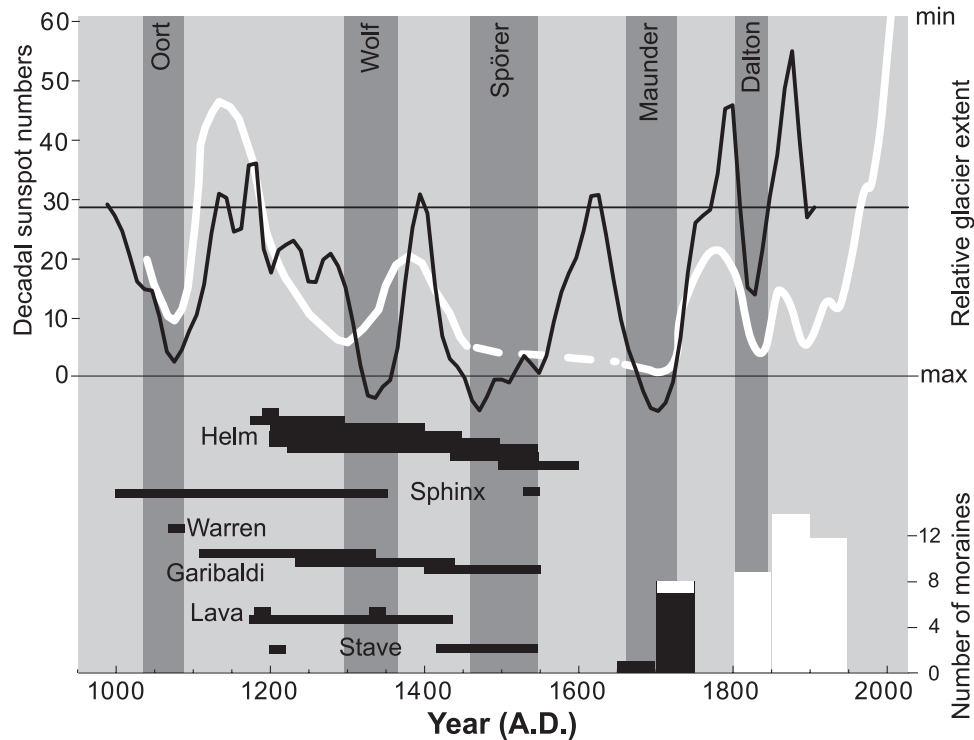
1460–1550), Maunder (A.D. 1645–1715), and Dalton (ca. A.D. 1795–1825) minima.

Conclusions

The record of Little Ice Age glacier fluctuations in Garibaldi Park is one of the most complete and best constrained in North America. The Little Ice Age started as early as A.D. 1000. Glaciers approached their Holocene maximum posi-

tions several times in the early and middle parts of the Little Ice Age. Middle Little Ice Age advances were underway in the 14th and 15th centuries, and culminated in the construction of the outermost moraines in Garibaldi Park in the late 17th century. These moraines stabilized between A.D. 1690 and 1720. Moraines were also built during less extensive advances in the 19th and early 20th centuries. Little Ice Age glacier advances appear to be synchronous throughout the park.

Fig. 15. Reconstructed decadal sunspot numbers (black line) (Solanki et al. 2004) and generalized history of glacier extent in Garibaldi Park (white line). Dark grey vertical bars denote intervals of sunspot minima (Stuiver 1961; Bond et al. 2001). Lower plot is the same as Fig. 12d.



The Little Ice Age record in Garibaldi Park is in agreement with regional and global glacier records and Northern Hemisphere temperature reconstructions, indicating global forcing of glacier fluctuations during the last millennium. Times of sunspot minima correspond to glacier advances and thus changes in solar radiation likely play an important role in late Holocene climate and glacier change.

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