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Calibrated *Rhizocarpon* spp. Growth Curve for the Mount Waddington Area, British Columbia Coast Mountains, Canada

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Abstract

A calibrated *Rhizocarpon* spp. lichen growth curve spanning the last 680 yr was developed for the Bella Coola and Mount Waddington areas, southern Coast Mountains of British Columbia (Canada). It is based on 18 control surfaces whose ages were determined using radiocarbon dates, tree-ring dated moraines, and ice front positions derived from historical air photographs. Population distribution statistics were used to assess the validity of each control lichen measurement. The relationship is characterized by logarithmic growth during the first 100 yr following surface stabilization, and is described as linear for the successive 600 yr. Application of the curve at Tiedemann Glacier revealed evidence for six periods of late-Neoglacial moraine formation in ca. AD 620, 925, 1118, 1392, 1575, and 1621. The study confirms the importance of incorporating a multisite approach and a lichen population dynamic assessment. Large samples sizes and replication are also noted as necessary in order to adequately assess any dating errors.

Introduction

Lichenometric dating is based on the assumption that the largest lichen growing on a suitable substrate provides an approximation of the minimum age of exposure of this surface (Andrews and Webber, 1969; Gellatly, 1982; Innes, 1985; McCarthy, 1997). Lichenometry is commonly used in arctic and alpine environments to provide relative ages for glacially deposited surfaces, where trees are unavailable for dendrochronological dating or where radiocarbon dating is impractical (e.g., Smith et al., 1995). Beschel was the first to use this technique in the European Alps, and since then it has been widely applied (Beschel, 1961, 1973; Porter, 1981; Smith et al., 1995; Harrison and Winchester, 2000; Smith and Desloges, 2000). The most widely used lichen growth curves have been developed for *Rhizocarpon* spp. (Gellatly, 1982; Innes, 1985; André, 1986; Broadbent and Bergqvist, 1986; Rodbell, 1992; Solomina and Calkin, 2003).

The application of lichenometric techniques necessitates the construction of local or regional lichen growth curves (i.e., a plot of diameter vs. age). Growth curves are normally sigmoidal in shape, as they encompass growth patterns that include a period of great-growth, uniform-growth, and senescence (Innes, 1985). Two approaches have been developed in order to describe lichen growth rates in a given area: one "traditional" and another "statistical". The statistical approach is normally used to build growth curves based on large sample sizes that are restricted to the single largest lichen found on individual boulders. Statistical models are used as means of interpreting thallus-size distributions (McCarroll, 1994; Bull et al., 1995; Bull and Brandon, 1998; McCarthy, 1999; Reynolds, 2001). This approach seems particularly useful for dating multiple events on diachronic surfaces, such as snow avalanche boulder (McCarroll, 1994) and rockfall deposits generated by earthquakes (Bull and Brandon, 1998).

The basic assumption of the traditional method is that the largest lichen growing on a rock surface or other suitable substrate is the oldest one, and thus provides a minimum date for the deposition or exposure of this surface (Andrews and Webber, 1969; Gellatly, 1982; McCarthy, 1997). Although some researchers use only the largest lichen found at a site to provide a relative surface age, others establish the mean diameter of the 5, 10, 20, 25, or 50 largest lichens to reduce the impact of anomalously large lichens (Bradley, 1985; Innes, 1985; McCarroll, 1994; Bull et al., 1995). Traditional growth curves are constructed by establishing the size of lichens found growing on surfaces of known age (Gellatly, 1982; Innes, 1985). The most commonly used surfaces include gravestones and glacial moraines that have been independently dated using historical records, radiocarbon dating or dendrochronology (e.g., Lewis, 2001; Wiles et al., 2002; Solomina and Calkin, 2003).

Both the traditional and the statistical approaches to lichenometry introduce systematic errors that are related to imprecise dating of the age-calibrated surface involved (Gellatly, 1982; Bradley, 1985; Rodbell, 1992; Bull and Brandon, 1998; Solomina and Calkin, 2003). If the sites to be dated are quite distant from the location where the growth curve is constructed, a calibration may be necessary in order to correct for any spatial variability in the growth rate. Other notable issues inherent to lichenometry include the application of curves that include several species of *Rhizocarpon* (Luckman, 1977; Wiles et al., 2002); and that do not reflect growth trends associated with different geologic substrates (e.g., Porter, 1981) or regional climate variability (e.g., Osborn and Taylor, 1975).

In the southern Coast Mountains of British Columbia, an aggregate *Rhizocarpon* spp. curve was developed by Smith and Desloges (2000) for the Bella Coola and Monarch Icefield areas. Twelve control points were included in the analysis, with surface age being derived from low elevation gravestones (55 m a.s.l.) and high-elevation (1300–1450 m a.s.l.) tree-ring dated moraines (including correcting factors for ecesis, missing pith, and height of coring). The relationship between thallus diameter and surface age covers a period of 20 to 165 yr.

The purpose of this paper is to verify and extend the applicability of the Bella Coola *Rhizocarpon* spp. lichen growth curve developed by Smith and Desloges (2000) to the Mount Waddington region (map sheet 92N, 1:50,000) in the British Columbia Coast Mountains (Fig. 1). The Bella Coola (BC) curve was suggested as representative of the regional growth of *Rhizocarpon* spp., as it is well constrained by both high- and low-elevation control points that display consistent lichen growth trends (Smith and Desloges, 2000). Additional control points developed during the course of our study of late-Neoglacial glacial activity in the Mount Waddington area provided the opportunity to extend the curve back to ca. 680 cal. yr BP and to increase its spatial applicability

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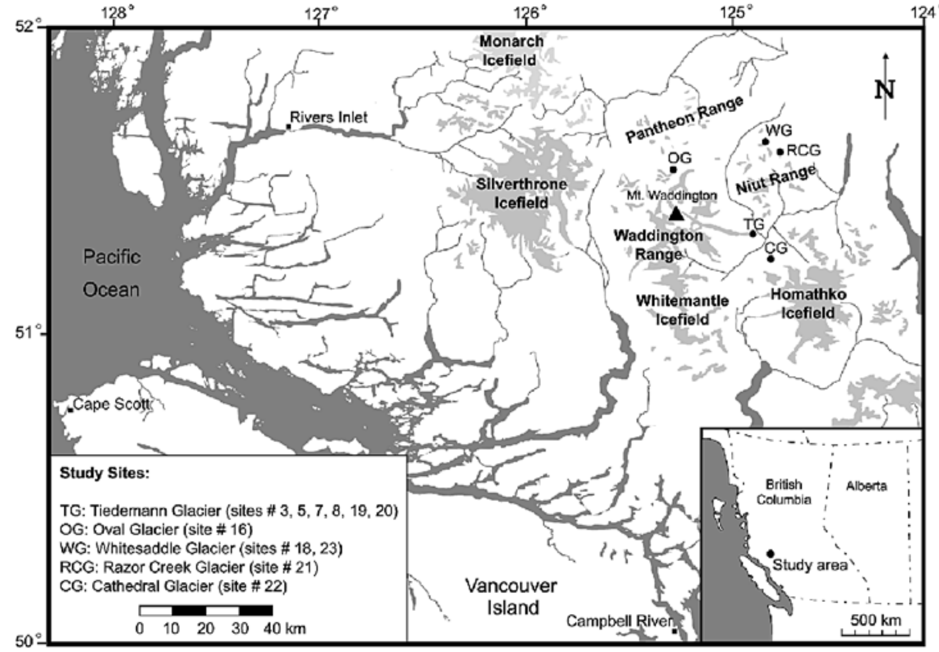

FIGURE 1. Location of control sites in the Mount Waddington area. In total, 11 control lichen measurement sites were sampled from five different glaciers.

(Larocque and Smith, 2003). In this paper, we provide previously unpublished data on our control points and calibrate a new lichen curve for the Mount Waddington area.

Study Area

The study area is located on the lee side of the Coast Mountains of British Columbia (Canada), between latitudes 51°14′N and 51°36′N (Fig. 1). It is located at the northern limit of the Cascade magmatic arc that formed in response to the subduction of the Juan de Fuca Plate under the North American Plate (Hickson, 1994). The Coast Mountains are largely composed of intrusive granodiorites and granites, volcanic andesites and rhyolites, and metamorphosed sedimentary and volcanic rocks (Hickson, 1994; Monger and Journeay, 1994). Some of the highest peaks in British Columbia are found in this area, with Mount Waddington reaching an elevation of 4019 m a.s.l.

Although the climate of high-elevation sites within the Mount Waddington region is unknown, precipitation totals decrease substantially from west to east within this portion of the Coast Mountains. While maritime climate conditions at Bella Coola (52°22′N, 126°41′W, 18 m a.s.l.; Meteorological Service of Canada, 2002) result in annual precipitation totals of 1677 mm yr^{-1}, rain shadow influences on the east side of the Coast Mountains result in precipitation totals averaging only 426 mm yr^{-1} at Williams Lake (52°11′N, 122°03′W, 940 m a.s.l.) in the Interior Plateau. Within the Mount Waddington area, precipitation totals at the most representative climate stations at Big Creek (51°43′N, 123°02′W, 1128 m a.s.l.) and Tatlayoko Lake (51°40′N, 124°24′W, 853 m a.s.l.) average 334 mm to 429 mm yr^{-1}, of which 30 to 40% falls as snow. Mean annual air temperatures at the two stations average between 2.2 to 4.2°C, with winter minimum and summer maximums averaging –9 to –17.5°C and 18.6 to 22.7°C, respectively (Meteorological Service of Canada, 2002).

