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GEOMORPHOLOGICAL MAP LEGENDS, THEIR PROBLEMS AND THEIR VALUE IN OPTIMUM LAND UTILIZATION

Denis St-Onge

ABSTRACT: Geomorphological mapping has many scientific and economic applications but is hindered by the lack of an adequate legend. This paper is a dissertation on legends now in use in various countries and an evaluation of their usefulness for optimum land utilization.

RÉSUMÉ: La cartographie géomorphologique se prête à plusieurs applications scientifiques et économiques, mais son efficacité est réduite en raison de l'absence de légendes adéquates. La présente étude traite des légendes actuellement en usage dans divers pays et évalue leur utilité pour l'utilisation maximale des terres.

INTRODUCTION

Population increase and the constant search for higher standards of living demand a rational use of natural resources. This can be attained through judicious planning or by trial and error. The latter method is exemplified in the semi-arid zone of southwest Saskatchewan. There, at the end of the nineteenth century, "sod-busters" ploughed large tracts of the Great Sand Hills, thus destroying the protective carpet of sod, sagebrush and various weeds and laying bare the fine aeolian sand. During the dry years, particularly in the 30's, wind erosion reached catastrophic proportions, and it became obvious that corrective measures were urgently needed. In 1935 the Canadian Parliament voted the Prairie Farmer Rehabilitation Act (P.F.R.A.), under which measures were introduced for the improvement of soil-erosion controls, the provision of water storage and irrigation, and better utilization of soil resources. Among the strong corrective measures that had to be taken under the P.F.R.A. were the permanent withdrawal of submarginal land from cultivation and its conversion into community pasture. This illustration shows how important systematic studies of an area can be for the attainment of optimal use of natural resources. Comparatively inexpensive investigations would often prevent very costly mistakes. Geomorphological studies should provide an essential basis for such measures.

The detailed study of landforms enables a geomorphologist to forecast man's effect on the landscape with a reasonable degree of certainty. The geomorphological map, which describes and explains the landforms of an area, is thus a valuable document and has an essential part to play in any

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regional planning program. In this paper the treatment of geomorphological legends is far from complete: only those are considered that are sufficiently extensive in their application to be of more than local interest, namely, the legends of the U.S.S.R. (Simonov *et al.*, 1960), Czechoslovakia (Balatka, 1963), Poland (Starkel, 1957 and 1962; Klimaszewski, 1960), France (Tricart, 1962), Belgium (Gullentops, 1962) and Canada (St-Onge, 1963).

GEOMORPHOLOGICAL MAPPING

Geomorphology, as an integral part of physical geography, is the science that describes the natural landscape and proposes an interpretation of its evolution. The geomorphological map must therefore give information about the appearance (morphography), the dimensions and slope values (morphometry), the origin (morphogeny) and the age (morphochronology) of each form. The adequate representation of these aspects on a single map is an extremely complicated problem; it is even more difficult when lithology has to be added to the four previous elements. Of the various legends prepared for detailed geomorphological mapping (at scales between 1:10,000 and 1:50,000), very few meet all the foregoing requirements. Many organizations have been interested in the problem of outlining the guiding principles of legend construction, the most important being the International Geographical Union's subcommission on geomorphological mapping.

Russian legend

The Russian legend for geomorphological mapping at scales from 1:25,000 to 1:50,000 is by far the most elaborate (Simonov *et al.*, 1960). It includes more than 500 items divided into two major groups: families of forms and single forms.

The families of forms are represented by a wide variety of shades, often difficult to distinguish from one another. The pattern in which the color is printed indicates the age of these forms. For instance, greyish blue (2.5 PB 7/4, Munsell) printed with white dots every 5 millimeters, indicates a marine terrace of Holocene age. The same color printed with a pattern of vertical and oblique lines indicates a marine terrace of Upper Pleistocene, and so on. The legend provides 36 such patterns, which make it possible to indicate the age of forms from the Mesozoic to the Holocene period.

Single forms—volcanic cones, glacial striae, nunataks, eskers, and so on—are shown by symbols, the colors of which indicate the origin. For example, red is for volcanic forms and blue for fluvial forms. The symbols are overprinted on the colors that indicate the family of forms. The only indication of the difference between active and fossil forms is conveyed by the appearance of the symbol—a solid line for an active form and a broken line for a fossil form. The symbols in grey indicate lithology. This legend can thus represent a terrace of fluvial origin of Upper Pleistocene age (a pattern of triangles printed in green with yellow binding lines), composed of silt (slanted grey lines) on which there is patterned ground (polygonal drawing in violet).

The foregoing might give the impression that the use of this legend would result in a medley of colors. This, however, is not so. The Russian maps are very attractive, but the complexity of the legend makes them difficult to read. Their greatest drawback is the absence of any morphometric data. Contours can give only a rough approximation of slope values and of the dimension of certain forms such as the edges of river terraces. The Russian maps concentrate on the origin and age of landforms but neglect the descriptive aspect of the relief. As a result, these maps are extremely interesting for specialists in geomorphology but are of limited value for practical purposes.

Czechoslovakian legend

Late in 1963 the Geographical Institute of the Czechoslovak Academy of Sciences, Prague Branch, published a geomorphological map legend for scales of 1:25,000 and 1:50,000. As no sample map, however, accompanied the legend, it is difficult to imagine what the finished product would look like.

The legend is based on a genetic classification, landforms being grouped under four main headings: structural, erosion-denudation, accumulation and anthropogenic. Colors indicate origin: volcanic forms in violet, karst in red and all accumulation forms in shades of blue. Age is shown by a pattern overprinted on these colors. A terrace of Upper Pleistocene VII would be shown, for instance, by dark-blue dots on a light-blue background. Individual forms are shown either by lined patterns or by symbols. Slope values are not given.

It is difficult to evaluate this legend until a map constructed from it is made available. The lack of morphometric indications, however, is a serious shortcoming.

Polish legend

Since 1950 the geomorphological survey of Poland has been one of the major undertakings of Polish geographers. The Poles were among the first to realize the great potential of geomorphological mapping in the field of applied geography. Since 1952 there has been very close liaison between the regional planners and the Geomorphological Section, Division of Geography, Polish Academy of Sciences (Klimaszewski, 1956, page 32). The Polish maps produced in Cracow at 1:50,000 are probably the most attractive and the easiest to read of any existing set of maps. A judicious use of color suggests relief in a remarkable way (Starkel, 1957 and 1962).

The Polish legend makes it possible to distinguish three periods (Neocene, Pleistocene and Holocene), three slope values (less than 4 degrees, from 4 to 20 degrees and more than 20 degrees) shown by shades of color, and at least three orders of magnitude for terrace edges. Fossil slopes of Neocene age are indicated in grey, while ridges, summits and similar features are indicated in black. Erosion-denudation forms of the Pleistocene are shown in orange, and those of construction-sedimentation in green; for the Holocene the red indicates erosion, and blue is used for sedimentation. Maps constructed with this legend are attractive, clear and very easy to read. Their principal shortcoming is the absence of lithological information: the nature of unconsolidated deposits, whether recent or old, is not given.

French legend

In December 1962, an international symposium was held in Strasbourg to compare various detailed geomorphological map legends. Professor Tricart presented a legend consisting of 265 symbols and six pages of explanatory text along with five sample maps: two at 1:50,000 and three at 1:25,000 (Tricart, 1962).

In this legend, lithology is shown by colors (orange for crystalline rocks, light blue for limestone, etc.). Solid colors indicate fresh rock, and lined patterns weathered rock. Landforms are denoted by symbols that are overprinted on the lithological colors, grouped according to process and drawn in such a way as to convey the visual impression of the form. The colors of the symbols indicate the age of the forms, which can be grouped into eight classes extending from the Neocene to the present.

Despite certain shortcomings, which will be explained later, the symbols used by Professor Tricart are particularly good, and maps constructed with this legend might be expected to be clear and easy to read. Clarity and legibility, however, are lacking, particularly in areas that depict unweathered rock. Even when printed in contrasting colors, the symbols do not stand out from the solid lithological color. Another limitation is that slope values are not given except for terrace edges and cornices. In short, Tricart's legend emphasizes lithology, genesis and age.

Belgian legend

The legend suggested by Professor F. Gullentops, of the University of Louvain, illustrates the interest of the Belgium geomorphologists in the study of slope development (Gullentops, 1962). The two-page legend makes it possible to give quantitative values for all landforms, including hydrographical forms.

Slopes are indicated by hachures, the density of which corresponds to the value. The slope classes are based on a geometric scale. For example, lines 6 millimeters apart indicate a slope of 0.5 to 1 degree, lines 4 millimeters apart a slope of 1 to 2 degrees, and lines 3 millimeters apart a slope of 2 to 4 degrees. Breaks in slopes are indicated by a line with arrowheads whose frequency shows the number of degrees missing between the two slope segments. There is a similar system for ridges, gulleys, banks and structural forms.

Landforms of sedimentary origin are denoted by dots of different sizes or by small symbols such as crosses for clay and very fine dots for silt. Where slopes are associated with these sedimentary landscapes, the dots or symbols are aligned along the slopes; the spacing between the alignments is related to the slope value as shown by the hachures already mentioned. A form is represented by symbols only where the scale of the map does not permit the breaking of the form into its slope elements. To avoid all possible confusion, the author insists that in such cases the landform be described with great care. The color of a sign (element of a form) or of the symbol (a small form) indicates its origin— carmine red, for example, denoting fluvial erosion, and bright green, sedimentation. Shades of the same color make it possible to date the forms, the brighter shades indicating active forms and the paler shades older.

The obvious advantage of this legend is that interpretation never obscures the description. The disadvantages are of a technical nature: these maps are difficult to draw and extremely complicated to print. With a legend made up of linear and dotted symbols, it is impossible to use patterns to obtain shades of color. Each shade must be in a different ink; this multiplies the number of printing plates. The printing cost, therefore, is comparatively high.

Canadian legend

In Canada, St-Onge has constructed a geomorphological map at a scale of 1:30,000 for the Isachsen area, Ellef Ringnes Island, N.W.T. (St-Onge, 1964). The map was part of a doctoral dissertation written under the supervision of Professor Gullentops, of Louvain. There is thus nothing surprising in the many similarities between this legend and the Belgian. The Canadian legend is nevertheless simpler and contains more symbols. Slopes are represented by lines the thickness of which indicates slope values. The unconsolidated material is shown on subhorizontal surfaces but not on slopes. Symbols are used to show different types of patterned ground, small nivation forms and other features. The color of the signs and symbols indicates origin. As the relief, save for the highest summits, is Pleistocene, the problems of chronology are not considered. The lithology of the area appears on a small inset map at a scale of 1:4,000,000. The advantages and disadvantages of Professor Gullentops' maps are found in this one also.

GENERAL DISCUSSION

The foregoing is a brief review of the more important geomorphological legends. All have advantages and disadvantages and the choice of one will depend to a great extent on the aims of the geomorphologist. It is likely that the legend used will often be a composite resulting from a compromise, probably between the French and the Belgian legends.

The essential difference between the French and the Belgian legends is that the signs used in the latter represent simple elements of the relief (for example, a slope of N degrees), while the symbols used in the former represent landforms (for example, badlands and slumping). The main drawback of symbols is that, unless multiplied indefinitely, they cannot show variations of a given form. On the other hand, the reproduction of a map based on symbols is comparatively simple. It would thus be an advantage to combine, to a certain extent, the maps of Tricart and Gullentops.

The Russian legend is not only very complex but is costly to print and contains no morphometric indications. The last-mentioned are an essential aspect and so could hardly be introduced into the legend without completely transforming it. The Polish legend, on the other hand, contains no lithological elements. These, if introduced would probably transform it into something very similar to the Belgian legend.

The essential purpose, however, is not to produce legends but to map the landforms to allow a more rational use of landscape. By interpreting landforms, the geomorphological map shows the nature of the subsoil, the importance of surface deposits, the texture of the relief, mass movements and the main aspects of hydrography. All this information is essential for planning—i.e. for determining the suitability of the area for traffic, the location of favorable sites for landing fields, and construction projects, and the assessment of the effectiveness of land management.

Most geomorphological maps are far too complex to be of immediate use to non-specialists. When such complexity exists, it is necessary to extract from these maps a series of documents that indicate the advantages and disadvantages of the area for any given purpose. These "bonitative" maps (Klimaszewski, 1960) can easily be extracted from the geomorphological map and are of great value to engineers, soil scientists, agronomists and others (Tricart, 1962, pages 38–42).

The problem of developing a geomorphological map legend to satisfy the requirements outlined in this paper is complex. It is not only of scientific and academic interest but of practical application, since geomorphological maps are an essential aspect of the ever widening field of applied geomorphology. The elaboration of a legend adapted to their needs is an urgent task that Canadian geographers will have to cope with.

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METEOROLOGICAL AND GLACIOLOGICAL OBSERVATIONS ON THE GILMAN GLACIER, NORTHERN ELLESMERE ISLAND, 1961

*R. B. Sagar**

ABSTRACT: Results are given of climatological and glaciological observations taken during the summer of 1961 in the névé area of the Gilman Glacier, northern Ellesmere Island. Long-term records from Alert weather station indicate that the summer season was relatively cool. Gross ablation was about 3 centimeters water equivalent at 1,660 meters above sea level and occurred almost entirely during two brief melt periods of 88 hours' duration in mid-July. The radiative-energy surplus was estimated to account for more than 85 per cent of the heat used to reduce subsurface cold content and promote melting. Comparison of the 1961 results with those of previous years indicates that an early summer snowfall or a small negative deviation from the present temperature mean, or both, can critically affect the Gilman Glacier economy.

RÉSUMÉ: On donne ici les résultats d'observations climatologiques et glaciologiques faites au cours de l'été 1961 dans l'aire du névé du glacier Gilman dans le Nord de l'île Ellesmere. Des observations à long terme effectuées à la station météorologique d'Alert indiquent que l'été a été relativement frais. L'ablation brute a été d'environ 3 centimètres en équivalent d'eau à une altitude de 1,660 mètres au-dessus du niveau de la mer et elle s'est produite presque entièrement au cours de deux brèves périodes de fonte d'une durée de 88 heures à la mi-juillet. L'énergie de radiation a représenté plus de 85 p. 100 de la chaleur qui a servi à fondre la neige et réchauffer les couches sous-jacentes. Une comparaison entre les résultats de l'année 1961 et ceux des années antérieures indique qu'une chute de neige au début de l'été ou une petite déviation négative de la présente température moyenne, ou les deux à la fois, peuvent influer gravement sur le filon glaciologique du glacier Gilman

INTRODUCTION

The Defence Research Board of Canada sponsored field investigations on the Gilman Glacier during the summers of 1957–60. Further investigations were planned for 1961 to add to previous knowledge of the glacier summer climate, to record specific meteorological parameters for use in an assessment of the upper-glacier heat balance, and to measure the role of accumulation and ablation in the economy of the glacier.

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*The author is now with the Geographical Branch, Department of Mines and Technical Surveys, but the present work was carried out for the Defence Research Board under contract to McGill University.

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Dr. G. F. Hattersley-Smith (Defence Research Board, leader and glaciologist), R. B. Sagar (McGill University, climatologist) and U.W.O. Embacher (McGill University, field assistant) occupied camps on the Gilman Glacier from May 17 to August 10. The glacier party was assisted by S. J. Windisch (McGill University, soil scientist) from May 17 to June 16. Scientific work carried on at Hazen Camp during the summer included a program of meteorological investigations conducted by Dr. C. I. Jackson, of the London School of Economics, with support from the Arctic Institute of North America and the Defence Research Board.

SITE

Figure 1 shows the sites of the two meteorological stations occupied during the 1961 season and of the 1958 meteorological station. The layout of the main 1961 station on the upper Gilman Glacier is shown in Figure 2. The station was at an altitude of 1,660 meters on a gently undulating névé in an area where the general southeastward slope varied from 0.5 to 3 degrees. The nunatak rim of the accumulation basin presented a maximum horizon interference of about 3 degrees on a bearing of 210 to 230 degrees in the Mount Oxford area.

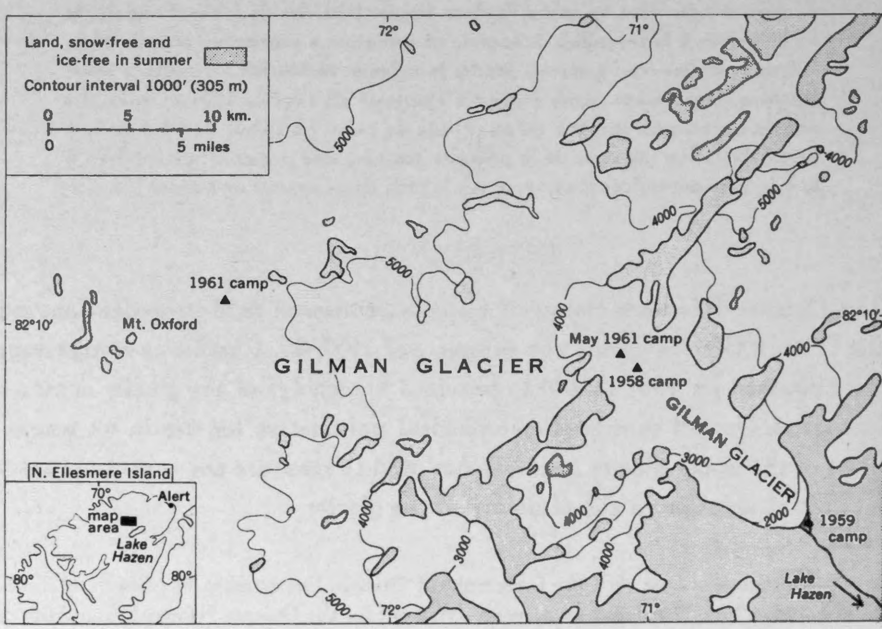

FIGURE 1. Location map.

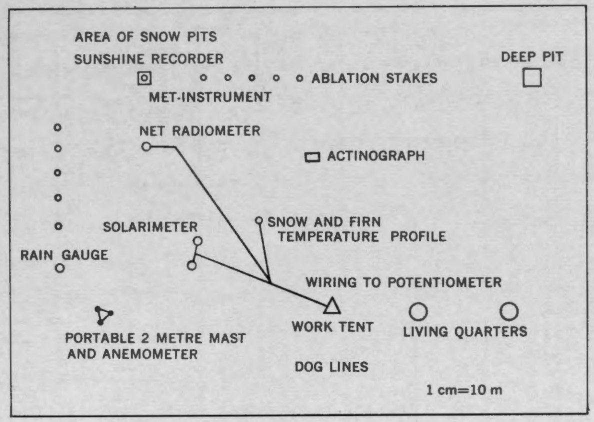

FIGURE 2. Camp layout, 1961.

PROGRAM

From May 17 to 29 the members of the party were occupied in measuring accumulation on the lower glacier, replanting ablation stakes and transferring supplies and equipment to the upper glacier. Until May 29, spot readings of temperature, wind speed and sky conditions were recorded, and a continuous record of insolation was maintained by actinograph. A full program of observations, synoptic and glaciological, was started on June 1. Hattersley-Smith, Embacher and Windisch made journeys by dog sledge to other parts of the ice cap during June and August, mainly for stratigraphic studies of snow and firn. During late June and in July, Hattersley-Smith and Embacher excavated a 16-meter pit and added cored extensions to 40 meters. They examined the structure and stratigraphy of the exposed firn.

METEOROLOGY

A qualitative analysis of surface-weather maps prepared by the Edmonton office of the Department of Transport for May to August, 1961, showed the pressure systems associated with observed conditions on the Gilman Glacier. The weather for the season was thus found to be of two main types. One, characterized by periods of high insolation, a scarcity of cloud and precipitation, a pronounced range of diurnal temperature, and calms or light winds, was usually associated with anti-cyclonic cells or ridges that had weak pressure gradients. The conditions accompanying the second

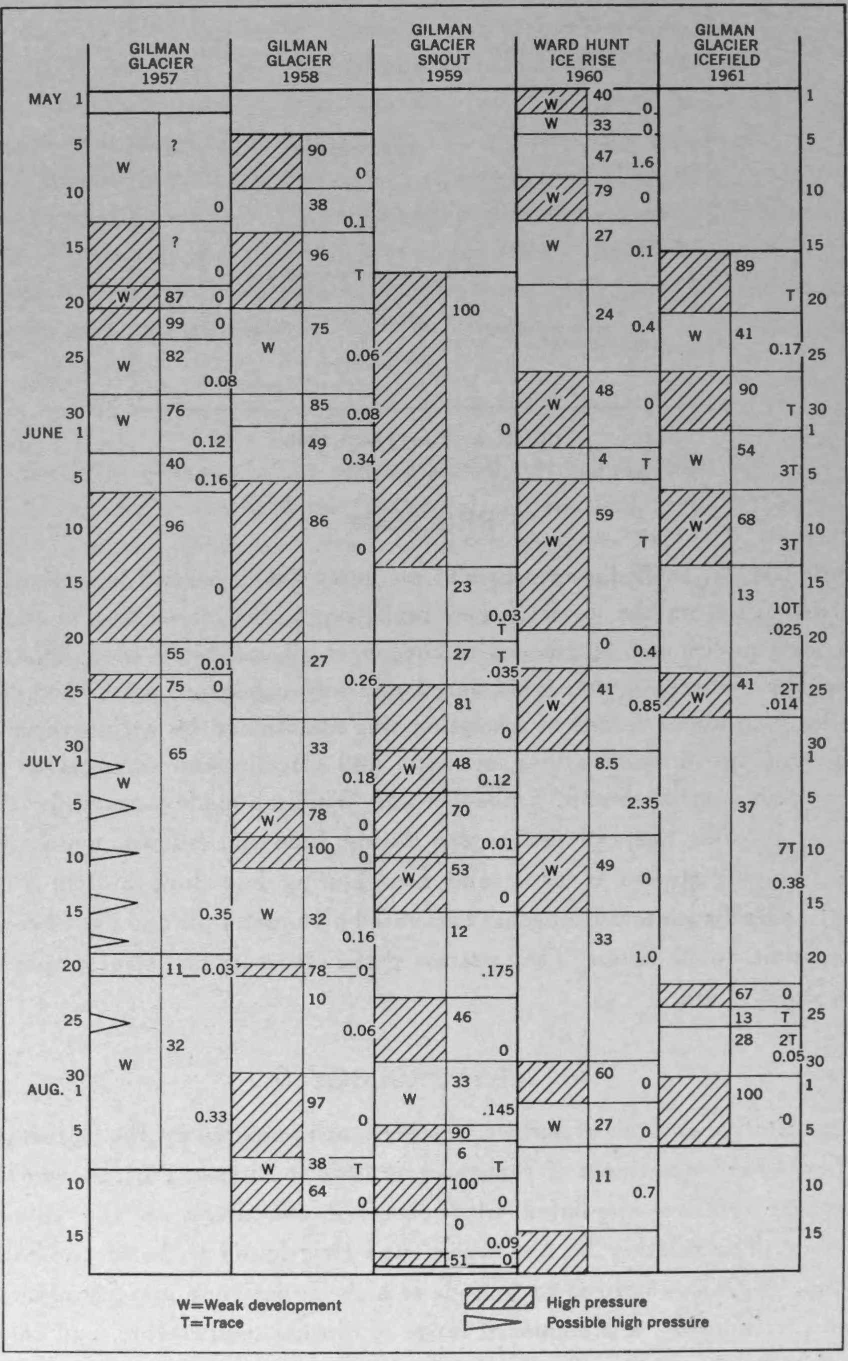

FIGURE 3. Dominant pressure field, sunshine (percentage) and precipitation (inches), N. Ellesmere Island, 1957–61.

type, which was observed when cyclonic systems lay over or near north Ellesmere Island, were the converse of those associated with high pressure.

