Late-Holocene glaciation and twentieth-century retreat, northeastern Brooks Range, Alaska

Leah H. Evison[1], Parker E. Calkin and James M. Ellis[2]

(Department of Geology, University at Buffalo, Buffalo, New York 14260-1550, USA)

Received 22 November 1993; revised manuscript accepted 5 June 1995

A HOLOCENE RESEARCH PAPER

Abstract: Lichenometric dating of moraines deposited by eight glaciers in the northeastern Brooks Range suggests major glacial advances or stillstands at about 2600, 1000, 450, and 60 lichenometric (L) years BP. The latter two advances of the early-middle and latest part of the 'Little Ice Age', respectively, formed prominent moraines at all glaciers studied. In response to overall twentieth-century warming, these glaciers have retreated at average rates of 2 to 19 m yr^{-1} from the distinct ridges formed in AD 1890. Glacier thinning at rates of 0.7 to 0.9 m yr^{-1} accounts for over 90% of the ice loss.

Key words: Glacier variations, late-Holocene, climatic change, 'Little Ice Age' moraines, neoglaciation, twentieth-century ice retreat, lichenometric dating, Brooks Range, Alaska.

Introduction

The northernmost glaciers in Alaska occur in the northeastern part of the Brooks Range (Figure 1), far inland of their major precipitation source in the Chukchi Sea. The area encompasses the Franklin and Romanzof Mountains that include the highest peaks in the Brooks Range (Figure 2) and the largest glaciers of Arctic Alaska (Meier *et al.*, 1971). Together with over 300 smaller subpolar cirque and valley glaciers, these glaciers provide the most complete records for glacier study in the northern part of the state.

Okpilak Glacier is the largest single glacier (9 km^2), and with other surrounding glaciers has been the subject of periodic investigation and ground photography since AD 1907 (Leffingwell, 1919). In addition, glaciologic and glacial geologic observations of varying detail have been undertaken at this and neighbouring glaciers over several intervals since the 1940s and 1950s (e.g., Dorrer and Wendler, 1976; Holmes, 1965; Sable, 1961; Trabant and Benson, 1986; Wendler and Weller, 1974).

The objectives of our study were to date the sequences of Holocene advances or stillstands represented by moraines on eight selected glacier forefields (Figure 2) using lichenometry, and to examine twentieth-century patterns of retreat for these glaciers based on fieldwork and aerial photography. The importance of this study hinges in part on the fact that these glaciers occur in the Arctic where the effects of past and future global climate change may be most pronounced (Houghton *et al.*, 1990). Furthermore, while the glaciers of the northeastern Brooks Range are among those with the lowest activity indices in the United States (Meier *et al.*, 1971), their responses to any major climatic changes should be marked (Paterson, 1980). Rabus *et al.* (1995) present additional data on marginal retreat (and downwasting) of the McCall Glacier in the northeastern Brooks Range. Calkin (1988) summarized the Holocene mountain glaciation in Alaska and northwestern Canada.

Physical and climatological setting

We mapped Holocene forefield deposits of eight small valley glaciers on the north flank of the mountains during July 1981. Five of the glaciers are in the headwaters of the Okpilak River including Okpilak and its tributary glaciers designated here as Ok-5, Ok-6, Ok-9 and Ok-10. The remaining three are the Leffingwell and Esetuk Glaciers, about 15 km to the north, and the smaller Chamberlin Glacier, about 35 km to the northeast of Okpilak Glacier. All these glaciers occur at mean altitudes between 1800 and 2200 m a.s.l., range in length from about 1.5 to 9 km and, like most mountain glaciers in Alaska, are rapidly wasting away from the limits reached during their pre-twentieth century ('Little Ice Age') expansions (Table 1).

Because the studied glaciers lie on the boundary between the

[1] Present address: Evison (née Haworth), US Environmental Protection Agency, 77 West Jackson Blvd., Chicago, IL 60604.

[2] Present address: Chevron Overseas Petroleum, Inc., 6001 Bollinger Canyon Rd., San Ramon, California 94583.