Five sites were selected for detailed lichenometric study and analysis: Tiedemann, Oval, Whitesaddle, Razor Creek, and Cathedral glaciers. The study sites range in elevation from 500 m a.s.l. at Tiedemann Glacier to 1675 m a.s.l. at Whitesaddle Glacier. All the surveys reported were undertaken below the local treeline and within glacial forefields established following maximum late-Neoglacial advances. Variations in temperature and precipitation are expected between the sites, as aspect, elevation, and local factors are not homogenous.

Methodology

The largest lichen thallus is considered the most appropriate parameter for providing the best estimate of surface age in lichenometric studies because its size is proportional to the length of time that the surface has been exposed or stabilized, and it represents the highest potential growth (Innes, 1985). In this study, the largest diameter of near circular thalli from the genus *Rhizocarpon* was measured using digital calipers (precision of ± 0.1 mm) and applied to calibrate the BC curve to conform to the methodology used by Smith and Desloges (2000; pers. comm.). No distinction between rock types was made as their influence is considered minimal (O'Neal and Schoenenberger, 2003), but lichens were mostly associated with andesitic, granodioritic, and granitic rocks. Anomalous lichens (non-circular, damaged, competing, merging, wrapped around corners) or those found below snow avalanche zones were systematically rejected.

As species of *Rhizocarpon* cannot be differentiated by visual inspection, 10 random lichen samples were identified (K. A. Glew, Department of Biology, University of Puget Sound) using chemical spot tests and microscopic descriptions of apothecia (reproductive structures) using the identification keys produced by Runemark (1956), Thomson (1967, 1997), Poelt (1988), and Purvis et al. (1992). This subset of lichens was from different locations and was found growing on a variety of rock lithologies.

Wherever possible, a minimum sample of 30 largest thalli was measured at each sampling point over a search area of ca. 100 m^2. The search areas were kept deliberately small in order to exclude any possible misinterpretation due to moraine morphology. However, because of the nature of some control points (one boulder or a small group of boulders; see control sites description), smaller search areas and fewer thalli ($n = 7$) were also included. In total, 11 control points were established by using historical air photographs to position glacier fronts, by dating historical structures, by applying radiocarbon dating, and by establishing the ages of living trees found growing on lateral moraines. A statistical procedure is proposed to determine the validity of the selected control sites (c.f. Bradwell, 2001). Frequency histograms of sampled lichen populations on each site were produced to assess the normality of the distribution and the presence of outliers. Sampling of largest lichens in other studies has shown that populations follow in most cases a Gaussian distribution (Smirnova and Nikonov, 1990; Bull et al., 1994; McCarroll, 1994; Bull and Brandon, 1998; McCarthy,

TABLE 1

Lichen species identification (n = 10) (K. A. Glew, 24 February 2002). Eight lichens were identified as Rhizocarpon geographicum *(L.) DC. from a variety of lithologies (gneiss, andesite, granite, granodiorite).* R. macrosporum *Räsänen was found in 2 samples of andesite.*

Sample no.	Location	Latitude	Longitude	Elevation (m)	Lithology	Species
00B1	Oval Glacier	51°29′N	125°15′W	1260	Gneiss	*R. geographicum* (L.) DC.
00C2	Siva Glacier	51°39′N	125°10′W	1500	Andesite	*R. geographicum* (L.) DC.
00CM2	Siva Glacier	51°39′N	125°10′W	1500	Granite	*R. geographicum* (L.) DC.
01BM43	Hope Glacier	51°31′N	124°53′W	1830	Andesite	*R. macrosporum* Räsänen?
01CM21	Whitesaddle Glacier	51°36′N	124°50′W	1525	Granodiorite	*R. geographicum* (L.) DC.
01IM2	Ragnarok Glacier	51°36′N	125°18′W	1520	Andesite	*R. geographicum* (L.) DC.
01IM31	Ragnarok Glacier	51°36′N	125°18′W	1520	Andesite	*R. macrosporum* Räsänen
01IM33	Ragnarok Glacier	51°36′N	125°18′W	1520	Gneiss	*R. geographicum* (L.) DC.
01JM14	Cathedral Glacier	51°14′N	124°52′W	1360	Quartz granite	*R. geographicum* (L.) DC.
01JM31	Cathedral Glacier	51°14′N	124°52′W	1360	Quartz granite	*R. geographicum* (L.) DC.

1999). Moreover, analysis of thallus measurements (on largest lichens, $n \geq 30$) used to date end and lateral moraines in the Mount Waddington area (Larocque and Smith, 2003), showed that 91.5% of all samples ($n = 142$ moraines) were normally distributed. Where the sample size was greater than 30 and there was a possibility that older lichen might be included in the sample (e.g., colonization of supraglacial debris), a Shapiro-Wilk normality test was employed to identify non-normally distributed lichen samples (Pearson et al., 1977). When a non-normal distribution was detected, outliers were rejected. Where the sample size was smaller than 30, the largest thalli were not eliminated, as the risks of underestimating surface ages are greater with fewer individuals and the statistical significance is greatly reduced.

The selected control measurements were added to the BC curve (Smith and Desloges, 2000) to evaluate the degree of correspondence between Bella Coola–Monarch Icefield and Mount Waddington regions. Selected points were translated into line equations defining the best fit of a particular statistical lichen growth relationship for the Bella Coola/Waddington (BCW) area. Following the methods used by Rodbell (1992), Reynolds (2001), and O'Neal and Schoenenberger (2003), 95% confidence intervals were established in order to assign age-specific error estimates. Detailed lichenometric sampling of morphologically prominent lateral and end moraine sequences at Tiedemann Glacier were undertaken along survey transects to evaluate the sensitivity of our calibrated curve.

Results

LICHEN IDENTIFICATION

The majority of lichens submitted were identified as *Rhizocarpon geographicum* (L.) DC. with two thalli identified as *Rhizocarpon macrosporum* Räsänen (Table 1). While the *Rhizocarpon geographicum* (L.) DC. were found on a variety of substrates, the *Rhizocarpon macrosporum* Räsänen thalli were both found growing on fine-grained andesitic substrates. Although this species has been reported to grow at a faster rate than *R. geographicum* (Luckman, 1977), its limited occurrence in the Mount Waddington area suggests the majority of lichen measured were likely *Rhizocarpon geographicum* (L.) DC.

LICHEN GROWTH CURVE

The lichen growth curve presented (BCW curve) is derived from control points established in the Bella Coola–Monarch Icefield (Smith and Desloges, 2000) and from new sites in the Mount Waddington area (Table 2; see Smith and Desloges [2000] for details of control points used to construct the original BC curve). Although these two areas are ca. 100 km apart, both include independently dated control sites located above 1300 m a.s.l. on the lee side of the Coast Mountains where the environmental conditions are relatively homogenous.

In the Mount Waddington area, 11 potential control points were examined to further calibrate the BCW (Table 2):

(1) At Tiedemann Glacier (51°19′N; 124°54′W), aerial photographs dating from 1954 to 1994 (BC1849-76; BC5148-69; BC7859-203; BCC286-95; BCC94039-178) were used to map the position of the receding ice front. Lichens were measured at 50-m intervals along a valley-bottom transect that extended downvalley from the 2000 ice-front position. Photograph overexposure in 1954 and intense glaciofluvial activity in the ice proximal area in 1965 greatly reduces the validity of the lichen measurements taken at sites 19 and 20. Lichen samples from sites 8 and 19 include abnormally large lichens that failed the Shapiro-Wilk normality test (Fig. 2, Table 3), which resulted in the deletion of three measurements at site 8 (sizes: 27.5, 22.1, and 21 mm) and four measurements at site 19 (sizes: 40, 34.9, 32.7, and 30.4 mm). Lichen measurements from sites 19 and 20 were not included in the analysis leading to the BCW growth curve presented in Figure 3. The remaining three control sites are considered reliable in local and regional dating application.

(2) At Oval Glacier (51°29′N; 125°15′W), control point 16 was derived from a subfossil log found partially buried by a large boulder on the distal slope of a prominent moraine. The maximum lichen diameter (34.4 mm) measured on the boulder provides an additional dated control point. Annual growth rings in the subfossil log were crossdated to a local living subalpine fir tree-ring chronology using standardized dendrochronological techniques (Stokes and Smiley, 1968), giving a kill date of 1864 that provides a minimum age for moraine formation.

(3) Radiocarbon dated subfossil wood found at Whitesaddle Glacier (51°36′N; 124°50′W) extends the BCW curve from 165 yr to 680 yr. Calibrated radiocarbon dates of approximately 30 outer rings (#18: 760 ± 50 ^{14}C yr BP, Beta-166885; #23: 540 ± 60 ^{14}C yr BP, Beta-165115) were obtained from two *in situ* stumps killed by distal spillage from the crest of the outermost lateral moraine. Lichens found growing on boulders included in a debris tongue directly related to the killing of the stump at site 18 were used to establish a control point dated to 680 cal. yr BP (max. diameter: 85 mm; Fig. 3). A lack of lichen on boulders overlying the second *in situ* stump (#23) and the lack of geomorphological evidence for a distal

TABLE 2

Control points used to develop the Bella Coola/Mount Waddington (BCW) lichen growth curve. Asterisks represent sites not included in the curve.

