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Lichenometry as Applied to Moraines in Alaska, U.S.A., and Kamchatka, Russia

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Abstract

A selective review of lichenometry as used to date Holocene moraines in five diverse regions of Alaska and in southeastern Kamchatka suggests that growth curves for this North Pacific area may be improved by attention to several factors. These included lichen identification, control point number and distribution, radiocarbon calibration, alternative curve models, and compatibility of lichen growth rate with climate. Support for control points presented for Kamchatka and published for Alaska areas will benefit from supplementary control at and beyond the break from the great growth curve segments of the last centuries. With regard to alternative—linear, logarithmic, and composite curve—models drawn for the published lichenometric data, the composite (logarithmic and linear composite models) appear the best fit for the Brooks Range and Wrangell–St. Elias areas of slow growth and continental interior climates. Calibration of ^{14}C ages make minor changes in well-controlled curves, but differences may be marked where a single age supports the long-term portion of growth curves.

Lichen subgenus *Rhizocarpon* section *Geographicum* and section *Alpicola* should, and usually can be, differentiated in North Pacific areas. Nevertheless, growth curves that may represent both yellow-green *Rhizocarpons* (e.g., central Brooks Range and southeastern Kamchatka) appear to allow derivation of reasonable surface dating where the taxa distribution is similar to that of the curves. Chronologies of glaciation based on lichenometry of moraines over the last millennium in these two areas across the Bering Sea are strikingly similar to each other and to more precisely dated tree-ring-based glacial chronologies in southern Alaska.

Introduction

Lichenometry has been of substantial use in reconstruction of Holocene glacier chronologies across parts of the North Pacific margin (Fig. 1). In Alaska, such applications began in the late 1960s (Reger, 1968; Denton and Karlén, 1973; Calkin and Ellis, 1980). Comparable moraine studies are unknown at similar latitudes of Siberian Russia; however, much work has been initiated farther south in southeastern Kamchatka (Solomina et al., 1995; Savoskul and Zech, 1997). In order for lichenometry to maintain its potential and reliability across these and adjoining sparsely forested and glaciated regions, we here critically review, update, and question aspects of our own work and that of others in these areas. For example, we provide additional, previously unpublished data for Kamchatka curve control points and calibrate new lichen curves for both Kamchatka and Alaska. However, we also consider questions related to models of growth curve construction and the time frames of their reliable application, and we correlate lichen-dated late Holocene glacier chronologies across the North Pacific. Our analysis is considered in terms of 5 published growth curves for lichen subgenus *Rhizocarpon* that span mainland Alaska and a single growth curve for this taxa from southeastern Kamchatka. Other lichenometric data may be found in the original published papers on each area.

Physical Settings

The Alaskan published and accepted lichen studies considered in this paper occur in 5 distinct areas. From north to south these are the central Brooks Range (Calkin and Ellis, 1980, 1984), the Kigluaik Mountains in the Seward Peninsula (Calkin et al., 1998), the east-

central Alaska Range (Begét, 1994), the southeastern Wrangell and northeastern St. Elias Mountains (Denton and Karlén, 1973; Karlén, 1973), and the southern Kenai Mountains of Alaska's Kenai Peninsula (Wiles, 1992; Wiles and Calkin, 1994). These sites are located between 69° and 59° N. The Kamchatka lichen area (Solomina et al., 1995, 1999) lies in the southeastern part of the peninsula between about 56° and 53° N (Fig. 1).

ALASKA

The topography and climate of Alaska (Table 1) is as diverse as its mosaic of bedrock terranes patched together by plate tectonics over the last 200 million yr. Present glaciers cover some 74,700 km², or about 5% of the state. Most of the ice occurs as large icefields with temperate glacier tongues. These are centered between 4000 and 6000 m a.s.l. in mountain ranges extending in an arcuate belt of 2000 km peripheral to precipitation sources in the Gulf of Alaska (Fig. 1).

The maritime Gulf air-sea climate is dominated by the Alaska gyre driven in spring and winter by the Aleutian Low (Wilson and Overland, 1987). Moist air masses penetrate north and eastward over glaciers near sea level in the Gulf and over the southern flanks of the very high Alaska Range and the Wrangell–St. Elias Mountains. The interior, northern mountain flanks are markedly drier and continental. In addition, glaciers are more dispersed and smaller northward, farther from precipitation sources, and occur on 1000- to 3000-m mountain surfaces. In central and arctic Alaska, snowlines and glaciation thresholds rise eastward, reaching 2000 m along the border with Canada.

Vegetation in southern Alaska is dominated by dense and tall *Picea* and *Tsuga* coastal forests (Viereck and Little, 1972).

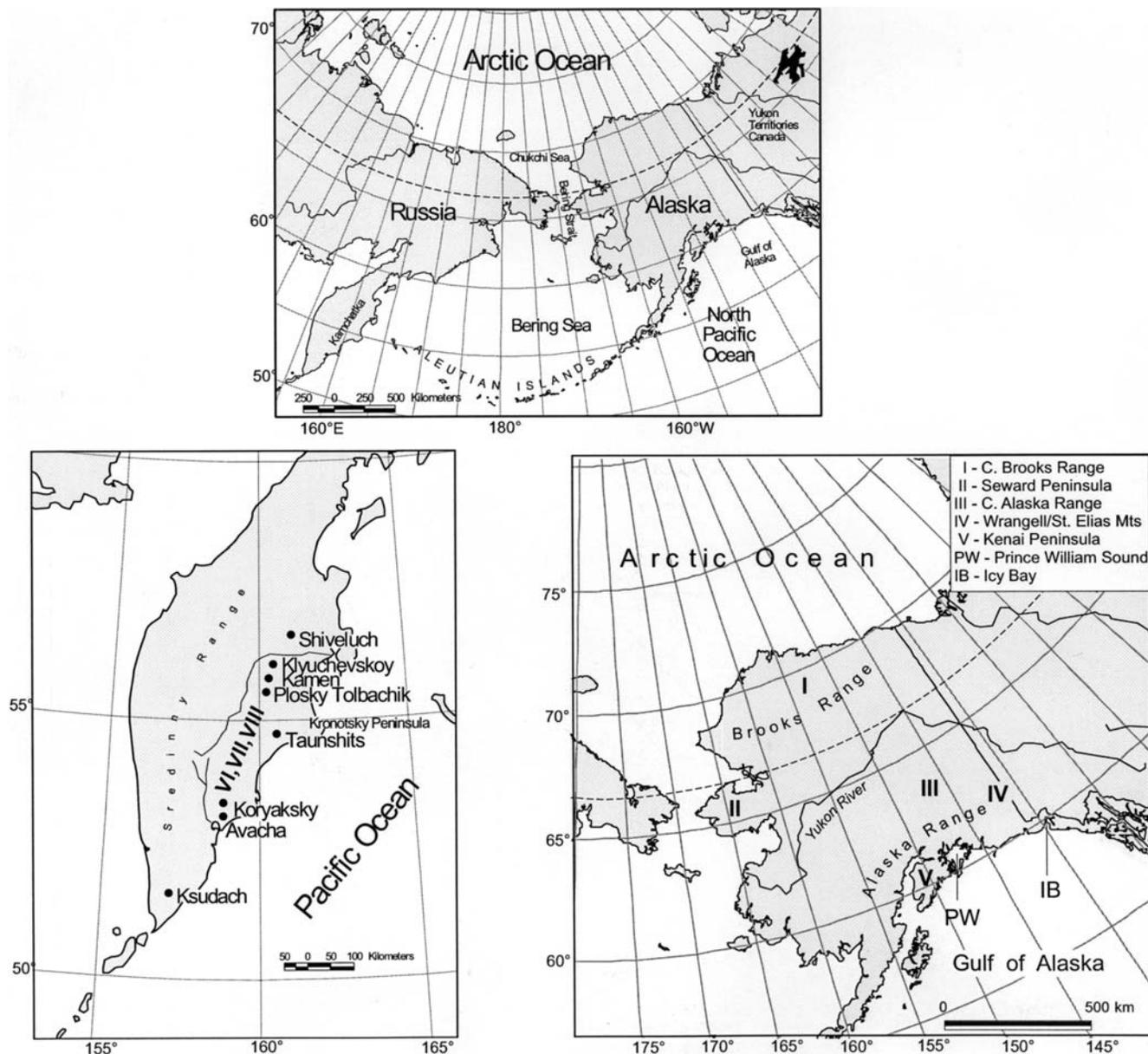


FIGURE 1. Location of glacial chronologies delineated in part or whole by lichenometry of moraines in Alaska (I–V) and Kamchatka (VI–VIII).

Slower-growing boreal, *Picea glauca*–*Betula papyrifera* forests (taiga) are scattered through interior Alaska to the south slopes of the Brooks Range. Treeless tundra occurs on the north slope of the Brooks Range and also along most of the western margin of Alaska, including the Aleutian Islands.

KAMCHATKA

This mountainous peninsula of the North Pacific (Fig. 1) is characterized by 29 active and at least 300 extinct volcanoes. The largest glaciated region in northeastern Asia, it includes 446 glaciers covering about 906 km². The main glacier centers occur in the highest Sredinnyy and Eastern ridges. The lichenometric studies were carried out in southeastern Kamchatka, to the north of the Avacha River and east of the Kamchatka River. The most prominent orographic features affecting Holocene glaciers are the Eastern Ridge and separate volcanic plateaus with the individual stratovolcano cones. The Kliuchevskaya Group, with the highest and most active volcanoes such as Kliuchevskoy and Plosky Tolbachik, encompasses a volcanic plateau

90 km long at 1000 to 1100 m altitude. The Avachinskaya group of volcanoes is closer to the ocean and consists of the active Avachinsky (2751 m) and Koryaksky (3456 m) as well as the extinct and partly eroded Kozel'sky, Aak, and Arik volcanoes (Vinogradov, 1968).