The association of weather and pressure in 1961 was much the same as on the Gilman Glacier and on the Ward Hunt ice rise (off the coast of Ellesmere Island) during the period 1957–60. Figure 3, a simplified chart of pressure periods from 1957 to 1961, gives the relevant data for measured sunshine frequency and precipitation. Although deep systems are not frequent in high latitudes, clear recognition of a cyclonic weather sequence was sometimes possible. During the 1961 season, for instance, the effects of five systems centred about the dates May 23, June 17, July 10, July 17 and July 27 were clearly seen. Gustiness, squalls and line-cloud formations were associated with the systems of June 17 and July 17. The mid-July system was associated with advection of relatively warm air and the promotion of the only prolonged ablation period of the season.

Temperature and precipitation means

The weather station nearest the Gilman Glacier area is Alert, 62 meters above mean sea level at 82°30'N, 62°20'W, about 160 kilometers northeast of the glacier. It is assumed that this station and the glacier are subject to the same major meteorological influences and the assumption is confirmed to some extent by the amount of agreement between their temperature trends. Mean temperature and precipitation data from Alert for the period 1950–61 and for the glacier budget year from August 1960 to August 1961 have been examined for an assessment of the normality of the 1961 season. Figures 4 and 5 give the Alert temperature data.

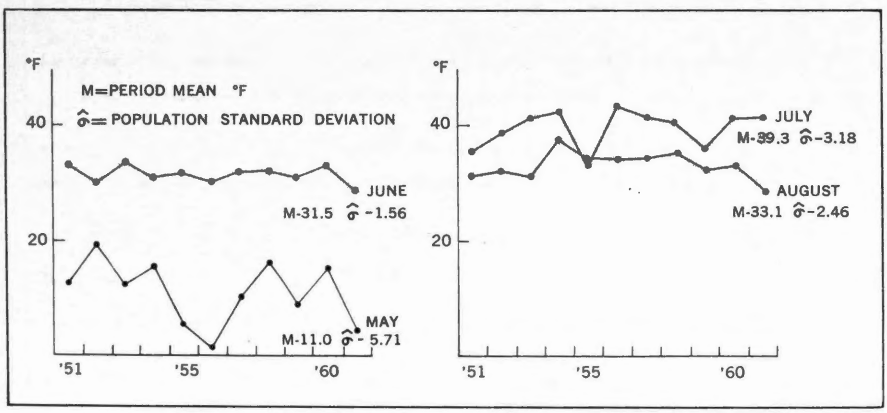

FIGURE 4. Mean monthly temperatures, Alert, N.W.T. 1951–61.

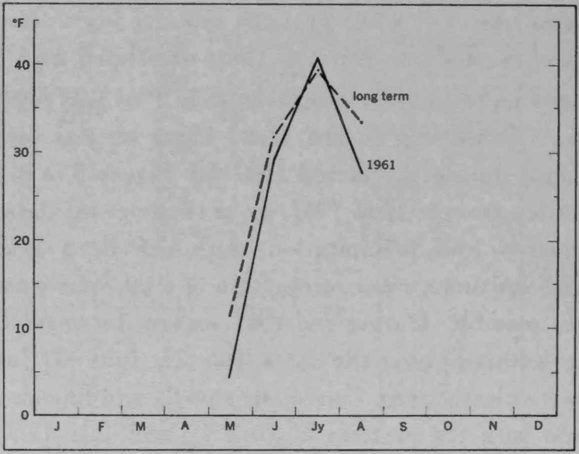

FIGURE 5. Long-term and 1961 mean monthly temperatures, Alert, N.W.T.

Mean monthly temperature data from Alert for May, June and July, 1961, taken from the 11-year records show negative anomalies of 6.5°F (3.6°C), 2.7°F (1.5°C) and 5.1°F (2.8°C) respectively. July had a positive anomaly of 1.7°F (0.9°C), which resulted from a markedly warm period extending from the 14th to the 22nd. The temperature records for the year indicate that Alert and, by implication, the Gilman Glacier-Lake Hazen region had a relatively short and cool summer. Alert precipitation data indicate that the 1961 budget year was relatively dry. Snow-pit studies suggest, however, that the budget-year precipitation on the upper Gilman

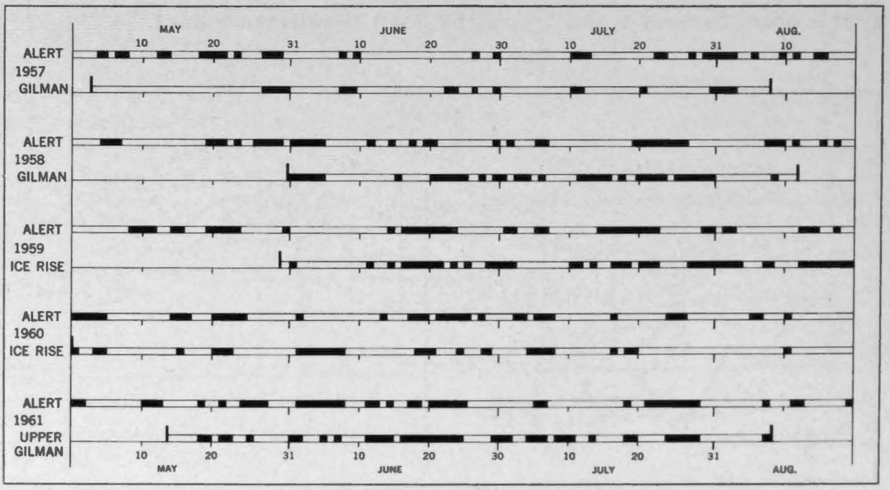

FIGURE 6. Days with precipitation, Alert, Gilman Glacier and Ward Hunt Ice Rise, 1957–61.

Glacier was greater than the average recorded for the 11 years. The Alert precipitation total (2.8 centimeters) for June and July, was lower than the comparable Gilman Glacier value (3.5–3.7 centimeters), but the agreement between periods of measurable precipitation at the two stations (Figure 6) was generally good.

The likelihood of orographic precipitation on the Gilman Glacier (Jackson, 1960a) could explain the lack of quantitative agreement with data from Alert.

TEMPERATURE

Air temperature at screen height was read at three-hour intervals from 0700 to 2200 EST, daily maximum and minimum temperatures were taken, and a thermograph record was kept from June 1 to August 5, 1961. The screen base was 110 centimeters above the snow surface on June 1 and about 120 centimeters above the surface on August 5. On occasions of strong solar radiation and low wind speed the screen instruments registered fictitiously high values. The temperature errors were recognized by comparison of simultaneous sling-psychrometer and screen readings. Correction charts were drawn (Figure 7) to reduce the observed errors.

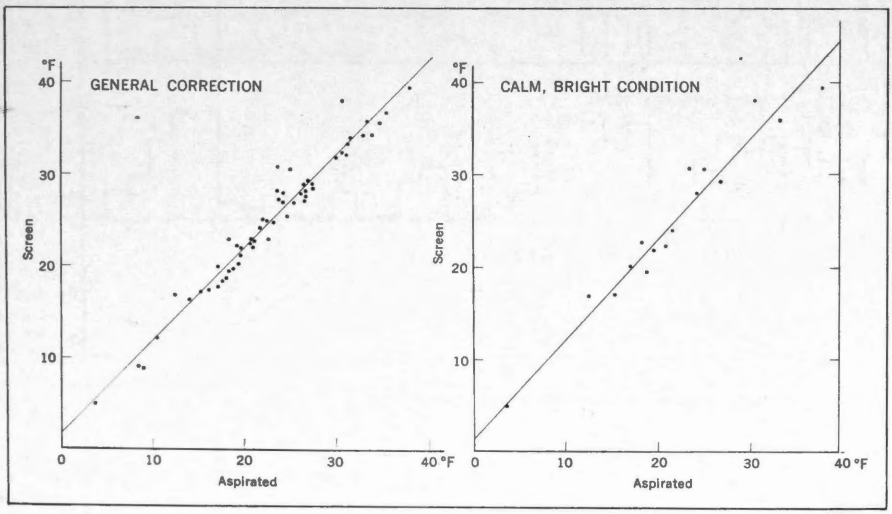

FIGURE 7. Correction curve for screen overheating (radiation error), 1961.

Daily mean temperatures from corrected thermograph records are included for June and July in Figures 8A and 9A. The thermograph record is judged to express the daily mean temperature with greater accuracy than the data given by maximum and minimum temperatures. The daily mean temperatures given represent the period 0001 EST to 2400 EST for each day. For close comparison with daily temperatures at Alert, climatological-day maxima (0701–0700) and minima (1901–1900) should be used. Appreciable disagreement between climatological-day and true-day data was occasionally shown. The 1961 climatological-day values for July 10 to 13, July 15 and July 20 to 26 are included in Figure 9A.

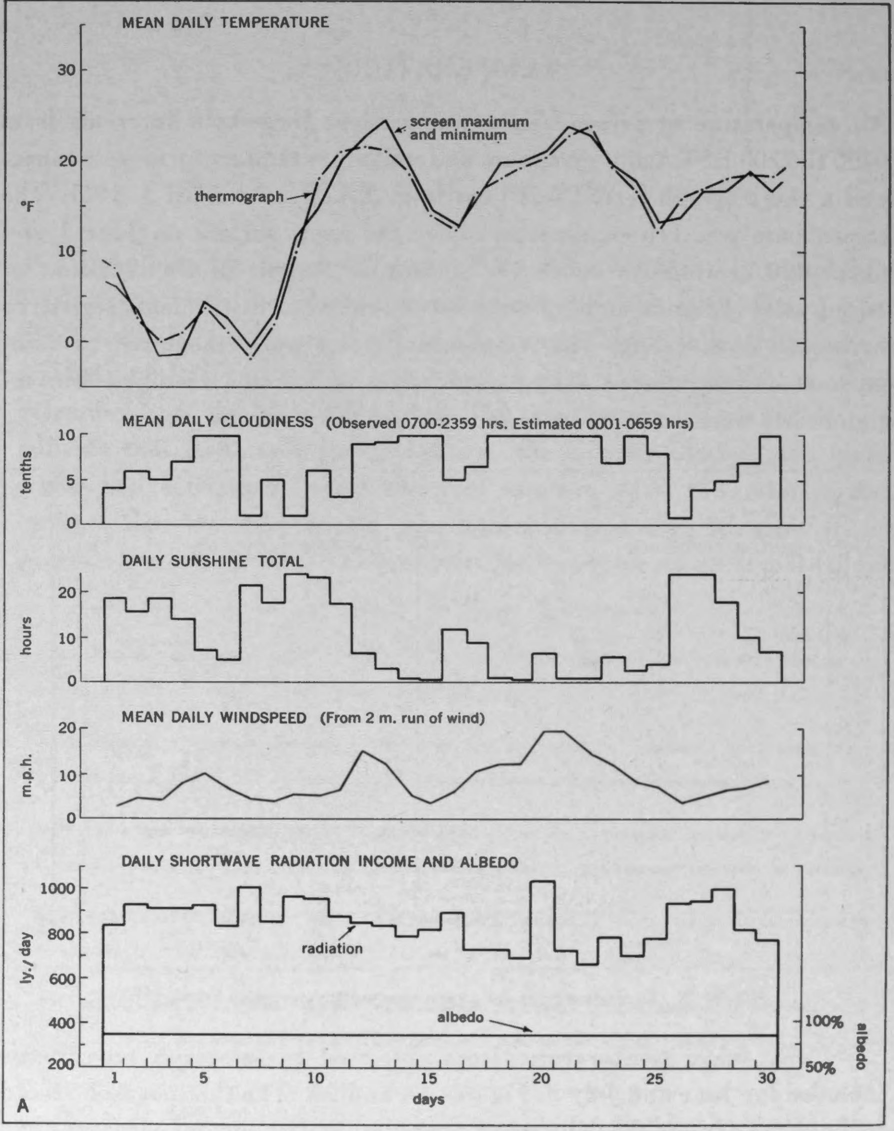

FIGURE 8A. Climatological data from upper Gilman Glacier camp, June 1961.

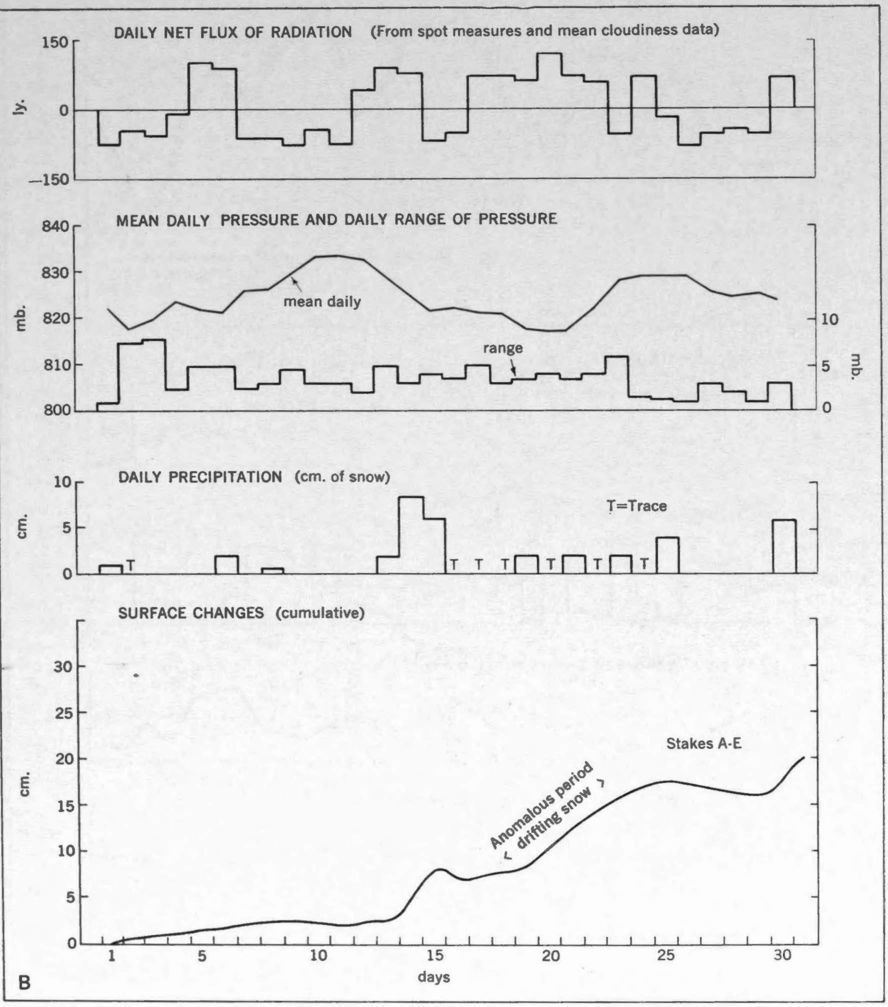

FIGURE 8B. Climatological data from upper Gilman Glacier camp, June 1961.

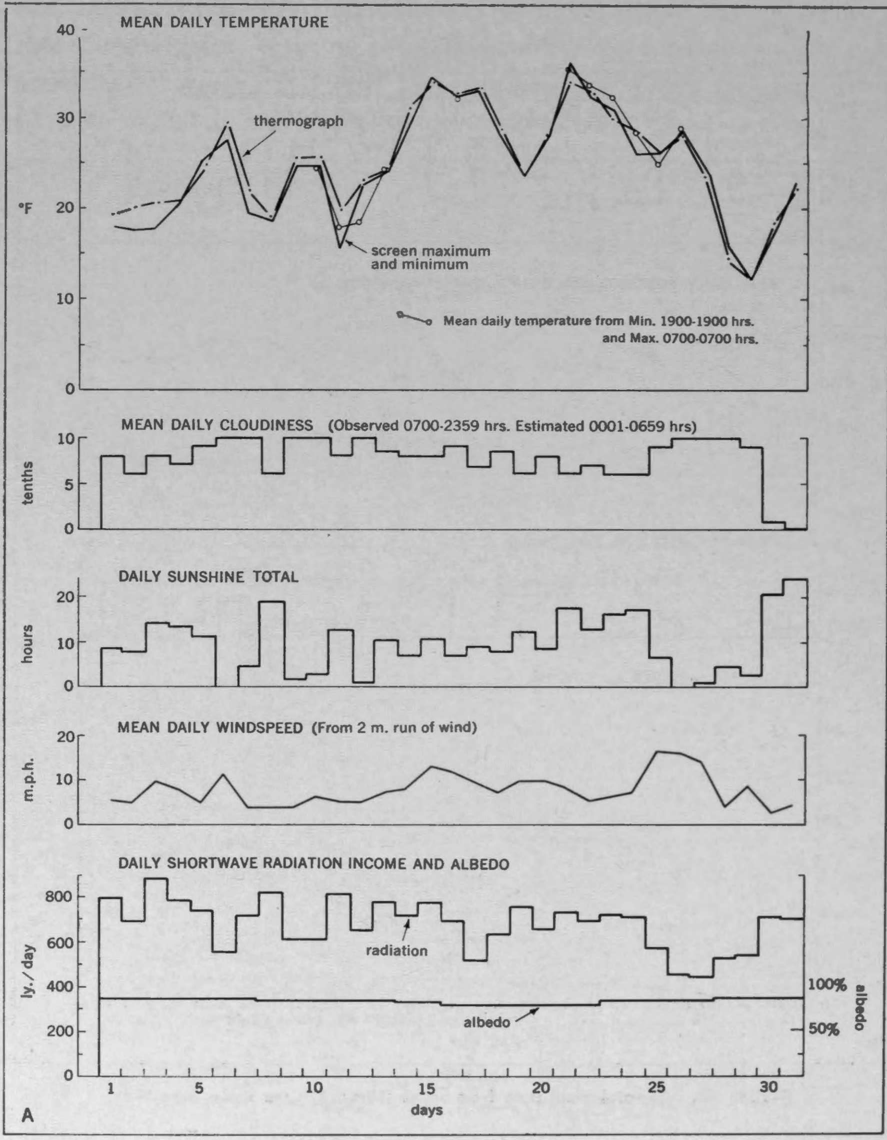

FIGURE 9A. Climatological data from upper Gilman Glacier camp, July 1961.

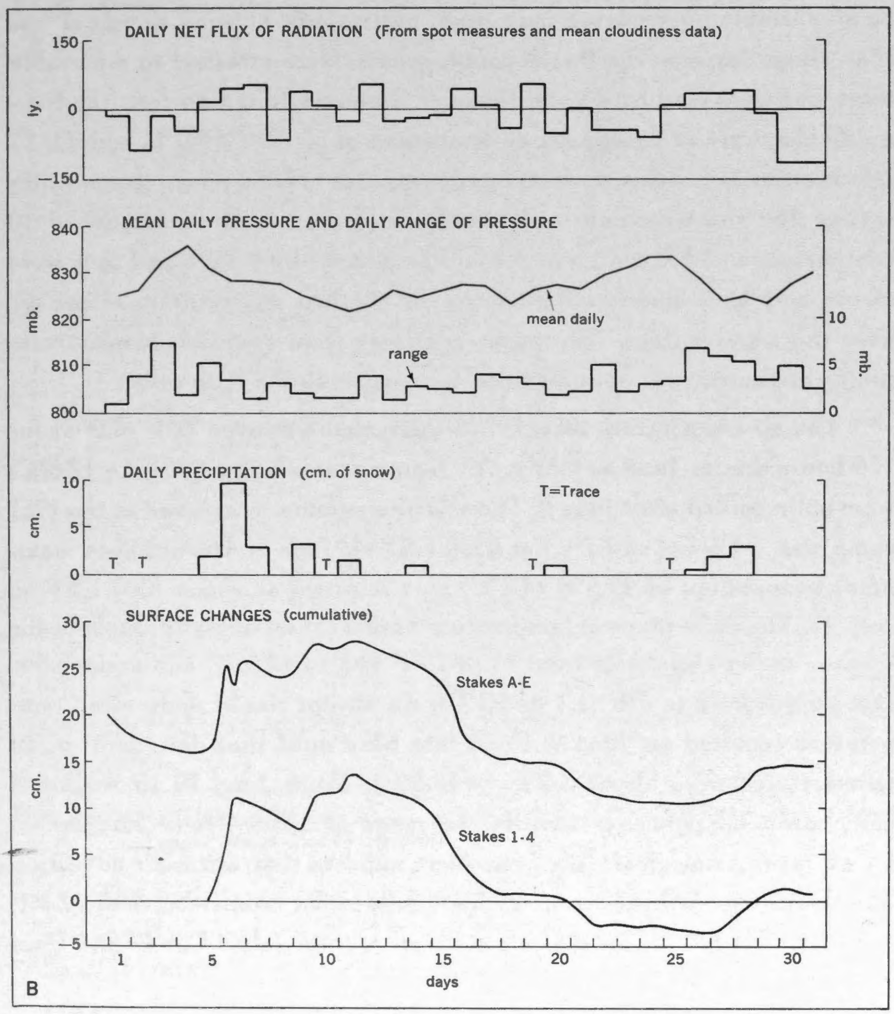

FIGURE 9B. Climatological data from upper Gilman Glacier camp, July 1961

From June 16 to July 26, air temperatures were measured at heights of 10, 50, 100 and 200 centimeters above the surface. The spot readings of temperature were made at synoptic observation hours. In addition, temperature profiles were measured frequently during selected periods on July 14, 15, 16, 20 and 21. The sensor circuit was made up in the field from 24- and 36-gauge copper-constantan thermocouples. The heavier-gauge thermocouples, at heights of 10 and 200 centimeters, were shielded by concentric burnished aluminum tubes that could be adjusted to point into the wind. The fine-wire probes were unshielded and unlagged and proved to be unstable temperature indicators, particularly at wind speeds of less than about 2m/sec. The thermocouple sensors were attached to a portable mast and were read by a potentiometer. In an early-season test, the thermocouples were in agreement at temperatures of 0.0°C, 5.0°C and 7.0°C. It was estimated, however, from interpolation of reliable screen temperature values that the temperature differences measured between heights of 10 centimeters and 200 centimeters could be in error by 0.25°C and thus were of use only as a qualitative guide to the thermal stratification of the air near the snow surface. The mean gradients from frequent temperature-profile measurements were assumed to be close to the true value.