No.	Location	Surface age (yr)	Max. diam. (mm)	Elev. (m)	Evidence	Source
1	Hagensborg	20	13	55	Gravestone	Smith and Desloges (2000)
2	Hagensborg	23	14	55	Gravestone	Smith and Desloges (2000)
3	Tiedemann Glacier	23	13.1	520	Photogrammetry	Larocque and Smith (this study)
4	Hagensborg	25	13	55	Gravestone	Smith and Desloges (2000)
5	Tiedemann Glacier	26	13.2	520	Photogrammetry	Larocque and Smith (this study)
6	Hagensborg	27	14	55	Gravestone	Smith and Desloges (2000)
7	Tiedemann Glacier	27	12.5	520	Photogrammetry	Larocque and Smith (this study)
8	Tiedemann Glacier	28	14.5	520	Photogrammetry	Larocque and Smith (this study)
9	Hagensborg	28	15	55	Gravestone	Smith and Desloges (2000)
10	Hagensborg	35	19	55	Gravestone	Smith and Desloges (2000)
11	Hagensborg	36	17	55	Gravestone	Smith and Desloges (2000)
12	East Smitley	55	25	1300	Oldest tree on moraine	Smith and Desloges (2000)
13	Hagensborg	62	27	55	Gravestone	Smith and Desloges (2000)
14	Hagensborg	100	31.5	55	Gravestone	Smith and Desloges (2000)
15	Deer Lake	111	35	1435	Oldest tree on moraine	Smith and Desloges (2000)
16	Oval Glacier	136	34.4	1320	Cross-dated fossil wood	Larocque and Smith (this study)
17	Talchako Lateral	165	40	1450	Oldest tree on moraine	Smith and Desloges (2000)
18	Whitesaddle Glacier	680	85	1675	Radiocarbon-dated wood	Larocque and Smith (this study)
19	Tiedemann Glacier	29	24.1*	520	Photogrammetry	Larocque and Smith (this study)
20	Tiedemann Glacier	31	27.6*	520	Photogrammetry	Larocque and Smith (this study)
21	Razor Creek Glacier	43	9.4*	1675	Survey post (cairn)	Larocque and Smith (this study)
22	Cathedral Glacier	309	94.9*	1550	Cross-dated fossil wood	Larocque and Smith (this study)
23	Whitesaddle Glacier	540	85*	1675	Radiocarbon-dated wood	Larocque and Smith (this study)

collapse of the moraine suggest the date is not as reliable. As a result, only the control point established at site 18 was considered reliable.

(4) Lichens found growing on a rock cairn constructed during a geological survey in 1958 on a terminal moraine at Razor Creek Glacier (site 21; 51°34′N; 124°46′W) were measured and initially included in the BCW curve. As shown on Figure 3, however, the largest lichen (9.4 mm) found on the cairn is well beyond the 95% confidence interval envelope and leads to an overestimation of surface age if integrated in the growth curve. It is likely that growth conditions (e.g., wind desiccation) on the raised structure may lead to slower annual increment rates.

(5) At Cathedral Glacier (site 22; 51°14′N; 124°52′W), located on the west side of the Homathko Icefield, maximum lichen diameters (94.9 mm) on the crest of the outermost lateral moraine do not correspond to the cross-dated age of a partially buried bole (Fig. 3). Given that the bole was found in a cavity of the distal moraine slope, proximal to a snow avalanche path, it was likely killed by a snow avalanche in ca. 1691. The multimodal distribution of the largest lichens sampled supports this hypothesis (Fig. 2). For this reason, this point was not integrated in the BCW curve.

Comparison of radial growth trends of lichens found growing in the Bella Coola and Mount Waddington areas indicates they share similar age-size relationships. For instance, the radial measurements from the low elevation Hagensborg graveyard site show a close association for younger ages to those measured at Tiedemann Glacier (sites 3, 5, 7, and 8; Table 2). The new BCW *Rhizocarpon* spp. lichen growth curve includes the 12 control points included in the original BC curve and six new points from the Mount Waddington area (Fig. 3; Table 2).

The first part of the BCW *Rhizocarpon* spp. curve is best described as a logarithmic relationship:

$$y = 13.4098 \ln x - 29.515 \tag{1}$$

with an r^2 of 0.981 ($P < 0.000$; Fig. 3). Using this relationship, the lichen ecesis interval is estimated at 9 yr (± 3 yr), which is similar to the 7- to 8-yr delay in lichen establishment found by O'Neal and Schoenenberger (2003) in the northern Cascades. The great growth interval extends from 9 to 60 yr (0 to 25.4 mm thallus diameter). The average growth rate during this period of time is about 0.52 mm yr^{-1}. Between 60 and 165 yr, the growth rate decreases to 0.28 mm yr^{-1}. Uniform growth, characterized by a linear function, starts at 100 yr and was estimated from the junction of the logarithmic and the straight-line functions. After 165 yr, only one radiocarbon dated calibration point is included in the curve. The line equation between 100 and 680 yr (32 to 85 mm thallus diameter) is:

$$y = 0.0909x + 23.2065 \tag{2}$$

While this portion of the curve from 165 to 680 yr could not be described by regression analysis, the average rate of radial growth (0.13 mm yr^{-1}) suggest that as lichens age, they experience a linear growth.

An error envelope was defined based on 95% confidence intervals of the regression analysis and the calibrated radiocarbon date of site 18. This error is minimal between 20 and 28 yr, where the measurements are numerous and form a compact group. For a 25-yr-old surface (13.6 mm lichen), the error is estimated to be +6 and –5 yr. In contrast, the inherent dating error increases to +45 and –30 yr for a 150-yr-old surface, as the number of points decreases. A large difference exists with the confidence intervals of the regression equation including the deleted points (#19–21). Using wider confidence intervals, a 150-yr-old surface is bracketed by +159 and –84 yr, which leads to meaningless age estimates. An error of +42 and –44 is found on a 300-yr-old surface, with decreasing negative errors to –31 yr on a surface dated at 650 yr and an increasing positive values almost doubling (+77) for the same surface age.

Application of the BCW Lichen Growth Curve to Tiedemann Glacier

The reliability of the BCW lichen growth-rate curve for surface-age dating was assessed at Tiedemann Glacier, where two nested sets of lateral moraines have been described by previous researchers (Ryder

TABLE 3

Statistics of lichen measurements on Mount Waddington control sites. Shapiro-Wilk test was applied on samples $n = 30$ to assess the normality of the distributions ($p \leq 0.01$). Fail tests represent non-normally distributed samples and include outliers that have been removed from the samples to construct the lichen growth curve.

No.	n	Max. diam. (mm)	Mean	Std. dev.	Normality test
3	30	13.1	9.2	1.7	Pass
5	30	13.2	9.2	2	Pass
7	30	12.5	8.4	2	Pass
8	30	27.5	10.3	5.1	Fail
16	10	34.4	27.6	3.68	N/A
18	7	85	58.6	13	N/A
19	30	40	18.4	7.1	Fail
20	30	27.6	19	3.6	Pass
21	10	9.4	5.5	2.1	N/A
22	30	94.9	75.1	9.8	Pass
23	7	85	58.6	13	N/A

and Thompson, 1986). While the outer set of well-weathered and forest-covered moraines is ascribed to the broadly recognized Tiedemann glacial advance (early-Neoglacial) at ca. 3300 ^{14}C yr BP, the inner sequence of largely unvegetated moraine ridges is associated with distinct late-Neoglacial advance-retreat episodes that were initiated prior to 900 ^{14}C yr BP (Fulton, 1971; Ryder and Thompson, 1986).

A lichenometric survey in July 2000, focused on samples collected along eight transects which crossed the best preserved of the late-Neoglacial moraine crests on the northern perimeter of the Tiedemann Glacier forefield (Figs. 4 to 6). Moraine crests were numbered according to their position on the transects (moraine 1 being the most distal), with moraine numbers from different transects at a site not necessarily being synchronous. The steep proximal slopes of the lateral moraine show evidence of massive slope failures and it is difficult to correlate the individual moraine crests (transects d to h) solely on the basis of their morphological characteristics. Transects positioned within distal sections of the forefield (a to c) revealed the presence of four nonfragmented and relatively well-preserved terminal moraines (Fig. 5). The most distal late-Neoglacial moraines on transects d to h exhibit a high degree of surface weathering. In general, the limited vegetation cover present on these late-Neoglacial moraines and their low elevation (ca. 700–900 m) suggests that lichen colonization patterns have probably not been influenced by either lingering snowpacks or competition. Independent dating control for moraine ages was obtained from radiocarbon and tree-ring dates, and existent North American Pacific Coast Neoglacial histories.