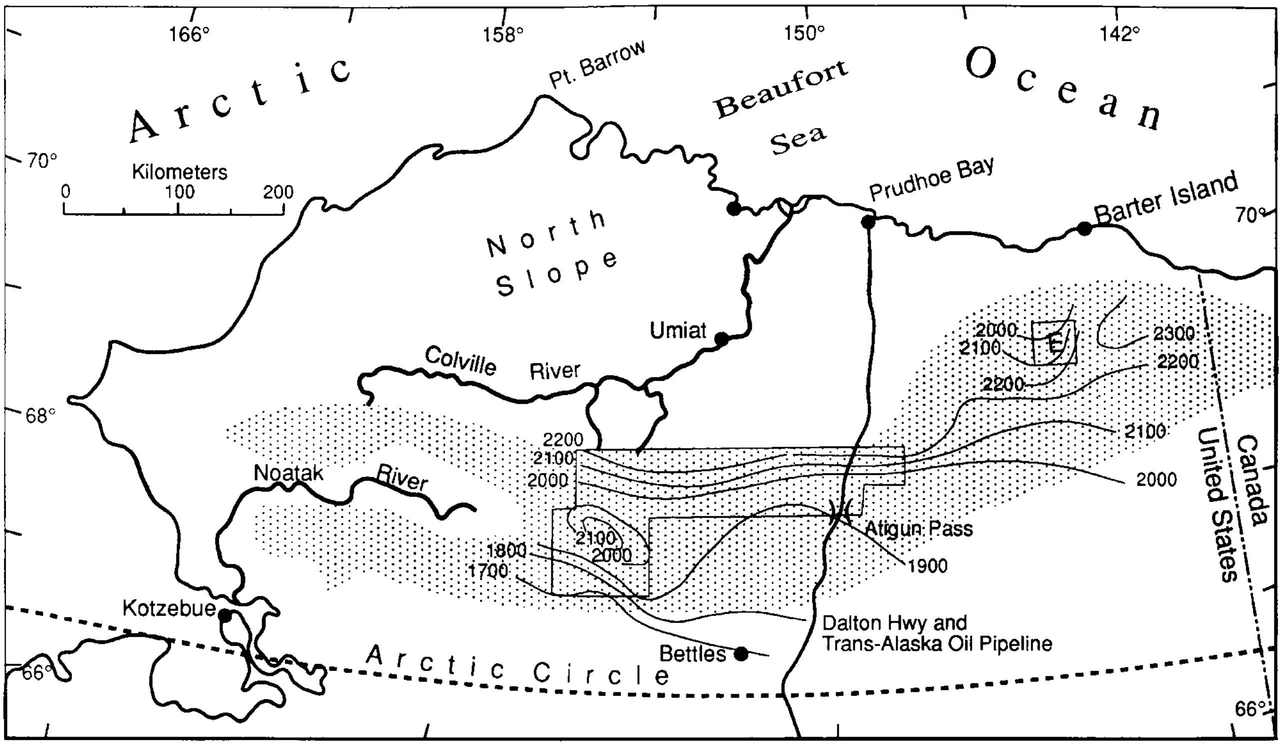

Figure 1 Location map showing the northeastern Brooks Range research area (NE) and our other research areas in the central Brooks Range. Stippled pattern represents area covered by the Brooks Range. Modern glaciation thresholds with contours in meters taken from Porter *et al.* (1983).

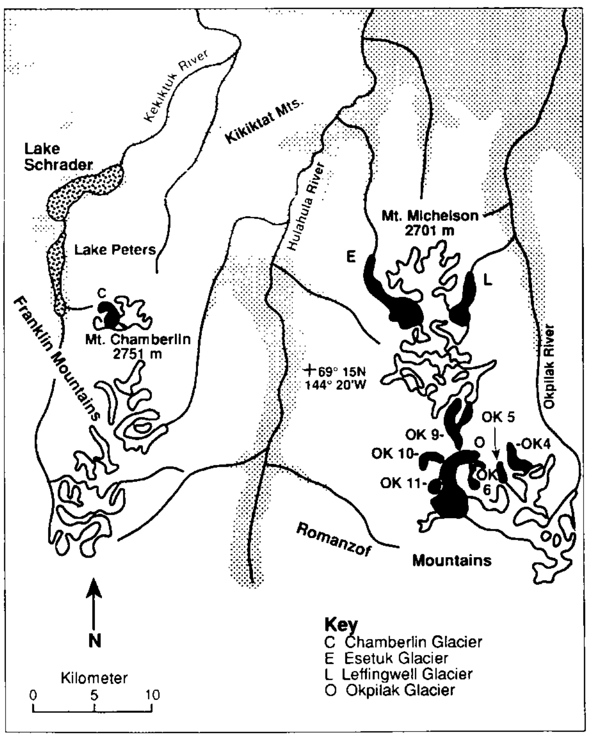

Figure 2 Location map of the research glaciers (black) in the northeastern Brooks Range. Map area is shown on Figure 1 as (NE).

continental climate of interior Alaska and the Arctic climate of the north slope, the local climatic regime differs from that of the nearest recording stations of Arctic Village (about 110 km to the south) and Barter Island (110 km to the north) (Figure 1). However, meteorological and glaciological data are available for various intervals between 1957 and 1972 from McCall Glacier (Figure 2), about 15 km to the northeast of Okpilak Glacier (e.g., Wendler *et al.*, 1975; Trabant and Benson, 1986). Surveys in 1993 have also allowed a summary of 1972 to 1993 mass balance changes (Rabus *et al.*, 1995). Some data are available from Chamberlin Glacier for July and August of 1958 (Larsson, 1960). Mean annual temperature at 1700 m on McCall Glacier is about −12°C (Trabant *et al.*, 1975) with maximum summer-ablation season temperatures for June, July and August about 0.5°C, 3.8°C, and 1.3°C respectively (Wendler and Weller, 1974).

Measurements from 1969 through 1972 indicate that mean annual precipitation at 2275 m in the accumulation zone of the McCall Glacier is about 500 mm (Wendler *et al.*, 1975). Almost daily precipitation during the summer, some of it snow that retards ablation, contributes to this total. The major sources of precipitation in the Brooks Range as a whole are moist air masses that originate over the Bering and Chukchi Seas, 1000 km to the west, and follow cyclonic storm tracks to the northeast. As a result, glaciation thresholds rise northward and locally eastward across Alaska and reach a maximum in the study area (Figure 1). Summer precipitation from sea ice surface melt and open water at the margin of the Beaufort Sea to the north may be of minor importance in the mass balance of the study glaciers. Glaciation thresholds in the northeastern Brooks Range follow the topography and rise from both north and south toward the continental divide (Figure 1; Larsson, 1960; Fahl, 1973; 1975; Porter *et al.*, 1983).

The mean orientation of 300 cirques occupied by glaciers in the northeast Brooks Range has an azimuth of 005° (Haworth, 1988). Thus, the majority of the glaciers face away from the sun at the time of higher afternoon temperatures. Glaciers in the north-facing cirques are, on average, 85 m lower than those in south-facing cirques. Screening by mountain slopes also modifies the heat budget by reducing direct solar radiation. The study glaciers generally follow these trends of orientation and screening (Table 1).

The present conditions of the study glaciers can be illustrated by the estimates and measurements of mean annual mass balance of the McCall Glacier; these fall between −100 mm and −350 mm of water equivalent for the 1958 through 1971 period (Wendler *et al.*, 1975; Dorrer and Wendler, 1976). These values are compa-

Table 1 Altitudes, dimensions, solar exposure and twentieth-century retreat of northeastern Brooks Range glaciers

