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To cite this article: Parker E. Calkin & James M. Ellis (1980) A Lichenometric Dating Curve and its Application to Holocene Glacier Studies in the Central Brooks Range, Alaska, Arctic and Alpine Research, 12:3, 245-264, DOI: [10.1080/00040851.1980.12004185](https://doi.org/10.1080/00040851.1980.12004185)

To link to this article: <https://doi.org/10.1080/00040851.1980.12004185>



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Published online: 02 Jun 2018.



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A LICHENOMETRIC DATING CURVE AND ITS APPLICATION TO HOLOCENE GLACIER STUDIES IN THE CENTRAL BROOKS RANGE, ALASKA

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ABSTRACT

Lichen growth curves for dating in the central Brooks Range have been developed and applied using *Rhizocarpon geographicum* s.l. and the fast-growing *Alectoria minuscula/pubescens*. *Rhizocarpon eupetraeoides* and *R. inarense*, nearly as common in this region, have a growth pattern which correlates with that shown by the *R. geographicum* curve for thallus diameters up to 150 mm. The *R. geographicum* curve has a great growth period lasting 200 yr based on his-

toric, dendrochronologic, and direct measurement control; this is followed by a linear growth phase of ~3 mm per century based on radiocarbon dates. The lichenometric technique has proved successful in developing the first detailed Holocene glacial chronology for the Brooks Range and indicates that major pulsations of cirque glaciers occurred as recently as 350 yr ago.

INTRODUCTION

Determination of the magnitude and chronology of Holocene glacial fluctuations has been a major goal of a hydrologic study begun in 1977 in the Atigun Pass area of the central Brooks Range. In this arctic and alpine environment, organic materials datable by the radiocarbon method are rare. However, our initial work, particularly at the valley heads near Atigun Pass (Figure 1), showed that high bouldery moraines that loop around the small cirque glaciers bear a lichen cover with certain species that are surprisingly consistent in maximum thallus diameters along individual ridges. Furthermore, these lichens are markedly smaller and more consistently sized than those on boulders of the older, Pleistocene drift sheets which extend several tens of kilometers farther down valley.

These observations and the abundant occurrence of a similar set of lichen species on rock substrates of a variety of deposits encouraged us to measure lichen diameters and to develop lichenometry as a dating tool in the central Brooks Range. Absolute dating control was obtained from radiocarbon, dendrochronologic, and historic records for the calculation of lichen growth rates. From this we developed preliminary lichen growth curves for absolute dating. Direct measurements were also obtained in 1979 on two species. Six lichen species were used with the principal curve being based on *Rhizocarpon geographicum* s.l.

Lichenometry was pioneered by Beschel (1950), and its basic concepts and limitations, as well as the major elements in its sophistica-

tion to the point of being an accepted dating tool, are well discussed in papers by Beschel (1950, 1961), Andrews and Webber (1964), Jochimsen (1966), Benedict (1967, 1968), Orwin (1970), and Worsley (1973). Lichenometry has been applied to construct Holocene chronologies in many areas of the world. In Alaska it has been applied in the central Alaska Range (Reger and Péwé, 1969) and in the St. Elias and Wrangell mountains farther south (Denton and Karlén, 1973a, 1973b).

The purpose of this paper is to present the

methods and control used in the development of lichen growth curves for the central Brooks Range and to outline some of their applications to Holocene glacial chronology. We hope that our preliminary work may stimulate similar or additional uses of the lichenometric curve in northern Alaska and adjacent Canada. Furthermore, we expect that it will help bring to light more absolute dating control which may be applied to rates of lichen growth in the Brooks Range.

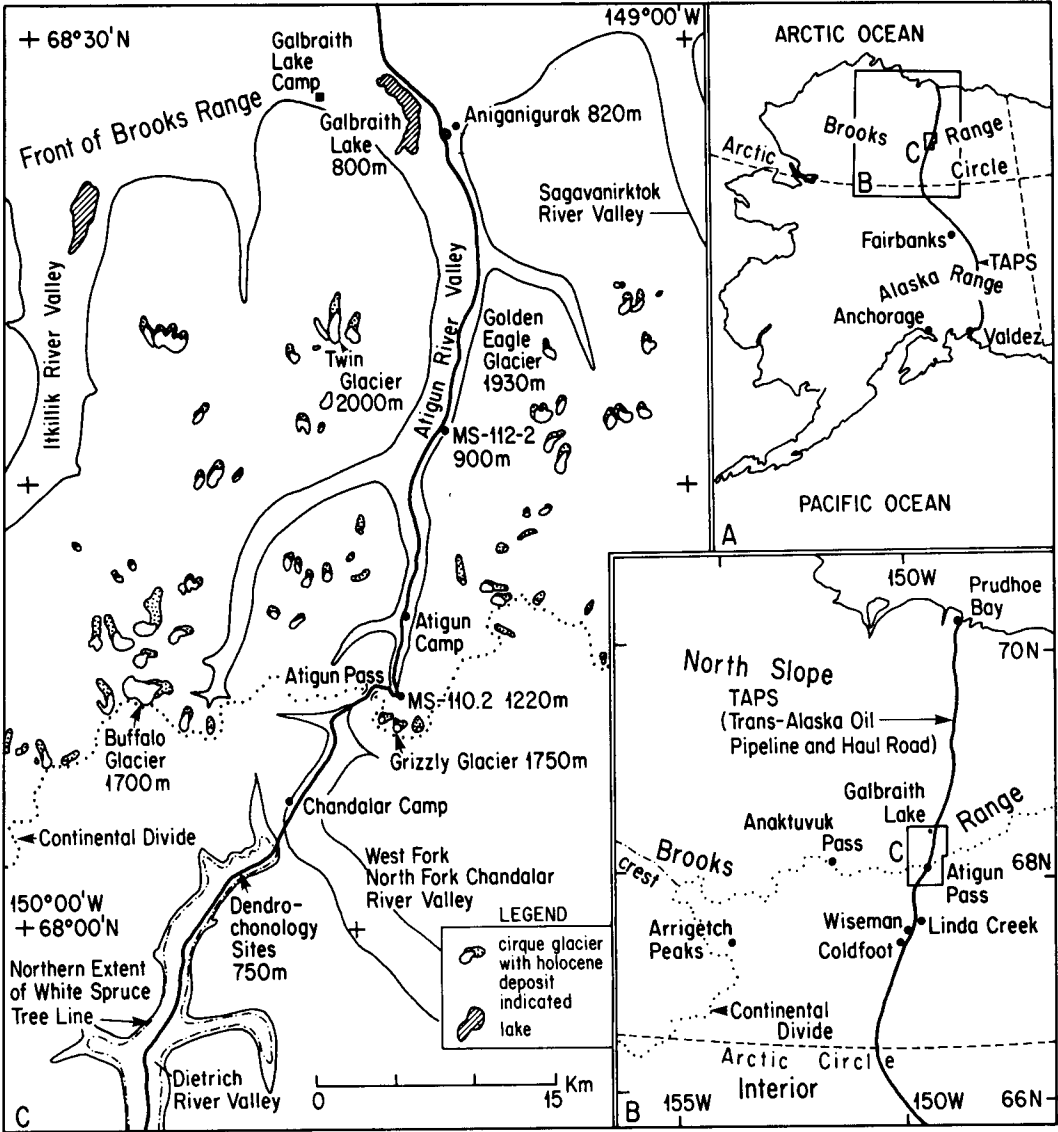


FIGURE 1. Location map showing the Brooks Range and Atigun Pass field area.

PHYSICAL SETTING

The work described in this paper has been undertaken mostly near Atigun Pass and within the headwater basins of the Atigun, West Fork North Fork Chandalar, and Dietrich rivers. Here the Trans-Alaska Pipeline System (TAPS) and its associated haul road cross the east-west-trending Continental Divide at 1440 m above sea level (a.s.l.) (Figure 1). Our applications of the lichen growth curve have been extended from Atigun Pass along the Continental Divide through Anaktuvak Pass to the Arrigetch Peaks 225 km to the west.