Lichenometric surveys were completed at 24 measurement sites (Table 4), which enabled a good replication of moraine dates. Data from three did not pass the Shapiro-Wilk normality test and these dates were therefore carefully analyzed. For the data analysis a conservative approach was adopted, so as to not discard abnormally large lichen where no sign of disturbance was noted; especially if smaller lichen populations were sampled. As a result, three outliers were removed from the distribution at sites A2 (91.2 mm), B2 (88.8 mm), and F1 (183 mm).

Using the BCW lichen growth curve equations, dates of substrate stabilization associated with an ± error envelope were calculated (Table 4), and transposed onto a frequency histogram (Fig. 7). Two dates do not show consistency with the transect moraine sequences: moraine D1 (AD 1499) is younger than D2 (AD 947), and G2 (AD 1600) is younger than G3 (AD 1472). At these sites, evidence of lichen disturbance by vegetation was encountered.

Six periods of late-Neoglacial moraine formation were recorded at Tiedemann Glacier, with minimum dates of AD 620, 925, 1118, 1392, 1575, and 1621. The lichenometric interpretations of multiple late-Neoglacial glacial events are supported by the findings of previous research efforts in the Pacific Northwest (e.g., Desloges and Ryder, 1990). A 7th-century glacial advance (620–684) was recorded at moraines E1 and F1, which shared similar morphological characteristics (accentuated weathering and similar emplacement). Supporting evidence of a pre-Little Ice Age advance at Tiedemann Glacier was

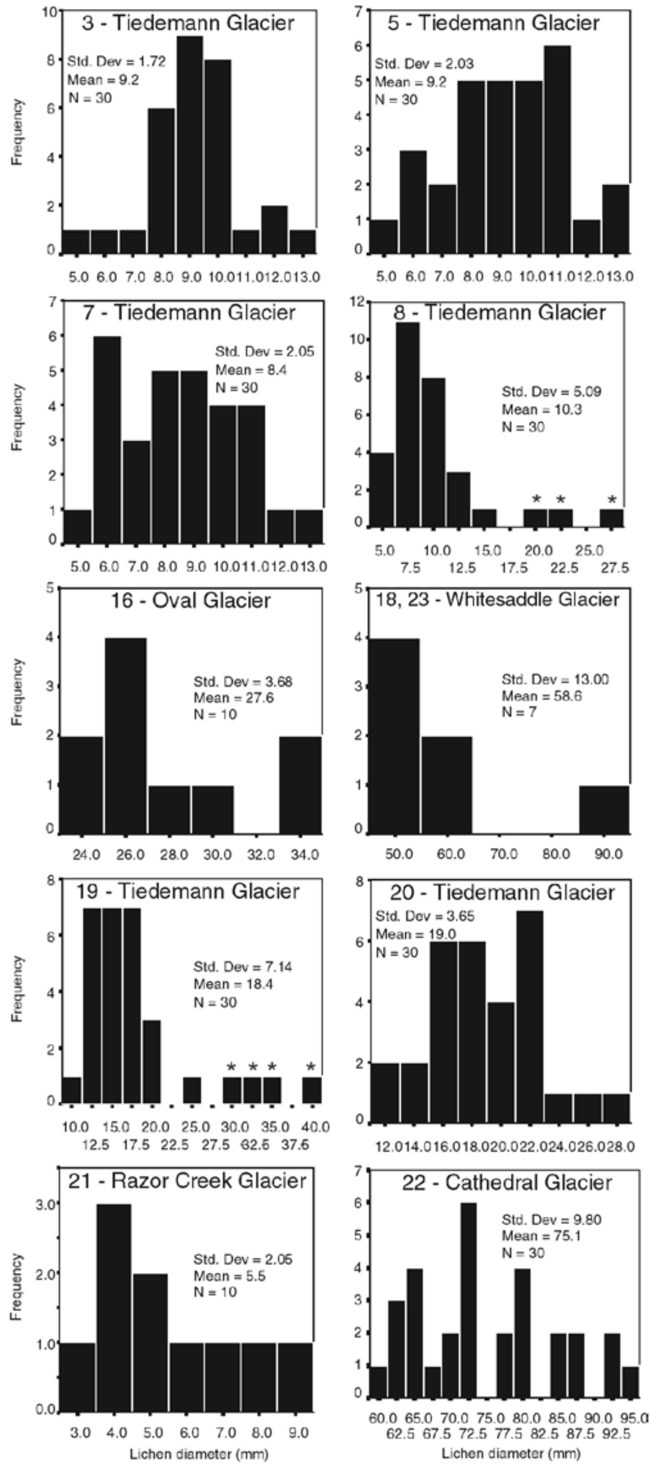

FIGURE 2. Distribution of lichen thalli on control sites. Most of the populations are normally distributed (Shapiro-Wilk normality test), except sites 8 and 19. At these sites, outliers (indicated by an asterisk) were removed from the distribution.

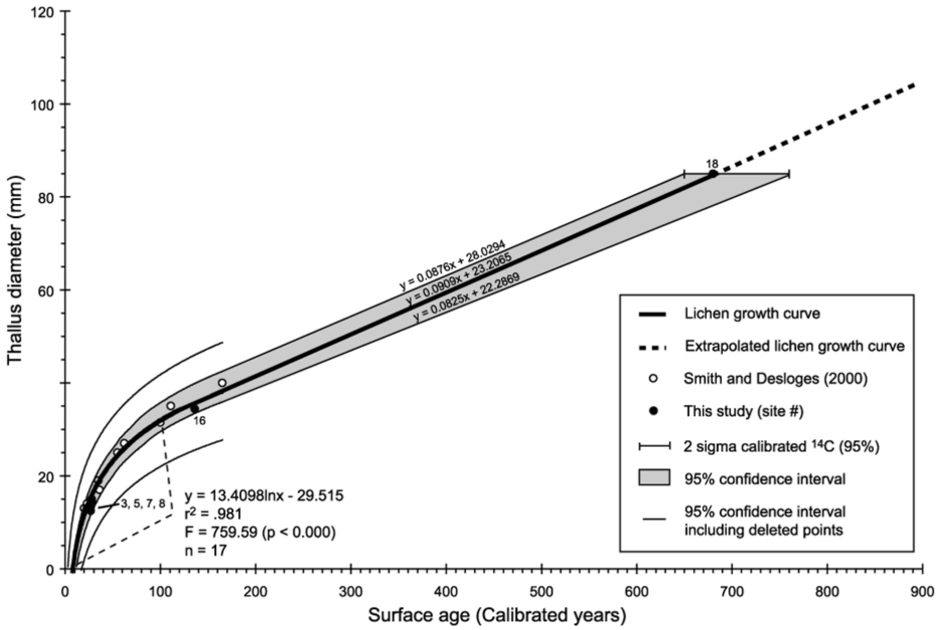

FIGURE 3. Lichen growth curve developed for the Mount Waddington area. A logarithmic relationship explains best the first 100 yr of growth. Between 100 and 680 yr, a linear function describes the growth. The error associated with the curve corresponds to the 95% confidence interval of the logarithmic regression and the ^{14}C calibrated 95% probability.

reported by Fulton (1971) from an 8th-century basal peat deposit (1270 ± 140 ^{14}C yr BP: AD 719, 746, 769) and by Ryder and Thomson (1986) from a glacially transported log (1330 ± 65 ^{14}C yr BP: AD 674). Other supporting evidence for a widespread glacial advance in the Coast Mountains at this time comes from Bridge Glacier, where an *in situ* glacially-sheared stump recovered in 2002 provided an age of 1500 ± 80 ^{14}C yr BP (AD 430–650), and from Alaska where investigations record the onset of a glacial advance in the Kenai Fjords (AD 596 to 653; Wiles and Calkin, 1991, 1993, 1994; Wiles et al., 1995), at Tebenkof Glacier (AD 590 to 695; Wiles et al., 1999), at Sheridan Glacier, and at Icy Bay (AD 560 to 601; Calkin et al., 2001).

Lichen measurements at D2, G1, and at location H1 indicate that a succeeding late-Neoglacial moraine-building episode occurred between AD 925 and 947. Despite the fact that the moraines are difficult to correlate on the basis of morphological characteristics, we believe the multiple and well-replicated lichen dates adequately support a 10th-century glacial event at Tiedemann Glacier. Although regional evidence for glacial activity during this period is sparse, advances in the St. Elias and Wrangell Mountains (AD 700 to 900; Denton and Karlén, 1973) and Kenai Fjords (AD 897 to 968; Wiles and Calkin, 1993) may correspond to this event.

FIGURE 4. Oblique aerial photograph of late-Neoglacial forefield of the Tiedemann Glacier, July 2001.

Lichen at A1, B1, C1, and possibly F2, suggest that a third glacial advance in the 12th century (1118–1310) led to the construction of moraines. This moraine-building event is presumably correlative to synchronous advances recorded at Klinaklini Glacier (900 ± 40 ^{14}C yr BP: AD 1160) in the Coast Mountains (Ryder and Thomson, 1986) and in the Monashee Mountains (910 ± 130 ^{14}C yr BP: AD 1071, 1079, 1128; Lowdon and Blake, 1975; referenced by Ryder and Thomson, 1986).