The climate of Kamchatka (Table 1) is characterized by strong cyclonic activity. The maritime eastern coast has mild and snowy winters, and summers are cool and rainy. Equilibrium-line altitudes (ELAs) vary from 700 to 1000 m a.s.l. for glaciers of the Kronotsky Peninsula to 2700 m a.s.l. for those of the Kliuchevskoy volcanic group (Fig. 1). *Betula* forests are typical for this region, whereas coniferous and mixed forests dominate in the central part of the peninsula. Here, climate is more continental with colder but less snowy winters and rather warm summers.

Field Methods

Lichenometry and dating of glacial moraines in Alaska and Kamchatka were undertaken with very similar procedures. For Alaska,

TABLE 1
 Meteorological data for Alaska and Kamchatka lichenometry sites^a

Regions	Met. station	Latitude N	Longitude W	Elevation m	Period of measurements	JJA T, °C	Mean annual T, °C	Mean JJA P, mm	Mean annual P, mm
C. Brooks Range	Wiseman	67° 25'	150° 06'	350	1936–1952 1996–2000	12.5	–5.5	493	267
Seward Peninsula	Nome	64° 31'	165° 27'	4	1948–2000	9.4	–3.2	561	342
Wrangell–St. Elias Mts.	Northway	62° 58'	141° 56'	522	1949–2000	13.3	–5.7	480	201
C. Alaska Range	Gulkana	62° 10'	145° 27'	479	1942–2000	12.6	–2.9	419	239
Kenai Peninsula	Seward	60° 60'	149° 20'	23	1922–2000	12.4	4.2	892	1435
Kenai Peninsula	Homer	59° 39'	151° 29'	27	1933–2000	11.1	3.0	432	518
SE Kamchatka, coast	Petropavlovsk	53° 05'	158° 34'	125	1915–1987	11.4	2.2	750	1050
SE Kamchatka, interior	Kliuchi	56° 19'	169° 50'	26	1915–1995 (T) 1927–1989 (P)	13.1	–1.3	520	558

^a Data from individual references given in Table 2a.

see Denton and Karlén (1973), Calkin and Ellis (1980), Wiles and Calkin (1994), and Calkin et al. (1998). Details for Kamchatka lichenometry methods are considered by Solomina et al. (1995) and Savoskul (1999).

Field workers measured the long axis of the largest *Rhizocarpon* subgenus, and we assume the lichens with distinct and circular or subcircular borders. Most searched the entire surface under investigation. Savoskul (1999) in Kamchatka subdivided the surfaces larger than ~1000 m² into zones and searched squares ~10 m on a side. The entire surface of smaller landforms was searched. For the moraines smaller than 400 m², lichens were reported from squares of 4 m on a side.

The size of the largest lichen measured was normally used as the age predictor for the site. Lichens were generally rejected as anomalous if their diameters exceeded the size of the next smaller one by more than 20% (Calkin and Ellis, 1980). In the Kigluaik Mountains of Alaska, Calkin et al. (1998) averaged the 5 largest lichens, but in all cases, the single largest lichen was very close to their average.

Perhaps the most important and unclear factor of lichenometric approaches among studies cited in this paper concerns identification of the section and species of the yellow-green subgenus *Rhizocarpon* measured. The specific lichen taxa that were described may reflect the occurrence of different lichens within the studied areas. Most workers seem to have used the aggregated “species” as noted by writing “*Rhizocarpon geographicum*, *R. g. sensu lato*” (s.l.), or giving other indications. Calkin and Ellis (1980), Begét (1994), and Calkin et al. (1998) stated this clearly; Calkin et al. (1998) attempted to use only *R. sect. Alpicola*. Denton and Karlén (1973) implied use of the species *R. geographicum* but admitted possible inclusion of *R. superficiale* thalli. Wiles and Calkin (1994) designated their curve in the Kenai Mountains to be for *R. sect. Alpicola*. In Kamchatka, Savoskul (1999) distinguished the species *R. geographicum L(DC)* and *R. sect. Alpicola*, presenting two separate and significantly different growth curves. Solomina et al. (1995) used the aggregate, *R. geographicum (s.l.)*, for moraines dated under 300 yr old.

Control Points

We summarize below both published and new lichenometric data of our own for settings and control points used by individual authors. The data of Solomina (1999) for Kamchatka is presented in more detail. Specific problems with these curves are addressed below under “Growth Curves.”

ALASKA

Brooks Range

Among the 5 published lichen curves considered for Alaska, the one developed in the central Brooks Range along the Dalton Highway and adjacent Trans-Alaska Pipeline may be the most critical for moraine dating. The 14 control points, which are listed in Table 2a and described with the original and updated curves of by Calkin and Ellis (1980, 1984, respectively), occur mostly along a 120-km transect between 450 and 1700 m altitude. This transect extends northward from below and south of treeline on the south flank of the range and across the Continental Divide at Atigun Pass. The glaciers and moraines of the Brooks Range occur to the north and above treeline, where wood or other materials for effective numerical dating of the late Holocene moraines are rare or absent. The original and updated curves incorporated linear extrapolations beyond local point control by analogy with measurements of *R. geographicum* obtained in other areas of the world, where climate was similar. In this form, they were applied to date glacier fluctuations both 250 km east into the eastern Brooks Range and 250 km west of the control-point transect of the central Brooks Range. Evison et al. (1996) argued that the climatic differences between the Dalton Highway sites and the moraine sites, which are more widespread along the divide, were negligible. Furthermore, the altitudinal distribution, and corresponding climatic environments, of the control sites is wider than those of the dated glacier moraines.

Seward Peninsula

Seven control points for a lichen curve were assembled to date moraines of 3 very small cirque glaciers in the Kigluaik Mountains of the Seward Peninsula, Alaska (Calkin et al., 1998: Fig. 1, Table 2a). These points, which yield calendar dates, occur at altitudes from near sea level at Nome to 600 m for the oldest point of about 210 yr. The original curve of Calkin et al. (1998) was extended beyond this control point only on the basis of bracketing curves for Swedish Lapland and the Wrangell–St. Elias Mountains area of Alaska (Karlén, 1973).

Central Alaska Range

The lichen curve of Begét (1994) for the central Alaska Range, and considered in this paper (Table 2a), supersedes one developed by Reger (1968; Reger and Péwé, 1969) applied to date moraines of 4 glaciers in this same east-central Alaska Range. Péwé and Reger

TABLE 2a
Control points for yellow *Rhizocarpon* growth curves in Alaska and Kamchatka

N	D, mm		Date of measurements	Age of surface		Location, site	Dating technique	Reference
	<i>R. geogr.</i> (L.) DC &	<i>R. sect.</i> <i>Alpicola</i>		AD/BP/years ago ^a	Used for growth curve			
	<i>R. geogr.</i> s. l.							
I. Central Brooks Range								
1	none		1979	AD 1962	17	Arrigetch Peaks glacier deposits	Photo	Calkin & Ellis, 1980
2	none		1981	AD 1958/1959	23	Chamberlin Glacier deposits	Photo	Calkin & Ellis, 1984
3	2		1979	AD 1950	31	100 km NW of Arrigetch Peaks	Photo	Calkin & Ellis, 1984
4	7		1978	39 yr ago	40	Linda Creek, gold mine tailings	Historical	Calkin & Ellis, 1980
5	10		1978	AD 1908–1909	70	Linda Creek, gold mine tailings	Historical	Calkin & Ellis, 1980
6	12		1978	AD 1901	77	Linda Creek, gold mine tailings	Historical	Calkin & Ellis, 1980
7	12		1978	AD 1880–1890	93	Aniganigurak Eskimo Village	Historical	Calkin & Ellis, 1980
8	10		1977	100–106 yr ago	104	Dietrich River, dry channel	Tree rings, spruce	Calkin & Ellis, 1980
9	9		1962	AD 1911	51	Arrigetch Peaks glacier deposits	Photo	Calkin & Ellis, 1980
10	12		1978	210 ± 90 yr BP (BGS-547)	208 ^b	Trans. pipeline, peat in alluvial fan	¹⁴ C	Calkin & Ellis, 1980
11	20		1977	320 ± 100 yr BP (BGS-522)	418 ^b	Buffalo glacier, woody peat bedrock	¹⁴ C	Calkin & Ellis, 1980
12	26		1978	310 yr ago	311	below Atigun Pass, alluvial fan	Tree rings, spruce	Calkin & Ellis, 1980
13	33		1978	800 ± 90 yr BP (BGS-548)	751 ^b	Trans. pipeline, peat in alluvial fan	¹⁴ C	Calkin & Ellis, 1980
14	50		1977	1300 ± 100 yr BP (BGS-640)	1264 ^b	Trans. pipeline, peat in alluvial fan	¹⁴ C	Calkin & Ellis, 1984
II. Seward Peninsula								
1	18		1985	AD 1924	61	Nome, gravestone	Historical	Calkin et al., 1998
2	17		1985	AD 1912	73	Nome, gravestone	Historical	Calkin et al., 1998
3	20		1985	AD 1912	73	Nome, gravestone	Historical	Calkin et al., 1998
4	21		1985	AD 1912	73	Nome, gravestone	Historical	Calkin et al., 1998
5	24		1985	AD 1907	78	Grand Cent. V. pipeline pad	Historical	Calkin et al., 1998
6	23		1987	AD 1906	81	Graphite Creek, tailings	Historical	Calkin et al., 1998
7	45		1987	AD 1770	217	Grand Cent. V. slushflow	Tree rings, alder	Calkin et al., 1998
III. Central Alaska Range								
1	14		>1980	AD 1939	41	Kantishna, mine tailings	Historical	Bijkerk, 1980
2	21		>1980	AD 1922	58	Denali area, mine tailings	Historical	Bijkerk, 1980
3	10		>1983	AD 1920	63	Gulkana Glacier, moraine	Historical	Péwé & Reger, 1983
4	14		>1983	AD 1890–1990	93	Gulkana Glacier, moraine	Historical	Péwé & Reger, 1983
5	48		>1983	c. 130 yr BP	130	Black Rapids Glacier, moraine	Tree rings	Péwé & Reger, 1983
6	50		>1983	c. 153 yr BP	153	Canwell Glacier, moraine	Tree rings	Péwé & Reger, 1983
7	50		>1983	≤200 ± 75 yr BP	233 ^b	Canwell Glacier, moraine	¹⁴ C	Péwé & Reger, 1983
8	170		>1983	≤3650 ± 125 yr BP	3708 ^b	Gulkana Glacier, moraine	Tephrochron.	Begét, 1994
IV. Wrangell–St. Elias Mts.								
1	none		1970	AD 1948	22	Sheep Glacier, deglaciated drift	Tree rings, willow	Denton & Karlén, 1973
2	6		1970	AD 1927	43	Sheep Glacier, channel of outwash fan	Tree rings, spruce	Denton & Karlén, 1973
3	4		1970	AD 1924	46	Russell Glacier, glacial drift	Tree rings, willow	Denton & Karlén, 1973
4	8		1970	AD 1914–1923	50	Russell Glacier, glacial drift	Tree rings, willow	Denton & Karlén, 1973
5	10		1970	AD 1920	50	Frederica Glacier, glacial drift	Tree rings, spruce	Denton & Karlén, 1973