The Atigun Pass area has been repeatedly glaciated since early Pleistocene time (Hamilton and Porter, 1975; Hamilton, 1978a, 1978b). Peaks reach to 2300 m with relief of 1000 to 1200 m around U-shaped valleys bordered by bouldery slope rubble and filled with several meters of late Pleistocene drift. More than 130 cirque glaciers with their associated Holocene deposits occur at the valley heads. These glaciers, 97% of which occur north of the Continental Divide, can be fitted to a trend surface that rises in altitude from about 1500 m just south of the Divide to 2000 m on peaks 33 km farther north (Figure 1; Ellis and Calkin, 1979).

Most of the field area lies north of the spruce tree line and within the zone of continuous permafrost (Figures 1 and 2; Ferrians, 1965; Péwé, 1975). The Continental Divide correlates with the transition zone between the continental climate of Alaska's interior with its temperature extremes and higher precipitation and the overall cooler arctic regime of the North Slope (Berg et al., 1978; Ellis and Calkin, 1978, 1979). Climatic data are

meager, with only discontinuous records available from Anaktuvak and Wiseman (100 km south of the pass), which are the nearest settlements (see Porter, 1966). However, more complete data have been collected along the TAPS corridor since 1975 (Haugen, 1979; Figure 2). Temperatures above freezing are attained in May through September in the Pass area, but the low insolation values during the rest of the year allow temperatures to reach below -45°C . The mean annual temperature of Atigun Pass is about -14°C with a freezing-index (cumulative number of degrees below 0°C per year) of about 4800 degree-days and a thawing index of only about 1000 or less. Temperatures during the thaw season decrease with increasing latitude and elevation across the Brooks Range (Figure 2). June, July, and August mean temperatures at Atigun Pass averaged 2.1, 7.3, and 7.3°C , respectively, from 1976 through 1978 (Haugen, 1979).

Precipitation decreases with latitude and increases with elevation across the Brooks Range (Figure 2; Hamilton, 1966; Péwé, 1975). Extrapolation of Cold Regions Research and Engineering Laboratory (CRREL) data (Haugen, 1979) and glacier snow-pit studies (Ellis and Calkin, 1978; Bruen, 1980), and records from Anaktuvak Pass 94 km to the west (Porter, 1966) suggest that annual precipitation at Atigun Pass ranges between 40 and 60 g cm^{-2} of which somewhat more than 50% is snow. Areas marginal to the cirque glaciers and downslope generally remain snow free from late June through August.

CONCEPT AND METHODS OF LICHENOMETRY IN THE BROOKS RANGE

The technique of lichenometry is based on the assumptions that (1) newly deposited material is free of lichen thalli; (2) colonization occurs shortly after the surface or deposit is formed; and (3) subsequent growth (increase in thallus diameter) occurs with a predictable pattern and, within a general region with the same macroclimate, is a function of time passed since colonization (Beschel, 1961; Karlén, 1973). Therefore, the diameter of the largest lichen thallus is proportional to the age

of the surface in question, if it may be assumed that the lichen is one that colonized shortly after glacial recession or other initial surface formation and that the lifespan of the species utilized is greater than the age of the surface.

LICHEN SPECIES UTILIZED

Six lichen species suitable for dating were measured during the 1977, 1978, and 1979 field seasons. Selection was based on their

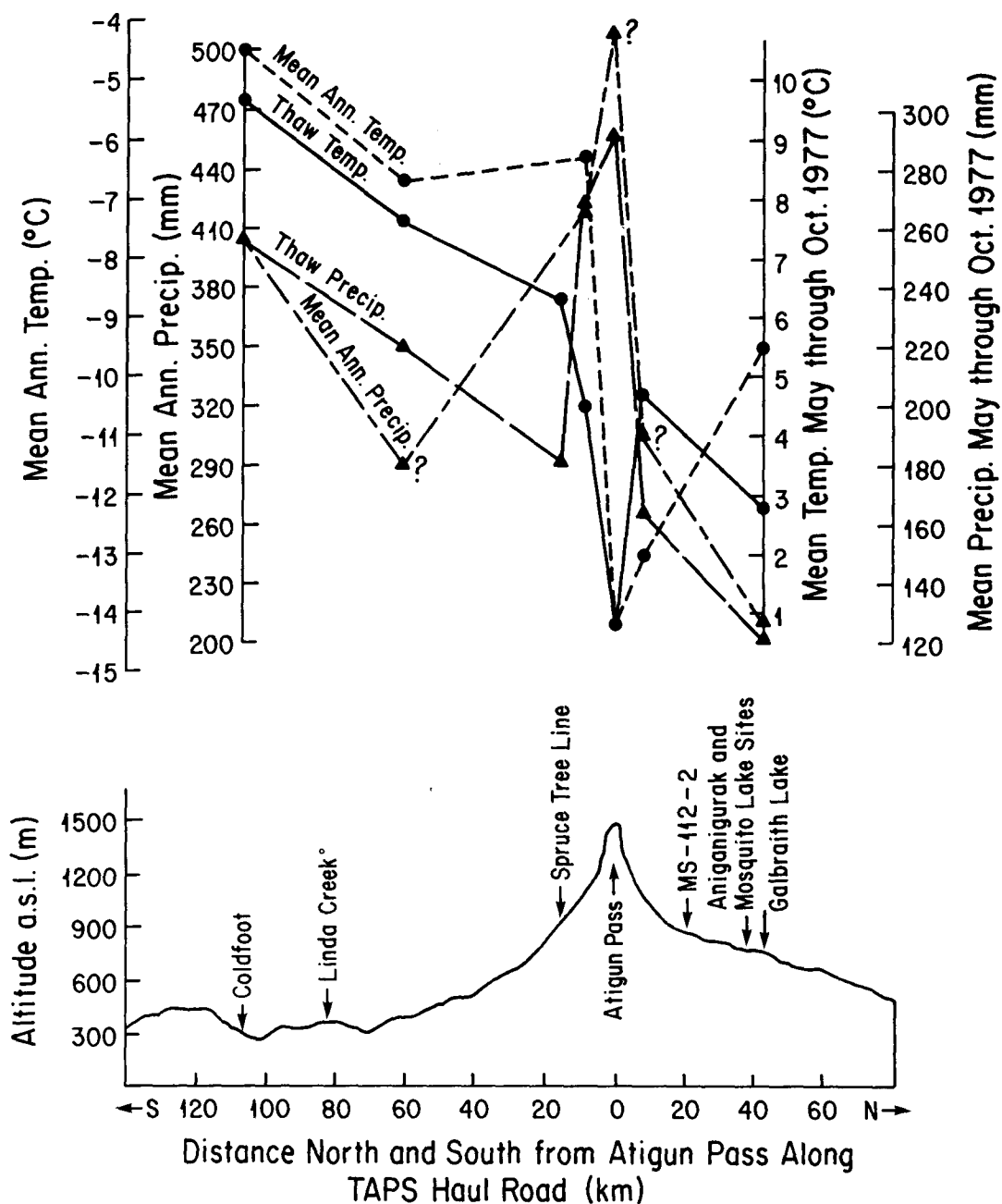


FIGURE 2. Temperature and precipitation transects along the trans-Alaska pipeline haul road between Coldfoot and Galbraith Lake construction camps. Means are derived from measurements between 1975 and 1979. Question marks (?) show estimates of mean annual precipitation obtained by doubling thaw season (May through October) data. Adapted with minor modifications from Haugen (1979). Arrows show control points for the lichen growth curve that occur near the haul road.

wide distribution in the field area and other similar regions as well as their characteristic morphologies and consistent growth rates. Four of them were introduced to us in the field area by P. J. Webber and are among the species studied on Baffin Island since 1950 (Hale, 1954; Andrews and Webber, 1964, 1969; Miller and Andrews, 1972; G. H. Miller, 1973; Andrews and Barnett, 1979). These four species are *Alectoria minuscula* Nyl., *Alectoria pubescens* (L.) Howe, *Umbilicaria proboscidea* (L.) Schrad, and *Rhizocarpon geographicum* (L.) DC. The first three are fast-growing; the last, *R. geographicum*, is a cosmopolitan, slow-growing, and long-living lichen used in more than 40 published lichenometric studies (Webber and Andrews, 1973). The other species used in dating are *Rhizocarpon eupetraeoides* (Nyl.) Blomberg and Forssell and *Rhizocarpon inarense* (Vainio) Vainio.