Measurements at A2, B2, and possibly G3, record a period of moraine building lichenometrically-dated to between AD 1392 and 1472. Prominent proximal slope failures at C2 have removed any corresponding evidence of this event. In the southern British Columbia Coast Mountains, there is evidence that Colonel Foster Glacier (AD 1397; Lewis, 2001), Purgatory Glacier (460 ± 50 ^{14}C yr BP: AD 1439; 480 ± 50 ^{14}C yr BP: AD 1434; Desloges and Ryder, 1990), Jacobsen Glacier (400 ± 60 ^{14}C yr BP: AD 1468; Desloges and Ryder, 1990), and other glaciers described by Ryder and Thomson (1986) were advancing and building moraines at this time. Synchronous advances in the Kenai Mountains (Bering: AD 1420, Gravingk: AD 1442, Tustemana: AD 1460, Bear, Exit, and Yalik glaciers: AD 1460) highlight the widespread nature of this activity.

Lichen dating to the late-16th century (1575–1641) corresponds to moraine-building events at A3, B3, C3, D3, and E2. The morphological continuity of the sampling locations supports this assumption. The moraine-building event may correlate to a high-water stage of glacially dammed Lake Alsek in 1582 (Clague and Rampton, 1982). Evidence for advanced terminal positions at Mount Baker (early-1500s to AD 1559; Heikkinen, 1984) and Mount Rainier (AD 1519, 1528, 1552; Sigafoos and Hendricks, 1972) in Washington state, at Hubbard Glacier in the Kenai Mountains (AD 1587 to 1650; Wiles and Calkin, 1994; 2001; radiocarbon date intercepting the calibration curve at AD 1525, 1558, 1631; Barclay et al., 2001), point to the probability that this was a regional event.

The most recent moraine-building episode recorded at Tiedemann Glacier dates to between AD 1621–1780. This interpretation is supported by a glacially transported log (300 ± 60 ^{14}C yr BP: AD 1637) located by Ryder and Thomson (1986) at a site farther up-valley and a tree-ring date of 1624 obtained on moraine C4 (Larocque

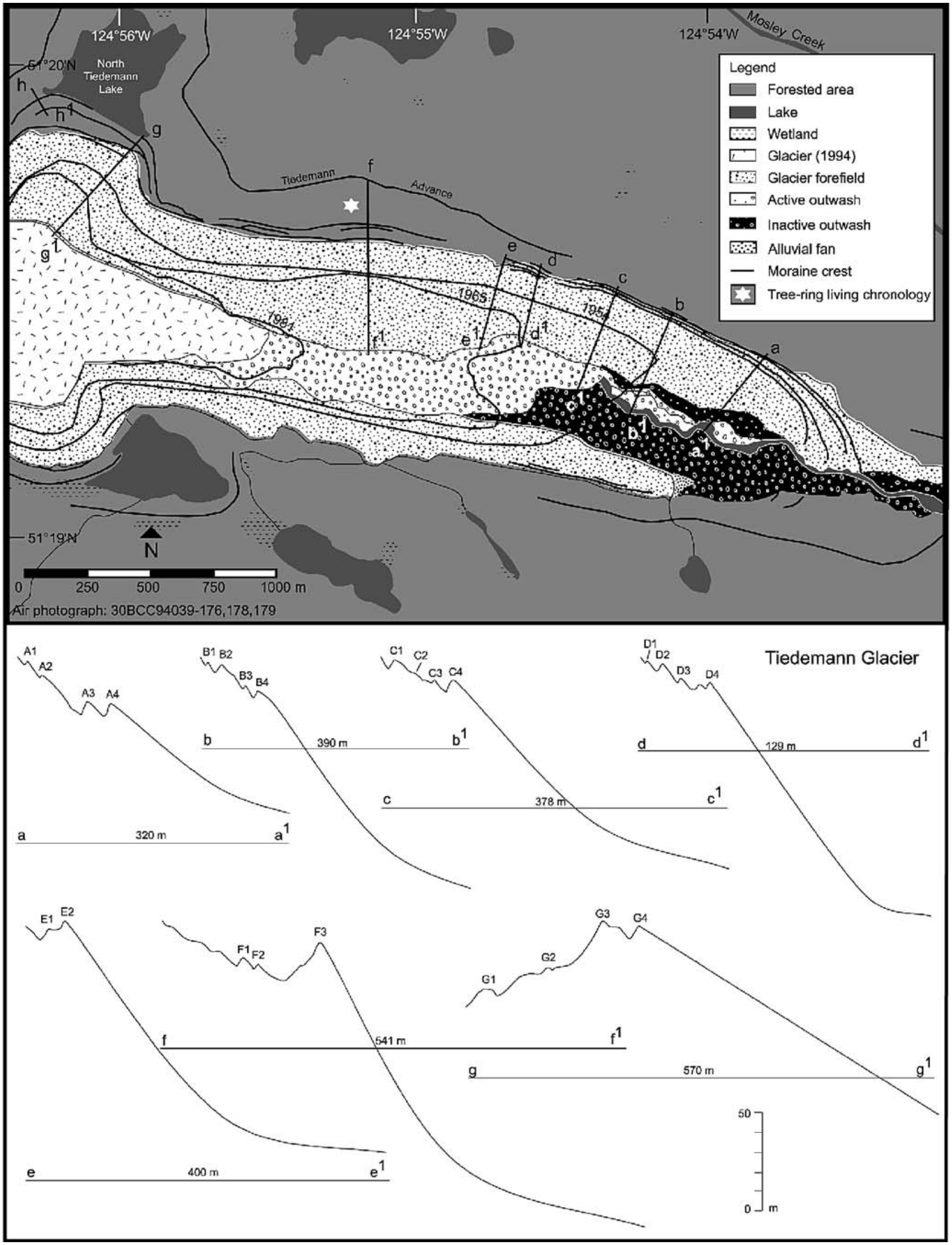

FIGURE 5. Location of lichen measurement transects at Tiedemann Glacier. Lichens were measured along eight transects, for a total of 24 sampling sites (see Table 4). One radiocarbon date of 1270 ± 140 yr BP was obtained from basal peat outside the outermost Little Ice Age moraine (Fulton, 1971).

FIGURE 6. Typical lateral moraines at Tiedemann Glacier, showing sparsely distributed trees (whitebark pine, subalpine fir, and Douglas-fir) on four successive bouldery ridges.

and Smith, 2003). This early-17th century advance closely matches time-synchronous moraines located at sites throughout the region (Clague and Mathewes, 1996; Smith and Laroque, 1996; Lewis, 2001).

Discussion

In the Pacific Northwest of North America and Alaska, nine lichen growth curves exist that are relevant to this paper (Fig. 8, Table 5). Solomina and Calkin (2003) reviewed five lichen growth curves previously developed in Alaska and proposed new relationships. Four of these are integrated in the following comparison, the exception being the curve that Denton and Karlén (1973) produced for the White River Valley and Skolai Pass in southeastern Alaska. Their lichenometric curve was based on the maximum diameter of the largest lichen measured at 13 dated control surfaces dominated by andesitic substrates, located between 1100 and 1700 m a.s.l. Their lichen growth curve shows an initial period of rapid growth, followed by a near linear period of growth that lasted for at least 2780 ^{14}C yr (wood within organic layer). In the same general area, Wiles et al. (2002) developed a *Rhizocarpon* growth curve for the Wrangell Mountains that was based on maximum lichen diameters from nine dated control sites between 61 and 202 yr in age. The difference noted after 100 yr between the two curves may be related to more maritime conditions encountered at the control sites incorporated by Wiles et al. (2002).

In northern Alaska, 14 control sites were used from Calkin and Ellis (1980, 1984) to develop a 1264-yr-old lichen growth curve along a 120-km transect located in the Central Brooks Range up to 1700 m altitude (Solomina and Calkin, 2003). Farther south at Seward Peninsula, on the western maritime portion of Alaska, seven control sites originally provided by Calkin et al. (1998) were reinterpreted into a 217-yr-long lichen-surface age relationship integrating low elevation growth (<600 m a.s.l.). In the southern Alaska Range, Solomina and Calkin (2003) used the lichen control measurements provided by Bijkerk (1980), Péwé and Reger (1983), and Begét (1994) to determine lichen growth on up to 3708-yr-old surfaces. The last relevant curve from Alaska is located on the maritime Kenai Peninsula, in the Gulf of Alaska, and was developed using *Rhizocarpon* section *Alpicola* (Wiles, 1992; Wiles and Calkin, 1994, Solomina and Calkin, 2003). The relationship between lichen growth and surface age is limited to 264 yr.

Lewis (2001) and Lewis and Smith (2004) constructed a *Rhizocarpon* growth curve for Vancouver Island, British Columbia, that was based on the maximum diameter of the largest lichen found at 26 control sites from a low elevation graveyard (160 m a.s.l.) and four tree-ring dated moraines found at 1300 m a.s.l. in Strathcona Provincial Park. This *Rhizocarpon* curve extends to 290-yr-old surfaces and suggests that lichen growth rates are dependent upon water supply and substrate (bedrock vs. boulder).

In Washington State, Porter (1981) undertook a detailed licheno-

TABLE 4

Statistics of lichen measurements at Tiedemann Glacier, and dates derived from the Bella Coola/Mount Waddington (BCW) lichen growth curve. Asterisks indicate samples where an outlier was removed from the distribution.