TABLE 2a

(Cont.)

N	D, mm		Date of measurements	Age of surface		Location, site	Dating technique	Reference
	<i>R. geogr.</i> (L.) DC &	<i>R. sect.</i> <i>Alpicola</i>		AD/BP/years ago ^a	Used for growth curve			
	<i>R. geogr.</i> s. l.							
6	12		1970	>AD 1890	80	Russell Glacier, glacial drift	Historical	Denton & Karlén, 1973
7	17		1970	AD 1870	100	Sheep Glacier, channel of outwash fan	Tree rings, spruce	Denton & Karlén, 1973
8	19		1970	AD 1862	108	Giffin Glacier, channel of outwash fan	Tree rings, spruce	Denton & Karlén, 1973
9	15		1970	AD 1835	135	Sheep Glacier, channel of outwash fan	Tree rings, spruce	Denton & Karlén, 1973
10	28		1970	AD 1970	180	Guerin Glacier, outwash deposits	Tree rings, spruce	Denton & Karlén, 1973
11	45		1970	>AD 1650		Guerin Glacier, moraine, min. age	Tree rings, spruce	Denton & Karlén, 1973
12	67		1970	Between 1050 ± 100 yr BP (Y-2506) and 1230 ¹⁴ C yr BP	1100 ^c	Unnamed glacier, moraine	Tephrochron.	Denton & Karlén, 1973
13	130		1970	2780 ± 90 yr BP (I-6469-C) (more accurate), 3040 ± 90 yr BP (I-6490)	2894 ^b	Seven Sisters Glacier, moraine	¹⁴ C	Denton & Karlén, 1973
V. Kenai Peninsula								
1		15	1987	AD 1955		Seldovia gravestone	Historical	Calkin, unpublished
2		20	1987	AD 1949		Seldovia gravestone	Historical	Calkin, unpublished
3		10	1989	AD 1953	36	Seldovia gravestone	Historical	Wiles & Calkin, 1994
4		15	1989	AD 1936	53	Seldovia gravestone	Historical	Wiles & Calkin, 1994
5		18	1989	AD 1950	39	Homer gravestone	Historical	Wiles & Calkin, 1994
6		22	1988	AD 1926	62	Grewingk Glacier deposits	Tree rings	Wiles & Calkin, 1994
7		22	1988	AD 1924	64	Exit Glacier deposits	Tree rings	Wiles & Calkin, 1994
8		23	1989	AD 1920	69	Tustemena Glacier deposits	Tree rings	Wiles & Calkin, 1994
9		24	1988	AD 1919	69	Wosnesenski Glacier deposits	Tree rings	Wiles & Calkin, 1994
10		21	1989	AD 1875	114	Nuka Glacier deposits	Tree rings	Wiles & Calkin, 1994
11		31	1989	AD 1925	64	Portlock Glacier deposits	Tree rings	Wiles & Calkin, 1994
12		31	1988	AD 1914	74	Grewingk Glacier deposits	Tree rings	Wiles & Calkin, 1994
13		40	1988	AD 1914	74	Wosnesenski Glacier deposits	Tree rings	Wiles & Calkin, 1994
14		35	1989	AD 1895	94	Yalik Glacier deposits	Tree rings	Wiles & Calkin, 1994
15		45	1989	AD 1889	100	Nuka Glacier deposits	Tree rings	Wiles & Calkin, 1994
16		40	1988	AD 1882	106	Dinglestadt Glacier deposits	Tree rings	Wiles & Calkin, 1994
17		42	1989	AD 1869	120	Skilak Glacier deposits	Tree rings	Wiles & Calkin, 1994
18		42	1988	AD 1861	127	Grewingk Glacier deposits	Tree rings	Wiles & Calkin, 1994
19		37	1988	AD 1860	128	Wosnesenski Glacier deposits	Tree rings	Wiles & Calkin, 1994
20		47	1989	AD 1845	144	Nuka Glacier deposits	Tree rings	Wiles & Calkin, 1994
21		63	1989	AD 1853	136	Nuka Glacier deposits	Tree rings	Wiles & Calkin, 1994
22		73	1989	AD 1866	123	Tustemena Glacier deposits	Tree rings	Wiles & Calkin, 1994
23		100	1989	AD 1725	264	Tustemena Glacier deposits	Tree rings	Wiles & Calkin, 1994
VI. SE Kamchatka								
1	8		1992	AD 1941	51	Plosky Tolbachik Volcano, lava flow	Historical	Solomina et al., 1995
2	13		1992	AD 1946	46	Klyuchevskoi Volcano, lava flow	Historical	Solomina et al., 1995
3	12		1992	AD 1956	36	Klyuchevskoi Volcano, lava flow	Historical	Solomina et al., 1995

TABLE 2a
(Cont.)

N	D, mm		Date of measurements	Age of surface		Location, site	Dating technique	Reference
	<i>R. geogr.</i> (L.) DC & <i>R. geogr.</i> s. l.	<i>R. sect.</i> <i>Alpicola</i>		AD/BP/years ago ^a	Used for growth curve			
	4	10			1992			
5	none		1992	AD 1977	15	Koselsky Glacier, moraine	Instrumental	Solomina et al., 1995
6	36		1992	AD 1855–1907	137	Koselsky Glacier, moraine	Tephrochron.	Solomina et al., 1995
7	76		1992	320 ± 40 yr BP (GIN-6893)	362	Koselsky Glacier, moraine	Tephrochron.	Solomina et al., 1995
8	35		1992	shortly before AD 1854	138	Ermans Glacier, moraine	Tephrochron.	Solomina et al., 1995
9	9		1997	1950s–1960s	37	Koryto Glacier, moraine	Historical	Solomina et al., 1999
10	23	23	1997	AD 1900–1910	92	Koryto Glacier, moraine	Tephrochron.	Solomina et al., 1999
11	37	20	1997	shortly before AD 1854	143	Koryto Glacier, moraine	Tephrochron.	Solomina et al., 1999
12	22		1997	AD 1926	71	Elizovskaya River, lakhar	Historical	Solomina et al., 1999
13	43		1993	AD 1827? 220 ± 40 yr BP, 70 ± 40 yr BP, 130 ± 40 yr BP	166	Avacha Volcano, lava (agglomerate?) flow	Historical + ¹⁴ C	Solomina, 1997
14	140		1997	~2500 yr BP	2500	Taunshits Volcano, lava flow	Tephrochron.	Belousov & Belousova, pers. comm., 1998
15	110	227	1997	3500–3900 yr BP	3700	Koryaksky Volcano, lava flow	Tephrochron.	Solomina et al., 1999
16	240	118	1997	>3900 yr BP	3900	Koryaksky Volcano, lava flow	Tephrochron.	Solomina et al., 1999
VII., VIII. SE Kamchatka								
6	36	64	1995	1200–1400 yr BP	1300	Kameñ Volcano, Ambon rockfall	Tephrochron.	Savoskul & Zech, 1997
7	46	86	1995	1400/1500–1700/1800 yr BP	1600	Klyuchevskoi Volcano, lava flow	Tephrochron.	Savoskul & Zech, 1997
8	83		1995	3000/3500–6000 yr BP	4500	Avacha Valley, rock glacier	Tephrochron.	Savoskul & Zech, 1997
9	7		1995	AD 1964	31	Shiveluch Volcano, debris avalanche	Tephrochron.	Savoskul, 1998
10	11		1995	AD 1946	49	Klyuchevskoi Volcano, lava flow	Tephrochron.	Savoskul, 1998
11	68	165	1995	2800–6000 yr BP	2800	Sredniaya Avacha, rock glacier	Tephrochron.	Savoskul, 1998
12	115	225	1995	5400/5500?–6000 yr BP	5500	Vakhtan Malkinsky, moraine	Tephrochron.	Savoskul, 1998
13		260	1995	6000–? yr BP	6000	Sredniaya Avacha, moraine	Tephrochron.	Savoskul, 1998
14		140	1997	2500–3000 yr BP	2500	Taunshits Volcano, lava flow	Tephrochron.	Savoskul, 1998

^a “Years ago” = the number of years between the date of the surface and the year of the measurements of lichens.