Alectoria minuscula is a black fibrous lichen that can be differentiated from the similar fruticose *Alectoria pubescens* by variation in the length and texture of the thallus fibers (see Figure 3a; Andrews and Webber, 1964). Its black fibers are very fine, and the mat-like appearance of the thallus shows a high fiber-branching ratio. In contrast, *A. pubescens* tends to be coarse textured, has long interwoven fibers with a relatively low branching ratio, and tends to be less common than *A. minuscula*. Larger specimens (>140 mm in diameter) are often deteriorated in the center of the thallus, perhaps indicating the onset of senescence.

Umbilicaria proboscidea is a dark gray to black lichen with thin and delicate "leafy" appendages radiating from a central substrate attachment structure. These are profuse on recent drift sheet surfaces about retreating cirque glaciers in the field area. They are difficult to measure when greater than 50 mm in diameter because the leafy margins of these older specimens are curled, and prone to breakage when dry and disturbed.

Four species of *Rhizocarpon* have been collected from the field area and identified by W. A. Weber (pers. comm., 1979). They are discussed below with voucher specimen numbers of the University of Colorado Museum Herbarium in parentheses. Detailed descriptions and ranges of these species may be found in Thomson (1967).

The *Rhizocarpon geographicum* (L.) DC. (COLO L-68908) is a rather variable species

(Thomson, 1967), and has been subdivided as a group by Runemark (1956a). Field differentiation of these variations is very difficult and so the name *Rhizocarpon geographicum* has been used in the general sense in the Brooks Range as it has in most lichenometric studies to date (c.f. Andrews and Webber, 1964; Birkeland, 1973). Examples of this durable crustose lichen species are shown in Figure 3b. We have measured distinct thalli to 250 mm in the central Brooks Range. *R. geographicum* s.l. are intolerant of, and therefore scarce on, calcareous substrates (see Osborn and Taylor, 1975). *Rhizocarpon superficiale* (Schaer.) Vainio (COLO L-68905) is similar in appearance but not of the *Geographicum* group (Figure 3c). This species may sometimes be confused with *R. geographicum* in the field and may be included in some of our measurements.

Rhizocarpon eupetraeoides (Nyl.) Blomberg and Forssell (COLO L-68906) and *R. inarense* (Vainio) Vainio (COLO L-68904) are especially noticeable on late Pleistocene and early Holocene surfaces in the central Brooks Range (Figures 3d and 3e). These very similar species belong to the *Rhizocarpon* group *Alpicola* Runem. (Thomson, 1967: 441). *R. eupetraeoides* can only be clearly distinguished from *R. inarense* in the field by a chemical iodine test on the medulla which is I+ or intensely blue for the former and I- or faintly blue for the latter (W. A. Weber, pers. comm., 1979). *R. alpicola* is also in this group and has been used in lichenometric studies in Scandinavia by Denton and Karlén (1973b, Figure 7). It is only distinguishable from *R. inarense* by a different reaction to potassium on the hymenium. However, *R. alpicola* is not known to occur in Alaska (Thomson, pers. comm., 1979).

R. eupetraeoides/inarense are dominated in the field area by more vivid yellow-green aureoles than *R. geographicum*, and these aureoles tend to be more variable in size and appear to coalesce around the margin of the thallus. The *R. geographicum* thallus generally has an outer periphery with a more marked black hypothallus, and more uniform-sized yellow-green aureoles across the entire thallus (Figure 3b).

In the field area, *R. geographicum* appears to be somewhat smaller in diameter than the associated *R. eupetraeoides/inarense* which attain thallus diameters greater than 450 mm. Although our data are not extensive enough to support an interspecific ratio other than 1:1

between *R. geographicum* and *R. eupetraeoides/inarens* at this time, the following ratios of thallus diameters (mm) are common on recent moraines we have mapped: 9:11, 19:22, 29:32. In this paper our references to *R. geographicum* generally can be applied to *R. eupetraeoides/inarens* for thallus diameters up to 150 mm.

Individual *R. geographicum* thalli above 150 mm often are less well defined and less circular than the more areally limited *R. eupetraeoides/inarens*.

It is yet uncertain whether *R. geographicum* lichens actually grow more slowly than the *R. eupetraeoides/inarens*, or are shorter lived. Our observations suggest that *R. geographicum* thalli tend to coalesce or disintegrate with time thus making them less useful for lichenometric dating of older surfaces. Nevertheless, our lichen growth curve is based on *R. geographicum* because of its ubiquitous distribution.

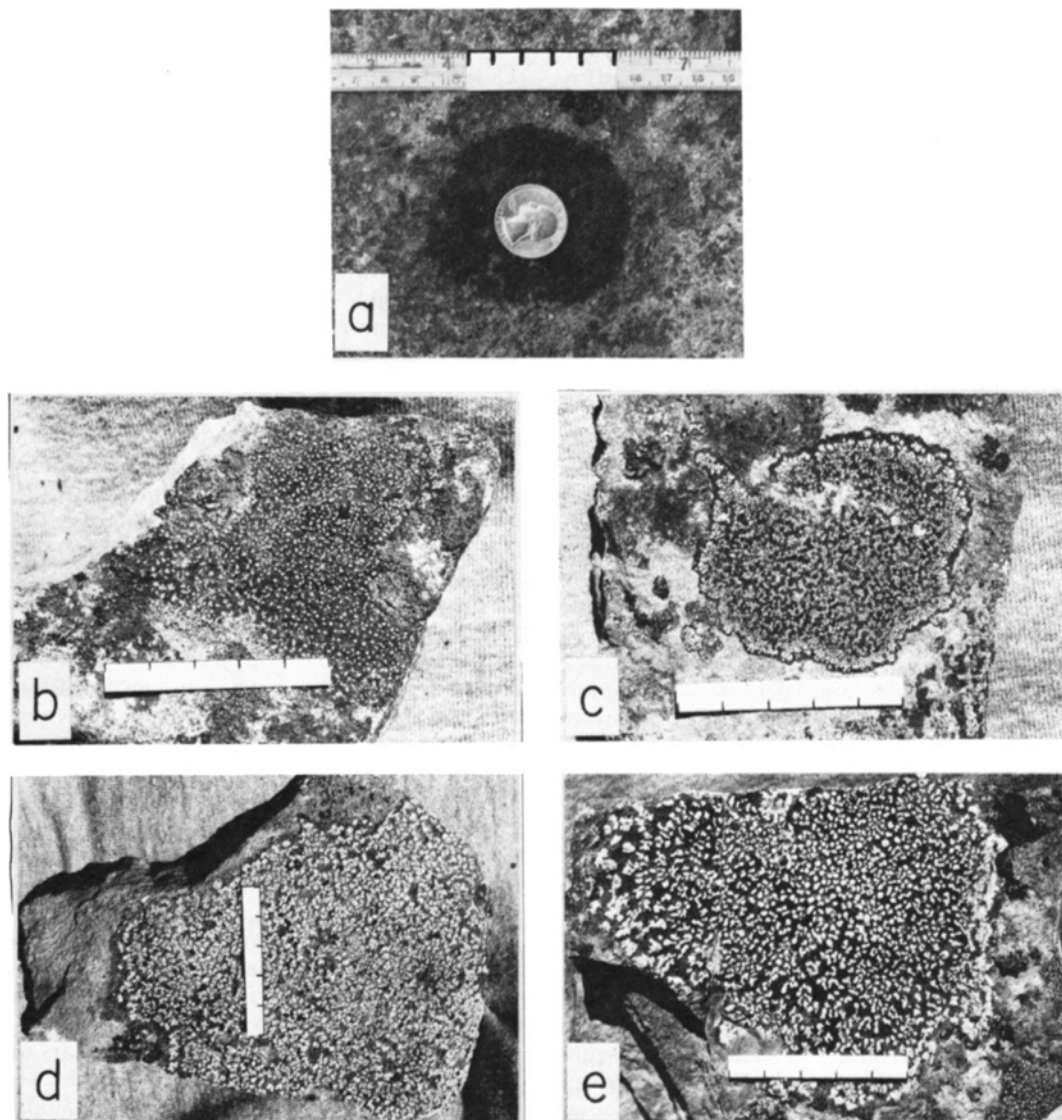


FIGURE 3. Photographs of lichens from the Atigun Pass area, central Brooks Range, including (a) *Alectoria minuscula*; (b) *Rhizocarpon geographicum*; (c) *Rhizocarpon superficiale*, sometimes confused with *R. geographicum*; (d) *Rhizocarpon eupetraeoides*; and (e) *Rhizocarpon inarens*. Scale on each photograph is 5 cm.