Glacier	Mean Alt.[a] (m)	Area (km)	Length (km)	Mean orientation ablation zone[b]	Radiation at ice toe (%)/moraine toe (%)[d]	Period of retreat record	Retreat (m)	Retreat rate (m yr^{-1})	Total period[e] retreat (m)	Mean period[e] retreat rate (m yr^{-1})	Total period[e] area loss (%)
Chamberlin	2210	1.44	2.91	W	80/92	(L)*c*.1900–1950	520	10	620	8	7
						1950–1958	50	6			
						1958–1981	50	2			
Esetuk	1950	5.38	6.59	NNW	74/80	(L)1910–1947	410	11	1330	19	6
						1947–1956	70	8			
						1956–1981	850	34			
Leffingwell	1845	4.96	6.15	N	58/73	(L)1890–1948	260	5	660	7	3
						1948–1955	150	21			
						1955–1981	250	10			
Okpilak	1220	9.12	8.74	E	91/92	(L)1890–1907	120	7	1180	13	3
						1907–1950	580	14			
						1950–1956	30	5			
						1956–1981	450	18			
Ok-4	2011	0.70	2.50	N	–	1907–1956	150	3	390	5	15
						1956–1981	240	10			
Ok-5	2090	3.03	4.94	N	63/83	(L)1920–1981	490	6	490	8	2
Ok-6	1950	0.48	1.58	N	81/–	(L)1890–1907	60	4	150	2	3
						1907–1956	70	1			
						1956–1981	20	1			
Ok-9	2000	1.89	3.86	SSE	–	(L)1900–1956	320	6	490	6	3
						1956–1981	170	7			
Ok-10	2045	0.65	2.28	SE	–	(L)1900–1907	30	4	490	6	10
						1907–1950	240	6			
						1950–1956	60	10			
						1956–1981	160	6			

[a] Altitudes and dimensions are from 1955–56 topographic maps.
[b] Orientation in 1981 in 2.5° segments (16 points of compass).
[c] Indicates date from lichenometry.
[d] Radiation available to horizontal surface at 1981 ice toe and Holocene moraine toe, both adjusted for topographic screening, as percentages of that theoretically available without topographic screening at same latitude.
[e] For total period of retreat record indicated (e.g., 1900 to 1981 for Chamberlin Glacier).

rable to the work of Rabus *et al.* (1995) who measured a mean mass balance of −330 mm ± 10 mm water equivalent for the succeeding 1972 to 1993 period. The equilibrium line altitude of the McCall Glacier is estimated by Rabus *et al.* (in press) at about 2100 m, similar to those at Chamberlin (Larsson, 1960) and Okpilak Glaciers (Sable, 1961) in 1958. The activity index of McCall Glacier is 2, which is the lowest of a set of representative glaciers across Alaska (Meier and Post, 1962). The extent of twentieth-century retreat of the McCall Glacier is comparable to most land-terminating glaciers throughout Alaska (Calkin *et al.*, 1985; Calkin, 1988; Rabus *et al.*, 1995).

Lichenometric dating of moraines

Woody material is scarce in the northeastern Brooks Range study area because the area is north of the tree-line and within the tundra zone. Therefore, we used lichenometric techniques and a calibrated lichen growth curve developed along the Dalton Highway corridor that crosses the central Brooks Range 250 km to the southwest (Calkin and Ellis, 1980; 1984; Figures 1 and 3; Table 2) to date the Holocene moraine ridges in the study area. The central Brooks Range curve is thought to be based primarily on *Rhizocarpon geographicum*; however, because some other species of the *Rhizocarpon* subgenus (Thompson, 1979) may have been unavoidably included, Calkin and Ellis (1980) referred to the lichens as *R. geographicum sensu lato* (s.l.). In particular, it is likely that some very small and medium-sized *R. eupetraeoides* and *R. inarense*, which are grouped in the section *Alpicola*, may be included in our measurements. Field differentiation of these species from *section Rhizocarpon* taxa (that include *R. geographicum*) at various growth stages is difficult (e.g., see discussion by Innes, 1982; Benedict, 1988; Haworth, 1988).

Calkin and Ellis (1984) extrapolated the lichen growth curve linearly beyond a 1300 ± 100 BP ^{14}C age, based on measurements of the aggregated species in other parts of the world with climate similar to that of the Brooks Range and on correlations of thallus diameters of 145 mm with deposits about 4500 years old in the Brooks Range. Redrafting the Calkin and Ellis (1980; 1984) lichen curve using calibrated radiocarbon ages (Stuiver and Reimer, 1993) suggests that the curve may overestimate by 20% the ages of lichen over 20 mm in diameter; however, because the curve is only partly based on radiocarbon ages, we do not at this time think it is justified to change the curve.

Lacking corroborative control points for the lichen curve in the northeastern Brooks Range area, we have argued elsewhere (e.g., Haworth *et al.*, 1983; Haworth, 1988) that climatic differences between the Dalton Highway (central Brooks Range) sites and the Franklin-Romanzof Mountains sites are negligible (Wendler and Weller, 1974; Calkin *et al.*, 1985). Furthermore, the altitudinal distribution and corresponding climatic environments of the central Brooks Range sites, where control points were obtained, are