^b For radiocarbon dates, see Table 2b and explanations in the text section “CALIBRATION OF RADIOCARBON AGES.”

^c This date is accepted as recommended in Denton & Karlén (1973).

^d I–VIII—Number of the curves, used further in the text, tables, and figures.

(1983), recognizing major flaws in the control points, subsequently abandoned this curve in favor of that of Denton and Karlén (1973), assembled 300 km to the southeast in the Wrangell–St. Elias Mountains area (below).

Begét’s (1994) curve utilizes 2 historical control points of Bijkerk (1980; Ten Brink, 1983, 1984) obtained from up to 250 km to the west in the Alaska Range. Five points come from Péwé and Reger (1983) and 1 point of Reger and Péwé (1991), developed at the Gulkana Glacier and 2 other nearby valley glaciers in the east-central area at near 1000 m altitude. Begét’s (1994) point 7 dated at ~800 yr BP appears to be anomalous and is not used here. In addition, Begét (1994) used a well-supported tephrochronological age of 3650 ± 125

yr BP for a 170-mm *Rhizocarpon geographicum* to complete the curve.

Bijerk (1980, 1984) adapted the curve of Denton and Karlén, considered below, along with 2 local control points to date moraines of surging glaciers in the Denali National Park area of the north-central Alaska Range. No further consideration is given to this work.

Wrangell–St. Elias Mountains

Denton and Karlén (1973, 1977) and Karlén (1973) discussed 13 control points (Fig. 1; Table 2a) for their lichen curve developed for the eastward (inland) draining White River valley and Skolai Pass area of

the Wrangell–St. Elias Mountains contact near the international border with Canada. The control points are dated by historical criteria, tree rings, tephrochronology, and radiocarbon; most are located on the moraines themselves between 1100 and 1600 m. Point 12 of Denton and Karlén (1973, 1977) relies in part on a near-maximum age of ~1230 yr BP determined for the age of the eastern lobe of the White River Ash. This age is confirmed by the ¹⁴C dating of other samples of wood and is now specified as ~1147 cal yr BP by Clague et al. (1995); the age is close to that used by Denton and Karlén for their curve (control point 12, Fig. 2a); therefore, no correction is applied.

Kenai Peninsula

A growth curve for *R.* section *Alpicola* is controlled by 18 tree-ring ages, distributed mostly on the alpine glacier moraines along 120 km of the northwest flank of the southern Kenai Mountains, Kenai Peninsula (Fig. 1, Table 2a). An additional 3 historical dates come from the southern part of the peninsula (Wiles, 1992; Wiles and Calkin, 1994). This curve has been applied sparingly over the same area where some glaciers and moraines are above treeline or devoid of datable vegetation.

Lichen growth is more rapid in this southern Alaska maritime area than at the other lichen sites in Alaska. However, the vigorous growth of other vegetation is inhibiting, so substrates and lichen are less useful with time. Therefore, the resulting curve constructed here is useful for only a few hundred years.

Northern Kenai Peninsula

An 80-to-100-yr linear curve for “*Rhizocarpon* sp.” (composite species) has been developed by Crossen (1997) for dating deposits of the Blackstone-Spencer Ice Complex tongues in the moist, northern part of the Kenai Mountains and Peninsula. Based on 4 historical control points and 1 dendrochronological age, it displays a growth rate compatible with that of the Wiles and Calkin (1994) curve but slightly higher. Details are not considered further in this paper.

KAMCHATKA

Two major growth curves for subgenus *Rhizocarpon* section *Rhizocarpon* have been proposed for the same general area of southeastern Kamchatka. The first was developed by Solomina et al. (1995); its original control and subsequent modification by new control points (Solomina et al., 1999) is the major topic of the notes in this section. A second curve was proposed by Savoskul and Zech (1997) with minor modification by Savoskul (1999), who also developed a curve for subgenus *R.* section *Alpicola*. These are considered under the last subheading of this section.

The first curve (Solomina et al., 1995) was based on a linear approximation from 7 control points on substrates younger than 320 ± 40 yr BP. Control points for a subsequent composite (*R. geographicum* s.l.) lichen growth curve were obtained in 1992, 1993, and 1997 in different parts of southeastern Kamchatka (Solomina, 1999) (Fig. 1; Table 2a, VI). These include the Avacha area, near the Kliuchevskoy and Tolbachik volcanoes, and Kronotsky Peninsula. Although we have defined some annual climatic differences between coastal and interior Kamchatka sites, the mean monthly summer temperature, which is critical for lichen growth, is very similar in both areas (e.g., 11° C in coastal Kamchatka and 13° C in the interior [Table 1]). The growth rates of lichens across this 400-km-long area of southeastern Kamchatka are found to be compatible. This conclusion is supported by the lichen data, including, for example, the similarity of the lichen diameters recorded on moraines deposited shortly before AD 1854–1855 at Kozel’sky, Koryto, and Ermann glaciers in coastal and more

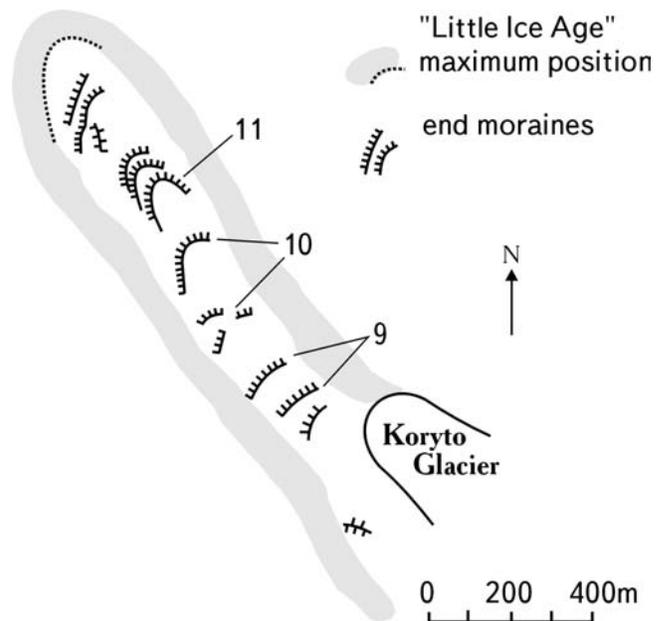


FIGURE 2. Koryto Glacier, Kronotsky Peninsula. Location of moraines dated by lichenometry. Numbers refer to data of Table 2a, Kamchatka.

interior areas of southeastern Kamchatka, respectively (Solomina, 1999).

The control points for Kamchatka (Table 2a, VI 1–16) include points on lava flows, moraine, and lahar deposits, ranging from 300 to 1000 m in elevation and dated by historical, tree-ring, and tephrochronological methods. The young lava flows (1–4) as well as the AD 1970s moraine of Kozel’sky Glacier (5) are reliably dated by observations. Two points on older moraines of Kozel’sky Glacier, AD 1855–1907 (6) and 320 ± 40 yr BP (7), were obtained by Avacha tephra markers. However, an older moraine (7) appears to have been washed, and few lichens occur on it; those that do range from 76 to 69 mm for the 5 maximum thalli. We use this site with caution as a control point for our curve. The moraine of Emann Glacier (8), with lichens as large as 35 mm, is directly covered by the Shiveluch’ tephra layer deposited in AD 1854. All these sites (1–8) are described by Solomina et al. (1995).

Control points 9–16 are discussed under specific geographic headings in the following sections because they deserve more comment, especially the moraines of Koryto Glacier. These have been described only briefly before (Solomina et al., 1999) and are of great importance. They represent the whole sequence of plant succession from the very young surfaces left by the retreating glacier in recent years to the Little Ice Age maximum moraines several hundred years old.

Moraines of Koryto Glacier, Kronotsky Peninsula

Tree-ring analyses and tephrochronology was used to constrain the age of moraines of Koryto Glacier (Fig. 2; Table 2a, VI 9–11). Solomina et al. (1999) dated 6 samples of alder (*Alnus hirsuta* Turcz.) growing on the moraines in 1998. Because no alders older than 90 yr were found, this technique could be used to date only moraines up to a century old. Initial forest colonization of the moraines in this region started 10 to 15 yr after glacier retreat. For example, following advances of the late 1950s, some small bushes were already growing on the newly exposed moraines.

Moraines of point 9 at Koryto Glacier were deposited in the late 1950s, according to Vinogradov (1968). The earliest alder to colonize were 9 and 13 yr old, and *Rhizocarpon* reached up to 9 mm in 1968.