The air temperature recorded in the screen was over 32°F (0.0°C) for 128 hours during June and July. Air temperatures below 0.0°F (−17.8°C) were not recorded after June 8. The absolute minimum observed at the 1961 camp was −8.8°F (−22.7°C) at 0300 EST on June 3. The absolute maximum temperature of 39.6°F (4.2°C) was recorded at about 1000 EST on July 21. The daily range of temperature varied considerably throughout the season—under clear skies from 15 to 23°F (8.3 to 12.8°C) and under overcast skies from 2 to 6°F (1.1 to 3.3°C). An abrupt rise of daily mean temperature occurred on June 9. From late May until that date daily mean temperatures were about 2.0°F (−16.8°C). From June 10 to August 6 daily mean temperatures were in the range of 22.0±4°F (−5.6±2.3°C) on 38 days. Aerological data from Alert indicate that warm-air advection was associated with the relatively high daily mean temperatures of 32.3°F (0.15°C) recorded at the 1961 glacier station from July 14 to 17 and from July 20 to 22.

A comparison of the deviations of the daily mean temperature from the monthly mean for the 1961 station and for Alert gives significant correlation coefficients of 0.85 for June and 0.78 for July. The data for July are plotted in Figure 10. A similar comparison with the July data for Hazen camp (supplied by C. I. Jackson) gives a correlation coefficient of 0.72. The 1961 data indicate that daily temperatures above 32.0°F (0.0°C) may occur on the upper Gilman Glacier when Alert and Hazen camp record more than 47°F (8.3°C). During the year, five days with a mean temperature more than 32.0°F were observed at the 1961 camp, and six days with a mean temperature more than 47.0°F are shown by Alert records.

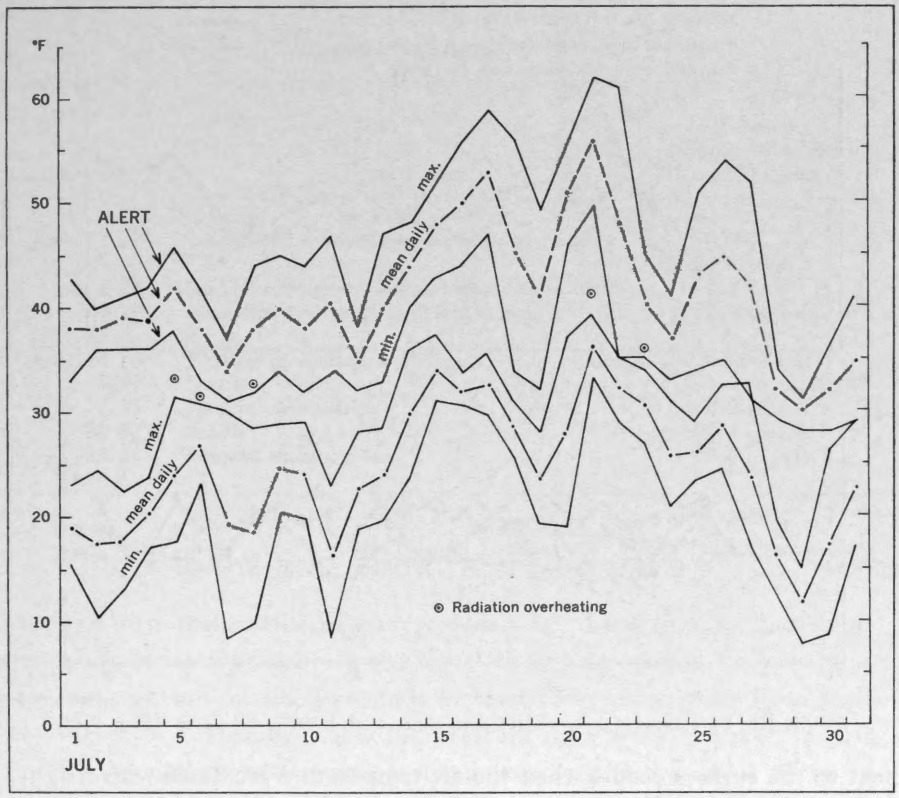

FIGURE 10. Comparison of daily mean, maximum and minimum temperatures, Alert, N.W.T., and upper Gilman Glacier, July 1961.

The daily-mean-temperature gradients between Alert, Hazen camp and the glacier station and between the Alert surface and the 825-millibar level (Figure 11) rarely show quantitative agreement. The difference in surface character at the three stations, the occurrence of grounded or raised temperature inversions, and the advection of warm or cold air aloft contribute to this lack of agreement. Monthly mean gradients between Alert and the 1961 camp were about 0.89°F/300 ft. (0.52°C/100m) for June and 0.91°F/300 ft. (0.55°C/100m) for July. Similar gradients have been reported from Greenland (Diamond, 1958). The comparable sonde data (sea level to 825 millibars) give 0.54°F/300 ft. (0.33°/100m) and 0.63°F/300 ft. (0.38°C/100m).

The mast temperature profiles measured during 1961 indicate the stability of the atmosphere near the surface at the time of observation. The atmosphere is considered stable when the temperature gradient is algebraically greater than the dry adiabatic lapse rate. Transfer of sensible

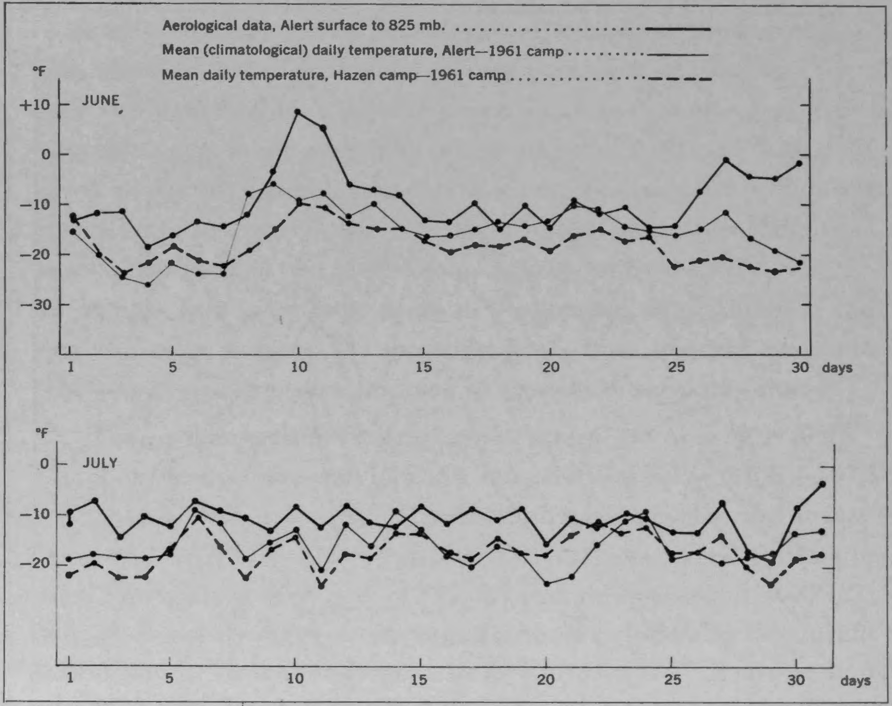

FIGURE 11. Differences in daily mean temperature, Alert, N.W.T., and Camp Hazen, 1961.

heat to the surface occurs when the air temperature increases with height; it is related quantitatively to the wind speed (Liljequist, 1957a; Lister and Taylor, 1961). Surface loss of heat by turbulent diffusion per unit of time under temperature-lapse conditions is, however, considerably greater than the corresponding heat gain with an equivalent temperature inversion (Priestley, 1959).

Relatively few of the attempted temperature profile measurements were considered acceptable for quantitative use, but more than 70 per cent of the approximately 140 profiles taken at three-hour intervals during the season indicate that the lower atmosphere was near neutral or stably stratified. During the ablation periods of July 14 to 17 and 20 to 22, a relatively high degree of stability occurred for prolonged periods (Table 1). A tendency to reversal of temperature gradient was noted when the measured net radiative flux changed sign. At surface temperatures below 0.0°C a positive radiative flux was often associated with unstable characteristics, and a negative radiative flux with a neutral or stable lower atmosphere. Further treatment of the vertical diffusion of sensible heat from temperature and wind-speed profile data is given in the section on wind observations.

Table 1

Temperature profiles, 1961

Date		Type of profile	Range of temperature from 10 to 200 cm in °C
June	17–21	Isothermal tendency to stability at midday	±0.0
			+0.2 to −0.5
	22–23	Stable with increasing stability during night	+0.2 to −1.5
	24–29	Unstable during all but noon hours	−0.2 to −2.0
	29 to		
July	14	Neutral or weak in stability	0.0 to −1.0
	15–17	Stable	+0.2 to −1.0
	17–19	Neutral or unstable	0.0 to −0.5
	20–22	Stable	+0.4 to −0.7
	23–26	Neutral or unstable	0.0 to −0.5

SNOW AND FIRN TEMPERATURES

Snow and firn temperatures were recorded by thermocouples buried at seven levels beneath the surface to a depth of about 5 meters. Observations of the temperature profile were made at least three times daily from June 5 to August 5. Additional snow temperature data were obtained in pits with Weston dial thermometers, and temperatures of the upper 15 to 24 centimeters of the snowpack were similarly recorded once or twice daily from June 24 to July 24. An accuracy of more than −0.25°C is not claimed for the individual recordings, since a calibration of the sensors was not undertaken. During the early part of the season, however, comparable thermocouple and snow-pit temperatures at similar depths were in close agreement. The accuracy of thermocouple measurements in the upper 10 to 25 centimeters of the snowpack decreased as the season progressed, owing to the formation of an air well around the bamboo guide pole and the penetration of solar radiation within the upper snowpack. Percolation of meltwater through the snowpack upset the regularity of the temperature decrease with depth after July 14.

Temperature-profile data (Figure 12) were used to estimate the change in heat content (Q_s) of the snow and firn during June and July. These data were substituted in the equation:

$$Q_s = c.\rho. \int_0^{\infty} \Delta T(z)dz \text{ cal. cm}^{-2} \text{ (langleys)}$$

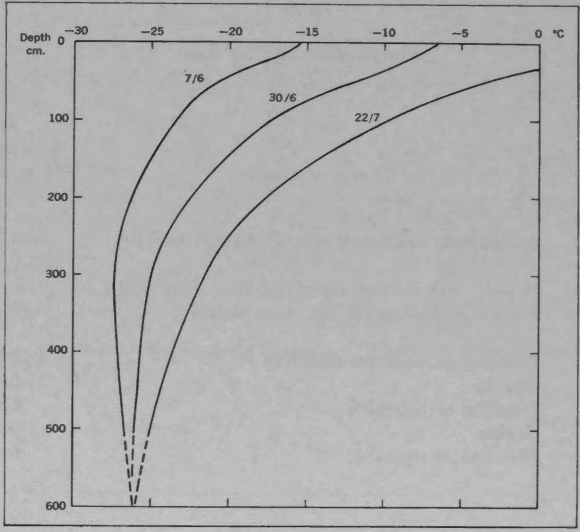

Figure 12. Seasonal change in snow and firn temperatures, 1961.

where c is the specific heat, ρ. the density and ΔT the mean temperature change, 0.0°C at depth 2 cm. From June 7 to July 22 the value of Δ T was found to be 7.1°C over a 550-centimeter column having a density of about 0.4g. cm^{-3}. During this 45-day period the snow and firn gained 780 langleys of heat content. It was estimated that from June 7 to July 13, the 550-centimeter column gained 535 langleys, or an average of 14.5 langleys a day. Smoothed temperature profiles from June 15 to July 10 give gradients ranging from 0.175°C/cm to 0.200°C/cm in the upper 100 centimeters of snow and firn. Substitution in a conductivity equation of the type given by Liljequist (1956c) gives a downward heat flux of 16.3 to 18.7 langleys a day for snow of density 0.4 gm cm^{-3}. The temperature gradient of the upper

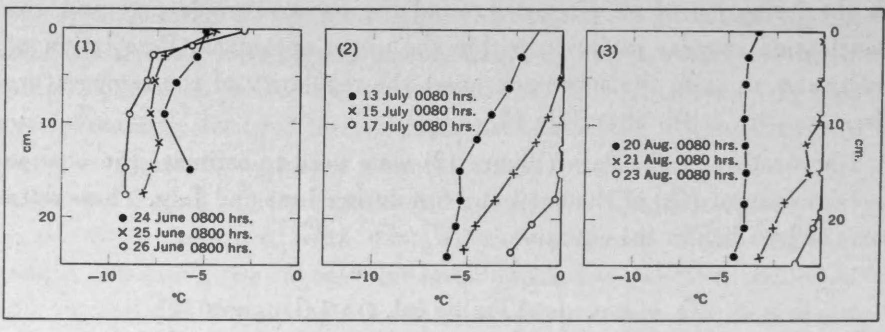

FIGURE 13. Temperature changes, upper snowpack, 1961.

snowpack was rapidly weakened after July 14 and became effectively zero by July 15. The latent heat of refreezing meltwater was the firn's dominant source of heat from July 14 to 22, providing about 240 langleys.

Diurnal and day-to-day changes in the temperature of the upper snowpack (Figure 13) have been treated quantitatively only on occasion as a guide to variations in radiative flux.

WIND

From June 1 to August 5 run of wind was recorded at a height of 2 meters above the surface with a Casella totalizing anemometer, instantaneous readings of wind speed were taken at the 2-meter level from a Lambrecht hand anemometer, and wind direction was noted by referring to a flag at three-hour intervals between 0700 and 2200 EST. Additional data relating to change of wind strength and direction were noted at the appropriate times. Few quantitative observations were made between 0001 and 0700 EST during the 1961 season.

At certain times, usually when the air-temperature profile was not isothermal, wind speeds were measured at heights of 10, 50, 100 and 200 centimeters over periods of 10 to 30 minutes. The anemometry was not entirely satisfactory, since the sensors were dissimilar in type and response. The totalizing anemometer, two Sheppard-type sensitive cup anemometers and a Davis air-flow meter were employed to measure the wind speeds. The responses of the anemometers under similar wind field conditions were compared in the field, with one of the sensitive cup anemometers as a standard (Figure 14). A small range of wind speed was, unfortunately, encountered during the tests. Few satisfactory four-point wind-speed profiles were obtained, owing in part to the instrument and mast limitations and in part to the frequently disturbed nature of the wind field. Almost all the satisfactory profiles (44 of 106 attempted measurements) were taken at selected times during the periods from July 14 to 17 and July 20 to 21.

Daily mean wind speed varied greatly during the 1961 season (Figures 8 and 9). Prolonged periods of high wind were rare, and calms were recorded on 54 of the 66 days from June 1 to August 5. The relatively high wind speeds of June 18 to 23, July 15 to 16 and July 25 to 27 were associated with cyclonic activity off the northwest coast of northern Ellesmere Island. Periods of calm or very light wind were usually associated with wind shifts. Welcome lulls in the wind persisted for lengths of time which varied from two minutes to three

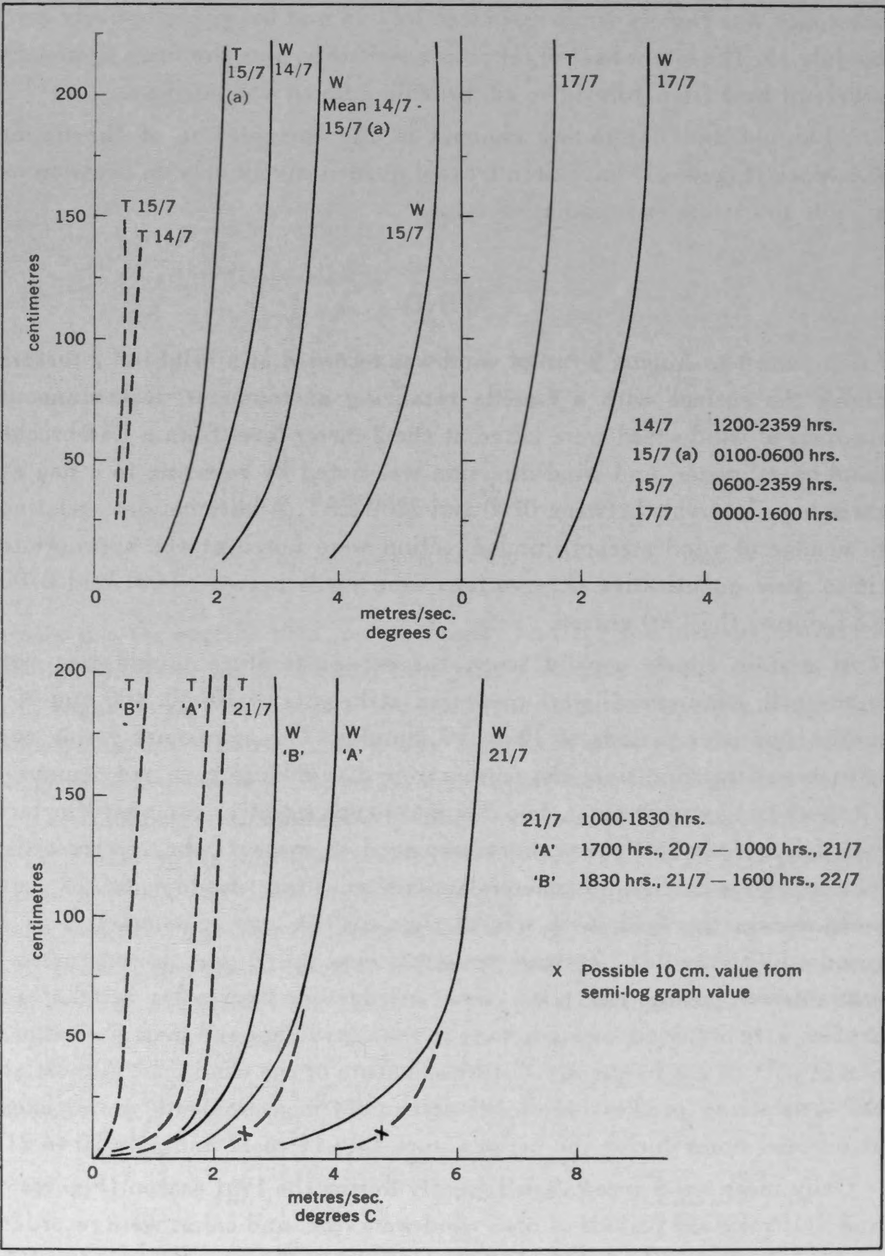

FIGURE 14. Measured and constructed wind and temperature profiles, 1961.

hours. Indirect evidence from the thermograph chart—namely, an upward surge of temperature due to weak aspiration—and from spot observations indicates that many calm periods occurred between 0001 and 0700 EST. A comparison of mean wind speeds for the periods 0700–1000 and 1900–2200 and for the periods 2200–0700 and 1000–1900 EST showed no significant diurnal variation.

Frequent shifts of wind within the sectors extending from 110 to 225 degrees and from 225 to 360 degrees were characteristic of the 1961 season. Wind reversals from a westerly to an easterly direction were occasionally noted during periods of weak air flow—for example, on June 1 and 15 and on July 2 and 12. The prevailing-wind directions from May 28 to June 24 were northwest and west, although a few short periods of light southeast winds were also observed. From June 25 to July 26 the wind was almost always from a southerly direction. An increase in the frequency of north and northwest winds occurred from July 27 to August 7. On a few occasions, local air flow was probably a response to surface cooling and gravity. At 2200 EST on July 5, for example, the surface air drift was from the west, whereas flare smoke about 15 meters above the surface was moving toward the west.

The 1961 data gave no clear association of temperature and wind direction. During the period from July 14 to 26 south and southwest winds were associated both with relatively high and with average air temperatures. Similarly, northwest and west winds prevailed before, during and after the relatively warm period of June 10 to 14.

Almost all the measured wind profiles showed a straight increase of speed with height. Exceptions were noted when changes occurred in the steadiness of the wind field, as when a sudden onset of calm preceded a wind shift. The profiles were graphed with velocity on a linear scale, and height was graphed on a logarithmic scale; straight lines through three points were usually obtained. The 10-centimeter reading often lay to the left and the 2-meter wind-speed reading occasionally to the right of the fitted straight line. The results agree closely with those of previous investigators—Sverdrup (1936), Deacon (1953) and Liljequist (1957a), for example, who found that the wind-speed increases with height near the surface can best be expressed by a logarithmic law. The deviation of the 2-meter wind speed from the logarithmic law was seen to occur—as Deacon had found—during conditions of moderately high stability in the atmospheric layer close to the ground. The roughness parameter z_0 was found graphically on semilogarithmic paper. For given surface conditions the value of z_0 should be about constant, at least until wind speeds exceeding 8 to 14 miles an hour (3.6 to 6.3 m/sec) in range cause the snow to drift. During 1961, however, measured values of z_0 varied from .001 to 0.4 centimeter. The variation perhaps indicates the presence of errors in the smoothed velocity profiles. Roughness parameters of 0.25 and 0.05 centimeter for conditions similar to those in the 1961 camp area have been reported by Sverdrup (1936) and Priestley (Deacon, 1949). It was assumed that during 1961 air flow was fully turbulent when wind speeds at the 2-meter level were greater than 2 m/sec, but some low z_0 values indicate that laminar flow may have occurred at greater wind speeds (Sutton, 1953).

The turbulent transfer of sensible heat in the atmosphere near the surface was calculated for selected periods of the 1961 season by substituting wind-speed and air-temperature profile data (Figure 15) in an equation of the type given by Liljequist (1957b) and Ambach (1960):

$$Q_z = C_p \varphi K_H \frac{dT}{dz} \text{ ly/sec}$$

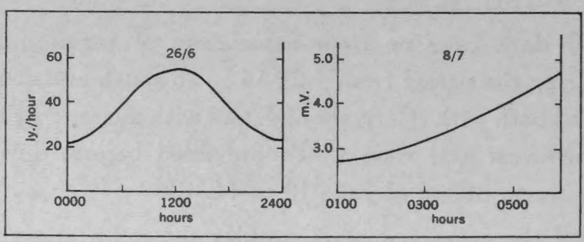

FIGURE 15. Incoming solar radiation per Kipp. 1654 for checking against actionograph record, 1961.

where Q_z = the amount of sensible heat transferred at height z cm, C_p = specific heat at constant pressure of air, φ = density of air, dT/dz = temperature gradient (°C/cm) at height z, and K_H = the exchange coefficient for sensible heat. K_H was derived by use of the mixing-length (l) concept of Prandtl (Sutton, 1953), in which $l = k (z + z_0)$ and k is von Karman's constant, 0.40 (Liljequist, 1957b). The assumption of equality for the exchange coefficients of heat and momentum derives from Ertel's demonstration that the shearing stress is almost constant in the lower atmospheric layers (Batchelor, 1950), whence K_H is given by l^2 du/dz. The velocity gradient was derived from an expression given in Wallén (1948).

$$\frac{du}{dz} = \frac{u}{(z + z_0)} \frac{(z + zo)}{z_0}$$

where du/dz is the velocity gradient at height z cm, u the wind speed (cm sec $^{-1}$) at height z, and z_0 the roughness parameter.