Moraine	n	Mean diam. (mm)	Std. dev.	Normality test	Max. diam. (mm)	Date AD	−error	−date	+error	+date
A1	30	69.4	10.5	Pass	98.1	1176	−24	1152	95	1271
A2	31	51.6	13.9	Fail	78.5*	1392	−32	1360	73	1465
A3	30	42.6	7.2	Pass	61.8	1575	−39	1536	54	1629
A4	30	26	4.5	Fail	43.2	1780	−47	1733	34	1814
B1	22	64.3	12.4	N/A	85.9	1310	−29	1281	81	1391
B2	24	58.4	10.2	N/A	72.8*	1454	−35	1419	66	1520
B3	30	40.1	7.3	Pass	61.8	1575	−39	1536	59	1634
B4	32	38	6.4	Pass	54	1661	−43	1618	45	1706
C1	31	55	12.4	Fail	103.4	1118	−22	1096	101	1219
C3	30	44.4	6.3	Pass	55.8	1641	−42	1599	47	1688
C4	30	33.6	5.4	Pass	45.3	1757	−46	1711	36	1793
D1	12	51.5	10.4	N/A	68.7	1499	−37	1462	62	1561
D2	30	64.9	16.5	Pass	118.9	947	−16	931	118	1065
D3	31	44.2	6.7	Pass	58.8	1608	−41	1567	51	1659
D4	30	35.1	6.8	Pass	57.7	1621	−40	1581	50	1671
E1	4	112.5	35.1	N/A	142.8	684	−6	678	145	829
E2	2	52.1	12.7	N/A	61.1	1583	−39	1544	54	1637
F1	30	96.6	29.9	Pass	148.6*	620	−4	616	151	771
F2	24	48.2	15.4	Pass	88.6	1281	−28	1253	85	1366
G1	3	104.8	25.8	N/A	120.9	925	−15	910	120	1045
G2	1	N/A	N/A	N/A	59.6	1600	−40	1560	52	1652
G3	30	51.3	9.2	Pass	71.2	1472	−35	1437	65	1537
G4	30	41.6	6	Pass	52.6	1677	−42	1635	44	1721
H1	8	81.8	18.3	N/A	120.5	930	−14	916	121	1051

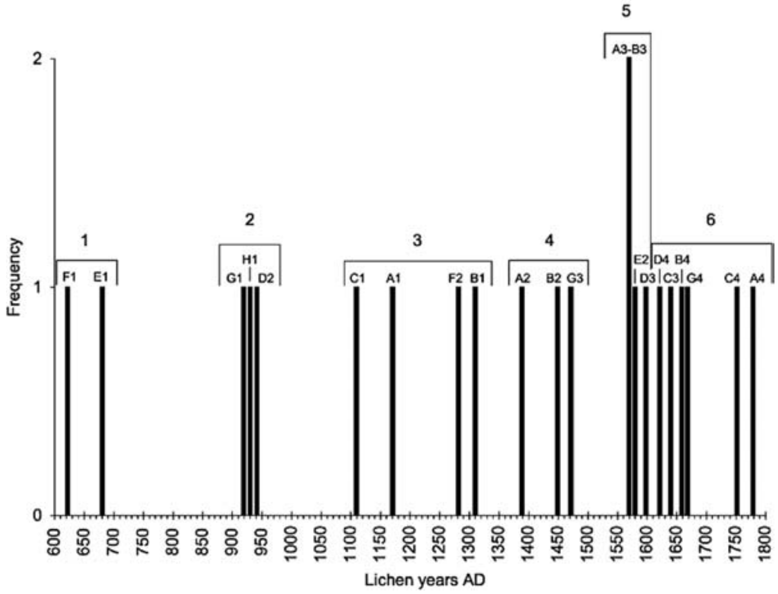

FIGURE 7. Frequency distribution of lichen dates obtained at Tiedemann Glacier. Moraine crests were numbered (capital letters) according to their position on the transects (moraine 1 being the most distal), with moraine numbers from different transects (lower letters) at a site not necessarily being synchronous. Stabilization of lateral moraine, leading to lichen colonization, occurred in six distinct periods: with minimum dates of AD 620 (1), 925 (2), 1118 (3), 1392 (4), 1575 (5), and 1621 (6).

metric analysis at Mount Rainier (1000–2000 m a.s.l.). Control measurements were obtained from the maximum diameter of the largest lichen discovered on historical rock structures as old as 120 yr. His investigations suggested there was a general reduction of lichen growth rate with time, notably following a 20-yr period of great growth after surface stabilization. Moreover, he provided evidence suggesting reduced growth rates at high-elevation sites were dependent upon whether the substrate was andesitic or granodioritic. The control measurements from this study and the ones provided for Mount Hood (Lillquist, 1988) and Mount Baker (O'Neal and Schoenenberger, 2003) were combined into a *Rhizocarpon* curve applicable to the Cascade Mountains of Washington and northern Oregon (O'Neal and Schoenenberger, 2003). The lichen growth-surface exposure relationship was developed for elevations between 1195 to 1825 m on up to 145-yr-old surfaces. Contrary to Porter (1981), this research suggests that substrate influences lichen growth insignificantly.

In general, most of the published lichen growth curves for the Pacific Northwest span a relatively short period of time, resulting in thallus growth rates that suggest a logarithmic or exponential relationship associated to the great growth period for the first 75 to 100 yr. Although an extrapolated linear relationship based on great growth rates is characteristically used to date older surfaces, Innes (1985) and Bradwell (2001) noted that the inherent assumptions possibly lead to dating errors. Innes (1985) suggests that a linear relationship may be safely applicable up to ca. 150 mm thallus diameter. The oldest lichen growth curves published in Pacific North America remain those by Denton and Karlén (1973) and by Solomina and Calkin (2003), which show linear rates of growth persisting for the past 3000 to 4000 yr. After the linear growth period, lichens tend to experience senescence, mortality or reduced rates of radial expansion. This behavior results in thallus growth rates that suggest a logarithmic, exponential, or composite relationship (Innes, 1985; McCarthy and Smith, 1995; Bradwell, 2001; Solomina and Calkin, 2003).

Lichen growth in the Bella Coola–Mount Waddington area is intermediate between growth rates observed in southern (Porter, O'Neal/Schoenenberger, and Lewis) and northern (Brooks Range) curves. The BCW growth curve appears to be similar to the first 60 yr of the Porter (1981), O'Neal and Schoenenberger (2003), and Lewis (2001) curves, but after that point, declining growth rates suggest a closer relationship to the growth curves developed by Solomina and Calkin (2003), Denton and Karlén (1973), and Wiles et al. (2002) in southern Alaska and Seward Peninsula (Fig. 8). The ecological reasons for these differential age-size relationships are difficult to assess, as there are few details available on specific environments at the various sites (Table 5). Although the role of lithology on lichen growth was documented by Porter (1981), it does not offer a complete explanation for the apparent spatial variation in *R. geographicum* growth trends emerging within the Pacific Northwest and Alaska, a conclusion supported by O'Neal and Schoenenberger (2003) in the northern Cascades. Faster rates of radial expansion at the more southerly sites suggest that environmental conditions in these regions favor lichen growth, whereas more extreme conditions in Alaska and in the Mount

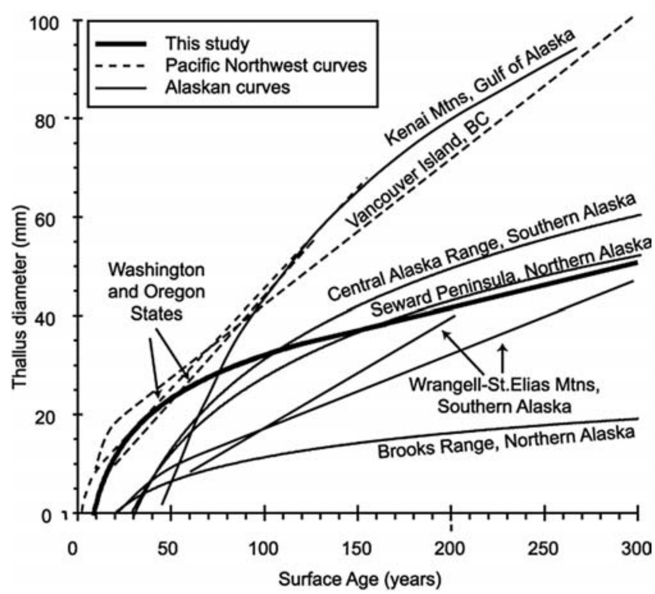

FIGURE 8. Comparative graph of lichen growth curves developed along the Pacific Coast of North America: Denton and Karlén (1973), and Wiles et al. (2002) in the Wrangell and St. Elias Mountains of Alaska; Solomina and Calkin (2003) in the Brooks Range, Seward Peninsula, Alaska Range, and Kenai Mountains; Lewis (2001) and Larocque and Smith (this study) in the southern B.C. Coast Mountains; Porter (1981) and O'Neal and Schoenenberger (2003) in the Cascade Range of Washington and Oregon.