The end moraine of point 10 (Fig. 2), which consists of 3 ridges with lichens as large as 19, 20, and 23 mm, was deposited by 1910 to 1920, according to the ring count on the 2 thickest alders growing on its surface. Although thickness may not correlate with age, tephrochronology supports a maximum 150 yr for the moraine: no tephra overlies the moraines of points 9 and 10; therefore, they are considered to have been deposited after AD 1854 (Sawaguchi et al., 1999).

An older moraine of point 11 with noticeably larger lichen (37 mm) must have been deposited shortly before AD 1854, as it is overlain directly by the ash deposited on this date by Shiveluch Volcano. On the next older moraine ridge, with lichens as large as 60 mm, a 4-cm-thick soil underlies the same AD 1854 ash of Shiveluch Volcano, indicating that the 60-mm lichen surface is several decades or more older than that of point 11 (Sawaguchi et al., 1999).

The Lahar of Elyzovskaya Dry River, Avacha Area

A huge lahar (Table 2a, VI 12), which followed the eruption of Avacha Volcano in AD 1926 in the Elizovskaya Dry River valley (Melekestsev et al., 1995), left a bouldery surface at 450 m that is several hundred meters long and partly covered by birch forest. Maximum diameters of *R. geographicum* on exposed boulders of this point 12 are 22 mm.

The Lava Flow of Avacha Volcano

One of the largest eruptions of the Avacha Volcano in the last 250 yr occurred in AD 1827. A photograph of a lava flow (Table 2a, point 13) with very distinctive lava fingers, slag cones, and hills, as well as fumaroles believed to be a product of this event, was taken shortly after eruption (Zavaritsky, 1977, p. 21). Radiocarbon ages of 220 ± 40 , 70 ± 40 , and 130 ± 40 yr BP obtained from charcoal in this flow (Melekestsev et al., 1995) are compatible with the 1827 year of formation. Lichens reach a maximum of 43 mm on this flow.

The Lava Flow of Taunshits Volcano

A. and M. Belousov (pers. comm., 1998) reported the maximum sizes of *Rhizocarpon* lichens of unidentified species on a lava flow of Taunshits Volcano to be 140 mm (Table 2a, VI 14). According to tephrochronological dating, the flow is believed to be about 2500 yr old (Melekestsev et al., 1990). Savoskul (1999) used this control point for the *R.* section *Alpicola* growth curve; Solomina et al. (1999) used it for a growth curve of *R. geographicum* s.l. We use this control point cautiously because it is the only one available to constrain the older portion of the lichen curve. The use of this point in the growth curve is, in part, justified because it is consistent with lichen growth in the similar climate of central Alaska (Watson, 1974).

Tephra Cone and Lava Flow of Koryaksky Volcano, Avacha Area

A tephra cone and lava flow at about 1000 m altitude on the southern slope of Koryaksky Volcano are dated by tephrochronology to about 3500 to 3900 BP and greater than 3900 BP, respectively. *Rhizocarpon* lichens (mainly section *Alpicola*) on their surfaces reach 230 mm and 240 mm, respectively. Because of the similarity in these lichen sizes and broad tephrochronological age range of the older deposits, we believe that they may be beyond the growth limit of lichens in this area. Points 15 and 16, presented in Table 2a, could be incorporated in the composite lichen curve if additional support is found to justify inclusion in the future.

Summary of Kamchatka Control Points

Several control points outlined here have some weakness concerning age, but taken together, they are internally consistent. They are also

sufficient in number to produce a preliminary growth curve in southeastern Kamchatka.

Control Points of Savoskul and Zech (1997) and Savoskul (1999)

The lichen curve for species *Rhizocarpon geographicum* by Savoskul and Zech (1997) used 5 of the 20th-century control points employed by Solomina et al. (1995) (Table 2a, VI 1, 4, 5). However, 2 older points of approximately 150 and 300 yr were rejected, and 3 new points dated by tephrochronology at between 1200 and 6000 yr old were introduced. Based on this curve, the growth rate of southeastern Kamchatka's *R. geographicum* lichens appears to be an order of magnitude slower than that shown by the curve developed by Solomina et al. (1995) and Solomina et al. (1999). We believe there is a problem with the newer curve (Savoskul and Zech, 1997). For example, we show here that the sequence of moraines at Koryto Glacier (Fig. 2; Table 2a) dated historically, by tree rings and by tephrochronology, demonstrates the regular increase of lichen size from 9 to 37 mm for the substrates designated as originating shortly before AD 1845 to AD 1950–1960. This increase yields a growth rate of ~ 24 mm per century for the Solomina et al. (1999) curve. Savoskul and Zech (1997; Savoskul, 1999) show a dramatic decrease from 0.25 mm yr^{-1} to 0.03 mm yr^{-1} after the first 50 yr of growth; this rate appears unreasonably slow to us. In addition to problems with the *R. geographicum* curve, we note that no control points younger than 1200 to 1400 yr are reported by Savoskul (1999) for the *R.* section *Alpicola* curve (see also the "Lichen Growth Rates and Climate" section below).

Growth Curves

CALIBRATION OF RADIOCARBON AGES

The choice between programs of calibration for the ^{14}C ages may result in significant differences among the choice of dates one may use in curve construction (Table 2b). Such choices may be particularly critical for the old part of the growth curves that are frequently constrained by one or a few scattered ages that produce a systematic bias to derived lichenometric ages.

For demonstration of calibration effects, we display in Figure 3 (see also Table 2b) ^{14}C data points used for the Brooks Range growth curve of Calkin and Ellis (1980, 1984) together with corresponding values calibrated with Calib rev. 4.2 program, methods A and B (Stuiver and Reimer, 1993). With the method A, radiocarbon ages are calibrated by a simple intercept with a linear interpolation of the data points of the selected calibration dataset; method B takes into account the probability distribution of the data. The 2-sigma interval is generally too large for lichenometric purposes, as some ^{14}C control point ages yield options up to a 600-yr range. In this paper, we used Calib method B, with 1-sigma confidence. In so doing, we took the midpoint of the age range associated with the calibration solution as having the highest probability. With the exception of 2 BP ages in the 200-yr range, all chosen age ranges had probabilities greater than 3 times that of the nearest alternative.

For the case of the Brooks Range, there is no major systematic change of the growth curve when we use uncalibrated versus calibrated ^{14}C control dates; calibration results in a 100-yr offset for surfaces about 1500 yr old. Three control points become younger, 1 older after calibration.

The linear phase of the Brooks Range growth curve is relatively well constrained by 4 ^{14}C dates, and there are several control points dated historically and dendrochronologically. Therefore, there is little difference in the equations for lines derived from calibrated versus

TABLE 2b

Calibrated radiocarbon ages used for growth curve constructions for Alaska and Kamchatka

Uncalibrated ¹⁴ C dates	Calibrated ¹⁴ C dates			
	Calib A		Calib B	
	(2 sigma)	(1 sigma)	(2 sigma)	(1 sigma)
I. Central Brooks Range				
210 ± 90 yr BP (BGS-547)	AD 1475 (1665, 1784, 1789) 1954	AD 1637 (1665, 1784, 1789) 1949	AD 1614–1952	AD 1723–1814
320 ± 100 yr BP (BGS-522)	AD 1415 (1526, 1557, 1631) 1949	AD 1448 (1526, 1557, 1631) 1662	AD 1414–1695	AD 1461–1657
800 ± 100 yr BP (BGS-548)	AD 1021 (1256) 1393	AD 1160 (1256) 1290	AD 1023–1320	AD 1157–1295
1300 ± 100 yr BP (BGS-640)	AD 561 (689) 977	AD 651 (689) 859	AD 596–904	AD 649–783
III. Central Alaska Range				
200 ± 75 yr BP (W-268)	AD 1495 (1668, 1782, 1795) 1953	AD 1644 (1668, 1782, 1795) 1948	AD 1624–1952	AD 1725–1813
3650 ± 125 yr BP	BC 2456 (2027, 1992, 1982) 1688	BC 2199 (2027, 1992, 1982) 1830	BC 2353–1727	BC 2201–1878
IV. Wrangell–St. Elias Mts.				
1050 ± 100 yr BP (Y-2506)	AD 734 (997) 1213	AD 892 (997) 1148	AD 774–1213	AD 885–1060
2780 ± 90 yr BP (I-6469-C)	BC 1210 (917) 797	BC 1014 (917) 828	BC 1132–797	BC 1020–827
VI. Kamchatka				
320 ± 40 yr BP (GIN-6893)	AD 1464 (1526, 1557, 1631) 1656	AD 1489 (1526, 1557, 1631) 1642	AD 1478–1650	AD 1516–1599

uncalibrated control-point dates (see captions for Fig. 4, Table 4). The 3 oldest and most reliable ¹⁴C control points for both the calibrated and uncalibrated curves for the central Brooks Range fall within the 20% error interval for the new, calibrated curve. Similarly, the logarithmic curve of Matthews (1974) also fits this error interval, although it shows the most prominent deviation from the control points.