The wind speed at 120 centimeters above the surface was read directly from the plotted curves (Figure 15) for the individual periods.

To establish the 120-centimeter wind speed for the total melt period, the mean 2-meter wind speed was computed from run-of-wind data and substituted in an equation developed by Rossby and given by Liljequist (1957a).

$$u_z = \frac{u}{k} \ln \frac{(z + zo)}{z_0} \frac{u^*}{k} \ln \frac{(z + zo)}{(\ z_0\ )}$$

where u_z is the wind speed at height z cm above the surface, u^* the friction velocity and k von Karman's constant (= 0.4).

Wind speed at 2m for the July 14 and total-melt period were almost equal (3.65 and 3.70 m sec $^{-1}$ respectively), and z_0 values were assumed to be equal to the .014 cm given by the July 14 plotted value. Then, with mean wind speed at 2.1 m of 3.70 m sec $^{-1}$, the friction velocity is 15.7 cm sec $^{-1}$ and wind speed at 120 cm is 336 cm sec $^{-1}$. The velocity gradient at 120 cm above surface was computed to be .33 cm sec $^{-1}$. The value of z_0 is rather critical. Had z_0 been .14 cm, a high value, the velocity gradient would have become .43 cm sec $^{-1}$. A logarithmic temperature profile was also assumed to derive the relevant temperature gradients. In spite of the inherent defects of turbulent-exchange theory (Priestley and Sheppard, 1952) and of errors in the measured data, the calculated heat transfer for the selected periods appeared to be of the right magnitude (Table 2).

RELATIVE HUMIDITY

Relative humidity was recorded in the screen by a Lambrecht thermohygrograph (hair sensor) from June 1 to August 5. The hygrograph data usually agreed well with relative humidity values determined by sling psychrometer. Adjustment to the instrument was occasionally necessary when blowing snow packed in the chart chamber and restricted the recording arm movement at relative humidities above 85 per cent. The inherent defects of the hair hygrograph are recognized (Landsberg, 1960); the time lag in response to humidity change, for instance, shows a progressive increase with decrease in air temperature. Fairly slow changes of relative humidity were nevertheless adequately indicated by the hygrograph record.

Measured relative humidity was high (over 85 per cent) for almost the whole 1961 season. On six days (Figures 8 and 9) mean humidity was below 85 per cent (June 9, 10 and 27 and July 24, 25 and 29). On eight days—June 9, 10, 17, 23 and 26 and July 8, 9 and 21— relative humidities of from 60 to 75 per cent were recorded for periods of one to five hours. Vertical vapor-pressure gradients, derived from measured temperature and humidity values at surface and screen height, were usually weak, thus indicating that from June 1 to August 5 little evaporation or condensation of water vapor took place by processes of turbulent diffusion. A complex relation, however, exists between the moisture content and the flux of water vapor in the atmosphere near the ground.

Table 2

Sensible heat transfer at 1.2m, 1961

Period	No. of hours	$\frac{du}{dz}$ (cm sec^{-1})	$\frac{dT}{dz}$ (°C cm^{-1})	Qh (ly period^{-1})
July 14	12.0	.30	.00028	2.1
" 15	23.0	.38	.00056	9.8
" 17	6.0	.45	.0030	8.5
" 21	8.5	.45	.0020	15.0
" 20–21	17.0	.45	.0020	30.0
" 21–22	21.5	.30	.001	13.0
Total	88.0			78.4
Total melt period	88.0	.33	.0009	52.0

Table 3

Latent heat transfer at 1.2m, 1961

Period	No. of hours	$\frac{du}{dz}$ (cm sec^{-1})	$\frac{de}{dz}$ (mm Hg cm^{-1})	Qc (ly period^{-1})
July 15	23.0	.38	.000044	1.75
Total melt period	88.0	.33	.00012	17.0

A mean downward vapor-pressure gradient was measured during the total melt period and assumed to follow the logarithmic profile. The relevant data (Table 3) were substituted in an expression similar to that given by Ambach (1960):

$$Qc = L.\,\varphi\, K_c \frac{de}{dz} \frac{.623}{p} \text{ ly sec}^{-1}$$

where Qc = the heat of condensation, L = the latent heat of evaporation or condensation, de/dz = the vapor-pressure gradient at height z cm, p = the atmospheric pressure in mm Hg, Kc = the exchange coefficient for vapor transfer and is assumed to equal Km, and φ has the usual meaning, to give a transfer of heat to the surface of about 17 ly.

PRESSURE

Variations in atmospheric pressure were recorded by an MSC-type microbarograph from June 1 to August 5 at the 1961 camp site. The barograph was set for use at the 825-millibar level (about 1,640 meters above mean sea level). The daily mean pressure regime (Figures 8 and 9) agreed closely with changes in the pressure field given by the Edmonton Arctic Forecast charts. Diurnal variations in pressure were irregular and masked by synoptic changes. Kinks in the barograph trace (occasionally exceeding 1 millibar in 30 minutes) were observed on June 12 and 13 and on July 14, 15 and 20. The monthly mean pressure for June (824.5 millibars) was lower than that of July (827.4 millibars). The daily range of pressure was greatest during the passage of cyclonic systems—for example on July 17, when the range was 4 millibars, and on July 27 and 28 when the ranges were 6.9 and 6.0 millibars respectively (Figures 8 and 9).

CLOUDS AND VISIBILITY

Sky cover, type of cloud and visibility were observed at three-hour intervals between 0700 EST from June 1 to August 5. The average amount of cloud cover was high during June and July (Figures 8 and 9). The average daily mean cloudiness for these two months, on the basis of systematic daytime records, sporadic night observations and indications from the sunshine recorder was 7.2 and 7.7 tenths respectively. A systematic diurnal variation of cloudiness was observed only during the few periods of almost clear, settled weather, when characteristic caps of cloud formed during the

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evening and spread from the highland peaks. The cloud most frequently observed was of varying stratiform type and its ceiling was from ground (1,660 meters) to about 6,000 feet (1,830 meters), but cirriform and altoform clouds usually prevailed when the sky was from 3 to 7 tenths covered. Lenticular clouds often developed over the mountains to the west and southwest of the 1961 station.

The opacity of the cloud deck to the solar rays was rarely uniform. Furthermore, cloud breaks and short-period partial clearances were frequently observed. For these reasons, daily sunshine totals were often greater than the daily mean cloudiness data (Figures 8 and 9) would indicate. On July 13, for example, the mean cloud cover was 8.5 tenths, but more than 40 per cent of the possible sunshine was recorded. There was ground fog only four times in June and July. Fog layers, apparently 15 to 45 meters thick, which rolled over the station from the northwest, west and southwest, were associated with almost calm, clear conditions favorable to radiative cooling. Blowing snow and low cloud were the main obstructions to visibility during June—for example, from the 18th to the 22nd. During July, low cloud and occasional heavy precipitation were associated with restricted visibility.

PRECIPITATION

Precipitation for the 1961 season was recorded in a standard rainfall gauge and by measurements of the depth and density of new snowfall. The problems of accurate measurement of precipitation in the Arctic are well known. Errors of measurement that occurred in the Lake Hazen area when snowfall and moderate winds were associated and when light sporadic falls of snow occurred are discussed by Jackson (1960b). Wind speeds of more than 5 miles an hour, with which the falls of snow were usually associated, can cause the actual precipitation to be underrecorded, sometimes by more than 100 per cent (Weiss, 1961). Snowfalls occurred on 35 of the 61 days from June 1 to July 31 (Figure 6), but precipitation was measurable by gauge on 12 days only (Figures 8 and 9). Accumulation of more than 15 centimeters of snow was measured at the ablation stakes from June 14 to 24. For the same period the gauge indicated a snowfall of from 1 to 2 centimeters. Reliable indications of the water equivalent of the snow were obtained by density observations. The measured density of new snow varied widely from 0.04 to 0.05 gm. cm^{-3} for the snow that fell on July 6 and 7, to about 0.15 gm. cm^{-3} for the snowfall of July 14. Rain did not occur during the 1961 season.

The total snowfall of June and July was from 40 to 44 centimeters with an estimated water equivalent of 3.5 to 3.7 centimeters. The comparable data from Alert give a 2.8-centimeter water equivalent for 30 days with precipitation (Figure 6); at the glacier station 5.0 centimeters snow fell during the low pressure period of July 9 to 11, whereas at Alert no trace of precipitation was recorded. There was a close temporal relation, however, between other periods of measurable precipitation at the two stations.

SUNSHINE

The duration of sunshine from June 1 to August 5 was recorded by a 24-hour Campbell-Stokes pattern instrument. The sun was more than 3 degrees above the horizon on all days of the 1961 season. Total possible sunshine was recorded on only four days during June and July (Figures 8 and 9). Less than 4 per cent (about one hour) of possible sunshine was recorded on each of eight days. The mean monthly percentage of possible sunshine was 44 and 38 for June and July, respectively. A decrease in recorded sunshine occurred after June 11. The estimated and the measured percentage of possible sunshine for May 15 to 31 and for June 1 to 11 were about 70 per cent. From June 11 to July 31, 50 per cent of the possible sunshine was recorded on only 14 days.

A markedly uneven distribution of bright sunshine through the day affects the income of short-wave radiative energy. Although the occurrence of bright sunshine was seldom evenly distributed during individual days, the June and July distribution of recorded sunshine gave only a slight maximum occurrence during the midday (0800–1600 EST) period (Table 4).

Table 4

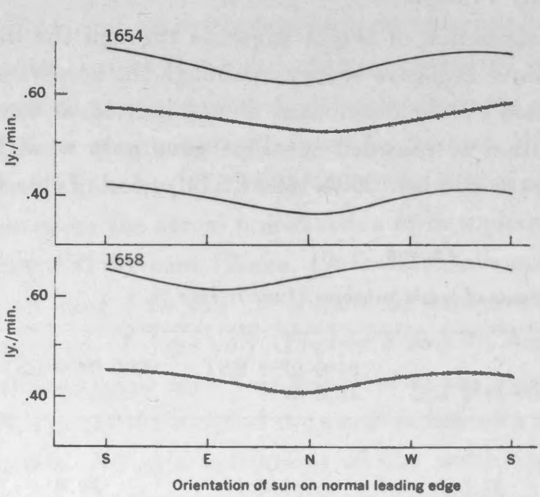
Percentage occurrence of bright sunshine, June 1–July 31

	0800–1559 EST	0400–0759 EST 1600–1959	0000–0359 EST 2000–2359
% of total recorded sunshine (600 hours)	37.0	33.0	30.0
% of possible sunshine (1,464 hours)	15.0	13.5	12.5

RADIATION

Short-wave radiation (0.3 to 3.0 μ wave length) was continuously recorded by a Casella bimetallic actinograph from May 17 to August 5. Instantaneous readings by potentiometer of up-facing and down-facing Kipp and Zonen solarimeters gave short-wave radiation data from June 4 to August 6, and the net flux of radiation was similarly recorded from a CSIRO (Funk) net radiometer. It was not possible to calibrate any of the instruments before departure to the field, and the sensitivity given by the manufacturers was initially assumed to be correct. A temperature correction was applied to the data given by the up-facing solarimeter on the assumption that the instrument was at ambient air temperature. In the case of the actinograph, a chart-area-conversion constant supplied by the Radiation Division of the Department of Transport in March 1961 was used.

Early-season data indicated that the sensitivity of each actinometric instrument deviated in some way from the given calibration constants. The converted actinograph record was compared with solarimeter data (Figure 16). The actinograph apparently underrecorded the daily mean income of solar radiation (for both direct beam and diffuse sky) by about 35 per cent, and the data were accordingly amended. The variation of solarimeter-instrument constant with solar altitude (for direct-beam radiation) has been



Date	Time (hrs)	Solar altitude	Variation of recorded income about mean
4 Aug.	1300	c 25°	c 4.5%±
3 Aug.	0730	c 21°	c 6.0%±
6 Aug.	1810	c 20°	c 9.0%±
6 Aug.	1300	c 24°	c 5.5%±
6 Aug.	1740	c 21°	c 7.0%±

FIGURE 16. Response of solarimeters 1654 and 1658 at different orientations under clear-sky conditions.

reported by Hoinkes (1961) and others but could not be determined with the actinometric instruments available. Variation of solarimeter sensitivity was also seen to occur with changes in the solar azimuth (Figure 17). Although a quantitative discussion of the 1961 radiation data was deferred until postseason calibration constants became available, it is not thought that further corrections will greatly change the qualitative features of the 1961 radiation regime.

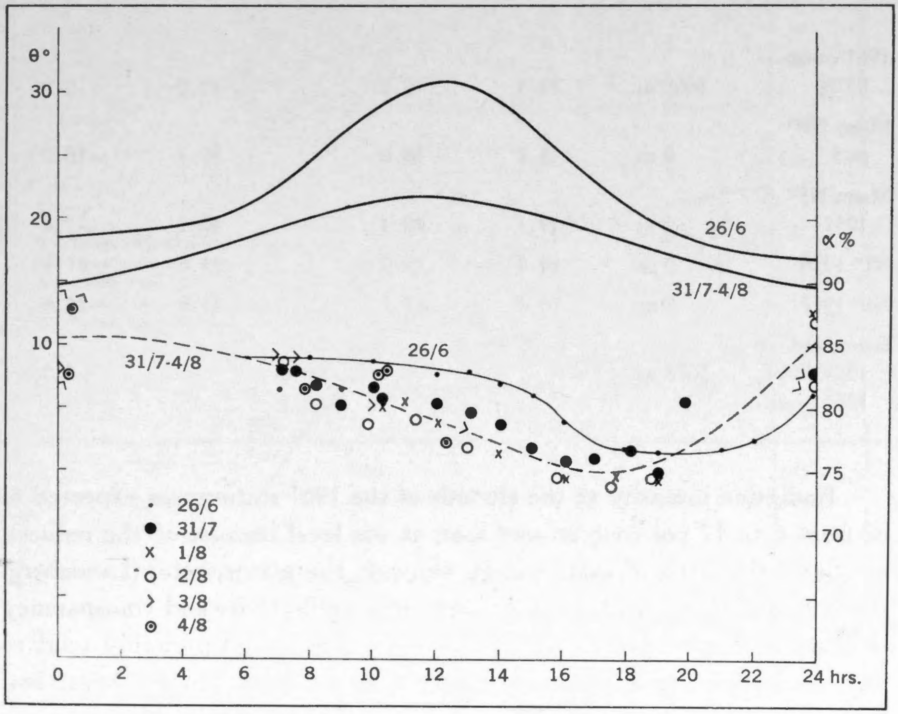


FIGURE 17. Measured albedo under clear-sky conditions in 1961—on June 26 and from July 31 to August 4. Solar altitude shown.

Short-wave radiation

Measured values demonstrate that the short-wave radiation income of the Arctic is high during the summer months (Andreeva and Paitnenkov, 1959). The June and July income of solar energy at the 1961 station was about 43.0k. cals cm^{-2}. Other actinometric data for comparable latitudes indicate that the 1961 values may be slightly high. Data for the 1961 station, floating stations NP-2, 3, 4, 5 and 7 (Andreeva and Paitnenkov, 1959; Gaevskii, 1959) and the Greenland ice cap (Diamond and Gerdel, 1956) are plotted in Table 5.

Table 5

Solar-radiation income

Position	Altitude	June	July	July 6 to August 7	Total	Percentage difference from income of 1961 camp
		(k. cals cm^{-2})				
1961 camp 83°N	1660 m	23.5	19.5		43.0	0.0
Mean NP[2] to 5	0 m	18.7	16.6		35.3	−16.0
Mean NP[2] 1951	0 m	19.7	20.4		40.1	−7.0
NP[5] 1956	0 m	18.8	15.0		33.8	−21.5
NP[7] 1947	0 m	18.4	13.5		31.9	−25.8
Greenland 1955 78°N	2073 m			20.6		+2.0
1961 camp				20.1		

Radiation intensity at the altitude of the 1961 station was expected to be from 6 to 12 per cent greater than at sea level because of the reduced length of the path of solar energy through the atmosphere (Landsberg, 1960). In addition, the effect of the high surface reflectivity and transparency of cloud on short-wave radiation at this altitude would probably tend to increase further the radiation intensity over sea level values (Angström, 1918). The daily income of solar radiation was dependent on the character of the sky cover. The occurrence of very intense solar-radiation values in conjunction with broken cloud associated with bright sunshine—a phenomenon reported by Wallén (1948)—was occasionally recorded. On June 20, incomes of 1.30 ly. min^{-1} were measured between 0800 and 1330 EST. On June 26, comparable clear-sky values ranged from 0.780 to 0.880 ly. min^{-1}. The reduction caused in short-wave radiation income by complete cloud cover varied from 30 to 40 per cent (Table 6) like that reported by other workers, such as Orvig (1954). Cloud density and, to a lesser extent, solar altitude seemed to determine the magnitude of the reduction in solar energy. The cloud cover of June 22, for example, appeared much less uniformly dense than that of July 6 (Table 6).

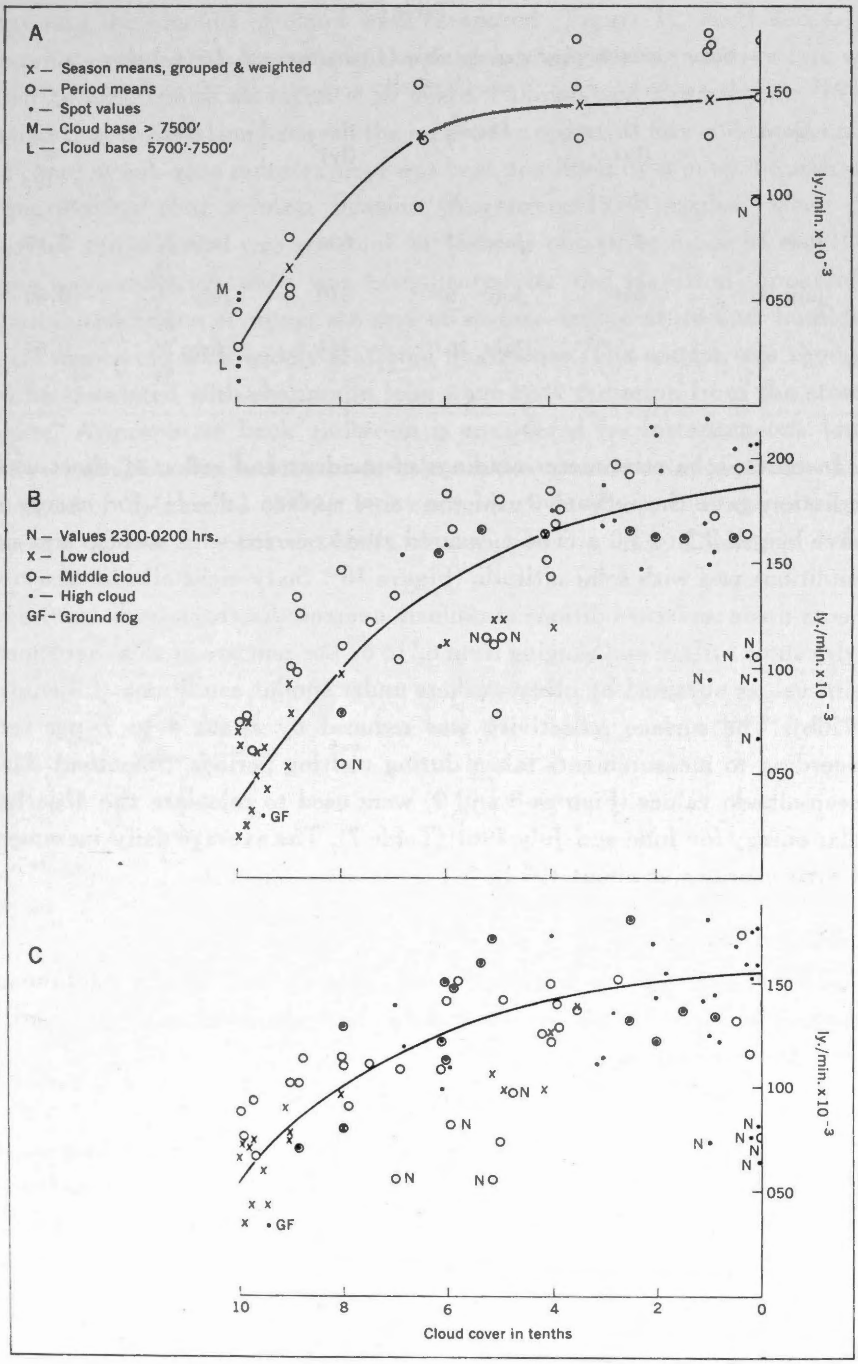


FIGURE 18. A—Net long-wave-radiation flux from raw instrument data.
B—Spot records, long-wave-flux raw instrument data.
C—Values in B corrected for albedo error.

Table 6

Solar radiation income under clear (I_0) and overcast sky (I_{10}) sky

Date	I_0 (ly)	Date	I_{10} (ly)	Date	$\frac{I_{10}}{I_0}$
June 27	870	June 22	604	June $\frac{22}{27}$	0.70
July 31	651	July 6	519	July $\frac{6}{27}$	0.60
		July 26	414	July $\frac{26}{31}$	0.64

Instantaneous solarimeter readings of incident and reflected short-wave radiation gave the reflectivity of the snow surface (albedo) for energy of wave length 0.3 to 3.0 μ. The measured albedo varied with surface and sky conditions and with solar altitude (Figure 18). Sixty-eight albedo measurements made under conditions of uniform overcast (isotropic radiation) over a dry snow surface and ranging from 82 to 87 per cent are in close agreement with values obtained by other workers under similar conditions (Liljequist, 1956b). The surface reflectivity was reduced by about 4 to 7 per cent according to measurements taken during melting periods. Smoothed daily mean-albedo values (Figures 8 and 9) were used to calculate the absorbed solar energy for June and July 1961 (Table 7). The average daily increment of solar energy was about 109 ly^{-2}.

Long-wave radiation

The net flux of long-wave radiation (R) was derived from instantaneous readings of the solarimeters (Iu and Id) and net radiometer (F), and is given by the formula

$$R = (Iu - Id) \quad F \text{ ly. min}^{-1}$$

Rapidly changing sky conditions made many of the derived long-wave-radiation data unrepresentative. The increment of short-wave radiation (Iu–Id) was usually too high when measured under clear sky conditions and was adjusted by reference to an estimated true albedo value. Observations made during conditions of uniform overcast were considered representative.