TABLE 5

Rhizocarpon *spp. Growth curves developed along the Pacific Coast of North America.*

Location	Elev. (m a.s.l.)	Substrate	Annual precipitation (mm)	Mean annual temperature (°C)	Curve length	Reference
Central Brooks Range, northern AK	450–1700	n.s.[b]	267	−5.5	1264 cal. yr	Solomina and Calkin (2003)
Seward Peninsula, northern AK	0–600	n.s.[b]	342	−3.2	217 cal. yr	Solomina and Calkin (2003)
Central Alaska Range, southern AK	n.s.[b]	n.s.[b]	239	−2.9	3708 cal. yr	Solomina and Calkin (2003)
White River Valley–Skolai Pass, southern AK	1100–1700	n.s.[b]	250–3360	−5.5 to 3	2780 ^{14}C yr	Denton and Karlén (1973)
Wrangell Mountains, southern AK	n.s.[b]	n.s.[b]	200–2440	n.s.[b]	202 cal. yr	Wiles et al. (2002)
Kenai Mountains, Gulf of Alaska[a]	n.s.[b]	n.s.[b]	518–1435	3 to 4.2	264 cal. yr	Solomina and Calkin (2003)
Bella Coola–Monarch Icefield–Mount Waddington area, southern BC	55–1675	Andesite, granodiorite, granite	334–1677	2.2 to 7.9	540 cal. yr	This study
Vancouver Island, southwestern BC	160–1300	n.s.[b]	2620	3	290 cal. yr	Lewis (2001)
Mount Rainier, WA	1000–2000	Andesite, granodiorite	n.s.[b]	n.s.[b]	120 cal. yr	Porter (1981)
Cascade Range, WA and northern OR	1195–1825	Andesite, granodiorite	n.s.[b]	n.s.[b]	145 cal. yr	O'Neal and Schoenenberger (2003)

[a] Rhizocarpon section Alpicola.
[b] n.s. = not specified.

Waddington area, induced by latitude and possibly elevation, result in declining rates of growth with age.

Many studies have demonstrated the impact of air temperature, moisture availability, altitude, and substrate on lichen growth (e.g., Innes, 1985; Benedict, 1990). Nevertheless, it is not unusual to encounter lichen growth curves applied to areas covering 100s of km^2, thereby implying that relatively homogenous growing conditions exist throughout a region (Rodbell, 1992; McCarthy and Smith, 1995; Calkin et al., 1998; Bradwell, 2001; O'Neal and Schoenenberger, 2003; Solomina and Calkin, 2003). The BCW curve does suggest that it is possible to extend to at least 100 km the applicability of a lichenometric dating curve for surfaces younger than 165 yr, without introducing major dating constraints. In the first 100 yr of calibrated lichen growth, uniform growth rates are apparent despite variations in elevation and environmental conditions (Smith and Desloges, 2000; Lewis, 2001, 2004; Porter, 1981) (Fig. 8, Tables 2 and 5).

Investigations at Tiedemann Glacier and other glaciers in the Mount Waddington area (Larocque and Smith, 2003) suggest that the BCW lichen growth curve provides comparative relative ages for surfaces independently dated using ^{14}C and tree-rings in this region. Nevertheless, its site-specific applicability is limited in some settings. For instance, at Tiedemann Glacier the assigned age on the same continuous moraine crest varied by 200 yr or more (Fig. 5, Table 4). While these findings are most likely due to factors such as variable rates of substrate stabilization (e.g., Gellatly, 1982; Innes, 1985; Rodbell, 1992) and lichen population dynamics (Innes, 1985; McCarthy, 1997, 1999), they do emphasize the importance of replication in lichen measurements. Further difficulties arise in assigning appropriate errors to lichen growth curves. While appropriate control points can be identified to permit the calculation of the 95% confidence intervals, this is rarely possible in remote settings where there is limited dating control. Although errors associated with confidence intervals do not include the entire range of dating errors encountered in lichenometric studies, it provides a useful statistical estimate. Reducing the confidence intervals by, for example, increasing the number of control measurement sites or the accuracy of independently dated surfaces is an important concern because it gives the opportunity to associate an acceptable error with the lichen date.

Conclusion

This paper confirmed and strengthened the dating applicability of the Bella Coola–Monarch Icefield lichen growth curve developed by Smith and Desloges (2000) to lichenometric studies in the Mount Waddington area. A significant contribution of the BCW curve is the extension back to 680-yr-old surfaces, which will permit the relative age dating of pre-Little Ice Age landforms. The study also stresses the importance of incorporating a statistically adequate number of radial measurements and statistical normality testing to eliminate outliers that are inherent to lichen populations. High replication is necessary as substrate stabilization, lichen population distribution, and local disturbance greatly affect lichen growth, leading to dating errors of several decades. These conditions satisfied, lichen dating likely leads to better estimate of glacial activity then tree-ring analysis, as lichens are abundant and establish shortly after surface exposure.

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References Cited

André, M.-F., 1986: Dating slope deposits and estimating rates of rock wall retreat in northwest Spitsbergen by lichenometry. *Geografiska Annaler,* 68A: 65–75.

Andrews, J. T. and Webber, P. J., 1969: Lichenometry to evaluate changes in glacial mass budgets: as illustrated from north-central Baffin Island, N.W.T. *Arctic and Alpine Research,* 1: 181–194.

Barclay, D. J., Calkin, P. E., and Wiles, G. C., 2001: Holocene history of Hubbard Glacier in Yakutat Bay and Russell Fiord, southern Alaska. *Geological Society of America Bulletin,* 113: 388–402.

Barendsen, G. W., Deevy, E. S. J., and Gralenski, I. J., 1957: Yale natural radiocarbon measurements III. *Science,* 126: 908–919.

Begét, J. E., 1994: Tephrochronology, lichenometry and radiocarbon dating at Gulkana Glacier, central Alaska Range, USA. *The Holocene,* 4: 307–313.

Benedict, J. B., 1990: Experiments on lichen growth. I. Seasonal patterns and environmental controls. *Arctic and Alpine Research,* 22: 244–252.

Beschel, R. E., 1961: Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry). *In* Raasch, G. O. (ed.), *Geology of the Arctic 2*. Toronto: University of Toronto Press, 1044–1062.

Beschel, R. E., 1973: Lichens as a measure of the age of recent moraines. *Arctic and Alpine Research,* 5: 303–309.

Bijerk, A., 1980: Lichenometric dating of Neoglacial deposits in the McKinley Park area, Alaska. Unpublished report submitted to the National Park Service and National Geographic Society. 55 pp.

Bradley, R. S., 1985: *Quaternary Paleoclimatology.* Boston: Allen & Unwin Inc. 472 pp.

Bradwell, T., 2001: A new lichenometric dating curve for southeast Iceland. *Geografiska Annaler,* 83A: 91–101.

Broadbent, N. D. and Bergqvist, K. I., 1986: Lichenometric chronology and archaeological features on raised beaches: preliminary results from the Swedish north Bothnian coastal region. *Arctic and Alpine Research,* 18: 297–306.

Bull, W. B. and Brandon, M. T., 1998: Lichen dating of earthquake-generated regional rockfall events, southern Alps, New Zealand. *Geological Society of America Bulletin,* 110: 60–84.

Bull, W. B., King, J., Kong, F., Moutoux, T., and Phillips, W. M., 1994: Lichen dating of coseismic landslide hazard in alpine mountains. *Geomorphology,* 10: 253–264.

Bull, W. B., Schlyter, P., and Brogaard, S., 1995: Lichenometric analysis of the Kärkerieppe slush-avalanche fan, Kärkevagge, Sweden. *Geografiska Annaler,* 77A: 231–240.

Calkin, P. E. and Ellis, J. M., 1980: A lichenometric dating curve and its application to Holocene glacier studies in the central Brooks Range, Alaska. *Arctic and Alpine Research,* 12: 245–264.

Calkin, P. E. and Ellis, J. M., 1984: Development and application of a lichenometric dating curve, Brooks Range, Alaska. *In* Mahaney, W. C. (ed.), *Quaternary Dating Methods.* Amsterdam: Elsevier, 227–246.

Calkin, P. E., Kaufman, D. S., Przybyl, B. J., Whitford, W. B., and Peck, B. J., 1998: Glacier regimes, periglacial landforms, and Holocene climate change in the Kigluaik Mountains, Seward Peninsula, Alaska, U.S.A. *Arctic and Alpine Research,* 30: 154–165.

Calkin, P. E., Wiles, G. C., and Barclay, D. J., 2001: Holocene coastal glaciation of Alaska. *Quaternary Science Reviews,* 20: 449–461.

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

Clague, J. J. and Rampton, V. N., 1982: Neoglacial Lake Alsek. *Canadian Journal of Earth Sciences,* 19: 94–117.

Denton, G. H. and Karlén, W., 1973: Lichenometry: its application to Holocene moraine studies in southern Alaska and Swedish Lapland. *Arctic and Alpine Research,* 5: 347–372.

Denton, G. H. and Karlén, W., 1977: Holocene glacial and tree-line variations in the White River Valley and Skolai Pass, Alaska and Yukon Territory. *Quaternary Research,* 7: 63–111.