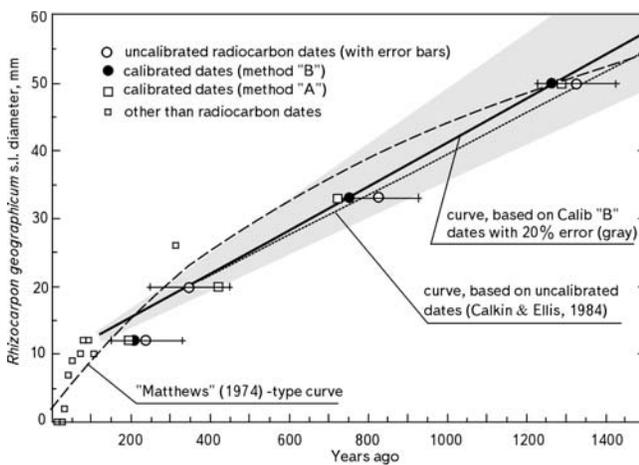


FIGURE 3. Comparison of uncalibrated radiocarbon dates (white circles and error bars), originally used for the growth curve construction by Calkin and Ellis (1980, 1984) and the same dates, calibrated. Calib method A, white quadrats, and Calib method B, black circles, represent mean values of dates with 1-sigma confidence. A qualitative 20% error area (gray) is shown for the new, calibrated (method B) curve (solid line) presented in this paper. The linear part of the growth curve is based on 4 radiocarbon ages and the 2 oldest nonradiocarbon control points (6 and 7, Table 2a) (see text). The dotted line is based on the same control points, but the ¹⁴C dates are uncalibrated. The logarithmic curve is constructed using the method of Matthews (1974) and is based on all control points listed in Table 2a for the Brooks Range. Equations for all curves are given in Table 3. The linear curves fit best to the long-term growth phase. The three oldest, most reliable ¹⁴C-constrained control points, both calibrated and uncalibrated, fall within the 20% error interval.

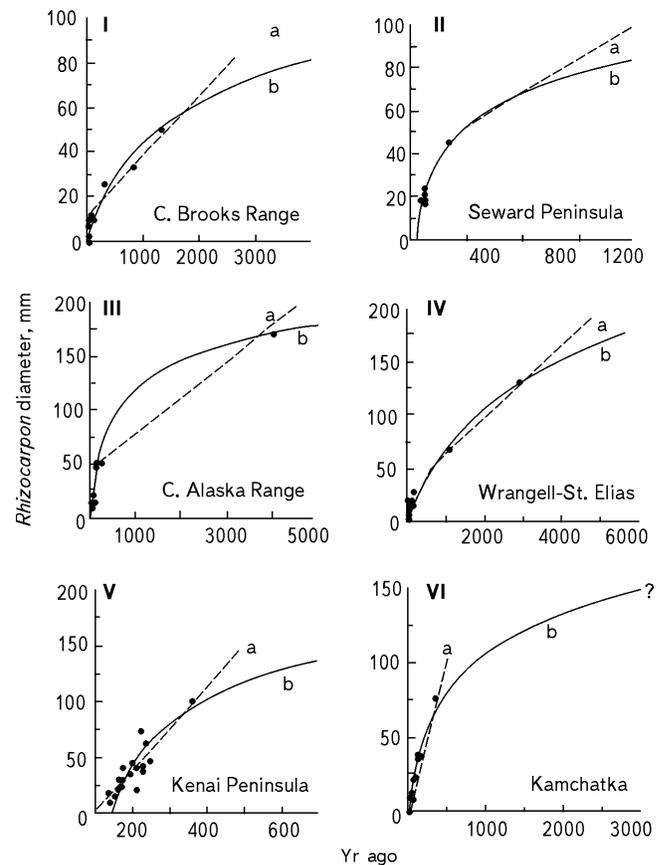


FIGURE 4. Different approaches to the construction of the *Rhizocarpon* growth curves. Radiocarbon dates are calibrated with Calib method B. Curves "a" are linear or composite curves. Composite curves consist of a logarithmic part for the great growth period and linear part describing the long-term growth. We followed the original published curves to estimate the length of the great growth period and the break from logarithmic to linear growth; however, the real duration of the great period in each case is still unknown. Curves "b" are full logarithmic curves. All equations are given in Table 3.

TABLE 3
Equations for new growth curves

Regions	Linear or composite curves (a) ^a	Various modifications of log-curves diameter vs. age (exponential equations for age derived from diameter) (b) ^a
Central Brooks Range	36.275*10 ⁰ (0.035476*D) (great period); –306.13 + 33.084*D (linear phase; based on uncalibrated ¹⁴ C dates, Table 2a) –262.36 + 30.747*D (linear phase, based on calibrated dates, Table 2a, b)	10 ⁰ (2.56005912 + 0.0131571*D) – 378.536074
Seward Peninsula	–385.85 + 16.834 (linear phase, in parallel to Swedish Lapland—Denton, Karlén, 1974)	(30.271*10 ⁰ (0.018632*D)
Central Alaska Range	–1430 + 32.074*D	(41.861*10 ⁰ (0.011679*D)
Wrangell–NE St. Elias Mts.	38.813*10 ⁰ (0.022408*D) (great period); –1018.4 + 30.095*D (linear phase)	10 ⁰ (2.95901034 + 0.00476362*D) – 952.0126
Kenai Peninsula	20.245 + 2.1035*D (linear approximation)	43.950*10 ⁰ (0.0081712*D)
Kamchatka	–14.46 + 4.6272	37.103*10 ⁰ (0.013566*D)

^a See Figure 4.

GROWTH CURVE CONSTRUCTION

The shape of the lichen curve depends significantly on the choice of a model for lichen growth as well as on the control points and their distribution (Tables 2a and 3; Fig. 4). Phases of prelinear growth, where thallus radius increases logarithmically, as well as linear and postlinear lichen growth have been described by Armstrong (1974). However, in the practice of lichenometry, only 2 segments, a “great period” of fast growth and a phase of slower growth, are considered to shape the curve (Beschel, 1961). Some authors (e.g., Webber and Andrews, 1973; Denton and Karlén, 1973; Calkin and Ellis, 1980) accept the post–great growth period as a “linear phase”; others assume that the growth of lichen follows a logarithmic pattern during their whole life (Matthews, 1974). The direct measurements of various sizes of *Rhizocarpon* lichens over 4 to 6 yr in the central Brooks Range (Haworth and Calkin, 1986) suggest a similar nonlinear relationship of lichen diameters and age of the surface.

The Brooks Range curve of Calkin and Ellis (1980) and that for the Wrangell–St. Elias Mountains of Denton and Karlén (1973) (Fig. 4, I and IV, curves a) were originally drawn by hand and include a semilogarithmic great growth segment and a linear growth, old segment. The control points can also be described by Matthews’s (1974) logarithmic model of growth. The choice between these two models is not always clear, but we showed previously, through Figure 3, that the composite curve used in the Brooks Range (Calkin and Ellis, 1980) fitted much better than the logarithmic to the control points. For the Wrangell–St. Elias area the composite curve may be only slightly better than the logarithmic. In the 2 cases of slow-growing lichens, we recommend keeping the previous model of composite growth curve until further control is available.

The Seward Peninsula curve of Calkin et al. (1998) (Fig. 4, IVa), relies partly on a linear regression for the function: lichen diameter vs. log₁₀ time. However, the long-term portion of this composite growth curve was originally drawn parallel to the Denton and Karlén (1973) curve from Swedish Lapland (Calkin et al., 1998). Thus, it contains the linear growth phase. In Figure 4 (IIb) we also show that the logarithmic curve fits these control points, like those for relatively fast-growing lichens (Figs. 4, 5, Regions III, V, VI); however, there are no Seward Peninsula control points beyond 215 yr to support or reject this model.

The linear curve from the Kenai Mountains (Fig. 4, IIIa) is reported to be preliminary (Wiles and Calkin, 1994); nevertheless, it is well enough constrained to date deposits within the framework of available control points without further extrapolation. The log curve instead of the linear one yields slower rates in the older portion, but faster between about 50 and 250 yr. Because the Kenai Peninsula

control points are obtained by ring counts of trees colonizing the moraines, it provides minimum age estimates. Therefore, the logarithmic curve based on the maximum dates may yield more realistic ages than the linear curve describing mean age values (Fig. 4, IIIb).

The central Alaska Range curve of Begét (1994) is not constrained between about 200 and 4000 yr ago. It can approach a polynomial or logarithmic curve (Fig. 4, II) or consist of logarithmic and linear parts (curve b), although the time of transition from the fast to slow growth is unknown. Until additional control points are found, we suggest maintaining the original shape of the curve (Fig. 4, IIa).

A linear approximation was used initially to describe the growth rate of lichens in Kamchatka over the last 300 to 350 yr (Fig. 4, VIa) (Solomina et al., 1995). Subsequently, Solomina et al. (1999) attempted to use Matthews’s (1974) modification of the log curve to extrapolate this growth curve back in time (Fig. 4, VIb). This latter curve is problematic because of the unique control point supporting its old part.

For lichenometric dating, we propose the use of the composite growth curves given by the authors in the Brooks Range and Wrangell–St. Elias Mountains. The linear part of these curves is relatively well constrained. Logarithmic curves may be most appropriate for Kenai, central Alaska Range, and Kamchatka. Original extrapolations beyond the last control point make the appropriate curves less reliable, and we have not used them in our analysis.

LICHEN GROWTH RATES AND CLIMATE

The curves for *Rhizocarpon* lichens along the North Pacific margin show that rates of growth are consistent with regional climate (Fig. 5; Table 4). In Alaska, the fastest-growing lichens, and probably the most subject to substrate weathering, are those along the Gulf of Alaska, including the Kenai Peninsula region, where warm marine currents and very high precipitation prevail.

The area of slowest growth and longest-lived lichens is that in the high-latitude Brooks Range (Fig. 1), far from the major precipitation sources of the Bering Sea. Brooks Range *Rhizocarpon* taxa reach at least 450 mm in maximum diameters over time periods probably extending back into the middle to early Holocene (Calkin and Ellis, 1980; Haworth, 1988).