The measured long-wave radiative flux was always negative. Adjusted values ranged from –0.175 ly. min^{-1} to –0.030 ly. min^{-1} for clear sky and heavy overcast conditions respectively. When net long-wave radiative flux and the amount of cloud were compared (Figure 18, A, B and C), a roughly exponential decrease in the outgoing long-wave radiative flux was seen to accompany an increase in cloud. Hoinkes and Untersteiner (1952) found that the relation between the long-wave radiative flux and the amount of cloud at sub-zero temperatures was best described by a partial quadratic equation but that a linear relation (Angström, 1934) applied when the surface temperature was constant at melting point. Analysis of the 1961 long-wave-radiation data was complicated by the fact that apparently similar conditions of upper air and of surface temperature and humidity were associated with widely scattered flux values. The scatter was thought to be associated with changes in long-wave back radiation from the atmosphere. Atmospheric back radiation is considered for instantaneous long-wave radiative flux values under clear skies as calculated by the chart method of Yamamoto (1954). It is recognized, however, that there are inherent defects in radiation-chart theory (Goodie and Robinson, 1951)

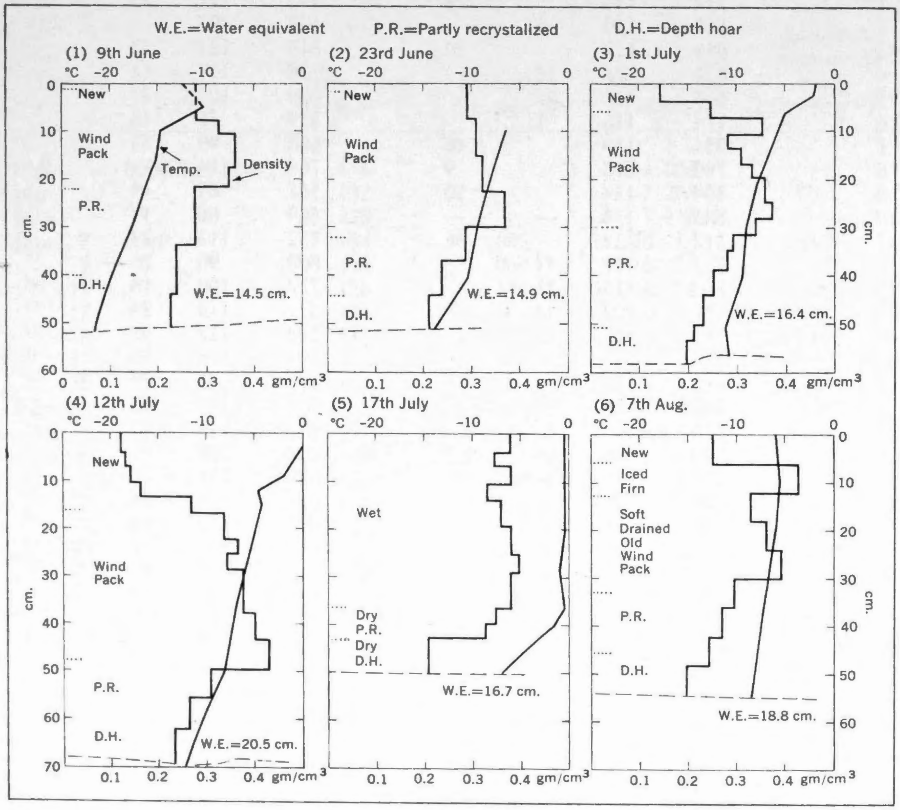


FIGURE 19. Snow density and temperature in camp area, 1961.

and that errors are possible in its application. For instance, the remoteness of the Alert weather station, which provides the only comparative data, and the undoubted disturbance of the atmosphere due to air flow over mountainous terrain (Corby, 1954) are complicating factors. Aerological data from Alert gave the basic parameters for computation of the atmospheric

Table 7

Daily flux of radiative energy, June and July, 1961

Is —Total incoming short-wave radiation (langleys)
S —Absorbed solar energy (langleys)
N.F.—Daily net flux of radiation (langleys)

	June				July			
Date	Is	S	N.F.		Is	S	N.F.	
			+	−			+	−
1	774	116		24	743	111	25	
2	865	130	5		648	97		23
3	849	127		10	818	123	33	
4	851	127	32		738	111	11	
5	858	128	63		689	103	27	
6	774	116	1		519	78	18	
7	931	139		46	668	99	34	
8	790	118		9	764	114		9
9	894	134		50	567	85	14	
10	883	133	—	—	569	86	14	
11	812	122		36	752	113	23	
12	782	117	37		600	90	25	
13	770	115	51		723	108	18	
14	725	109	44		672	114	24	
15	753	112		18	718	122	32	
16	826	124	9		643	128	56	
17	670	100	35		473	95	23	
18	669	100	35		586	117	22	
19	632	95	30		697	139	67	
20	956	144	69		604	121	11	
21	670	100	35		679	136	46	
22	604	90	25		637	127	17	
23	725	109		1	667	113	18	
24	641	96	31		660	112	2	
25	720	108	8		535	91	19	
26	864	130		55	414	70	10	
27	870	130		25	409	69	9	
28	921	138		2	488	73	13	
29	749	112	1		502	75	3	
30	709	106	6		656	99		76
					651	98		76
Total	23,537	3,525	517	276	19,489	3,217	614	184
Net gain or loss			+241				+430	

temperature and water content. Charts were constructed for times when aerological observations gave wind data at the 800-, 850- and 900-millibar levels comparable to those collected at the glacier station. Surface temperature and humidity data were taken for chart origin. Twenty-seven flux values were computed (Table 8). It was considered permissible to use monthly meaned aerological data (London, 1957) which indicate a downward trend from -0.144 ly. min^{-1} in May to -0.120 ly. min^{-1} in the average net outward flux for July. Other chart data gave values varying from -0.141 ly. min^{-1} for a cold dry atmosphere and warm surface to -0.093 ly. min^{-1} for a warm moist atmosphere and melting surface.

Table 8

Net long-wave-radiation flux, 1961 camp, from measured and chart values

E = Estimated and measured
H = High cloud > 15,000′
L = Low cloud < 6,000′
M = Midcloud 6,000′–15,000′

Date	Time (GMT)	Chart value (ly. min^{-1})	Measured (ly. min^{-1})	Mean cloud (tenths)	Adjusted measured value (ly. min^{-1})
May	0000 and 1200	.144		E 4.0M	—
June	" "	.132		7.2ML	—
July	" "	.120		7.7ML	—
June 7	0000	.134	.065	10 L	.070
" 9	"	.135	.064	10 L	.071
" 11	"	.126	.133	1 H	.105
" 17	"	.124	.161	0	.132
" 22	"	.115	.033	10 L	.049
" 27	"	.125	.164	0	.114
" 30	"	.132	.164	4 M	.094
July 5	"	.141	.149	1 M	.099
" (5	1200	.141	.112	6 M	.131
" (6	"	.140	.053	10 L	.062
" 8	"	.130	.154	7 H	.125
" 9	"	.123	.112	10 ML	.085
" 14	0000	.135	.123	9 HM	.086
" 15	"	.122	.025	9 ML	.037
" 16	"	.116	.089	9 M	.079
" 17	"	.107	.042	10 L	.026
" 17	1200	.093	.046	10 ML	.036
" 19	"	.133	.074	10 ML	.040
" 21	0000	.090	.027	10 ML	.018
" 21	1200	.104	.186	5 M	.057
" 22	0000	.103	.029	8 ML	.057
" 27	1200	.112	.023	10 L	.030
" 30	0000	.114	.069	10 ML	.049
" 31	"	.104	.135	0	.094

Total flux of radiation

For short periods in the 1961 season, the net radiative-energy transport was derived from net radio-meter data. Daily values of the net radiative flux were computed by actinograph, mean albedo and net long-wave radiation data (Figures 8 and 9). The effect of cloud cover on the long-wave radiative flux was calculated by means of an equation given by Angström (1918):

$$R = Ro\ (1 - k.\ c)$$

where R = the actual flux, Ro = flux under clear sky, c = cloudiness as a fraction, and k = a constant given a value from .8 for low cloud to .5 for high cloud.

The daily mean long-wave radiative energy was calculated to be about -100 ly day^{-1} for the period from June 16 to July 31. Since arbitrary constants and monthly mean flux values were used, short-period errors are likely to be great with this method of calculation.

The energy gained by radiative transfer was computed to be about 670 g. cal cm^{-2} from June 1 to July 31, which is about 3.4 ly day^{-1} higher than the gain estimated to have occurred at 2,050 meters in 1955 at 78°N in Greenland (Diamond and Gerdel, 1956).

ACCUMULATION AND ABLATION

The accumulation at the 1961 camp was measured during early June at snow pits and by probes in the 1960-61 snowpack. Summer precipitation data were added to give the total budget-year accumulation. Systematic measurement of surface-level change was made at five stakes from June 1 to August 5 and at four dowels from July 5 to August 5 (Figures 8 and 9). The marker stakes and dowels were planted at measured depths in the firn in accordance with a method given by Lachapelle (1959) for assessing the relation between surface-level changes, snow settling and ablation. Measurement indicated that there was not a systematic variation of the surface level from marker to marker. For this reason, the Lachapelle method could not be used to analyze surface-level changes on the upper Gilman Glacier. The failure is probably due to the association of a shallow snowpack and an underlying crust of water-soaked firn. A mean snow depth of about 50 centimeters was measured during the period from May 29 to June 5.

Determination of snow density gave an accumulation of about 15 centimeters' water equivalent (Figure 19). The addition of 3.5 centimeters' precipitation between June 1 and July 22 gave a budget-year accumulation of 18.5 centimeters; according to deep-pit data, mean budget-year accumulation at the station from 1951 to 1961 was 16.2 centimeters (Hattersley-Smith, 1964). Data from Alert indicated a relatively low 1961 budget-year accumulation, the precipitation from August 1960 to July 1961 being 2.6 centimeters less than the 11-year mean value of 14.3 centimeters. There was, in fact, some correspondence between the seasonal distribution of precipitation at Alert and that of precipitation on the glacier as estimated from stratification and snow-density data (Table 9).

Table 9

Precipitation data, Glacier station and Alert

	Glacier station		Alert	
	Cm water	%	Cm water	%
1960–61 budget year	18.5		11.9	
August–October, 1960		40.0		50.0
November 1960–February 1961		12.0		6.5
March–May, 1961		30.0		19.5
June–July, 1961		18.0		24.0

The mean stake data (Figures 8 and 9) and evidence from other markers indicated that summer accumulation of snow increased the snow depth by 5 to 8 centimeters, a value confirmed by depth and density data from snow pits on August 7 (Figure 19). An almost continuous rise of snow level took place from June 1 to 30 (Table 10). Between July 1 and 11, settling of the snowpack and possibly some very slight melting reduced the measured rise of the snow surface from 17.0 to 8.3 centimeters. From July 12 to 22 a continuous fall of surface level was associated with melting and settling of the snowpack. For the purpose of this report, ablation was considered to include melting and sublimation of snow and evaporation of meltwater. Free water was first detected in the upper snowpack about 1300 EST on July 6. The free water, which was insufficient to permit measurement by a compaction method described by Williams (1956), formed a refrozen water-soaked layer 2.5 centimeters below the surface. Appreciable thawing did not occur, however, until July 14, when measurement showed the upper 5 centimeters of the snowpack to have a free-water content of more than 5 per cent. Conditions favorable to snow-melting prevailed for some 110 hours between 1200 EST on July 14 and 1600 EST on July 22. It was difficult to measure the total melt precisely, but physical evidence—ice-layer thickness and density change in the snowpack—indicated that from 10 to 14 centimeters of snow had melted to form from 2 to 3 centimeters (water equivalent) of ice (Table 11).

ABLATION AND METEOROLOGICAL FACTORS

The melting of snow does not involve the loss of mass from the glacier. Sublimation of snow and evaporation of meltwater, on the other hand, do involve a small amount of such loss. Because of their high latent heat, these two processes are also of importance in the energy balance of the upper glacier. Sublimation and evaporation were probably associated with the surplus radiative energy measured (or calculated) for certain periods in June and July.

Air temperature is dependent on the interrelation of many meteorological parameters, such as cloudiness, wind speed and insolation, which concern the ablation process. It was found that the recorded air temperature was the one meteorological factor that gave a direct and systematic relation with ablation (Figures 8 and 9). Surface melting was never observed with air temperatures below 32.0°F (0.0°C), although subsurface melting was associated with penetrating short-wave radiative energy on occasion, as, for example, at 1600 EST on July 16, when the screen temperatures were between 29.0 and 31.9°F (−1.7 and −0.05°C). It was noted that during the 1961 season these relatively high air temperatures were associated with cyclonic activity and warm-air advection at levels from 700 to 900 millibars.

The following terms are required to solve the heat-balance equation for a melting snow surface:

(1) heat supplied or lost by radiative transfer;

(2) heat supplied or lost by turbulent diffusion;

(3) heat required for melting;

(4) heat required for evaporation;

(5) heat supplied by condensation;

(6) heat conducted into the snow.

Measured and estimated heat balance data for the 88 hours of ablation in the periods from July 14 to 17 and July 20 to 22 indicate that the association of a positive radiative and convective energy flux was necessary to promote ablation (Table 12). The energy involved in the melting of snow (3.0 cm water equivalent) and in the reduction of the cold content of the snow and firn (about 12 ly day^{-1}) is a maximum value.

Determination of a seasonal heat balance would be greatly limited in accuracy, since only the term for change in the heat content of the snow and firn would be given a reliable value. Sverdrup (1936) pointed out that the relative importance of the radiative and convective heat terms cannot be satisfactorily determined when long-period means are used in energy-balance computations. The principal role of the net radiative flux is, however, suggested by the 1961 data. Between June 7 and July 22, about 680 langleys were supplied by radiative transfer; 780 langleys were required to reduce the cold content of the snow and firn pack and to promote melting.

Table 10

Change of snow-surface level, 1961

(centimeters)

Period	Gross increase	Gross decrease	Net change
June 1–30	+20.0	−3.5	+16.5
July 1–11	+17.2	−8.9	+8.3
July 11–22		−16.1	−16.1

Table 11

Estimate of 1961 snow melt

Period		Mean snow depth (cm)	Mean density (g.cm³)	Water equivalent (cm)
May 31	Snow	50.0	0.30	15.0
July 22	Snow and ice	55.0	0.34	18.7
July 22	Dry snow	41.0	0.30	12.3
	Water-soaked snow	11.0	0.40	4.4
	Ice layers (varied)	2.0	0.90	1.8
	Total (July 22)	54.0	0.34	18.5
June 1 to July 22	New snow	40.0	0.09	3.6

95604—4

Table 12

Heat balance during melting periods, 1961

(langleys)

	Energy source	Energy sink
(1) Radiative transfer	195	—
(2) Turbulent transfer	80	—
(3) Condensation	17	—
(4) Evaporation	—	—
(5) Melting	—	240
(6) Heating of snow	—	48
	292	288

BUDGET-YEAR ECONOMY OF GILMAN GLACIER

The areal extent of the Gilman Glacier (480 km^{-2}) and its areal distribution by altitude were measured by planimeter on a large-scale map* supplied by the Defence Research Board. These data were used with accumulation and ablation records extending from 1956 to 1961 to estimate variations in the budget-year economy (Figures 20 and 21). The total accumulation and ablation for each altitude area (Figure 21) was the product of area and mean accumulation or ablation values extracted from the smoothed curves in Figure 20. In 1961, for instance, the mean ablation was 12 centimeters for the 70.9 km^{-2} within the altitude range from 914 to 1067 meters (Group 5), and this gave an areal-mass loss of $8.50 \times 10^{-3} km^3$. The foregoing technique differs from that used by Hattersley-Smith (1961b) to evaluate the 1957–58 budget-year economy. Each method gives disparate values, particularly for accumulation and consequently in the budget-year mass-loss total, as shown in the following tabulation.

		Total ablation (A) (km^{-3})	Total accumulation (S) (km^{-3})	$\frac{A-S}{S}$
1957–58	By 1961b method	8730×10^{-5}	5430×10^{-5}	.60
	By 1961 method	9580×10^{-5}	4270×10^{-5}	1.24

*Prepared by the Legal Surveys and Aeronautical Charts Division, Surveys and Mapping Branch, Department of Mines and Technical Surveys.

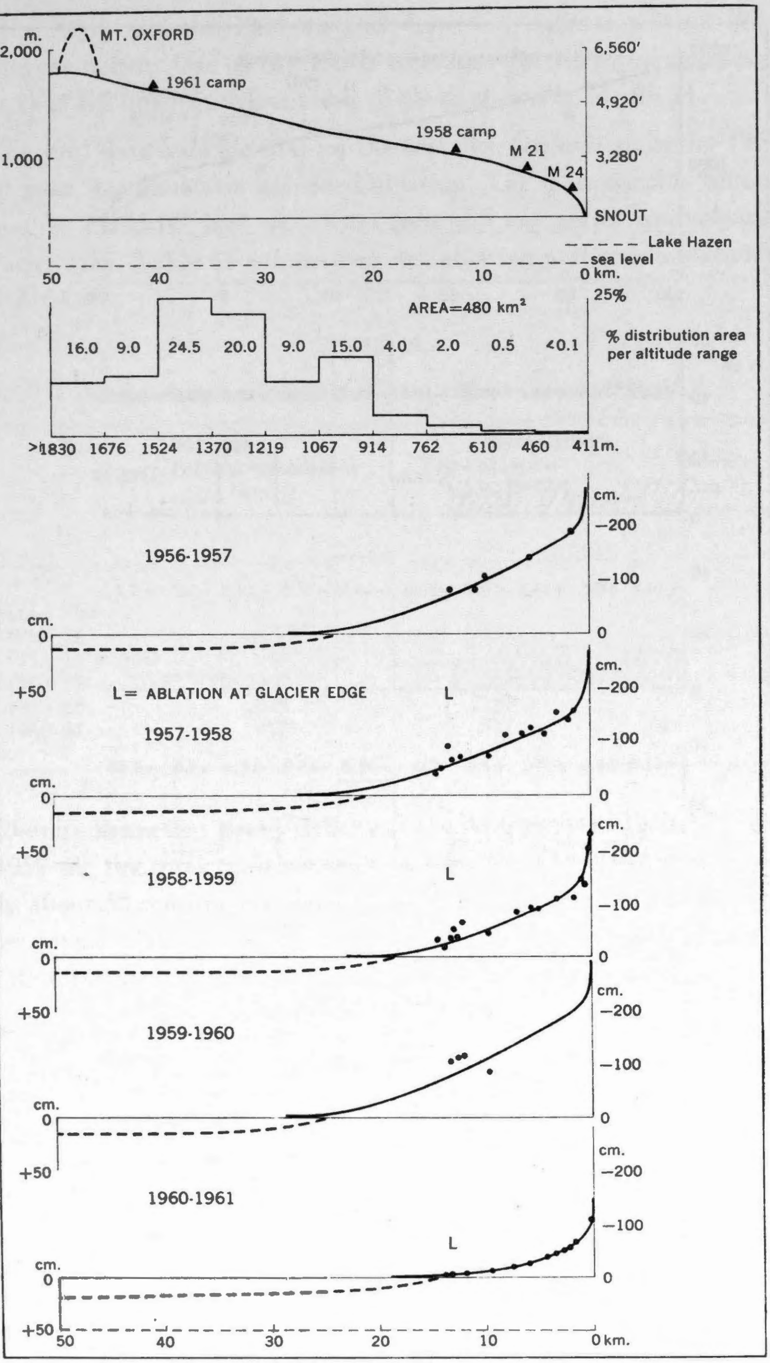


FIGURE 20. Accumulation and ablation (in centimeters) for each altitude area, Gilman Glacier, 1957–61.

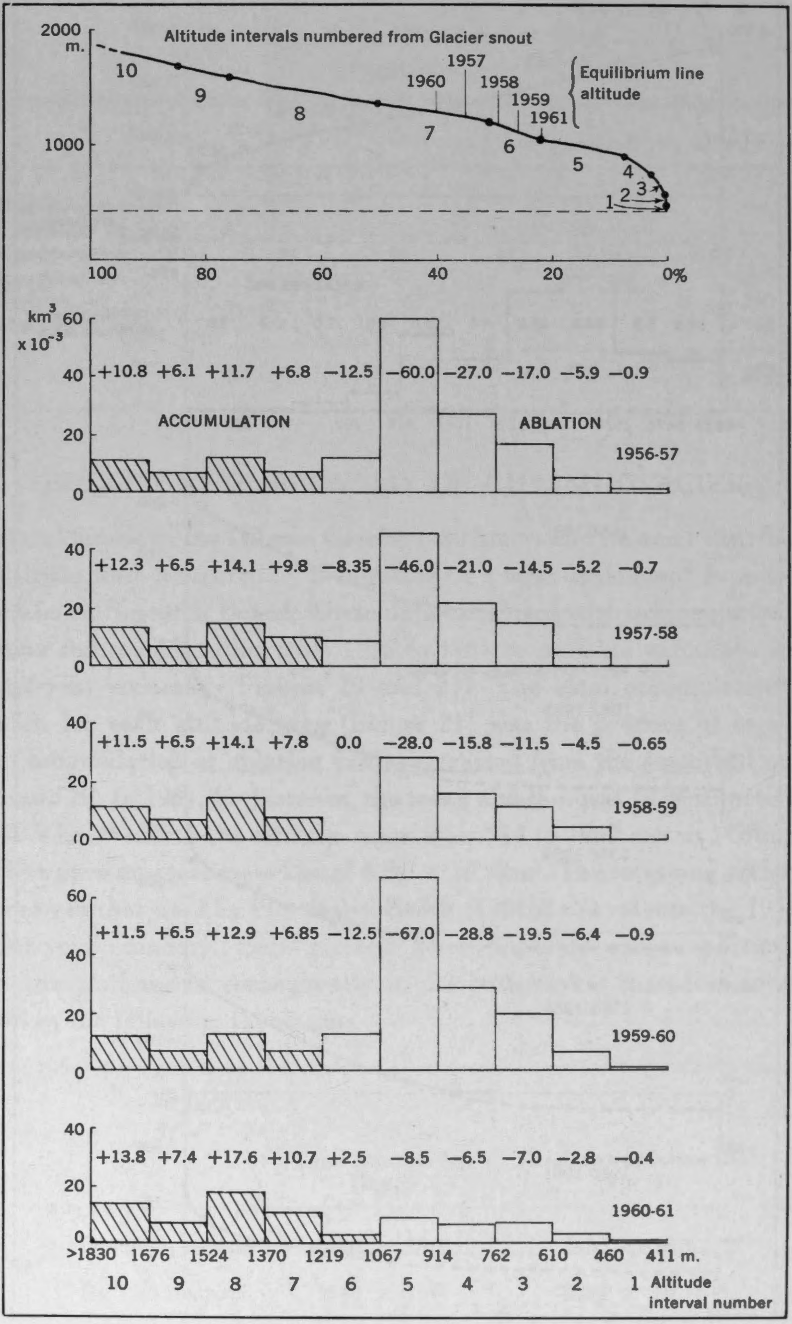


FIGURE 21. Accumulation and ablation (as percentage) for each altitude area, Gilman Glacier, 1957-61.