MEASUREMENT TECHNIQUES

Various techniques for the measurement of lichen thalli including diameter averaging are reported in the literature (Reger and Péwé, 1969; Webber and Andrews, 1973). However, based on the experience of Webber (Andrews and Webber, 1964; pers. comm., 1977), Benedict (1968), and Karlén (1973), we have adopted the fundamental assumption of Beschel (1950, 1961) for use in the Brooks Range: only the *maximum* diameter of the largest lichen thallus is an indicator of substrate age, because it is assumed to be the oldest and to possess the optimum growth rate for the site being studied. Each site or map unit is therefore characterized by the maximum thallus measured that is indicative of the oldest age. However, if the maximum diameter of the largest thallus on a map unit was found to be 20% above the next largest diameter or a cluster of diameters, it was generally discounted and assumed to have been inherited from a preexisting surface. Only lichens with distinct thallus margins were used and, of these, only thalli ranging in shape from slightly elliptical to circular were measured. Data recorded included both maximum and minimum diameters to the nearest 1 mm as well as lichen species, location, aspect, and inclination of the rock substrate.

Lichen mapping was undertaken on a wide variety of landforms but principally on morainal ridges. Geologic and geomorphic maps were made at the same time. This involved investigating as much area as possible on each geomorphic unit and scrutinizing all sides and upper surfaces of boulders and cobbles for measurable lichen thalli while recording the state of development of other relative age indicators, e.g., weathering and stratigraphic position. Karlén (1973) found that an area in excess of 500 m² was necessary to obtain valid results for dating of Neoglacial moraines in the Kebnekaise Mountains of Swedish Lapland, and our observations confirm this. Ridge crests on stable moraines and rock glaciers bear the most consistent lichen diameters, whereas on less stable landforms, areas of lower relief provided the most consistent lichenometric evidence. Chronologic interpretation of the lichenometric record on the less stable deposits may require considerable field experience. Time limits on sampling, and short selective traverses across the terrain (Rampton, 1970; Birkeland, 1973), or other

areally limiting sampling techniques (Andrews and Webber, 1964; Matthews, 1974) provide data which may be most useful for statistical treatment such as size-frequency distribution of lichen diameters but limit the effectiveness of mapping, and study of overall glacial history.

SOME LIMITING FACTORS IN THE ATIGUN PASS AREA

Many factors limit the application of lichenometry in the Brooks Range as in other areas. Reger and Péwé (1969) considered the most important microenvironmental controls in the central Alaska Range 500 km south of Atigun Pass to be the availability of sunlight and moisture and stability of the substratum. Rock faces hosting the largest lichen thalli there displayed a dominant southwest orientation, in contrast to the Front Range of Colorado (Birkeland, 1973) or the Swiss Alps (Haeberli et al., 1979) where *Rhizocarpon geographicum* is absent from south-facing rock surfaces. No strong relationships between lichen growth and orientation or height above the moist ground surface showed up in our Brooks Range field work. For the most part, our measurements incorporated surfaces with a wide range of orientations and positions; most surfaces were part of well-drained topographic forms.

Substrate stability is a major limiting factor. Creep of bouldery rubble (including ice-cored moraines or rock glaciers) on slopes is as important and widespread a phenomenon in the Brooks Range (Ellis and Calkin, 1979) as it is in the alpine areas farther south in Alaska (Wahrhaftig and Cox, 1959; Denton and Karlén, 1973b). The maximum lichen diameters on glacial drift are less reliable for determining the age of initial ridge construction where there has been a shifting of the surface due to melting of the ice cores or where rock glacier creep has occurred. Nevertheless, a variety of useful information may be gained by careful application and interpretation of lichenometric measurements on such deposits.

The effect of lithologic variations on lichen growth is not clearly understood, and studies usually minimize this potential problem by measuring lichens on rocks of similar composition (cf., Denton and Karlén, 1973b; Andrews and Webber, 1974). In the east-central Brooks Range, the Continental Divide and most of the higher peaks in the region to

the north supporting the cirque glaciers are composed of siliceous conglomerates and sandstones or quartzites of the resistant Devonian Kanayut Conglomerate (Brosgé et al., 1979). Holocene drift in the cirques and late Pleistocene glacial drift lower in the valleys as well as the upper surfaces of most lobate and tongue-shaped rock glaciers are comprised of cobbles and boulders of this formation. Therefore, it has provided a uniform and extensive lithology upon which to base the lichenometric dating curve in the central Brooks Range. Varying amounts of silica in the members of the Kanayut formation do not seem to noticeably affect the lichen growth. The granitic terrain of the Arrigetch Peaks and other plutons provides a comparable base for growth farther to the west and south.

The lichens used in this study are very rarely associated with limestones such as the crystalline Lisburne limestone that forms the northernmost part of the Range and Skagit Limestone which forms part of the south flank of the Brooks Range. The only exceptions are where growth occurs on associated chert nodules. Lichens are able to grow on a variety of rock types, including the metamorphic rocks at the mining district near Wiseman and on the shales and phyllites of the Hunt Fork formation which crops out immediately south of the Continental Divide. However, *R. geographicum* typically are limited to diameters of less than 25 mm on easily weathered shaley substrates.

It is extremely difficult to determine the end of active growth or arrival of senescence for lichens (Llano, 1956, cited in Reger and Péwé, 1969) and the ultimate lifespan of the *Rhizocarpons* (Beschel, 1961). Apparently the lifespan can be in excess of 9000 yr (Denton and Karlén, 1973b; Andrews and Barnett, 1979).

The validity of the lichenometric method as

a measure of age in the central Brooks Range is substantiated by the internal consistency of the results of our field study. A series of stable looped end moraines of Neoglacial age which front small cirque glaciers along the Continental Divide near Atigun Pass (Figure 1) has been particularly useful in this regard. These moraines contain extensive portions which are ice cemented although they are not glacier cored; they occur in open areas where shading by surrounding mountain terrain is minimal, and have similar snow-covered and snow-free periods. These moraines show the following characteristics of lichen growth: (1) Lichens are numerous on exposed surfaces of conglomerate and sandstone boulders; however, recently deglaciated surfaces at the glacier margins rarely display lichens. (2) Lichen diameters measured on the looped moraines extending out from the individual glaciers are successively greater on drift units shown to be progressively older on the basis of independent geologic criteria. (3) A substantial number of lichens along the moraine ridges are close to the maximum measured diameter. A variation in maximum diameter of only 2 to 3 mm occurs for up to 1 km along individual ridges and several measurements on individual drift units give the same results. Changes in lichen diameters between adjacent morainal ridges are sharp and predictable. (4) Measurements of lichen diameters on deposits of similar apparent age are frequently uniform across stable zones which are both ice cored and ice free.

Additional evidence that lichenometry can be used successfully in the central Brooks Range is derived from broader regional relationships. These include consistent interspecific lichen diameter ratios and the similarity in lichen size on historically and isotopically dated surfaces.

CONTROL FOR LICHEN GROWTH CURVE

Growth rate is not constant over a lichen's life span (Benedict, 1967). It is initially rapid over a *great growth* period lasting from 40 to 500 yr, but decelerates with time until a generally linear long-term growth rate is attained (Figure 4). Webber and Andrews (1973) compiled the growth rates (lichen factors) of 29 *R. geographicum* curves, and concluded that high precipitation, long growing

season, and high temperatures favor more rapid growth. That this climatic control strongly affects the rate and duration of the initial great growth period has been particularly well shown by data of Beschel (1961) from Greenland. However, Miller and Andrews (1972) suggest that climatic differences may have less control on the long-term growth rate of *R. geographicum* since those of

Baffin Island, the Colorado Front Range (Benedict, 1967), and the St. Elias and Wrangel mountains of Alaska (Denton and Karlén, 1973b) have growth rates of approximately 3 mm per century.