Growth rates are only slightly faster under the continental climate of the inland-facing eastern flanks of the Wrangell–St. Elias Mountains (Denton and Karlén, 1973) (Fig. 5), where the summers are short, warm, and dry. More moisture is available and growth rates faster than those of Wrangell–St. Elias sites in the maritime-

TABLE 4

Lichen growth data estimated for new, calibrated curves

N	Regions	Interval of colonization, years	D, mm, estimated by growth curves (this paper) ^a			
			100 years	200 years	300 years	1000 years
I	Central Brooks Range	30	12–13	15–16	18–19	44–45
II	Seward Peninsula	17	27–28	44	?	?
III	Central Alaska Range	?	32–33	58–59	73	117–118?
IV	Wrangell–St. Elias Mts.	between 22 and 43	18–19	31–32	39–40	67–68
V	Kenai Peninsula	less than 36	43–44	80–81	?	?
VI	Kamchatka	25	32–33	53–54	67–68	106–107?
VII	Kamchatka (<i>R. geographicum</i>)	no data	12	14	16	30
VIII	Kamchatka (<i>R. sect. Alpicola</i>)	no data	no data	no data	no data	30

^a See Table 3 and the text section “GROWTH CURVE CONSTRUCTION.”

continental regime encompassing the high-subarctic Kigluak Mountains site of the Seward Peninsula. With low summer temperatures and moderate rainfall, *Rhizocarpon* reach 250 to 300 mm here. The Gulkana Glacier area of the east-central Alaska Range is also within or at the margin of the maritime-continental transitional climate zone, but it is also in the path of decaying maritime air masses that penetrate northward from the Gulf of Alaska (Watson, 1974; Calkin, 1988). Thus, in this setting lichens may be expected to grow faster than in the Seward Peninsula.

The Kamchatka lichen curve (Fig. 5, VI) is developed over a wide area encompassing both coastal maritime and inland transitional climatic regimes. In general, the climate is much milder than in the Brooks Range or Wrangell–St. Elias Mountains but colder than in the Kenai Mountains (Table 1). Kamchatka is periodically influenced by cold air masses from the Okhotsk Sea, whereas the climate of southern Alaska is, on the contrary, affected by the warm, counterclockwise Gulf of Alaska current. So we can expect the Kamchatka growth curve to be between curves of Figure 5, IV (Wrangell–St. Elias) and V (Kenai), which is the case.

The only curves that do not fit the general climatic pattern of slower and longer growth toward the north and more interior regions are VII and VIII of Figure 5 from Kamchatka (Savoskul, 1999). Several aspects of the two Kamchatka lichen curves of Savoskul (Fig. 5; Table 2a) suggest that both may be unrepresentative for *R. geographicum* and *R. section Alpicola* growth rates and should not be used for dating. Both curves lack sufficient control points for the initial rapid growth phase; the *R. section Alpicola* curve, which lacks any control for this initial phase (Savoskul, 1999, Fig. 2), appears to begin at about 800 yr ago (Fig. 5). Control points reach back in time about 6000 yr. Lichens are unlikely to live as long as 6000 yr in such areas with a climate of moderate to high moisture. The very slow lichen growths indicated by Savoskul and Zech (1997) and Savoskul (1999) relative to lichen curves for Alaska are not justified by the climatic pattern of the North Pacific or by any other special circumstances.

Discussion

TWO TYPES OF GROWTH CURVES

Two curve models seem to be appropriate to describe the growth of lichens in the North Pacific. In the maritime areas, where growth is relatively rapid, the logarithmic or even linear curves fit the control points best, and the long-term linear growth phase is absent (Fig. 4). These curves were used in Norway (Matthews, 1974), New Zealand (Birkeland, 1981), and Iceland (Gordon and Sharp, 1983). For regions of continental climate such as the Brooks Range or Wrangell–St. Elias Mountains, where the lichens are slower growing, the composite

curve, including the linear part of constant growth, appears appropriate. This type of curve was applied first in the Colorado Front Range by Benedict (1967) and discussed by Webber and Andrews (1973) in their early, short review on lichenometry.

TIME FRAMES FOR USE OF LICHENOMETRY IN THE NORTH PACIFIC

The faster lichens grow, the shorter the time interval for possible dating. Potential lengths of dating range from 3 to 4 centuries or even less for the Kenai Mountains to almost the entire Holocene for the Brooks Range. In addition, the length of potential lichenometric dating is limited by an absence or insufficient number of numerical ages for old surfaces. In Kamchatka, as well as the Kenai and Seward Peninsulas, and even in the central Alaska Range, where the growth curve is constrained by a single tephrochronological age of 3650 ± 125 yr BP, the most reliable lichenometric ages available go back only about 300 yr. This limitation results in uncertainties in lichenometric dating during this interval. Extension of the curves beyond the oldest reliable control point is problematic. However, it is least insecure in the regions with slower growth rates, where two phases of growth are suggested and constrained by a number of reliable control points, as in the Brooks Range and the Wrangell–St. Elias Mountains areas. The choice of a single logarithmic curve model that also fits the control points (Fig. 4) changes the results of dating of old moraines significantly.

TWO COMMON LICHEN TAXA

The problem of field identification, and particularly the differential growth rates of the two taxa most often used in lichenometry, *R. geographicum* s.l. and *R. section Alpicola*, have been discussed by several authors (e.g., Denton and Karlén, 1973; Lock[e] et al., 1979; Innes, 1982, 1983). *R. geographicum* s.l. will generally colonize a surface first and dominates on young surfaces; later-colonizing *R. section Alpicola* lichens, which grow slightly faster, begin to dominate and frequently are the taxa to reach the maximum diameters on the oldest surfaces (Innes, 1982, 1983). Growth ratio of sizes of the largest diameters of the two taxa, *R. geographicum* and *R. section Alpicola*, was reported as 1:1.5 and 1:1.6, respectively, by Beschel (1956) and Løken and Andrews (1966). In Kamchatka it is about 3:2 for the great growth interval (up to a diameters of ~60 mm) and 1:2 for the older surfaces. Innes (1983) suggests that dating errors may occur where maximum lichen over ~70–100 mm of the aggregated *Rhizocarpon* (*R. geographicum* s.l., this paper) curve is used.

Here, where we focus on the consistency of the *R. geographicum* s. l. growth rate with climate, we can use the very young portions of

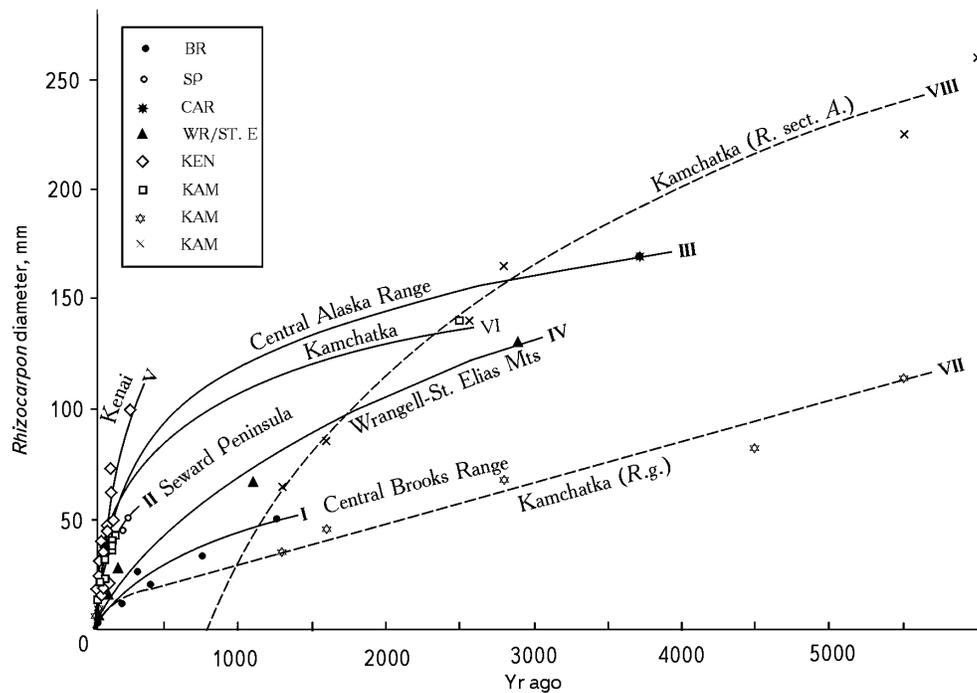


FIGURE 5. Control points and logarithmic curves (Matthews, 1974) (except VII) used for uniformity to compare growth rates of lichens in each area of Alaska and Kamchatka. The numbers of the curves identified below correspond with those lichenometric regions given in Figure 1, Table 2a, and through the text; lichen taxa used in curves and/or dated surfaces are as designated by authors. I. central Brooks Range—*R. geographicum* included species *R. geographicum* (L)DC and *R. section* *Alpicola*, *R. eupetraeoides*, *R. inarense*, possible *R. superficiale* [Calkin and Ellis, 1980]. II. Seward Peninsula—*R. geographicum* (s.l.) may have included some species of I above, but mostly *R. section* *Alpicola* (Calkin et al., 1998). III. Central Alaska Range—*R. geographicum* (undifferentiated species) (Begét, 1994). IV. Wrangell—St. Elias Mountains—*R. geographicum* species and possible *R. superficiale* (Denton and Karlén, 1973). V. Kenai Peninsula—*R. section* *Alpicola* (Wiles and Calkin, 1994). VI. Southeastern Kamchatka—*R. geographicum* s.l. (this paper). VII. Kamchatka—*R. geographicum* (L)DC. (Savoskul, 1999); curve approximated by a linear curve. VIII. Kamchatka—*R. section* *Alpicola* (Savoskul, 1999).

the curves only (e.g., 500 yr old), which are most likely to be homogeneous in terms of species. The old portions of our growth curves (Fig. 5) would be more secure with additional control. Nevertheless, we believe that in principle, the current control points, if obtained on surfaces with a sufficient number of lichens of both *R. geographicum* and *R. section* *Alpicola* taxa, can be used to date moraines with a similar set of lichens. That is, one can use an enveloping curve where the young part describes the growth rate of *R. geographicum* and the older part the growth rate of *R. section* *Alpicola*. However, this approach needs field-testing.