Both the 1961b and the 1964 method, however, indicate a large 1957–58 budget-year deficit. Use of the 1961b technique for the other periods gives results that are qualitatively similar to those shown in Figure 21.

The 1961 data indicate that for the first year, at least since the 1956–57 budget year, accumulation exceeded ablation. The mass surplus amounted to about $+ 25 \times 10^{-3} km^3$, or a total gain of 5 cm, water equivalent over the glacier area. Table 13 summarizes net ablation and accumulation data for 1956–61.

Table 13

Estimated accumulation and ablation, Gilman Glacier, 1956–61

	Total accumulation (km^{-3})	Total ablation (km^{-3})	Balance (km^{-3})	
			+	–
Budget Year				
1956–57	.035	.123		.088
1957–58	.043	.096		.053
1958–59	.040	.060		.020
1959–60	.038	.135		.097
1960–61	.052	.027	.025	

Despite the rather heavy deficits of the budget years 1956–57, 1957–58 and 1959–60, the total surface reduction for 1956–61 (specific net ablation) is only about 50 centimeters water equivalent. The economy of the Gilman Glacier seems highly sensitive to variations in the intensity of ablation, since its total accumulation does not usually vary significantly.

CONCLUSION

On the basis of the 11-year record of the Alert weather station and of other climatological and ablation records, the summer of 1961 on northern Ellesmere Island was relatively cool. The coolness was associated with the lowest ablation data measured during the last five years of the period. Melting occurred for a short time at the 1961 camp when air temperatures exceeded 32°F (0°C) and were associated with warm-air advection. The high temperatures of mid-July raised the mean monthly temperature above Alert's 11-year average. The net thermal energy gain of the upper Gilman Glacier was supplied primarily by the small positive radiative flux.

The evidence of the 1961 summer considered in relation to the results of the four previous years seems to indicate that a small change in the monthly temperatures for June and July has a critical effect on the economy of the Gilman Glacier. The mass of ice is nevertheless so huge that the change would have to persist for many years to cause any great alteration in the areal extent of the glacier or in the flow regime.

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A RECONNAISSANCE GLACIER AND GEOMORPHOLOGICAL SURVEY OF THE DUART LAKE AREA, BRUCE MOUNTAINS, BAFFIN ISLAND, N. W. T.

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ABSTRACT: The author describes the survey of glacier snouts in the Duart Lake area. This is part of Canada's contribution to a world-wide study of the variations in existing glaciers, which was recommended by the Snow and Ice Commission of the International Association of Scientific Hydrology. He also considers the geomorphological and botanical evidence of the former extent of glacierization and compares the more recent phases of this process with those of other countries.

RÉSUMÉ: L'auteur décrit l'étude qu'il a faite de fronts de glaciers dans la région du lac Duart. Cette étude constitue l'apport du Canada à une étude mondiale des variations des glaciers existants, faite à la demande de la Commission de la neige et des glaciers, de l'Association internationale d'hydrologie scientifique. Il tient compte aussi des indices géomorphologiques et botaniques de l'ancienne extension des glaciers et il compare les stades les plus récents de cette extension avec ceux d'autres pays.

INTRODUCTION

Duart Lake lies 40 kilometers from the open sea at the western end of the long pass that links Duart Bay, on Dexterity Fiord, with Cape Adair (Figure 1). The pass cuts through the Bruce Mountains, which rise to more than 1,500 meters above sea level and form a high point in the east-coast mountains. In this lake area the mountains are alpine and numerous glaciers arise in cirques that are separated by arêtes and matterhorn peaks. South of the pass the alpine topography is subdued, small plateau ice caps and rounded summits becoming more prominent.

The 48-kilometer-long pass is very narrow and is bounded by cliffs hundreds of meters high. Its floor is covered with braided meltwater streams and small lakes, some of which are blocked by the end moraines of glaciers that flow out to this floor.

No previous scientific work has been attempted in the area apart from the exploratory survey of Dexterity Fiord made by Wordie in 1937 (Wordie, 1938).

The main purpose of the 1963 summer survey was the mapping and photographing of mountain-glacier snouts, part of Canada's contribution

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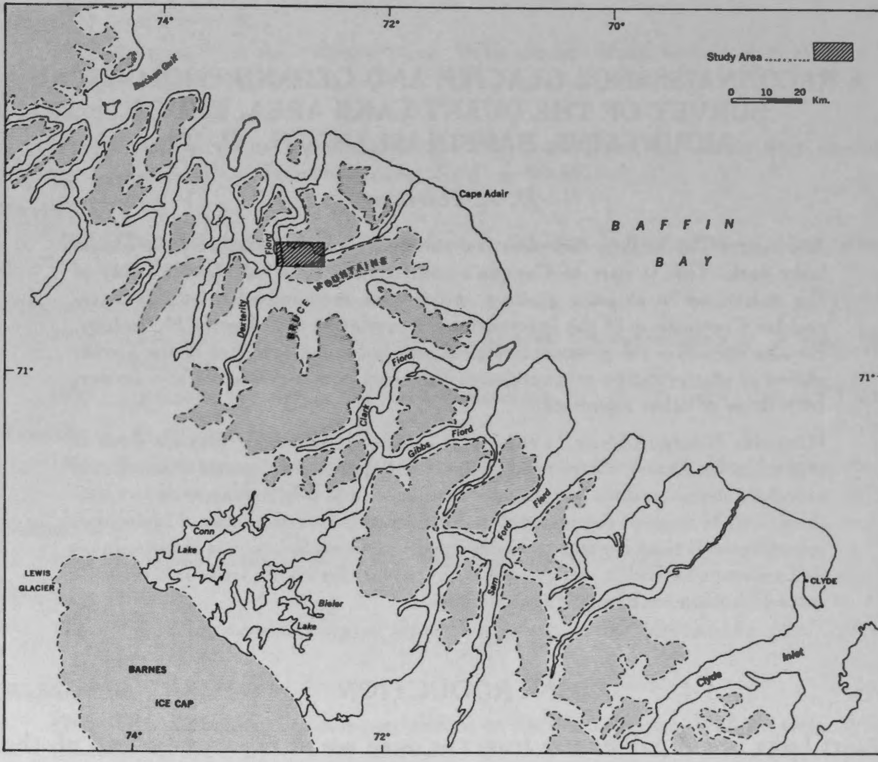

FIGURE 1. Location map.

to a worldwide study of glaciers. This study was proposed by the Snow and Ice Commission of the International Association of Scientific Hydrology at Helsinki in 1960 and a subcommittee on variations of existing glaciers was subsequently formed. This subcommittee recommended that the study of as many as possible of the world's glaciers should begin in 1963 and proceed on an annual or a five year basis.

Not only were mountain glaciers surveyed, but geomorphological and botanical data were collected to ascertain the extent of past glacierization.

GLACIER-MAPPING

The 15 westernmost of the glaciers that flow down into the pass from the cirques and ice caps lying to the north and south were photographed from known positions and the snouts of two of them were mapped in detail. The glaciers on the north side of the pass were designated by the letter N, and those on the south side by the letter S. Each glacier surveyed or photographed was also numbered, the enumeration starting at the western end of the pass.

The two glaciers surveyed in detail are S2 and N2 (Figures 2, 3 and 4). They were chosen because of their opposing aspect and their close proximity to the base camp. The high end moraines that bounded them made it impossible to survey their snouts directly from theodolite stations on the stable ground outside these moraines.

A base line was measured on the stable ground between the two snouts by tacheometry involving the use of a Wild T2 theodolite and a 4-meter rod. From this base, theodolite stations were set up on the firmer parts of the outer end-moraine ridge and minor stations were set up close to the ice margin. The position of the ice margin along known bearings taken from the theodolite stations was also measured by tacheometry.

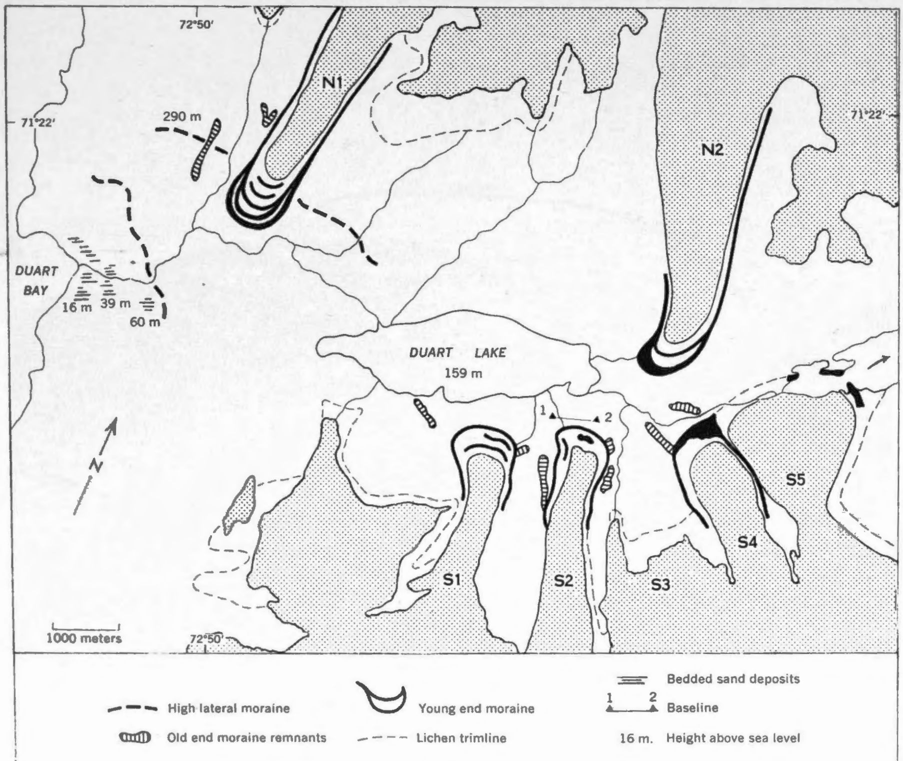

FIGURE 2. Detailed location map of Duart Lake area.

FIGURE 3. View of snout and young end moraines of glacier S2 from near cairn 4. Photo: DAH-63-1317.

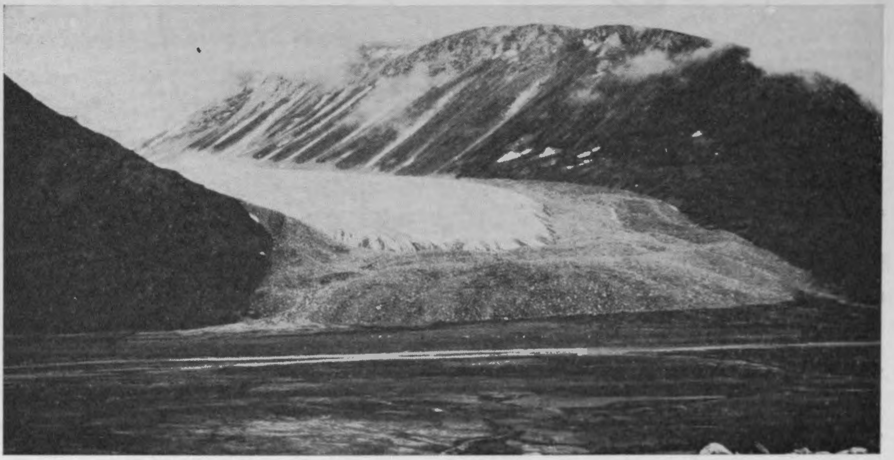

FIGURE 4. View of snout and young end moraines of glacier N2 from cairn 8. Photo: DAH–63–1326.

Cairns more than 1 meter high marked the location of theodolite stations 1 to 9; but 10 and 11, because of the instability of the ice-cored morainic debris at these points, were marked only by small temporary cairns. The principal cairns were marked with paint and red fluorescent cloth.

Figures 5 and 6 show the detailed surveys of the snouts of glaciers S2 and N2. The ice margins were mapped from survey data only whereas the location of the end moraines was mapped from both survey data and the 1958 air photographs.

Cairns were also placed at known bearings and distances from the ice margins of glaciers S1, S5 and N1. The snouts of these three are different in aspect and in their location with regard to the centre of the pass floor. The snout of glacier S1 lies on the steep north-facing slope of the pass, and

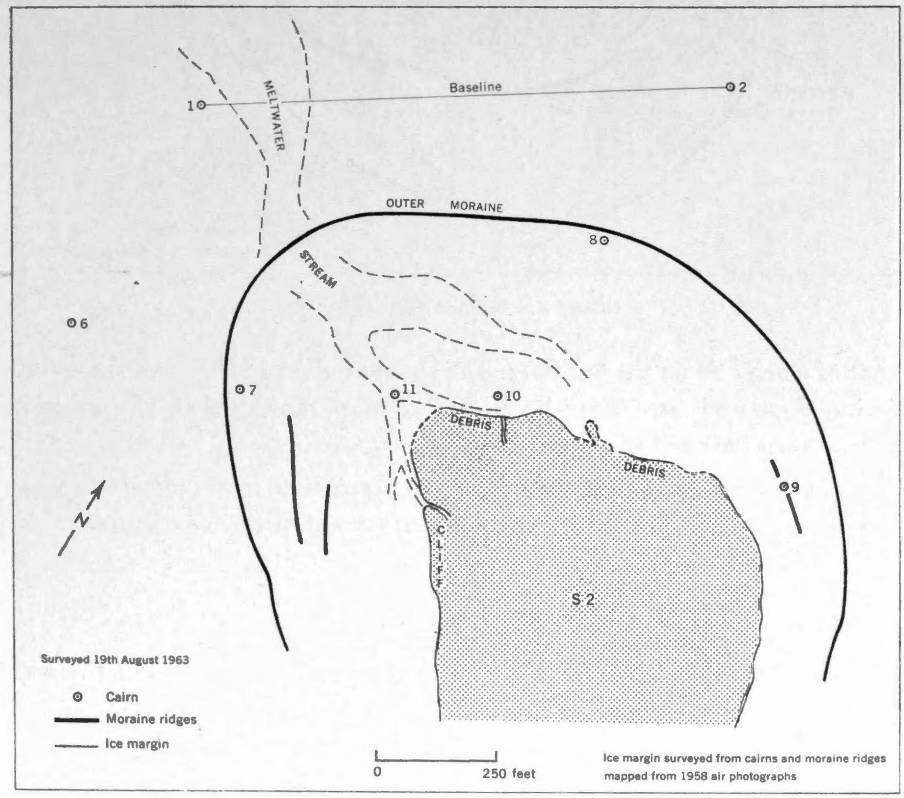

FIGURE 5. Detailed map of snout S2.

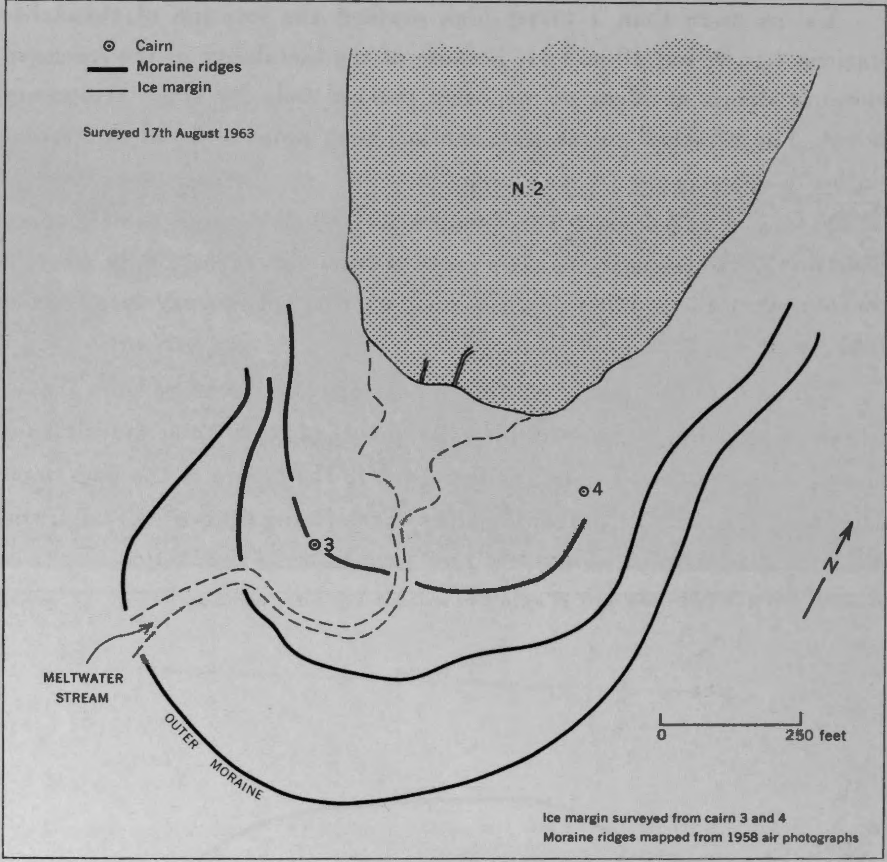

FIGURE 6. Detailed map of snout N2.

that of glacier S5 on the flat floor. The snout of glacier N1 lies on the south-facing slope and appears to be retreating more rapidly than any other in the western part of the pass.

A resurvey of all these snouts in five years' time may indicate to what extent the various factors affect the linear retreat of the ice margin.

GLACIAL GEOMORPHOLOGY

The moraines that indicate phases in the former glacierization of the area are in three distinct groups: the high-level lateral moraine, on the wall of the main pass; old, subdued remnants of the end moraines of formerly more extensive mountain glaciers; and large, fresh, younger end moraines enclosing the snouts of the present glaciers (Figure 2).

The high-level lateral moraine lies east of Duart Bay at a height of some 290 meters above sea level on the north side of the pass and is breached by two end-moraine systems of glacier N1. It forms a distinct ridge separated from the valley side by a wet gully 9 meters wide and 2.5 to 4 meters deep. East of glacier N1, the ridge appears to continue but its elevation is only about 227 meters. Similar moraines have been noted in the air photographs of the Baffin Bay and Home Bay areas. They are probably formed by the outlet glaciers of the main inland ice sheet that covered Baffin Island during the late Clyde phase (Ives and Andrews, 1963, page 35). A much lower lateral moraine lying closer to Duart Bay marks an even later Clyde phase (Figure 2).

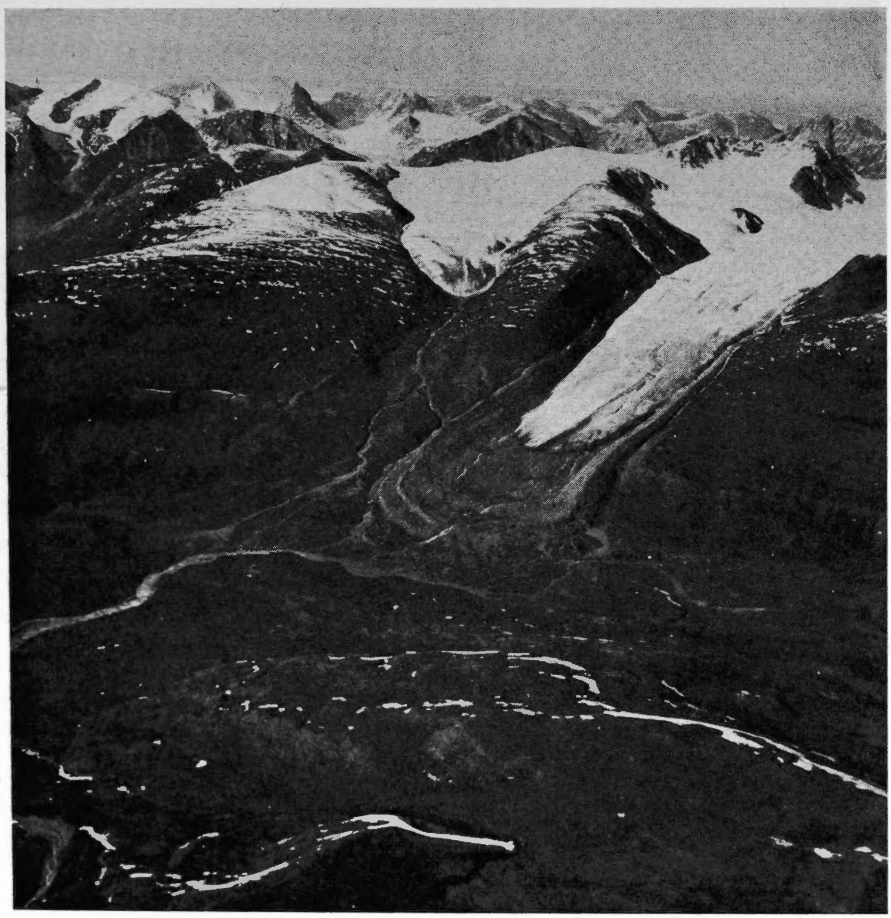

FIGURE 7. View of glaciers, Duart Lake area. Photo: JDI–63–2–3.

The high-level moraine is cut through by two end moraines that indicate an expansion of the local mountain glaciers after the retreat of the outlet glaciers.* No evidence was found to indicate that the mountain glaciers had coalesced with the outlet glaciers during the Clyde phase.

The end moraines of the older group are well developed around the snout of Glacier N1 and the small glacier to the northwest (Figure 7). Remnants of these older end moraines are seen partially covered by the most recent end moraines of glaciers S1, S2, S4 and S5 (Figure 2). They are well rounded and thickly vegetated.

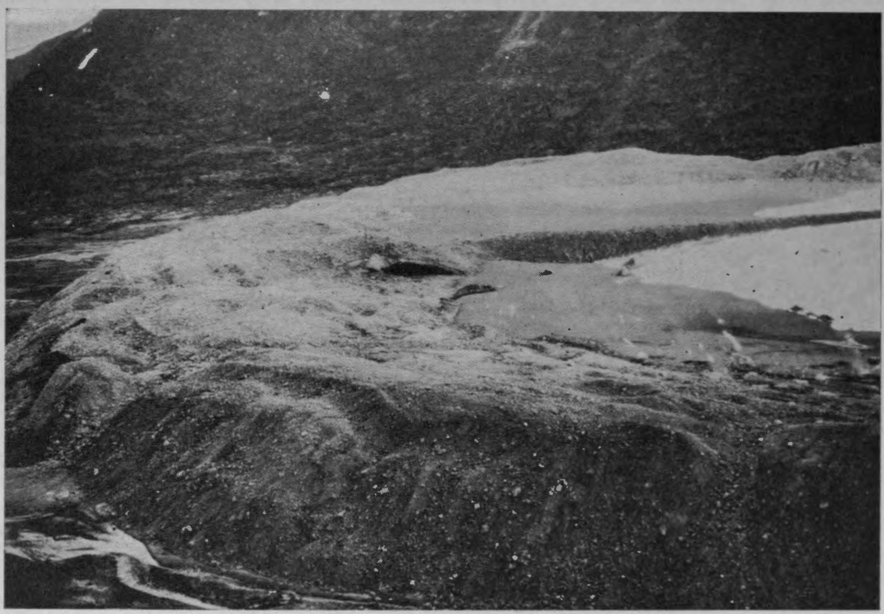

FIGURE 8. View of high ice-cored moraine surrounding snout of glacier S8. Photo: DAH–63–1321.