Desloges, J. R. and Ryder, J. M., 1990: Neoglacial history of the Coast Mountains near Bella Coola, British Columbia. *Canadian Journal of Earth Sciences,* 27: 281–290.

Fulton, R. J., 1971: *Radiocarbon Geochronology of Southern British Columbia.* Geological Survey of Canada, Paper 71-37.

Gellatly, A. F., 1982: Lichenometry as a relative-age dating method in Mount Cook National Park, New Zealand. *New Zealand Journal of Botany,* 20: 343–353.

Harrison, S. and Winchester, V., 2000: Nineteenth- and twentieth-century glacier fluctuations and climatic implications in the Arco and Colonia valleys, Hielo Patagonica Norte, Chile. *Arctic, Antarctic, and Alpine Research,* 32: 55–63.

Heikkinen, O., 1984: Dendrochronological evidence of variations of Coleman Glacier, Mount Baker, Washington, U.S.A. *Arctic and Alpine Research,* 16: 53–64.

Heusser, C. J., 1957: Variations of Blue, Hoh, and White Glaciers during recent centuries. *Arctic,* 10: 139–150.

Hickson, C. J., 1994: Character of volcanism, volcanic hazards, and risk, northern end of the Cascade magmatic arc, British Columbia and Washington State. *In* Monger, J. W. H. (ed.), *Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia.* Geological Survey of Canada, 231–250.

Innes, J. L., 1985: Lichenometry. *Progress in Physical Geography,* 9: 187–254.

Larocque, S. J., and Smith, D. J., 2003: Little Ice Age glacial activity in the Mt. Waddington area, British Columbia Coast Mountains, Canada. *Canadian Journal of Earth Sciences,* 40: 1413–1436.

Lewis, D. H., 2001: Little Ice Age investigations in Strathcona Provincial Park, Vancouver Island, B.C. M.Sc. thesis, University of Victoria, Victoria. 147 pp.

Lewis, D. H. and Smith, D. J. 2004: Little Ice Age glacial activity in Strathcona Provincial Park, Vancouver Island, British Columbia, Canada. *Canadian Journal of Earth Sciences,* 41: 285–297.

Lillquist, K. D., 1988: Holocene fluctuations of the Coe Glacier, Mount Hood, Oregon. M.Sc. thesis, Portland State University.

Lowdon, J. A. and Blake, W. J., 1975: *Radiocarbon dates XV.* Geological Survey of Canada Paper 75–7: 32 pp.

Luckman, B. H., 1977: Lichenometric dating of Holocene moraines at Mount Edith Cavell, Jasper, Alberta. *Canadian Journal of Earth Sciences,* 14: 1809–1822.

McCarroll, D., 1994: A new approach to lichenometry: dating single-age and diachronous surfaces. *The Holocene,* 4: 383–398.

McCarthy, D. P., 1997: Habitat selection and ecology of *Xanthoria elegans* (Link) Th. Fr. in glacier forefields: implications for lichenometry. *Journal of Biogeography,* 24: 363–373.

McCarthy, D. P., 1999: A biological basis for lichenometry? *Journal of Biogeography,* 26: 379–386.

McCarthy, D. P. and Smith, D. J., 1995: Growth curves for calcium-tolerant lichens in the Canadian Rocky Mountains. *Arctic and Alpine Research,* 27: 290–297.

Meteorological Service of Canada, 2002: *Canadian climate normals 1961–1990.* URL:http://www.msc.ec.gc.ca/climate/climate_normals_1990/index_e.cfm

Monger, J. W. H. and Journeay, J. M., 1994: Basement geology and tectonic evolution of the Vancouver region. *In* Monger, J.W.H. (ed.), *Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia.* Geological Survey of Canada, 3–25.

O'Neal, M. A. and Schoenenberger, K. R., 2003: A *Rhizocarpon geographicum* growth curve for the Cascade Range of Washington and northern Oregon, USA. *Quaternary Research,* 60: 233–241.

Osborn, G. and Taylor, J., 1975: Lichenometry on calcareous substrate in the Canadian Rockies. *Quaternary Research,* 5: 111–120.

Pearson, E. S., D'Agostino, R. B., and Bowman, K. O., 1977: Tests for departure from normality: comparison of powers. *Biometrika,* 64: 231–246.

Péwé, T. L. and Reger, R. D., 1983: Delta River area, Alaska Range. *In* Péwé, T. L. and Reger, R. D. (eds.), *Richardson and Glen Highways, Alaska: guidebook to permafrost and Quaternary geology.* Fairbanks, 47–136.

Plafker, G. and Miller, D. J., 1957: Glacial features and surficial deposits of the Malaspina district, Alaska. *U.S. Geological Survey open file report.* 13 pp.

Poelt, J., 1988: *Rhizocarpon* Ram. em. Th. Fr. subgen. *Rhizocarpon* in Europe. *Arctic and Alpine Research,* 20: 292–298.

Porter, S. C., 1981: Lichenometry studies in the Cascade Range of Washington: establishment of *Rhizocarpon geographicum* growth curves at Mount Rainier. *Arctic and Alpine Research,* 13: 11–23.

Purvis, O. W., Coppins, B. J., Hawksworth, D. L., James, P. W. and Moore, D. M. (eds.), 1992: *The Lichen Flora of Great Britain and Ireland.* London: The British Lichen Society and The Natural History Museum. 710 pp.

Reynolds, N. D., 2001: Dating the Bonneville landslide with lichenometry. *Washington Geology,* 29: 11–16.

Rodbell, D. T., 1992: Lichenometric and radiocarbon dating of Holocene glaciation, Cordillera Blanca, Peru. *The Holocene,* 2: 19–29.

Runemark, H., 1956: Studies in the genus *Rhizocarpon*. I. Taxonomy of the yellow species in Europe. *Opera Botanica,* 2: 1–152.

Ryder, J. M. and Thomson, B., 1986: Neoglaciation in the southern

Coast Mountains of British Columbia: chronology prior to the late Neoglacial maximum. *Canadian Journal of Earth Sciences,* 23: 273–287.

Sigafoos, R. S. and Hendricks, E. L., 1972: Recent activity of glaciers of Mount Rainier, Washington. *U.S. Geological Survey Professional Paper* 387-B: B1–B24.

Smirnova, T. Y. and Nikonov, A. A., 1990: A revised lichenometric method and its application dating great past earthquakes. *Arctic and Alpine Research,* 22: 375–388.

Smith, D. J. and Desloges, J. R., 2000: Little Ice Age history of Tzeetsaytsul Glacier, Tweedsmuir Provincial Park, British Columbia. *Géographie physique et Quaternaire,* 54: 135–141.

Smith, D. J. and Laroque, C. P., 1996: Dendroglaciological dating of a Little Ice Age glacial advance at Moving Glacier, Vancouver Island, British Columbia. *Géographie physique et Quaternaire,* 50: 47–55.

Smith, D. J., McCarthy, D. P., and Colenutt, M. E., 1995: Little Ice Age glacial activity in Peter Lougheed and Elk Lakes provincial parks, Canadian Rocky Mountains. *Canadian Journal of Earth Sciences,* 32: 579–589.

Solomina, O. and Calkin, P. E., 2003: Lichenometry as applied to moraines in Alaska, U.S.A., and Kamchatka, Russia. *Arctic, Antarctic, and Alpine Research,* 35: 129–143.

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

Thomson, J. W., 1967: Notes on *Rhizocarpon* in the Arctic. *Nova Hedwigia,* 14: 421–481.

Thomson, J. W., 1997: *American Arctic lichens. II. The Microlichens.* Madison: University of Wisconsin Press.

Wiles, G. C., 1992: Holocene glacial fluctuations in the southern Kenai Mountains, Alaska. Ph.D. dissertation, State University of New York at Buffalo. 333 pp.

Wiles, G. C., Barclay, D. J., and Calkin, P. E., 1999: Tree-ring-dated 'Little Ice Age' histories of maritime glaciers from western Prince William Sound, Alaska. *The Holocene,* 9: 163–173.

Wiles, G. C. and Calkin, P. E., 1991: Dendrogeomorphic refinement of a ^{14}C chronology from McCarty fjord, Alaska. *GSA Northeastern Section, 26th annual meeting, Southeastern Section, 40th annual meeting*. Geological Society of America, 150.

Wiles, G. C. and Calkin, P. E., 1993: Neoglacial fluctuations and sedimentation of and iceberg-calving glacier resolved with tree rings (Kenai Fjords National Park, Alaska). *Quaternary International,* 18: 35–42.

Wiles, G. C. and Calkin, P. E., 1994: Late Holocene, high-resolution glacial chronologies and climate, Kenai Mountains, Alaska. *Geological Society of America Bulletin,* 106: 281–303.

Wiles, G. C., Calkin, P. E. and Post, A., 1995: Glacier fluctuations in the Kenai Fjords, Alaska, U.S.A.: an evaluation of controls on iceberg-calving glaciers. *Arctic and Alpine Research,* 27: 234–245.

Wiles, G. C., Jacoby, G. C., Davi, N. K. and McAllister, R. P., 2002: Late Holocene glacier fluctuations in the Wrangell Mountains, Alaska. *Geological Society of America Bulletin,* 114: 896–908.

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