ACCURACY AND RELIABILITY OF LICHENOMETRIC DATES

Several attempts have been made to improve the accuracy, predictability, and reliability of lichenometric ages by using more sophisticated statistics rather than the single maximum diameter of lichen as a predictor of the surface age (Matthews, 1974, 1975; Bull, 1996). However, in practice these techniques do not replace the traditional approach of moraine dating. The accuracy of lichenometric dates obtained by traditional methods is estimated to be of the order of $\pm 15\text{--}20\%$ (Miller and Andrews, 1972; Calkin and Ellis, 1980; Bickerton and Matthews, 1992). This error estimate, though a useful parameter, is not directly related to the real reliability of lichenometric ages that depend mostly on the number, accuracy, and distribution in time of control points that constrain the growth curve.

Lichenometric ages obtained with well-controlled growth curves may distinguish surfaces at least to century precision and rival some numerical or calendar dating methods. This is particularly true where,

for example, radiocarbon analyses yield several control points for calibrated dates over the last millennium (e.g., Stuiver, 1982). Tree-ring dating, in turn, shares some problems with lichenometry—minimum ages for moraine surfaces, uncertain time of colonization, and the danger of mixing first-generation plants with advanced stages of succession (e.g., Reger and Péwé, 1991). However, lichenometry by itself is often superior in obtaining statistically significant data sets of ages for various deposit types in the same locality. For cold regions or high mountains beyond treeline, such as the Holocene moraines of the Brooks Range, or southeastern Kamchatka, it may be the only practical dating option.

Application of Lichenometry: Moraine Chronologies of the Brooks Range and Kamchatka

Holocene glacial chronologies that rely to varying degrees on historical, tree-ring, radiocarbon, tephrochronological, or lichenometric data are available for several regions of Alaska (e.g., Calkin, 1988; Begét, 1994; Barclay et al., 2001). However, only the moraine chronology along the Brooks Range, south of the Arctic Ocean, utilized mainly lichenometry (Calkin and Ellis, 1984; Haworth, 1988; Calkin, 1988).

Lichenometric data from 94 glaciers, most confined to cirques of the central Brooks Range, but also 8 larger valley glaciers in the eastern Brooks Range, allow definition of 3 and possibly 4 clusters of glacier advances or terminal stands over the last millennium (Fig. 6). The earliest advance, centered on about 1175 AD, follows several

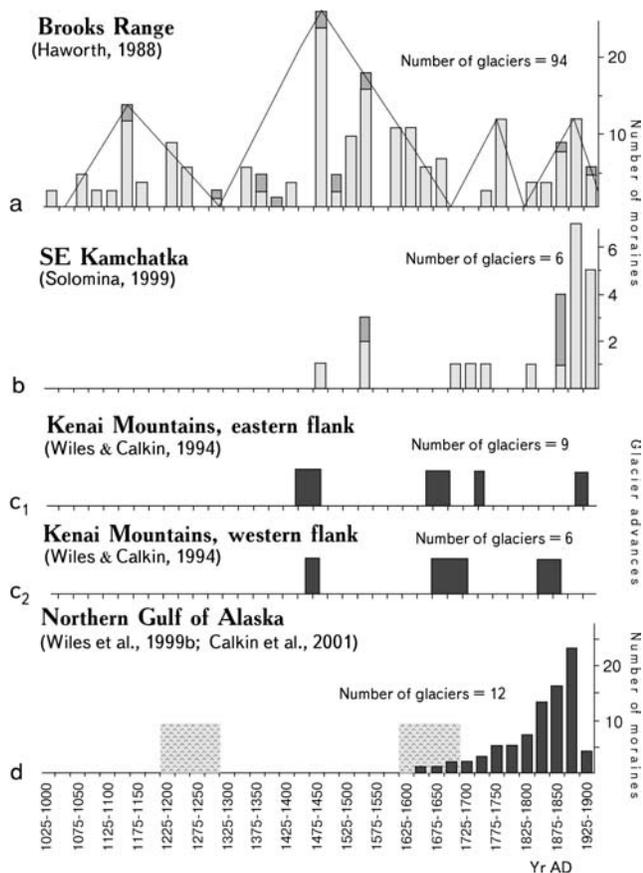


FIGURE 6. Correlation of late Holocene chronologies for land-terminating, mountain glaciers of Alaska and Kamchatka. Frequency histograms of end moraine ages based on lichenometry from (a), the central and eastern Brooks Range (after Calkin, 1988; Haworth, 1988), but based on the new curve (Figs. 3, 4 1a); and (b), south-eastern Kamchatka (from Solomina, 1999). These chronologies are similar to each other and to those based on tree-ring, radiocarbon, or historical data, and lichens from (c₁) the warmer and wetter east flank of the Kenai Mountains, Kenai Peninsula area, and (c₂) the drier and cooler western flank of the Kenai Mountains. The most precise Holocene glacial chronologies are those along the Gulf of Alaska (d). Light gray blocks represent tree-ring calendar dates of the overridden coastal forests on forefields of glaciers in the Prince William Sound area, eastward to Icy Bay, Alaska (Fig. 1); histogram shows minimum tree-ring dates of glacier moraines from the subsequent (most recent) of the 3 Little Ice Age glacier advances depicted (from Wiles et al., 1999a, 1999b).

centuries of retracted glacier conditions and was in turn followed by an early-16th- and 17th-century interval of glacier advance. This interval is the most pervasive and is also controlled locally by radiocarbon ages of AD 1566 and 1637 from glacially overrun organics. In the eastern Brooks Range, end moraines dated at about 1875 to 1900 are more prominent than in the central Brooks Range (Evison et al., 1996). Several hundred meters of recession has occurred from moraines of these advances.

Lichenometric ages of moraines in Kamchatka, although sparse, are similar to those of the Brooks Range (Fig. 6). In the Avacha region, the oldest and most prominent end moraines of the last millennium are those of the 19th century, although some older moraines may have been destroyed by lahars of this active volcano (Solomina, 1997). The moraine sequence in Kronotsky Peninsula is more complete; however, the oldest moraines of the last millennium afford only minimum ages of the late 15th and 16th centuries. Possible older events may be obscured by subsequent advances. The most prominent advances of the

late Holocene occurred in the mid-16th, early to mid-17th, and late 19th centuries. The Kamchatka glaciers have, on average, thinned about 100 m and retreated about 600 m from Little Ice Age maxima (Solomina, 1999).

Both lichen-dated glacier chronologies of the Brooks Range and Kamchatka (Fig. 6a, 6b) are surprisingly similar to the more precisely dated Holocene glacial chronologies on the Gulf of Alaska. These include ages derived from tree rings, radiocarbon, and lichen on the east and west flanks of the Kenai Mountains, Kenai Peninsula (Fig. 6 c₁, 6 c₂) and the chronologies calendar-dated by tree rings from glacially overrun forests on glacier forefields of Prince William Sound through Icy Bay (Fig. 6 d). Luckman and Villalba (2001) have shown that there is a broad synchronicity of initiation and timing of these very precisely dated Little Ice Age glacial events with others along the western cordillera of the Americas.

Conclusions

In this review of lichenometric studies at the North Pacific borderland, we have expanded or updated some of our data but have also raised other critical issues:

1. Updated growth curves based on calibrated ¹⁴C ages are presented for Alaska and Kamchatka; the differences between calibrated and uncalibrated curves are slight in the case of the Brooks Range. Differences may be dramatic where a unique date supports the long-term portion of the growth curve.
2. Confident application of lichenometry in Alaska and Kamchatka will depend on obtaining new control points. These should not only extend the old-growth portions of the curve from its present limits of a few centuries to a millennium but should also help define the break from the early to the rapid-growth stages. In addition, where possible, both *Rhizocarpon geographicum* species and *R. section Alpicola* lichens should be recorded for control points for differentiation on separate curves.
3. The composite model of lichen growth, consisting of logarithmic and linear intervals, appears appropriate for regions of continental climate and slow growth rates. Fast-growing lichens may lack a long-term, linear portion of the curve.
4. Growth curves for Alaska and Kamchatka are compatible with climate, showing decreasing growth rates with continentality and increases with maritime conditions.
5. Chronologies of late Holocene glaciation based heavily on lichenometry of moraines in the Brooks Range of northern Alaska and southeastern Kamchatka are surprisingly similar considering their relative physical and climatic settings. They are, in turn, quite similar to more precise, tree-ring-dated chronologies along the Gulf of Alaska and western cordillera of the Americas. This is likely to be a real relationship and hence may support the reliability of our lichenometry.

We are convinced that where used judiciously, lichenometry is a useful dating tool in mountains and at high latitudes, and in the North Pacific in particular.

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