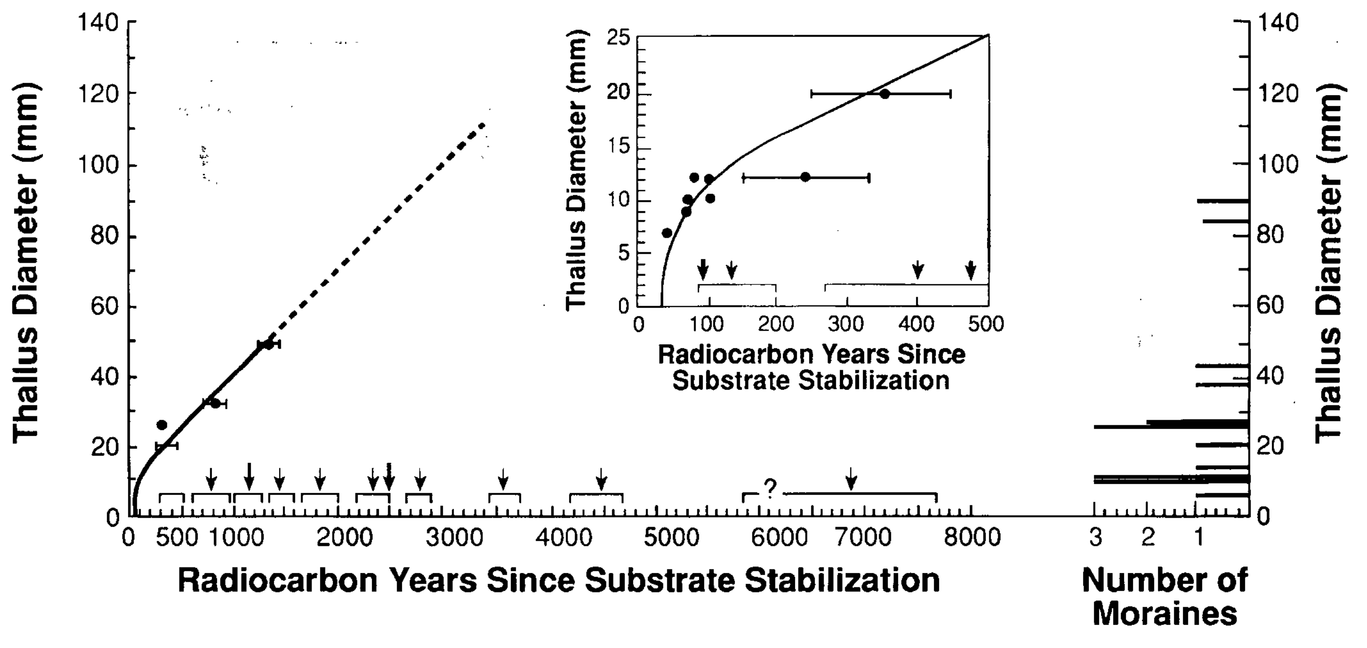

Figure 3 Frequency histogram (on right) of *Rhizocarpon geographicum* s.l. maximum diameters from moraines of eight small glaciers of the northeastern Brooks Range with lichen growth curve. Long and bold arrows show mean moraine stabilization times from this data set (Table 2). Brackets and short arrows show grouped data with respective mean stabilization times from moraines of 97 small glaciers across the northeastern and central Brooks Range (boxed areas of Figure 1). Curve is not fixed to a given date; subtract difference between 1950 and date of lichen measurement from curve reading to get radiocarbon years before 1950 (Calkin *et al.*, 1985). For example, the lichens of the histogram were measured in 1981, therefore 31 years must be added to the ages indicated by the long and bold arrows to get the yr BP ages of Table 2.

Table 2 Mean of the five largest *Rhizocarpon geographicum* s.l. lichen diameters and local correlation of moraines, northeastern Brooks Range

Glacier	Lichen	Diameters		(mm)
Esetuk	**13**	**26**		
Leffingwell	**11**	**25**		**90**
Chamberlin	**10**	20	43	85
Okpilak	**11**	**25**		
Ok-5	**7**	**26**		
Ok-6	**11**			
Ok-9	**10**	25	38	
Ok-10	10			
Group mean (mm)	10.4	25.5	40.5	87.5
Lichen age (yr BP)	60	453	987	2553

wider than those of the Holocene glacier moraines dated by this method throughout the Brooks Range, including those of this study.

We estimate that the dating error inherent in the Brooks Range lichenometry is about 15% to 20%, a range suggested for single lichenometric dating curves in southern Norway (Bickerton and Mathews, 1992). The ages of the moraines in the study area were based on the mean of the five largest Section *Rhizocarpon (Rhizocarpon geographicum* s.l.) lichen diameters measured on correlative ridges of each glacier forefield. We refer to dates based on lichenometry on Table 1 and elsewhere in this paper with '(L)'.

Late-Holocene glacier advances

We correlated moraines deposited by each of the eight glaciers in the study area (Figure 2) based on the largest mean lichen diameters (Table 2). As can be seen in the generalized moraine maps of Figure 4, single lichen maxima sometimes varied greatly along a single moraine ridge. Table 2 lists the mean of the five largest lichens along correlated moraine ridges. The ages for these mean lichen diameters and associated moraines are derived from the lichen growth curve (Figure 3). These data are compared to grouped data from these glaciers and 89 small glaciers in the central Brooks Range to the west (Figure 3; Ellis and Calkin, 1984; Calkin, 1988; Haworth, 1988). The lichen data yield minimum ages of moraine stabilization or initial ice margin retreat from moraines produced by distinct readvances or stillstands that occurred as much as 1.3 km downvalley from present active glacier margins. In the northeastern Brooks Range, such events occurred at 2553, 987, 453 and 60 (L) years BP (before 1950) as determined from the lichen curve (Figure 3), or, given the probable error in these ages, at about 2600, 1000, 450 and 60 (L) years BP.

We differentiated the oldest Holocene moraines at Chamberlin and Leffingwell Glaciers into 4 and 3–5 glacier events respectively (Figure 4; Table 2). The toe of the Chamberlin Glacier moraine forefield displays evidence of rock glacier remobilization. The outer terraced slope shows maximum lichen diameters of 95 mm, while a distinct inner ridge was host to lichen with diameters of about 45 mm. Just upslope of this deposit were two very closely associated ridges characterized by lichens averaging 20 and 10 mm respectively (Figure 4). Holmes and Lewis (1961), Holmes (1965), and Reed (1968) recognized a maximum of three distinct Holocene glacier advances at Chamberlin Glacier that they grouped together as their 'Katak Glaciation'.

In the Leffingwell Glacier forefield, a closely nested set of three very short moraine ridges at the toe display mean maximum lichen diameters of about 90 mm, about 50 mm, and 25 mm (Figure 4); these are truncated upslope by many more persistent and long ridges of younger advances. We are confident that the moraines characerized by the 90-m and 25-mm-diameter lichen, as well as one with 11-mm-diameter lichen, represent distinct glacier advances or long stillstands.