CLIMATIC CONTROL

The climatic regime of the Atigun Pass area may be similar to that recorded for central Baffin Island (Andrews and Webber, 1964) where mean annual temperature is -10°C and annual precipitation is about 37 g cm^{-2} . If climatic parameters are a paramount control of the growth rate, then as a first approximation a *R. geographicum* curve for the central Brooks Range should resemble the relatively well controlled curve for Baffin Island shown in Figure 4 (Miller and Andrews, 1972; Andrews and Barnett, 1979).

INTERSPECIFIC COMPARISONS

The relative growth rates between the three fast-growing species and *R. geographicum* were determined so that potential diameter and age relationships or control points found for one species could be transplanted to the other three. In particular, this enables us to transfer growth rates determined from direct observations of the fast-growing *Alectoria minuscula* to the *R. geographicum* curve. It also allowed comparison to the work done on Baffin Island (Andrews and Webber, 1964, 1969; Miller and Andrews, 1972; G. H. Miller, 1973). Only the maximum diameter lichens charac-

terizing the age of a landform or map unit were used in these comparisons as it was assumed that these would represent the optimum growth rate of the species. Growth rates for the three fast-growing species are relatively similar and can tentatively be used interchangeably to reach a lichenometric date.

Alectoria minuscula is the most profuse of the three fast-growers. It attains well-defined maximum diameters approaching 140 mm prior to deterioration. Table 1 shows that this species grows seven times faster than *Rhizocarpon geographicum* in the Brooks Range, and our data suggest that the two species colonize and/or become visible to the unaided eye on surfaces contemporaneously along with *A. pubescens* and *Umbilicaria proboscidea*. The same ratio was obtained by Webber and Andrews (1964), but they indicate that the fruticose *Alectoria* colonized before the crustose *R. geographicum*. More recent work by Andrews and Webber (1969), Miller and Andrews (1972), and G. H. Miller (1973), which utilized direct measuring methods, indicates a continuously changing interspecific ratio that approaches 7 when *A. minuscula* ranges from 70 to 160 mm in diameter (G. H. Miller, 1973, Figure 2). *U. proboscidea* also has a growth rate seven times faster than *R. geographicum* for thallus diameters of less than 70 mm (Table 1).

DIRECT MEASUREMENTS

Thalli of *Alectoria minuscula* and *A. pubescens* lichens ranging in maximum diameters from

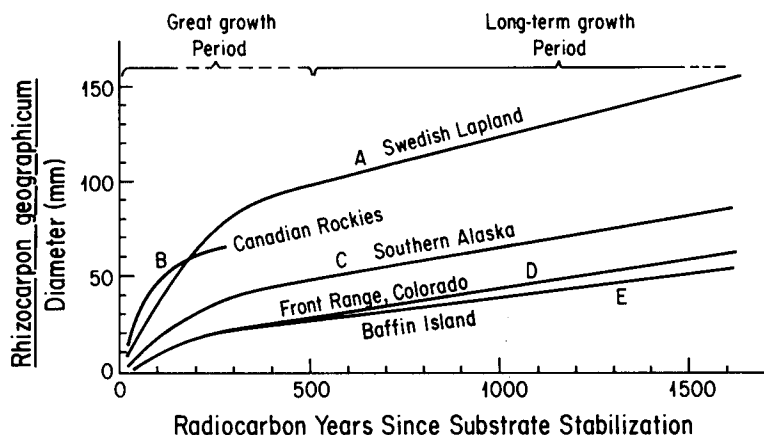


FIGURE 4. Selected *Rhizocarpon geographicum* growth curves showing the impact of climate. Generally decreasing precipitation, temperature, and length of growing season result in slower growth rate. Curves are from: A—Denton and Karlén (1973b); B—Luckman (1977); C—Denton and Karlén (1973b); D—Benedict (1967); and E—Miller and Andrews (1972).

30.0 to 71.3 mm were traced in early August 1977 and remeasured in early August 1979 allowing growth rates to be computed for thalli of this diameter range. The lichens were located on bouldery Neoglacial drift associated with Grizzly Glacier at an elevation of 1680 m, about 1 km east of Atigun Pass (Figure 1). Changes in thallus diameters were determined from these tracings by the plani-

metric method (diameter = $0.5 (\text{area}/\pi)^{1/2}$) with results that show a progressively decreasing growth rate with increasing diameter for both *Alectoria* species (Table 2). These direct measurements were extrapolated to the indirectly controlled growth curve of the slow-growing *Rhizocarpon geographicum* by use of the 7:1 interspecific ratio (Table 1). This suggests that as diameters increase from 5.0 to

TABLE 1
Interspecific ratio correlations

Species compared	No. ^a	Linear regression slope	r correlation	Limiting species diameter range (mm)
<i>A. minuscula</i> :				
<i>A. pubescens</i>	25	1.04	.95	160 (?)
<i>A. minuscula</i> :				<i>A. minuscula</i> < 70
<i>U. proboscidea</i>	19	1.06	.87	<i>U. proboscidea</i> < 60
<i>A. minuscula</i> :				<i>A. minuscula</i> 8-150
<i>R. geographicum</i>	108	6.5	.93	<i>R. geographicum</i> 1-22
<i>A. pubescens</i> :				<i>A. pubescens</i> 8-150
<i>R. geographicum</i>	24	6.8	.95	<i>R. geographicum</i> 1-22
<i>U. proboscidea</i> :				<i>U. proboscidea</i> < 70
<i>R. geographicum</i>	29	6.7	.89	<i>R. geographicum</i> < 10
				<i>U. proboscidea</i> > 70 < 90
	11	2.1	.73	<i>R. geographicum</i> > 10 < 20

^aOnly maximum diameter lichens characterizing the age of a map unit or landform are used for interspecific comparisons.

TABLE 2
Direct growth measurement data for Alectoria minuscula and Alectoria pubescens extrapolated to Rhizocarpon geographicum

<i>A. minuscula</i> and <i>A. pubescens</i>		<i>R. geographicum</i>	
Maximum diameters (mm)	Planimetrically-determined diameter change (mm yr ⁻¹) ^a	Extrapolated great growth rate (mm 100 yr ⁻¹)	For effective diameter range ^b (mm)
1977	1977-1979		
30.0	+ 1.8	25	5.0-5.5
31.5	+ 1.7		
35.0	+ 1.2		
35.5	+ 1.9		
42.5	+ 1.6	24	6.0-6.7
47.3	+ 1.8		
63.0	+ 1.3	18	9.0-9.7
64.0	+ 1.4		
68.0	+ 1.0		
71.3	+ 1.0	14	10.1

^aDiameter = $0.5 (\text{area}/\pi)^{1/2}$ from tracings made in early August of 1977 and 1979.
^bSee Table 1 for 7:1 *A. minuscula/pubescens*: *R. geographicum* interspecific ratio data.

10.1 mm, the growth rate of *R. geographicum* thalli decreases from ~ 25 mm 100 yr⁻¹ to ~ 14 mm 100 yr⁻¹ (Table 2).

The range in growth rate of the two *Alectoria* species, 1.0 to 1.9 mm yr⁻¹ (Table 2), is slightly faster than that measured from 1969 to 1971 in eastern Baffin Island (Miller and Andrews, 1972; G. H. Miller, 1973, Table 2). In Baffin Island the growth rate range for *A. minuscula* was from ~ 0.3 to 1.6 mm yr⁻¹. Whether either of these sets of measurements reflects the long term growth and climatic conditions of respective areas is uncertain.

HISTORIC CONTROL

Gold Mines

Abandoned gold placer mines and shafts occur 70 km south of Atigun Pass. The tailings are composed of siliceous conglomerates and sandstones such as those found in the Atigun Pass area as well as schists, graywackes, and other metamorphic cobbles and boulders. The production and abandonment of these mining operations is documented by Maddren (1910, 1913), Cobb and Kachadoorian (1961), and Cobb (1976).