The moraines of the third and youngest group are the most conspicuous. Consisting of large angular boulders of pale-colored granite gneiss, they form ramparts 20 to 50 meters high along the edges of most of the glacier snouts flowing into the pass (Figure 8). The outer moraines are comparatively stable while the inner morainic debris, seen to be underlain by ice, is very unstable. In places, the young moraines overlie old entrenched outwash fans as well as the older end-moraine ridges.

*Thompson (1957) noted a similar advance of the mountain glaciers after the retreat of the through glacier in Pangnirtung Pass, southern Baffin Island.

Not all the glaciers are bordered by high end moraines. Glacier S5, for example, which has the largest snout in the area, is bounded by very little morainic debris; and glacier N4, which has a small snout but a large catchment area, has no end moraine (Figure 9). This variability in size of glacier and character of end moraine has been commented on by Østrem (1960 and 1962).

FIGURE 9. View of snout of glacier N4. Note lack of end moraine. Photo: DAH–63–1287.

LICHEN MEASUREMENTS

The positions of the three groups of moraines make it possible to assign relative ages to the three corresponding phases of glacierization. (1) The high lateral moraines indicate the earliest phase, when ice filled the western part of the pass and Dexterity Fiord. (2) The moraine remnants indicate an advance of the local mountain glaciers after the retreat of the outlet glaciers. (3) The fresh moraines partially covering the older moraine remnants and outwash fans indicate a readvance of the mountain glaciers in recent times.

A more precise dating of the moraines was attempted by lichenometry. This method has been successfully used by Beschel in the Alps and Greenland (1961) and intensively applied by Andrews and Webber (1964) in north-central Baffin Island.

The maximum diameters of lichen species *Alectoria minuscula* s.l., *Rhizocarpon geographicum* s.l. and *Rhizocarpon jemtlandicum* were measured on the moraines, mainly on the young end moraines. Some measurements, however, were also made on the end-moraine remnants.

Table 1 does not include the maximum lichen diameters for the lateral moraines. Altogether lichens were measured in 26 localities. The growth ratios between *R. geographicum* s.l. and *A. minuscula* s.l. and *R. geographicum* s.l. and *R. jemtlandicum* compare favorably with ratios calculated from results obtained from more than 200 lichen stations in north-central Baffin Island (Andrews, personal communication, 1963) (Table 2).

Table 1

Maximum lichen diameters for outermost young end moraines
(in millimeters)

Glacier	*Alectoria minuscula* s.l.	*Rhizocarpon geographicum* s.l.	*Rhizocarpon jemtlandicum*	Ratio *R. geographicum* s.l. to *A. minuscula* s.l.
N1	90	19	22	1:4.7
N2	70	—	27	—
N3	87	14	20	1:6.2
S1	44	7	15	1:6.3
S2	45	7	14	1:6.4
S4	44	5	8	1:8.8
S5	27	3	10	1:9.0
Old end-moraine remnants	—	110	180	—

Table 2

Comparison of lichen growth ratios

	Ratio *R. geographicum* s.l. to *A. minuscula* s.l.	Ratio *R. geographicum* s.l. to *R. jemtlandicum*
Duart Lake	1:5.9	1:1.92
North-central Baffin Island	1:6.82	1:2.066

The rate of growth of the lichens was not established with any high degree of accuracy, its only basis being the association of one 20-year-old willow bough with a specimen of *A. minuscula* s.l. 11 millimeters in diameter. Growth-rate estimates will vary considerably according to the time required for both the willows and the lichens to become established. On the assumption that the aforementioned *A. minuscula* s.l. and the willow became established simultaneously, the growth rate was 0.55 millimeter a year. For

Alectoria species growing on Disko Island, Greenland, where the climate is oceanic and slightly milder than that of the east coast of Baffin Island, the rate is 0.56 millimeter a year (Beschel, 1963). There, however, the lichen measurements were made at greater elevations. With 10 years allowed for the establishment of the thallus, the growth rate of *A. minuscula* s.l. in the higher continental interior of Baffin Island has been calculated at 0.4 millimeter a year.

In this paper the growth rate of 0.55 millimeter a year will be used, although it needs further confirmation by detailed studies similar to that carried out around the perimeter of the Barnes Ice Cap (Andrews and Webber, 1964).

Table 3

Estimated age of end moraines

N1	A.D. 1790
N2	A.D. 1825
N3	A.D. 1800
S1	A.D. 1875
S2	A.D. 1870
S4	A.D. 1870
S5	A.D. 1905 (lichen trim line)
Old end-moraine remnants	100 B.C. ?

Table 3 lists the dates when the end moraines formed a suitable substrate for the growth of lichens, i.e., when permanent snow cover, deposition and movement and excessive rolling of the moraine boulders were absent. Such absence would occur when the glacier snout began to retreat or when it was stable and producing no fresh debris. Thus the dates indicate the time of retreat of the ice or toward the end of a maximum stillstand. The lichens on the lateral moraines of the south-facing glaciers are about 210 years old and may indicate that the ice was advancing at that time (A.D. 1750).

These measurements and especially those of the south-facing glaciers agree with measurements taken in Scandinavia, other parts of Europe, Greenland and Central Africa. Weidick (1959) reports that in the middle of the eighteenth century there was a period of maximum advance in western Greenland and in the period 1850–1900 a general, although locally varying, glacier retreat. Beschel (1961) indicates a period of glacier advance in Italy, Austria and Central Africa between the middle of the seventeenth century and the latter half of the nineteenth. On the basis of geobotanical

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methods of investigation, Bergström (1954) and Faegri (1948) state that in Scandinavia in the middle of the eighteenth century there occurred a major stillstand and period of moraine formation.

The lichens on the old end-moraine remnants were large and often coalescent and gave a minimum age of about 2,100 years.* The lichens on the high lateral moraines showed much coalescence, and lichenometrical techniques could not be used. This implies at least that their age is appreciably greater than 2,500 years.

It must be stressed that the age of the young end moraines, as indicated by the lichen measurements, is only a minimum. The moraines may have been built up by several returns of the glacier snout to the same position over hundreds or thousands of years. Recent work by Østrem (1961) in Scandinavia has shown that ice-cored moraines similar to those in the Duart Lake area were forming at least 2,600 years ago. This method of determining the age of end moraines involves radiocarbon-dating of the wind-blown organic material in the recrystallized snow that forms part of the ice core of the moraine ridge. The organic samples are subject to contamination because of the length and difficulty of the process of collecting them and the possibility of their coming in contact with carbonaceous rock particles. Samples from ice-cored moraines along the west side of the Barnes Ice Cap, north-central Baffin Island, have been collected, but so far no positive dates have been established.

Although the age of the high lateral moraine cannot be estimated by lichenometry, it can be deduced that the outlet glaciers that filled the fiords excluded the sea and that on their retreat the newly uncovered land was open to marine incursion. In Duart Bay shell fragments were found at 60 meters above sea level, and shells *in situ* at distinct delta levels (38.5 meters above sea level ± 4 meters and 16.4 meters above sea level ± 3 meters). The shells at 16.4 meters above sea level, which are 5,070 years old (I–1238 JTA–63–1S, 5,070 ± 200 years), give a minimum time lapse from the retreat of the outlet glaciers. Shells from near the marine limit in the inner part of Tay Sound were assigned an age of 8,350 years (I–724 GF–62–2S, Falconer, 1963: personal communication) and the retreat of the ice from this area probably antedated them. Ives and Andrews (1963) postulate that the outlet glaciers lay at the heads of the fiords at about 6,725 years ago (I–406, GB–VWS–61–1S, 6,725 ± 250 years). From the evidence it is

*This date is calculated from the 110-millimeter diameter of a *Rhizocarpon geographicum* s. l. thallus that grows at approximately 0.054 millimeter a year.

estimated that the high lateral moraine is at least between 7,000 and 8,500 years old and that the corresponding Clyde phase, which it represents, occurred as many years ago.

RECENT GLACIER RETREAT

A striking point is the difference in age between the young end moraines of the north-facing and those of the south-facing glaciers. This may be due partly to the differences in ablation and accumulation that resulted from opposing aspects during the recent climatic improvement.

The three outermost of the five young-end-moraine ridges that lie around glacier N1 (Figure 7), can be dated by lichenometry. The dates are similar to those of moraines of the Lewis Glacier, north-central Baffin Island (Andrews and Webber, 1964), Scandinavian glaciers measured by Bergström (1954) and Faegri (1948), and Greenland glaciers measured by Beschel (1958) (Table 4).

Table 4

Comparison of ages of end moraines

Glacier N1	Lewis Glacier	Northern Sweden	Western Norway	Greenland
1790	1793	1735 ± 50 years	1750	1740–80
1860	1888	1807	1840	1880
1925	1920	1908	1924	

The retreat of the glacier snouts in the Duart Lake area has been variable since 1948, south-facing glaciers having retreated farther than north-facing. At the time of the survey, glacier N1 had retreated 300 meters and glacier S1 about 180, thus making respective linear withdrawals of 20.0 and 12.0 meters per annum.

Falconer (1962) also reports minor retreats of small ice caps and glaciers in northern Baffin Island.

CONCLUSIONS

The reconnaissance glacier survey of the Duart Lake area has shown that there is a certain correlation between glacier advance and moraine formation in this area and other parts of the world, particularly in high latitudes.

There is, however, a need for techniques to date the initial formation of the young end moraines and the old moraine remnants.

The retreat and advance of glaciers depends on climatic factors but may be delayed or accelerated by local conditions of aspect and relief and by the shape of the glacier catchment area. Many more glaciers and moraines must be examined before any precise statement can be made concerning glacier retreat and advance on a regional scale. On Baffin Island this type of study is to be extended in 1964 and during the International Hydrological Decade.

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ICE CRYSTALS FROM AN ICE-CORED MORAINE ON BAFFIN ISLAND, N.W.T.

Gunnar Østrem

Abstract: This paper, which is based on field work carried out in north-central Baffin Island by the Geographical Branch in 1962 and 1963, explains the methodology of a technique for the study of ice-cored moraines. Ice crystals from such a moraine were examined in detail to ascertain whether they came from buried glacier ice or from ice formed in another way. Thin sections were photographed both in white transmitted light and in polarized light. Some were photographed in color. Crystal size was measured on full-scale prints, and crystal orientation in a Rigsby-type universal stage. The striking difference in crystal size between the buried ice and the glacier ice at the margin of the ice cap suggests that the former is *not* an old deposit of the latter.

The paper also explains digging and sampling methods and laboratory analysis.

Résumé: Dans cette étude, fondée sur des travaux faits sur le terrain dans le centre Nord de l'île Baffin par la Direction de la géographie en 1962 et 1963, l'auteur explique comment il a procédé pour étudier des moraines à noyau de glace. Il en a examiné soigneusement des cristaux de glace pour s'assurer s'ils provenaient de la glace d'un glacier enfoui ou de la glace qui se serait formée d'une autre manière. Il en a photographié des lames minces, d'abord à la lumière blanche, puis à la lumière polarisée. Il a photographié en couleur certaines lames. Il a mesuré la dimension des cristaux sur des photocopies, grandeur naturelle, et leur orientation, sur un plateau Rigsby à tous usages. Il a noté une différence frappante entre la grosseur des cristaux de la glace enfouie et ceux de la glace située à la bordure de la calotte glaciaire, et en a cru que la première *n'est pas* celle du noyau d'une ancienne moraine déposée sur la calotte glaciaire.

L'auteur explique aussi les méthodes d'extraction et d'échantillonnage utilisées par lui et l'analyse qu'il a faite au laboratoire.

INTRODUCTION

The existence of ice-cored moraines in arctic areas has already been reported. After studying some of those at the southern part of the Barnes Ice Cap on Baffin Island, Goldthwait (1951) suggested that they consist of stagnant glacier ice (dead ice) that has been covered with morainic material. According to him, this material has been brought to the surface along shear planes situated between the outermost stagnant part of the glacier and the still active part of it.

MS submitted December 1963.

Recent investigations in Scandinavia have shown that the occurrence of ice-cored moraines is more extensive than previously assumed (Østrem, 1960 and 1962a). Air-photograph interpretation by the method developed in Scandinavia strongly suggests that a large number of the moraines in front of existing glaciers on Baffin Island are also ice-cored.

To examine the buried ice more closely, field investigations were carried out in 1962 and 1963.

During the summer expeditions sent by the Geographical Branch to north-central Baffin Island, a pit was dug in one of the morainic ridges that run parallel to the western edge of the Barnes Ice Cap (Figures 1 and 2). These ridges are about 70°N and 74°20'W and are marked on the Isortoq River map of glacial features (Ives and Andrews, 1963).

Samples of the buried ice were taken for different laboratory analyses, and the results of the crystallographic studies are reported in this paper.

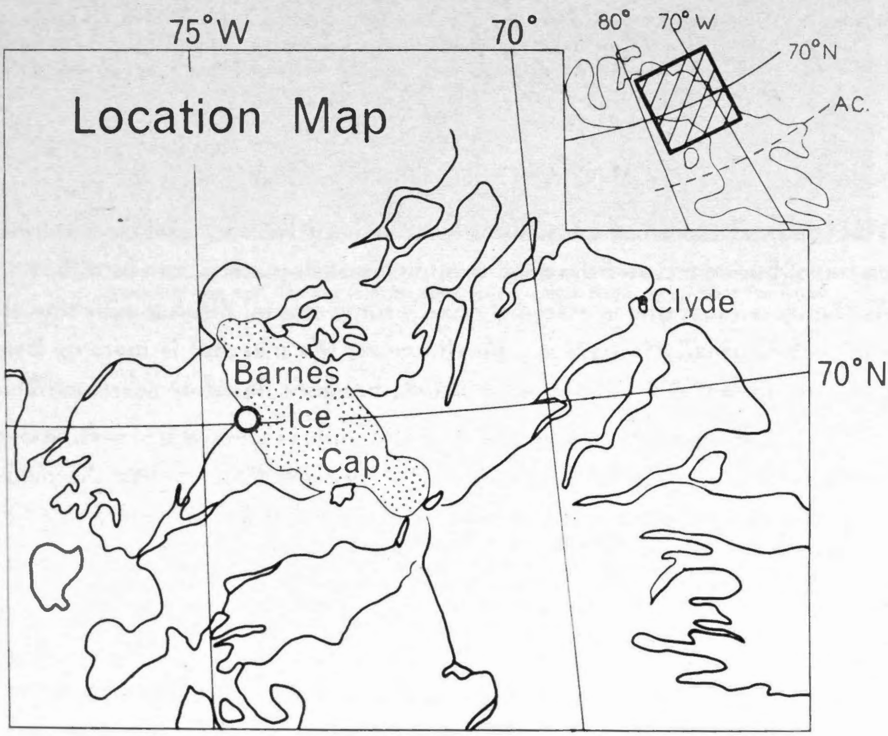

FIGURE 1. Location map showing area of investigation (encircled).

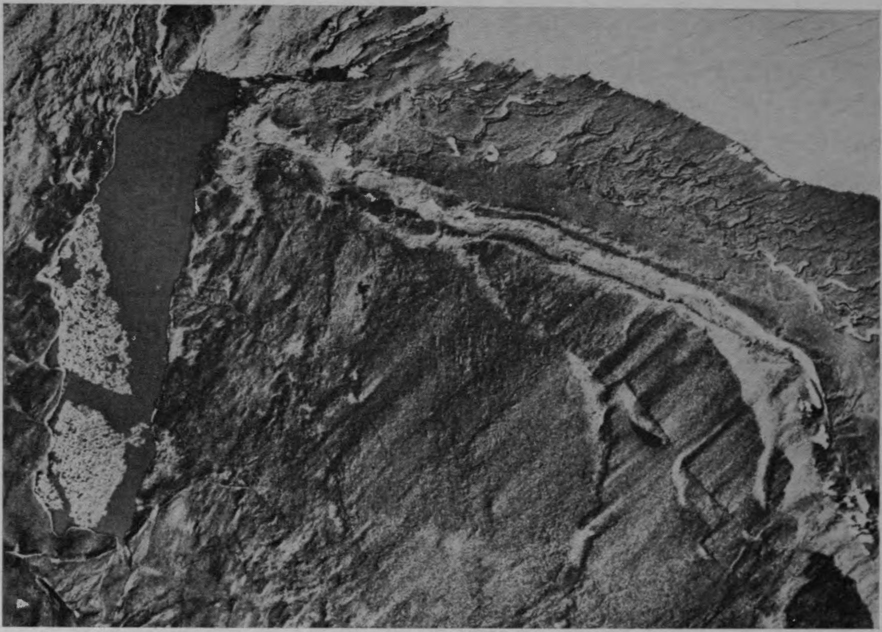

FIGURE 2. Vertical air photograph showing a part of the ice cap and the two parallel ice-cored moraines. The pit was dug in the outermost ridge, and the samples were flown out from the small lake at the left. Approximate scale 1:24,000 (enlargement of a part of vertical no. A-17046-72).

DIGGING AND SAMPLING METHOD

The ice-cored moraines normally consist of hard frozen morainic material on top of buried ice, and the digging of pits in such material can be difficult. As the frozen moraine is extremely hard, conventional digging with shovel and pick is usually impossible. Furthermore, the material is more or less water-saturated and, as soon as it thaws, becomes liquid or porridge-like.

The best method, therefore, is to make a pit in the frozen moraine by means of a motor-driven drill and explosives. The drill used in the field work was also serviceable as a crowbar and proved useful in digging.

The buried ice was found under about 1 meter of moraine, and samples were taken with a SIPRE corer (Figure 3). Some samples, because taken with an ice-pick, have an irregular form.

For comparison, samples of the glacier ice were also taken from the margin, as well as from the top, of the Barnes Ice Cap. The marginal samples were cut out with an ordinary ice axe; those from the top were obtained with a SIPRE corer. After transportation by air to Ottawa, the samples were cut into thin sections in the coldrooms of the National Research Council's Division of Building Research.

FIGURE 3. The buried ice was found under about 1 meter of frozen moraine in a pit dug by means of a motor-driven drill. The ice samples were taken with a SIPRE corer. Note the motor drill, equipped with a crowbar.

CRYSTAL SIZE AND CRYSTAL ORIENTATION

All the thin sections were photographed in white transmitted light and in polarized light (i.e., between crossed polaroids). Some of them were also photographed with color film.

The crystal size was measured on full-scale prints of the pictures taken in polarized light. Where the crystals were small, they were counted within an area of known size, and the mean crystal cross-sectional area was computed. The result thus obtained is called the crystal size.

The crystal orientation was measured in a universal (Rigsby) stage of conventional design. (For a more detailed description, see Rigsby, 1951, or Langway, 1958.)

RESULTS

The crystals in the buried ice appeared very small, their mean size being about 0.04 cm^2 for all but the surface layer, where it was 1.14 cm^2. Those in the glacier ice at the margin of the Barnes Ice Cap were considerably larger, their sizes ranging between 2.37 cm^2 and 4.33 cm^2. The crystals in the sample of comparatively young glacier ice from the top of the ice cap were smaller (about 1 cm^2) but were far larger than most of the crystals in the buried ice.

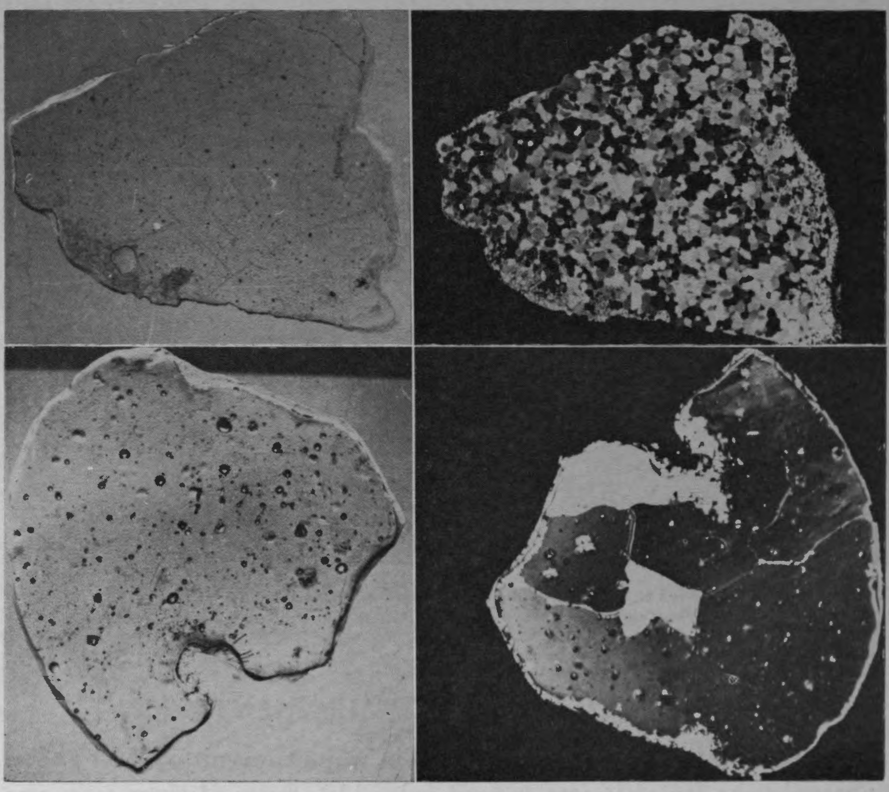

FIGURE 4. Samples from Baffin Island. On the left are thin sections photographed in transmitted, white light; on the right are the same sections photographed in polarized light. The top sample is taken from the ice-cored moraine; the bottom sample from the margin of the Barnes Ice Cap. About natural size.

The results of the crystal-size measurements are shown in the table.

From the observation of crystal size it is obvious that the buried and the glacier ice are quite unlike. When photographed in white light, the thin sections also differed in appearance: the glacier ice contained numerous air bubbles, whereas the morainic ice contained several mineral particles. This

Two thin sections of ice samples collected in 1963. The big crystals were found at the margin of the Barnes Ice Cap. The small ones lay within the ice core, 82 centimeters below its surface, which, in turn, was 1 meter beneath the surface of the moraine.

difference, as well as that in crystal size, can easily be seen in Figure 4. The difference in crystal size is also demonstrated in the colored plate, where a sample of the morainic ice is compared with a sample of glacier ice from the margin of the ice cap.