Moraines characterized by 45-m to 50-mm-diameter lichen are

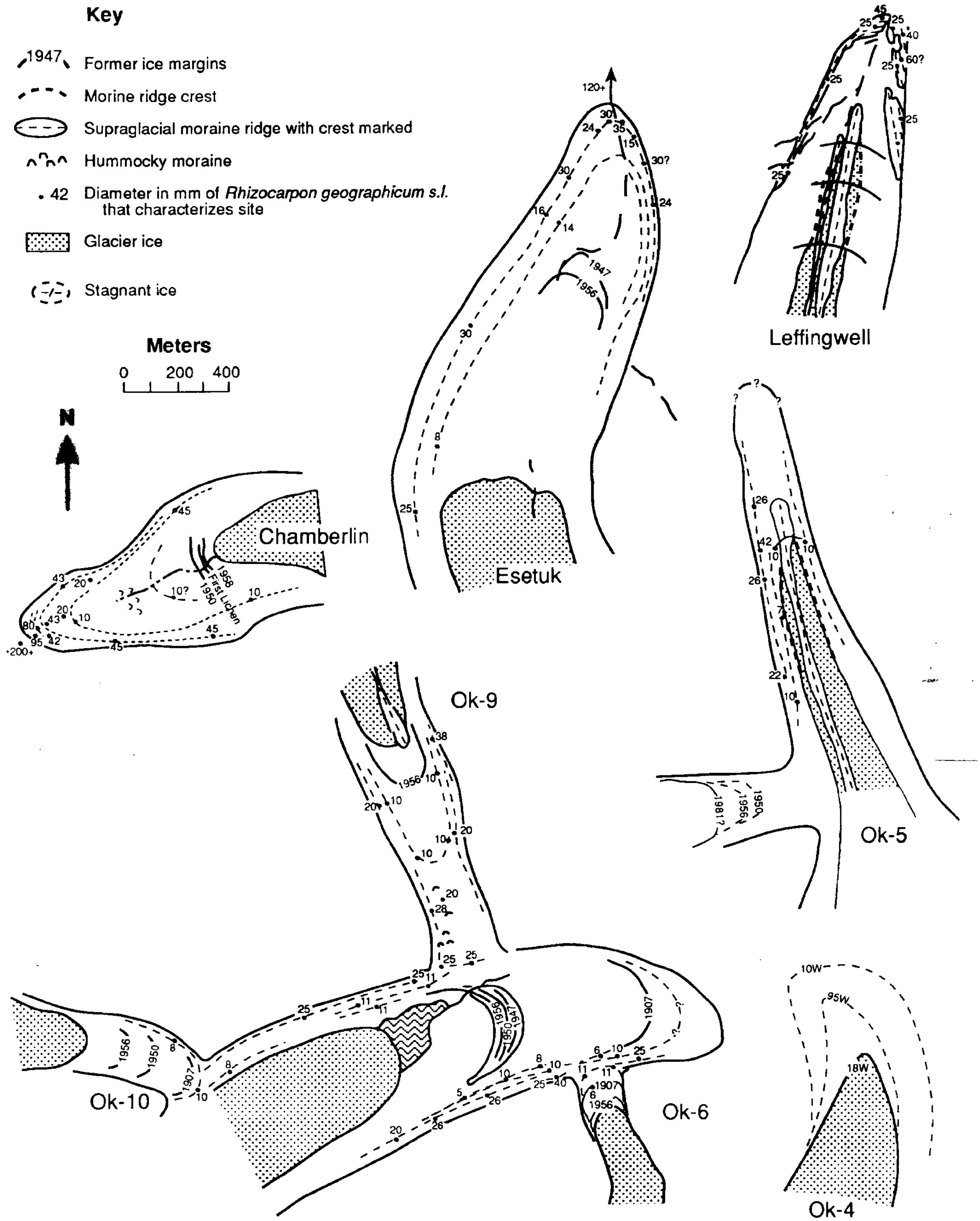

Figure 4 Generalized moraine maps showing the distribution of representative single maximum lichen diameters in the glacier forefields studied in the northeastern Brooks Range. Outer solid lines represent the outer margin of Holocene moraine deposits. See Table 2 for mean of five largest lichen along correlated moraine ridges.

evident at Chamberlin and Ok-9 glaciers, in addition to the less distinct moraine with lichens of this size at Leffingwell Glacier. This suggests that an advance or stillstand at about 1000 (L) years BP may have been widespread in the northeastern Brooks Range.

The most complete evidence of glacier expansion is based on sets of moraine ridges marked by 20-m to 26-mm-diameter, and 7-m to 13-mm-diameter lichen present at all of the major ice tongues (Table 2). Together these moraines dominate the margins of