Rhizocarpon geographicum attain maximum diameters of 10 mm on stones in tailings from shafts dug into a buried tributary to Linda Creek, 85 km south of Atigun Pass at 430 m a.s.l. (Figures 1, 2, and 5). The majority of abandoned shafts in this area were dug in 1908 or 1909.

Handworked placer operations downslope of these shafts, believed to have been aban-

doned soon after 1901 (Maddren, 1913), host *R. geographicum* which attain maximum diameters of 12 mm. Since the summers are warmer in this southern mining district than near Atigun Pass (Figure 2; Haugen, 1979) these *R. geographicum* diameters should be considered as maximum values for the growth curve which is constructed for an area centered about Atigun Pass.

Aniganigurak Eskimo Village

Thirty-seven kilometers north of Atigun Pass at 820 m a.s.l. in the Galbraith Lake area (Figures 1 and 2) is an abandoned Nunamiut Eskimo village named Aniganigurak. Rifle cartridges recovered from the site indicate occupation no earlier than 1873, and abandonment between 1880 and 1890 (Corbin, 1971: 272-296). *R. geographicum* attain diameters of 12 mm on a few siliceous erratics which appeared to have been disturbed during this occupation.

Arrigetch Peaks Glacier Survey

Photographs taken in 1911 by P. S. Smith and again in 1962 by T. D. Hamilton document recession of a cirque glacier in the granitic Arrigetch peaks of the south-central Brooks Range (Figure 1; Hamilton, 1965, Figure 4B). Comparative photographs of the glacier were taken by Hamilton and Ellis in 1979.

The 20th-century drift was deposited directly on bedrock in two extensive, ice-marginal areas, thus providing an unusually



FIGURE 5. Abandoned gold mine shaft with associated stable tailings formed in 1908-09 at Linda Creek, 15 km north of Wiseman, Brooks Range, Alaska. The tailing boulders carry *Rhizocarpon geographicum* of 10 mm diameter.

stable substrate for lichen colonization. However, no visible lichen colonization was found in the ice-marginal zone exposed during the 17 yr since 1962. In addition, a fresh boulder surface of a cairn constructed by Hamilton in 1962 to mark his 1-62 photographic station (Hamilton, 1965) displayed no visible crustose lichen population 17 yr later, although the foliose *Umbilicaria* genera (not including *U. proboscidea* species) had attained diameters of ≤ 3 mm. However, *Rhizocarpon geographicum* thalli increase progressively in diameter up to at least 9 mm with distance from the retreating glacier within the area apparently exposed in the 51 yr between 1911 and 1962. Some attain diameters of 11 mm where formed on boulders deposited directly on bedrock. *Alectoria pubescens* reached diameters of 62 mm and *R. eupetraeoides/inarensense* reached 10 mm diameters in associated areas that were apparently being exposed about the time of the 1911

RADIOCARBON CONTROL

Three radiocarbon dates obtained on deposits in the Atigun Pass area could be correlated with maximum *Rhizocarpon geographicum* thalli occurring on the overlying surficial deposits. The youngest radiocarbon control point, dated 210 ± 90 yr BP (BGS-547), is a peat layer at 0.65 m depth in an alluvial fan at 900 m a.s.l. located 11 km north of Atigun Pass along the TAPS corridor (Alyeska Material Site MS-112-2; Figure 1). The debris above the organic zone represents subsequent alluviation, and stones on its upper surface host *R. geographicum* lichen up to 12 mm in diameter.

Woody vegetation growing in bedrock joints at the margin of a cirque glacier (Buf-

falo Glacier) was preserved when buried during deposition of the outermost Holocene lateral moraine (Figure 6); it has been dated at 320 ± 100 yr BP (BGS-522). The Buffalo Glacier site occurs 13 km west of Atigun Pass at an altitude of 1615 m (Figure 1). This represents the first direct radiocarbon control on Neoglacial moraines in the Brooks Range. The maximum diameter *R. geographicum* on the moraine directly above the site is 20 mm. Thalli of *Alectoria minuscula* here approach diameters of 140 mm.

A date of 800 ± 90 yr BP (BGS-548) was obtained from an exposed peat layer 0.95 m below the surface of an alluvial fan at 1220 m a.s.l. north of Atigun Pass near Alyeska Material Site MS-110.2 on the haul road (Figure 1). Maximum *R. geographicum* diameters of 33 mm were measured on boulders on the fan surface in the vicinity of the dated material.

DENDROCHRONOLOGIC CONTROL

The white spruce tree line is located 15 km south of and 750 m below Atigun Pass along TAPS (Figures 1 and 2). The oldest tree on an alluvial fan there displayed 310 rings; the largest *R. geographicum* thallus of associated boulders was 26 mm in diameter. White spruce ranging from 0.42 to 0.88 m in girth in three small channels on the west side of the Dietrich River provided very consistent ages from 100 to 106 yr; *R. geographicum* in the same channels commonly attained diameters up to 10 mm.

In the Linda Creek placer gold mining area, a white spruce adjacent to a relatively recent shaft tailing pile was 39 yr old. Diameters of the *R. geographicum* on the surrounding stones reached 7 mm.



FIGURE 6. Photograph looking north at radiocarbon site at interface between bedrock and overlying Neoglacial lateral moraine of Buffalo Glacier (see Figure 8). Boulders host *Rhizocarpon geographicum* with maximum diameters of 20 mm.

GROWTH CURVE CONSTRUCTION

Climatic, historic, radiocarbon, direct measurement, and dendrochronologic controls have allowed us to construct an initial *Rhizocarpon geographicum* growth curve for the central Brooks Range (Figure 7). From 0 to 800 yr the curve was fitted among the 10 control points discussed in the preceding paragraphs. All control dates are adjusted to AD 1979, and are given in radiocarbon years on Figure 7. With each radiocarbon date, some estimates of the time lag between death/burial of vegetation and stabilization of the lichen-bearing rock surface had to be incorporated into the curve. This results in the curve being offset to the left (younger part) of the points themselves. Direct *A. minuscula/pubescens* thallus measurements over two growing seasons were extrapolated to assist in constructing the *R. geographicum* curve for the first 400 yr by using the interspecific ratio 7:1 (Table 1).

The lag period between substrate stabilization and initial lichen colonization for the above species is ill defined, but indications of direct measurement from the glacial geologic literature suggest that it ranges from 10 to 50 yr under similar climatic conditions (Webber and Andrews, 1964; Benedict, 1968; Ramp-ton, 1970; Miller and Andrews, 1972; Beschel and Weidick, 1973; and Karlén, 1973). *A. minuscula*, *A. pubescens*, and *R. geographicum* appeared on bedrock and boulder surfaces in the Arrigetch Peaks area between 17 and about 68 yr following glacial retreat (see "Historic Control"). Based on this we have assumed a colonization period of 30 yr, and have incorporated this into the growth curves of Figure 7. A qualitative $\pm 20\%$ age accuracy is shown by the shaded zone about these growth curves (see Miller and Andrews, 1972).

The *R. geographicum* curve from 0 to 800 yr

indicates a great growth period lasting for 200 yr after substrate stabilization, which is followed by linear growth approximating 3 mm per century. This growth curve is extrapolated beyond the 800 ± 90 yr BP radiocarbon date (Figure 7). The linear extrapolation is not based on data from the Brooks Range; it is inferred from measurements of *R. geographicum* obtained in other areas of the world that are controlled by radiocarbon dates ranging from 1050 to 9000 yr BP (see Benedict, 1967; Miller and Andrews, 1972; Denton and Karlén, 1973b; Andrews and Barnett, 1979).

One point of indirect evidence supporting this growth curve extension may be drawn from correlations between Holocene stream terraces and cirque glacier deposits in the east-central Brooks Range. Hamilton (1979, in press) suggests that a relatively mild climatic interval that occurred during middle Holocene time in the central Brooks Range terminated about 4000 yr BP. This was followed by intensification of cold-climate processes, and a significant and radiocarbon-dated episode of terrace alluviation downstream of cirques presently occupied by large ice masses. The oldest Holocene cirque moraines in the region that may be associated with this ~ 4000 yr BP terrace-building, display *R. geographicum* with thallus diameters up to 145 mm (see following section).