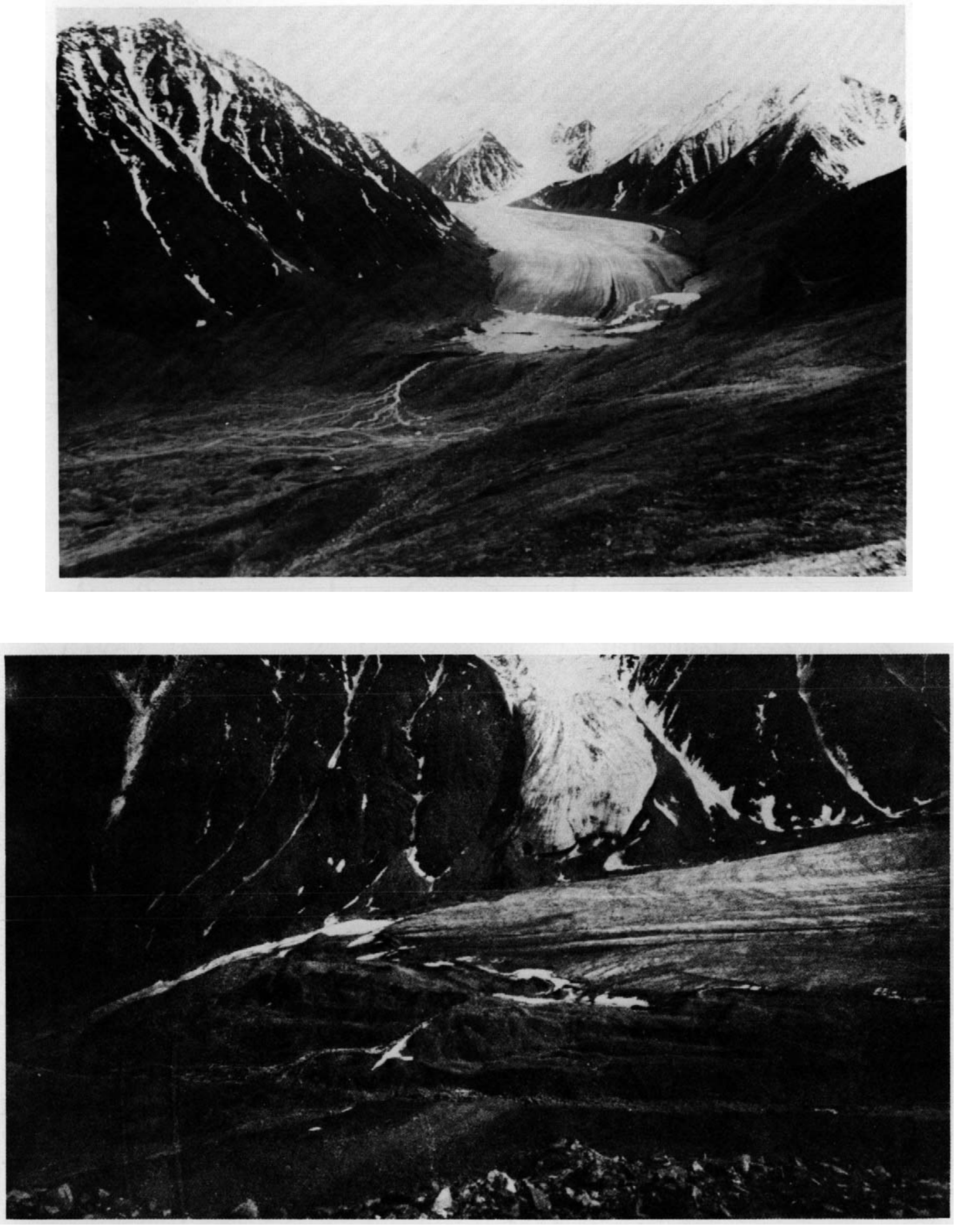

Figure 5 Views of Okpilak Glacier (terminus). (a) Top photograph southeastward in 1907 by Leffingwell (1919) also shows terminus of Ok-6 on opposite wall. (b) Bottom photograph from same position looking southwestward in July 1981 after retreat of 1060 m. Ok-6 lies out of view to the left.

Holocene deposits associated with Esetuk Glacier, Leffingwell Glacier, Chamberlin Glacier, Okpilak Glacier, and associated Ok-5 and Ok-9 (Table 2; Figure 4). Deposition of the older of the two ridges, dated at about 450 (L) years BP, generally represents the most extensive period of Holocene glacier expansion in the Brooks Range (Ellis and Calkin, 1984; Calkin, 1988). In the northeastern Brooks Range, moraines of this readvance are similar in size and distance from the present ice terminus to those formed during the succeeding event at about 60 (L) years BP, or about AD 1890. These two advances occurred during the 'Little Ice Age', generally dated between about AD 1200 and 1850 (Grove, 1988; Bradley and Jones, 1992).

Glaciers in the central Brooks Range, southwest of the study area, readvanced little, if at all, during the late nineteenth-century episode of glacial readvances that is ubiquitous in the northeastern Brooks Range (Calkin, 1988; Haworth, 1988). The more recent glacier activity in the northeastern mountains may be related to Bering Sea moisture sources, which may cause the southward-rising glaciation thresholds here (Figure 1). In addition, this area is higher, farther north, and perhaps colder than areas to the southwest. Finally, more extensive latest Holocene glacier advances in the northeastern Brooks Range may have overridden earlier Holocene moraines which remain exposed in the central Brooks Range (Haworth, 1988).

Twentieth-century glacier retreat

Historical ground photographs, aerial photographs, and lichenometry allow us to reconstruct glacial retreat for the eight valley glaciers discussed above, and another designated Ok-4 (Figure 4), from the ubiquitous late nineteenth-century moraines to 1981 (Table 1). Leffingwell (1919) first examined many of these glaciers and their deposits in 1907; he also photographed some glaciers such as Okpilak. Whittington and Sable (1948) photographed snout positions of the Leffingwell Glacier and others from the ground in the late 1940s. In 1958, Sable (1961) documented recession and thinning of the Okpilak Glacier that had occurred since Leffingwell's visit. Holmes and Lewis (1961) photographed the terminus of Chamberlin Glacier in 1958; Reed (1968) again photographed this ice margin in 1960. Aerial photographs obtained by the US Geological Survey also record glacier margin positions by a series of low-angle oblique photographs taken in July 1947, August 1950 and August/September 1956, and by a series of vertical photographs taken in 1955 and 1956. Ground photographs taken of the study glaciers in 1981 are available from Parker Calkin at the University at Buffalo. The photographs in Figure 5 show the terminus of Okpilak Glacier in 1907 (Leffingwell, 1919) and in 1981.

Comparisons between late nineteenth-century terminus positions based on the most recent lichen-dated moraine and the 1981 terminus positions suggest that the glaciers of this study have retreated upvalley about 150 to 1330 m, losing 2–15% of their total surface area (Table 1). The average rate of marginal retreat during this period varies from 2 to 19 m yr^{-1}. Despite this large upvalley retreat, the altitude of trimlines estimated from photographs of Chamberlin, Okpilak and Esetuk Glaciers indicates that glacier thinning accounts for over 90% of net ice loss. Average rates of thinning over the past century for these glaciers are between 0.7 and 0.9 m yr^{-1}. These thinning estimates appear to be supported by comparable measurements obtained at the McCall Glacier by precision optical and GPS profiles for the 1972 to 1993 period (Rabus *et al.*, in press).

All the glaciers we have studied in the northeastern Brooks Range have retreated significantly since the beginning of the century; however, there is no simple pattern of variation in retreat rates on a decadal scale (Figure 6). Since the 1950s, four glaciers have in general increased their recession rates (Esetuk, Leffingwell, Okpilak and Ok-4), three have maintained relatively unchanging rates (Ok-6, Ok-9 and Ok-10), and retreat at Chamberlin Glacier has slowed.

Our historical record of the studied glaciers broadly parallels the temperature record compiled for the Arctic between 1881 and 1981 (Kelly and Jones, 1981; Kelly *et al.*, 1982) and compiled for Alaska from 1875 to 1965 by Hamilton (1965). There is much less information available about precipitation changes in northern Alaska during this period. Like glaciers elsewhere in the Brooks Range (Calkin, 1988), the small valley glaciers of this study appear to have readvanced quickly in response to lower temperatures in the last few decades of the nineteenth century. At the turn of the century, the Arctic experienced a warming interval with mean annual temperatures increasing 0.7°C (Kelly and Jones, 1981). This initiated retreat from distinct end moraines, which at six glaciers were nested behind those of the main 'Little Ice Age' moraine. At Ok-6 and Ok-10 tributary glaciers, these moraines represented the earliest separation from the main glacier. Our retreat record in this study is not detailed enough to warrant fruitful correlations with temperature records (or precipitation records, for the few periods for which they are available) on a decadal scale, but may help broaden knowledge of glacial recession in Arctic Alaska which are ongoing in more detail at a few locations, such as McCall Glacier.

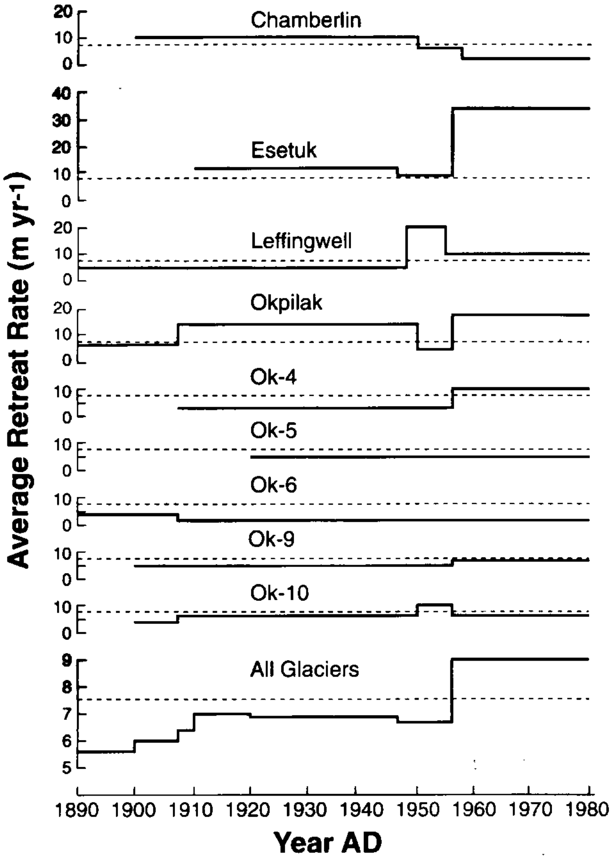

Figure 6 Average retreat rates of nine northeastern Brooks Range glaciers, individually and as a composite, between 1890 and 1981, as tabulated in Table 1. Dashed line indicates 7.5 m yr^{-1}, the average retreat rate for the nine glaciers for the study period as a whole (1890 to 1981).

Summary and conclusions

The glaciers of the northeastern Brooks Range are among the least active in the United States because they are remote from major precipitation sources. They are apparently maintained by their low radiation budgets, high altitudes and possibly by their proximity to sources of summer precipitation along the margin of the Beaufort Sea. They are presently wasting away at rates comparable to other glaciers in Arctic Alaska.

Lichenometric dating of end moraines formed by four of Arctic Alaska's largest glaciers, and by four former tributaries of one of these tongues, suggests that readvances or significant ice margin stillstands occurred about 2600, 1000, 450 and about 60 (L) years BP. The most recent two events were the most prominent; the ~1890 AD (60 (L) years BP) advance or stillstand was recorded at all eight of the studied glaciers. Almost certainly, these last two events, and probably earlier ones, have obscured significant evidence of climatic change by overriding older moraines; hence it is also useful to view the Brooks range record as a whole.

A distinctive record of ice-margin retreat in northeastern Alaska has been documented here for the first eight decades of the twentieth century. Recession rates have varied greatly among the northeastern Brooks Range glaciers. Studies of trimlines suggest that up to 90% of the net ice loss may be due to glacier thinning. Lateral losses, which are usually easier to measure, are greatest for the larger glaciers and reached a long-term maximum of 19 m yr^{-1} at the margin of Esetuk Glacier. Ice-margin retreat rates are generally compatible with twentieth-century warming in the Arctic. Because a twentieth-century chronology has been established, further monitoring of these and surrounding high Arctic mountain glaciers will be better able to provide clues to future global climate change.

Acknowledgements

Parker E. Calkin and James M. Ellis conducted fieldwork for this study in 1981, supported by National Science Foundation Grant DPP7819982. We thank Douglas Von Brock for field assistance, and Edward G. Sable for loan of photographs. We are also indebted to three reviewers whose comments helped us to improve the manuscript, and to Barnhard Rabus who provided access to new data on McCall Glacier as well as comments on the manuscript. This paper does not necessarily reflect the views of the US Environmental Protection Agency and no official endorsement should be inferred.

References

Benedict, J.B. 1988: Techniques in lichenometry: identifying the yellow Rhizocarpons. *Arctic and Alpine Research* 20, 285–91.

Bickerton, R.W. and **Mathews, J.A.** 1992: On the accuracy of lichenometric dates: an assessment based on the 'Little Ice Age' moraine sequence of Nigardsbreen, Southern Norway. *The Holocene* 2, 227–37.

Bradley, R.S. and **Jones, P.D.** 1992: *Climate since* AD 1500. London: Routledge, 679 pp.

Calkin, P.E. 1988: Holocene glaciation of Alaska (and adjoining Yukon Territory, Canada). *Quaternary Science Reviews* 7, 159–84.

Calkin, P.E. and **Ellis, J.M.** 1980: A lichenometric dating curve and its application to Holocene glacier studies in the central Brooks Range, Alaska. *Arctic and Alpine Research* 12, 245–64.

——1984: Development and application of a lichenometric dating curve, Brooks Range, Alaska. In Mahaney, W.C., editor, *Quaternary dating methods*, Stroundsberg, Pennsylvania: Milo Dowden, 227–46.

Calkin, P.E., Ellis, J.M., Haworth, L.A. and **Burns, P.E.** 1985: Cirque glacier regime and neoglaciation, Brooks Range, Alaska. *Zeitschrift für Gletscherkunde und Glazialgeologie* 21, 371–78.