Our *R. geographicum* growth curve can be applied with reservation to *R. eupetraeoides/in-arens* for thallus diameters less than 150 mm. The *A. minuscula* growth curve (Figure 7) also represents the *A. pubescens* growth pattern (see Table 1), and can be reliably used for dating deposits up to 400 yr old. This same curve incorporated *Umbilicaria probovscidea*, but this species is useful only for deposits less than 100 yr old (Table 1).

APPLICATION OF THE LICHEN GROWTH CURVES

We have applied lichenometry to our Holocene studies in the Atigun Pass area in a variety of ways, but principally to date glacial and rock-glacier movements above 1500 m altitude during this epoch. The lichen curve has also been applied through field studies to the moraine sequences displayed near Anak-tuvak Pass, and the deposits beyond eight cirque glaciers in the Arrigetch Peaks. The

initial chronology of events extending back in time from contemporary glacial transport through late and middle Holocene glacier fluctuations and moraine-building is summarized below.

Cirque glaciers in the central Brooks Range presently are wasting away, and equilibrium-line altitudes are on the order of 100 m above the glacier heads (Porter, 1966; Ellis and

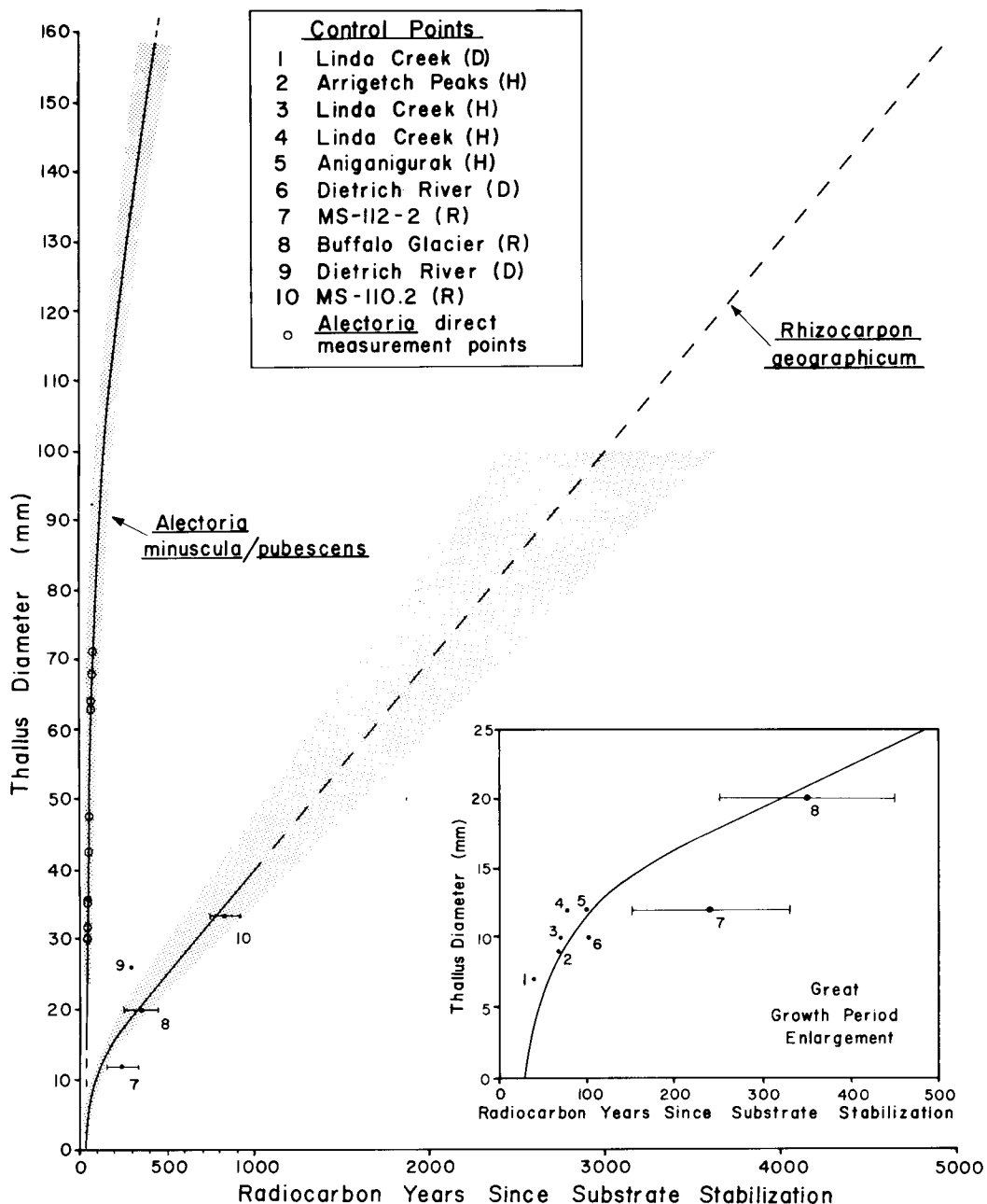


FIGURE 7. *Rhizocarpon geographicum* and *Alectoria minuscula/pubescens* growth curves, central Brooks Range. See Table 1 for interspecific ratio correlation. Shaded zone indicates qualitative $\pm 20\%$ age accuracy for the growth curves. Colonization is assumed to occur 30 yr after substrate stabilization as shown by the growth curve placement. Control points 1-10 are indicated as dendrochronologic (D), historic (H), or radiocarbon (R).

Calkin, 1979). Sharp lichen trimlines occur above the margins of many of these glaciers and, when combined with lichenometric evidence of length expansions, allow three-dimensional reconstructions of former ice masses. This negative regime has prevailed for at least several decades (Sable, 1961; Hamilton, 1965), while the glaciers continue to transport debris from headwalls to their termini.

While mapping the deposits of some 40 receding cirque glaciers, we found that stable supraglacial boulders and glacier-cored medial moraines often were populated by *Alectoria* and *Umbilicaria* taxa, and by *Rhizocarpon geographicum* thalli ≤ 4 mm in diameter (see also Matthews, 1973). These boulders apparently can remain sufficiently stable to permit continued growth of lichens while the glacier masses are progressively shrinking.

Although detailed velocity measurements are not yet available for these glaciers, we have been able to compute mean surface velocity from the lichen data. Twin Glacier (Figure 1) at 2500 m length is the longest glacier in the Atigun Pass field area. A mean velocity of 6 m yr^{-1} has been derived from measurements of the progressive increase in lichen diameter made through a train of supraglacial boulders spread from the headwall 1200 m along a flow line in the middle zone of the glacier. This velocity is compatible with measurements on the 9-km-long McCall Glacier in the eastern Brooks Range (Wendler et al., 1975).

Little evidence is found for supraglacial lichen cover surviving debris redeposition or ridge construction during glacier advances. However, we found evidence at Golden Eagle Glacier in the Atigun Pass area (Figure 1) that lichens may be preserved intact for long periods under active glacier ice (see also Goldthwait, 1960; Beschel, 1961; Falconer, 1966). Recession of the gently inclined toe of Golden Eagle Glacier from distant ridges marked by *R. geographicum* lichen thalli of 14 to 19 mm diameter is exposing a surface about 500 m^2 in area that bears *in situ* dead moss, lichen-covered boulders, and unsorted patterned ground. A ^{14}C age of $1120 \pm 180 \text{ yr BP}$ (BGS-614) has been obtained from the moss at the foot of the boulders. Thalli of *R. geographicum* on these associated boulders attain maximum diameters of 61 to 65 mm, are brightly colored, and indistinguishable from living

lichens. They become progressively deteriorated (apparently with time of exposure) and disappear on the drift within a distance of 20 m away from the glacier snout.

These and other field relations suggest that the moss as well as the *R. geographicum* thalli have been preserved until recently beneath the glacier ice for a period following advance some 1120 yr BP. Although preservation of lichen in a freezing state is possible (Kappen, 1973; W. A. Weber, pers. comm., 1979), the lichen would not have grown beneath the ice; therefore the *R. geographicum* thalli larger than 60 mm diameter suggest that an ice free period of at least 1500 yr (Figure 7) preceded this glacial advance.