Dorrer, E. and **Wendler, G.** 1976: Climatological and photogrammetric speculations on mass-balance changes of McCall Glacier, Brooks Range, Alaska. *Journal of Glaciology* 17, 479–90.

Ellis, J.M. and **Calkin, P.E.** 1984: Chronology of Holocene glaciation, central Brooks Range, Alaska. *Geological Society of America Bulletin* 95, 897–912.

Fahl, C.B. 1973: Relationships between glaciers and climate in Alaska. PhD dissertation, University of Alaska, Fairbanks, 191 pp.

——1975: Mean sea level pressure patterns relating to glacier activity in Alaska. In Weller, G. and Bowling, S.A., editors, *Climate of the Arctic: twenty-fourth Alaska Science Conference Proceedings*, Fairbanks, Alaska: Geophysical Institute, University of Alaska, 339–46.

Grove, J.M. 1988: *The Little Ice Age*. London: Methuen.

Hamilton, T.D. 1965: Alaskan temperature fluctuations and trends: an analysis of recorded data. *Arctic* 18, 105–17.

Haworth, L.A. 1988: Holocene glacial chronologies of the Brooks Range, Alaska, and their relationships to climate change. PhD dissertation, State University of New York at Buffalo, 260 pp.

Haworth, L.A., Calkin, P.E. and **Ellis, J.M.** 1983: Glacier recession through the twentieth century, northeastern Alaska. *Geological Society of America Abstracts with Programs* 15, 593.

Holmes, G.W. 1965: Quaternary geology of the Mount Chamberlin area, Brooks Range, Alaska. *US Geological Survey Bulletin* 1201-B, 32 pp.

Holmes, G.W. and **Lewis, C.R.** 1961: Glacial geology of the Mount Chamberlin area, Brooks Range, Alaska. In Raasch, G.O., editor, *Geology of the Arctic*, Volume 2, Toronto: University of Toronto Press, 848–64.

Houghton, J.T., Jenkins, G.J. and **Ephraums, J.J.** 1990: *Climate change – the IPCC scientific assessment*. New York: Cambridge University Press, 194–237.

Innes, J.L. 1982: Lichenometric use of an aggregated *Rhizocarpon* 'species'. *Boreas* 11, 53–57.

Kelly, P.M. and **Jones, P.D.** 1981: Annual temperatures in the Arctic, 1881–1981. *Climate Monitor* 10, 122–24.

Kelly, P.M., Jones, P.D., Sear, C.B., Cherry, B.S.G. and **Tavakol, R.K.** 1982: Variations in surface air temperatures: Part 2. Arctic regions, 1881–1980. *Monthly Weather Review* 110, 71–83.

Larsson, P. 1960: A preliminary investigation of the meteorological conditions on the Chamberlin Glacier, 1958. *Arctic Institute of North America Scientific Report 2*, 88 pp.

Leffingwell, E. deK. 1919: The Canning River region, northeastern Alaska. *US Geological Survey Professional Paper 109*, 251 pp.

Meier, M.F. and **Post, A.S.** 1962: Recent variations in mass net budget of glaciers in western North America. *International Association of Scientific Hydrology* 58, 63–77.

Meier, M.F., Tangborn, W.V., Mayo, L.R. and **Post, A.S.** 1971: Combined ice and water balances of Gulkana and Wolverine glaciers, Alaska and South Cascade glacier, Washington, 1965 and 1967 hydrologic years. *US Geological Survey Professional Paper 715-A*, 23 pp.

Paterson, W.S.B. 1980: *The Physics of Glaciers*, second edition. Oxford: Pergamon, 380 pp.

Porter, S.C., Pierce, K.L. and **Hamilton, T.D.** 1983: Late Wisconsin glaciation in the western United States. In Porter, S.C., editor, *Late Quaternary environments of the United States, Volume 1, the Late Pleistocene*, Minneapolis: University of Minnesota Press, 71–111.

Rabus, B., Echelmeyer, K., Trabant, D. and **Benson, C.** 1995: Recent changes of McCall Glacier, Alaska. *Annals of Glaciology* 21, 231–99.

Reed, B.L. 1968: Geology of the Lake Peters area, northeastern Brooks Range, Alaska. *US Geological Survey Bulletin 1236*.

Sable, E.G. 1961: Recent recession and thinning of Okpilak Glacier, northeastern Alaska. *Arctic* 14, 176–87.

Stuiver, M. and **Reimer, P.J.** 1993: Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35, 215–30.

Thompson, J.W. 1979: *Lichens of the Alaska Arctic Slope*. Toronto: University of Toronto Press, 314 pp.

Trabant, D.C. and **Benson, C.S.** 1986: Internal accumulation and superimposed ice on McCall Glacier, Alaska; part of the IHD Glacier Mass Balance Program. *Glaciological Researches No. 58*. Moscow: Soviet Geophysical Committee, Academy of Sciences of the USSR.

Trabant, D.C., Harrison, W.D. and **Benson, C.** 1975: Thermal regime of McCall Glacier, Brooks Range, northern Alaska. In Weller, G. and Bowling, S.A., editors, *Climate of the Arctic: twenty-fourth Alaska Science Conference Proceedings*, Fairbanks, Alaska: Geophysical Institute, University of Alaska, 347–49.

Wendler, G. and **Weller, G.** 1974: A heat-balance study of McCall Glacier, Brooks Range, Alaska: a contribution to the International Hydrological Decade. *Journal of Glaciology* 13, 12–25.

Wendler, G., Benson, C., Fahl, C., Ishikawa, N., Trabant, D.C. and **Weller, G.** 1975: Glacio-meteorological studies on McCall Glacier. In Weller, G. and Bowling, S.A., editors, *Climate of the Arctic: twenty-fourth Alaska Science Conference Proceedings*, Fairbanks, Alaska: Geophysical Institute, University of Alaska, 334–38.

Whittington, C.L. and **Sable, E.G.** 1948: Preliminary geologic report of the Sadlerochit River area, Geologic Investigations in Naval Petroleum Reserve No. 4, Alaska, Preliminary Report 20. *US Geological Survey Open File Report*.