Stable, middle to late Holocene (Neoglacial), ice-cemented and ice-cored morainal edges (Østrem, 1964, 1974) can be clearly distinguished by their consistent maximum lichen diameters from unstable glacier-cored rock-glacier deposits. Ages derived from the lichen growth curve do not strictly date the period of maximum glacier advance (Andrews and Barnett, 1979), but rather the onset of glacier retreat from the advanced ice position and stabilization of the ridges constructed.

The lichenometric mapping and analysis of these moraines (e.g., Figure 8) reveal a Neoglacial chronology much more complicated than postulated by previous investigators (Detterman et al., 1958; Porter, 1964, 1966; Hamilton, 1966; Porter and Denton, 1967). At least five glacial expansions are recorded with one of the most extensive advances represented by 20 to 25 mm *R. geographicum* diameters tied by the lichen curve to a period 300 to 500 yr BP (Calkin and Ellis, 1978). The glacier expansions were usually limited to 1.5 times their present-day lengths with the maximum advance being 800 m in the Atigun Pass area. The oldest Neoglacial moraine yet found has *R. geographicum* with maximum diameters of 145 mm, indicative of cirque glacier expansions leading to end moraine construction and stabilization on the order of 4500 yr ago.

Remobilized deposits between ice-cored rock glacier tongues and their parent upslope ice masses, the "transition zones" of Foster and Holmes (1965; Ellis and Calkin, 1979; Johnson, 1980), suggest a history of Neoglacial activity less clear than, but similar to, the stable moraine chronology. Similar lichenometric studies on rock glaciers have been undertaken by C. D. Miller (1973), Birkeland (1973),

Luckman and Osborn (1979), Haeberli et al. (1979), and Johnson (1980). In the central Brooks Range both ice-cemented and glacier-cored rock glaciers display upper surfaces near the snouts with maximum lichen diameters in-

dicative of surface movement and stability back into early Holocene time. However, our lichenometric data indicate that the major glacial expansions in the central Brooks Range were mid- to late-Holocene events.

CONCLUSIONS

(1) Lichenometry has proved to be a useful tool for absolute and relative dating of Holocene glacial deposits in portions of the central

Brooks Range dominated by sandstone, conglomerate, and granite.
(2) *Rhizocarpon geographicum* s.l. is wide-

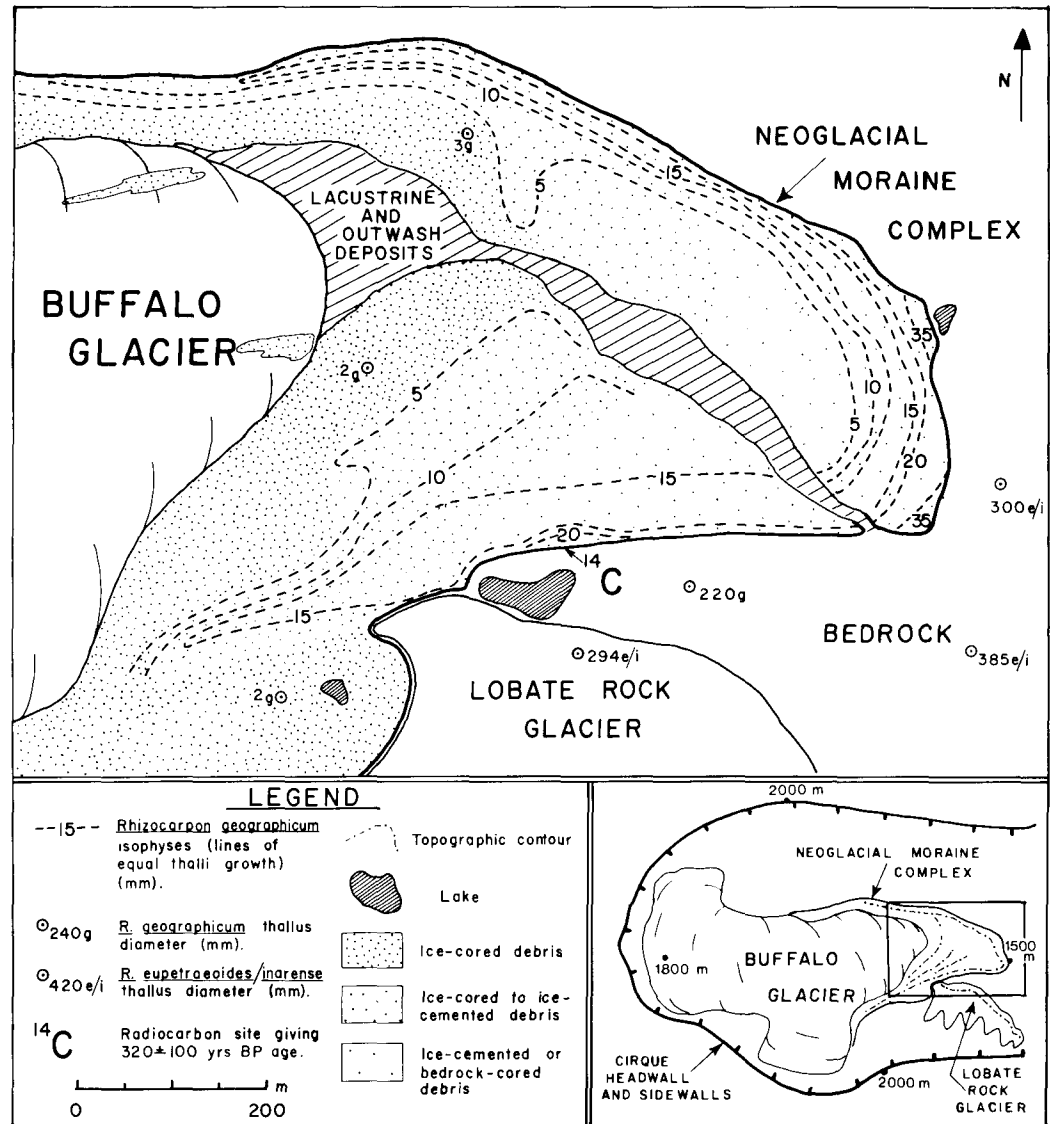


FIGURE 8. Lichenometric map of Neoglacial moraines of Buffalo Glacier (see Figures 1 and 6). Dashed lines (isophyses) connect points bearing *Rhizocarpon geographicum* of equal diameter.

spread in this area, attaining measurable thallus diameters up to 250 mm. *R. eupetræoides/inarensis*, similar crustose species, are also profuse on Holocene surfaces. This group may grow somewhat faster than *R. geographicum* but the general growth pattern of the three species is similar for thalli diameters ≤ 150 mm. The *R. geographicum* curve may be applied with reservation when lichenometrically dating surfaces populated by *R. eupetræoides/inarensis*. Three species, of which *Alectoria minuscula* may be the most useful, grow seven times faster than *R. geographicum*.

(3) Climatic data, and historic, radiocarbon, and dendrochronologic dates, and direct

measurements over a 2-yr period of *A. minuscula/pubescens* were used to define a growth curve for *R. geographicum*. This curve includes a colonization period of 30 yr, a great growth period of about 200 yr, and a long-term linear phase of approximately 3 mm per century. That is, a maximum thallus diameter of 100 mm indicates an age of 3000 yr.

(4) Lichenometric mapping of Holocene glacial deposits has allowed the definition of a sequence of multiple glaciations during the last 4500 yr. It also has been useful as an indicator of stability, and can be used for reconstruction of Holocene ice limits and glacier velocities.

ACKNOWLEDGMENTS

This study was funded by NSF grants DPP-7619575A01 and DPP-789982 through the Research Foundation of State University of New York. Sigma Xi provided support for photographic inventory. We are grateful to W. A. Weber for identification of lichens and to P. J. Webber, J. T. Andrews, and other

personnel of INSTAAR, University of Colorado, for help and encouragement during this study. T. D. Hamilton provided logistical help and, with L. Onesti, M. Bruen, S. Walti, and D. Cooper, aided in the collection of field data.

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