Owing to technical difficulties, crystal-orientation measurements could not be carried out on the glacier ice; but three horizontal thin sections of the morainic ice have been analyzed, and the result has been plotted in the conventional manner on the lower hemisphere of a Schmidt equal-area net (Langway, 1958, pages 8–11). From the plotting, shaded diagrams have been prepared (Figure 5).

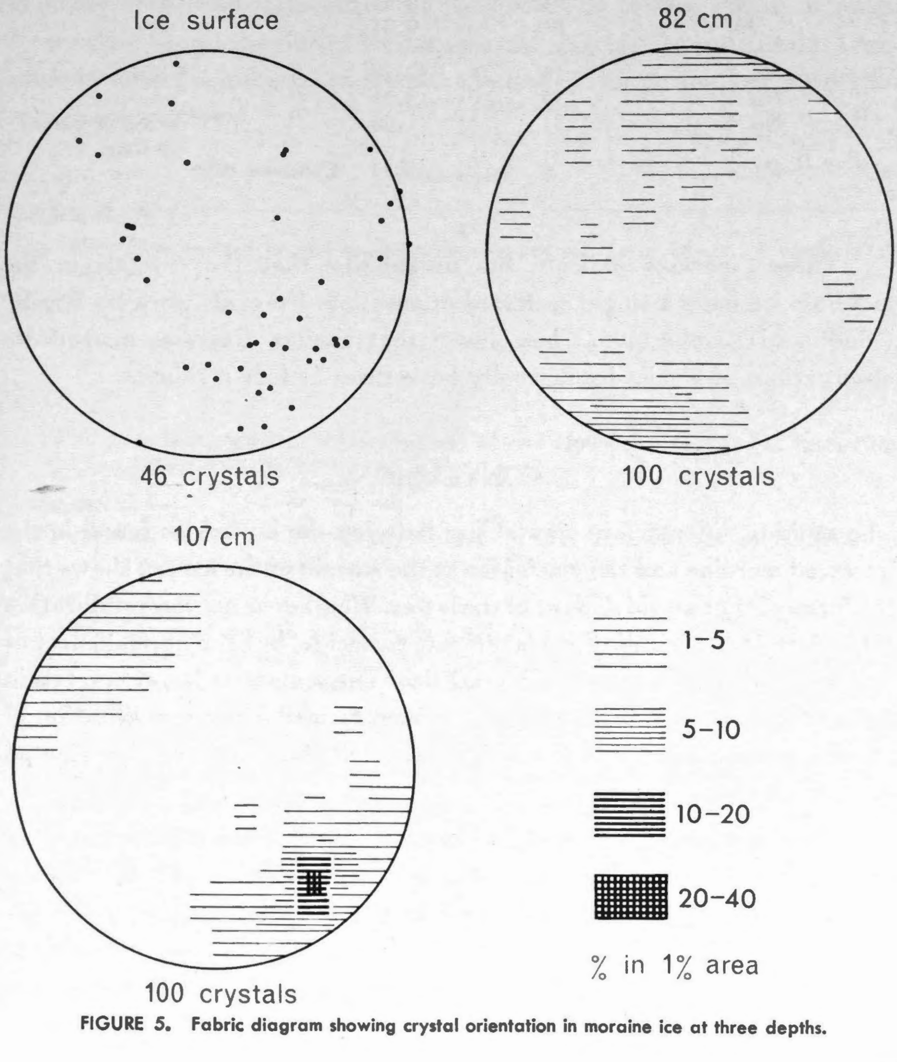

FIGURE 5. Fabric diagram showing crystal orientation in moraine ice at three depths.

Crystal sizes, samples from Baffin Island

Sample	Number of measured crystals in the thin section	Mean crystal area (cm²)	Remarks
Morainic ice A	56	0.036	Typical selection of pieces collected in 1962 from different parts of pit
" " B	51	0.039	
" " C	76	0.039	
" " D	81	0.037	
" " E	116	0.026	
Morainic ice, surface	42	1.14	Collected 1963
" " 76 cm	82	0.04	" " See colored plate
" " 82 "	91	0.03	" "
" " 107 "	84	0.04	
Glacier ice No. 7	19	2.37	" " See colored plate
" " No. 5	15	4.33	" "
" " No. 4	51	1.08	" " At top of Barnes Ice Cap
" " F	6	3.33	Collected 1962

These diagrams indicate the probability that the crystals in the morainic ice have a single preferred orientation. Previous work by Rigsby (1960) and Kizaki (1962) has shown that similar diagrams made from observations of glacier ice normally have three or four maxima.

CONCLUSION

The striking difference in crystal size between the buried ice found in the ice-cored moraine and the glacier ice at the margin of the ice cap shows that the former is not an old deposit of the latter. Whether or not recrystallization took place in the morainic ice is difficult to decide, but the normal effect of recrystallization is a *growth* in crystal size. The somewhat larger crystals in the surface layers may therefore have been formed by recrystallization of the fine-grained ice, but it is very unlikely that the morainic ice originated from glacier ice.

From similar investigations in Scandinavia it is clear that ice buried in ice-cored moraines can originate from snowbanks (Østrem, 1962a). A zone of light color that can be seen outside the morainic ridges on the air photograph (Figure 2) evidently indicates an area of frequent long-term snow cover. (During the field work it was also observed that the area was nearly vegetation-free.)

This area thus seems favorable for heavy snow accumulation and the formation of snowbanks, and it is assumed that morainic material is delivered from a stationary glacier snout (or perhaps from an advancing glacier. The conditions are in fact present for the formation of a "buried snowbank.") Further, under some meters of snow in perennial snowbanks is normally found massive ice (Østrem, 1962b, pages 247–248). This has been formed by the refreezing of meltwater within the snow. It is presumed that the ice buried in ice-cored moraines originated in this way or perhaps directly from the snow.

As the ice contains small amounts of organic material, particles presumably once wind-transported to the surface of the snowbank, it might be possible to use the buried ice for moraine-dating (Østrem, 1961). Large samples were therefore taken from the buried ice for dating, but results are not as yet available.

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A LICHENOMETRICAL STUDY OF THE NORTHWESTERN MARGIN OF THE BARNES ICE CAP: A GEOMORPHOLOGICAL TECHNIQUE

J. T. Andrews and P. J. Webber†*

ABSTRACT: The outcome of lichen measurement around the northwestern margin of the Barnes Ice Cap, Baffin Island, is reviewed. Although those who did the sampling were not fully trained in botany, the results suggest that lichenometry can be successfully applied. The main species used in the study are described and their growth rates, which are very consistent, are calculated on the assumption of a linear retreat of the glacier from the present margin to the first *Alectoria minuscula*. The growth rate indicated for this species was 0.40 millimeter a year, from which the growth rates of the other species were derived by the use of calculated mean ratios. The results have been used in studying the recent history of the Lewis Glacier and of the ice-cap margins. This suggests the existence of a major end-moraine system of Sub-Atlantic age and of other important moraines dating back to A.D. 1680, 1790, 1890 and 1920. These moraines are compared in age with others on the southeastern margin of the ice cap, which has a different history, and in areas of Greenland. As lichenometry covers the time period for which C14 dating is relatively inaccurate, it is important in an arctic enviroment.

RÉSUMÉ: Les auteurs examinent les résultats des travaux de classement par grosseur des lichens (lichénométrie) qui bordent la partie Nord-Ouest de la calotte glaciaire Barnes (île Baffin). Bien que les échantillonneurs de lichens ne fussent pas diplômés en botanique, les résultats obtenus militent en faveur de l'application de la lichénométrie. Les auteurs décrivent les principales espèces utilisées au cours de l'étude et calculent leurs taux de croissance, qui sont très uniformes, en se fondant sur l'hypothèse d'un recul rectiligne du glacier à partir de la bordure actuelle jusqu'aux premiers lichens de l'espèce *Alectoria minuscula*. Ils ont calculé que cette espèce poussait à raison de 0.40 millimètre par année, ce qui leur a permis de constater les taux de croissance des autres espèces à l'aide de facteurs moyens calculés. Les résultats obtenus ont été appliqués à l'étude de l'évolution récente du glacier Lewis et des bords de la calotte. On en a déduit l'existence d'un grand ensemble de moraines terminales qui remonte à l'âge "sub-atlantique" et d'autres moraines importantes qui remontent aux années 1680, 1790, 1890 et 1920. Les auteurs ont comparé l'âge de ces dernières avec celui d'autres, qui bordent la partie Sud-Est de la calotte, dont l'évolution diffère, et celui de moraines de certaines régions du Groenland. Comme la lichénométrie couvre une période de temps pour laquelle la radiodatation au carbone 14 ne donne pas des résultats trés précis, elle garde toute son importance quand on l'applique à un milieu arctique.

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INTRODUCTION

The Barnes Ice Cap lies on a subdued plateau-like surface between 400 and 700 meters above sea level on north-central Baffin Island (70°N, 74°W). In 1950, an expedition from the Arctic Institute of North America studied its southeastern lobe, and Hale (in Ward, 1952) made botanical transects from the ice-cap margin to the area of mature lichen colonization. On the basis of an assumed growth of 1 millimeter a year for *Alectoria minuscula* Nyl., he concluded that recession following a readvance began about 1860. In 1961 the Geographical Branch began a long-term research program in north-central Baffin Island, and from 1961 to 1963 the research effort was concentrated about the northwestern margin of the Barnes Ice Cap. During the first summer, large differences in lichen diameters were noted above and below the shoreline of Glacial Lake Lewis, a former ice-dammed lake, and were measured by Andrews (Ives, 1962). In 1962 systematic observations based on a standard method and the use of more species of lichens resulted in two important conclusions: (1) that the maximum lichen diameters increase in size away from the ice cap; (2) that the maximum diameters are similar both on contemporaneous moraines and within former glacial-lake basins. These conclusions led to a detailed consideration of lichenometry, which makes it possible to date substrates when historical records are inadequate.

The aims of this paper, which presents the results of three field seasons, are (1) to assess the usefulness of lichenometry for glacial geomorphological studies when its basis is the work of observers whose botanical training is limited and (2) to provide a relative time scale for the glacial fluctuations that occur about the margin of the Barnes Ice Cap. This paper is thererore complementary to Beschel's basic analysis of lichenometry as applied to glaciology and physiography (Beschel, 1961a).

CONCEPT AND METHOD OF LICHENOMETRY

The colonization of a new surface by lichens and their growth on it depend upon substrate type, climate and microenvironment. This study concerns only epipetric lichens. The rock types of central Baffin Island belong to the typical Archaean basement complex, the predominant type being granite gneiss. As no species in this area was seen to have a clear preference for a rock type, the preference factor receives no further consideration. The factors of temperature and the availability of liquid water are of prime

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importance in the growth of lichens. Beschel (1961a) found proof of this when he observed a decrease in the growth rate of *Rhizocarpon tinei* (Tornab.) Runem. (*R. geographicum* s.l.) along a gradient from the wet coastal to the dry continental regions of West Greenland.

The climate of central Baffin Island is severe, having a precipitation of about 37 centimeters water equivalent a year, an annual mean temperature of −10°C and a continentality index of perhaps 50 per cent (Mackay and Cook, 1963). The index for Disko, West Greenland, is 23 per cent. Table 1 compares growth rates of *R. geographicum* for various regions and shows the necessity of establishing a series of growth rates for each species in each region. The effect of microenvironment on lichen growth, combined with the possibility of successive colonizations by more thalli, would perhaps preclude the usefulness of lichenometry for dating, but using a species' maximum diameter reduces these disadvantages to a minimum (Beschel, 1957). The assumption is that lichens of maximum diameter are both the oldest and the optimally growing. It can be applied, however, only to the most common and successful species in an area and to those species whose thalli retain their identity.

Table 1

"Lichen factor" of R. Geographicum *(L.) DC. of different regions*

Region	Author	"Lichen factor" (mm per century)
Greenland (Søndre Strømfiord area)	Beschel (1961a)	2 to 45
Baffin Island	Andrews and Webber	5.4
Greenland (Disko area)	Beschel (1963a)	15
Axel Heiberg	Beschel (1963b)	4 to 15
Italy (Gran Paradiso)	Beschel (1957)	13 to 25
North Sweden	Stork (1963)	20
Austria	Beschel (1957)	21 to 93
South Norway	Stork (1963)	46
Switzerland (Steingletscher)	Beschel (1957)	60

The rate of growth of crustose and foliose lichens is not constant over their life span. It is initially sigmoidal and then becomes generally linear until the onset of senescence, when growth decreases or even stops. During the linear phase, the length of which varies with species, the diameter of the thallus may be considered directly proportional to its age, providing there has been no great change of climate during the life of the lichen. (For an account of lichen growth-curve patterns, see Beschel, 1961a, pages 1045–1047). Diameter measurement rather than the more accurate but time-consuming planimetric method of Hale (1959) is used at this stage as a means of rapidly determining lichen size.

A basic assumption of lichenometry as an indication of time since deglaciation is that the substrate is devoid of all living lichens immediately before deglaciation. No evidence was seen of the survival of lichens under the Barnes Ice Cap, and it is unlikely that any survivors were measured in the present study. Lichen thalli in association with ice bodies have been reported by Goldthwait (1960), Beschel (1961b) and Falconer (1963: personal communication), but as yet there is no positive proof that these thalli were alive. Similarly, no evidence was noted of lichen survival in the former snowbank areas, although in the differences of diameter and density there were variations that may reflect differences in the duration of lichen survival. Survival beneath ice requires rapid freezing and thawing and absence of movement within the ice. Stork (1963) suggests that lichens may begin to grow on boulders that have been carried along on the glacial surface, but the nature of the ice cap is such that this possibility is remote.

As 10 observers contributed to the sampling at 290 lichen stations, the method used had to be simple and as close as possible to uniformity. A lichen station was established at a point along a transect or on a geomorphological feature. Sampling at each station covered a circular area of 10-meter radius. Beschel (1961a) recommended at least 100 square meters, and Stork (1963) five separate 5x5 meter quadrats. When a station was situated on a slope, sampling was usually restricted to the contour. Whenever a special feature was sampled, care was taken to limit the sampling to some specific and uniform part of the feature, for example, to the proximal side of a moraine. Wet and snowpatch sites were not sampled. Each station was diligently searched and the diameters of all large thalli of the common lichens were measured and recorded to the nearest half millimeter. For each species only the 10 largest diameters were permanently recorded, and in this study only the maximum value is used. The act of measuring and recording other large thalli is a means of encouraging observers to be careful and adhere to some degree of consistency. At each lichen station a record was made of site aspect, slope and substrate type, and additional notes on vegetation and geomorphological features were taken as required. When

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sampling was carried out in recently deglaciated areas, willow and soil samples were occasionally collected. The data from each site were later transferred in the field to printed cards.

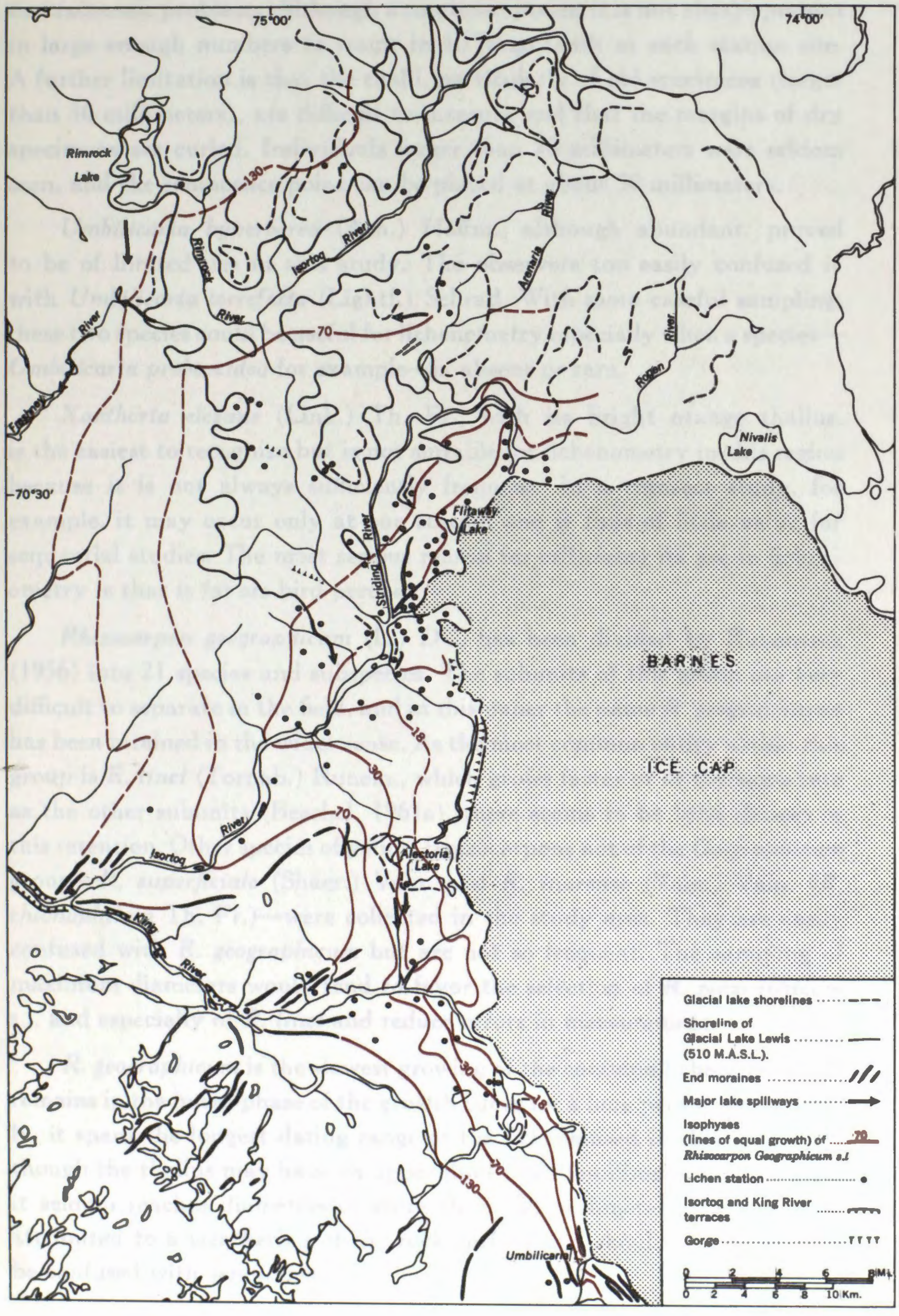
The greatest density of sampling was around the Lewis Glacier. The station locations within the whole study area are shown in Figures 1 and 2. Isophyses (Greek: *isos*, equal; *physis*, a growth) of two lichens have been plotted on these figures by interpolation between sample points.

Lichen determinations

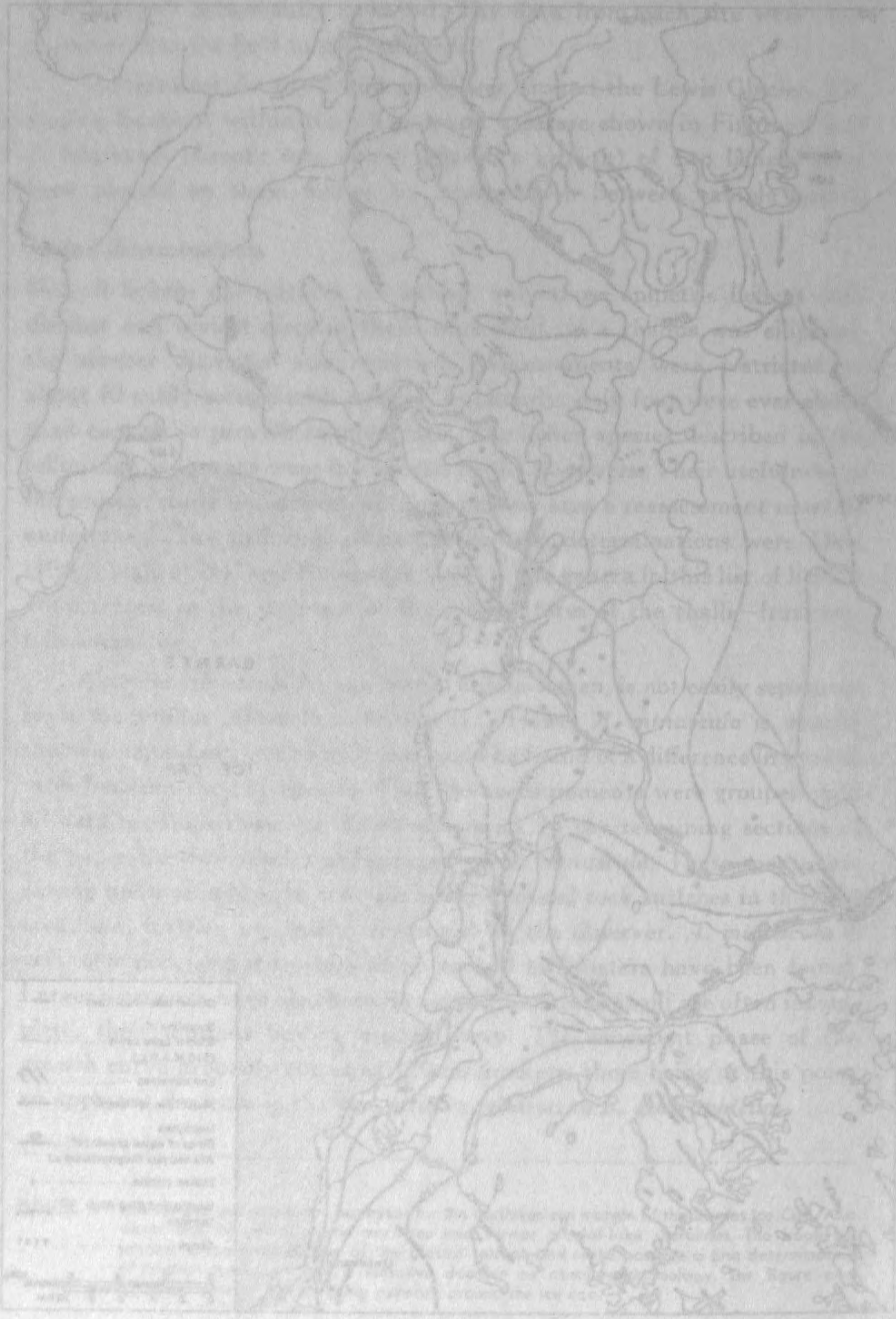
Not all lichens are suitable for dating; only those epipetric lichens with distinct and almost circular thalli were used. If a thallus was elliptical, the shorter diameter was recorded. Measurements were restricted to about 10 easily recognizable species; frequently, only four were ever abundant enough to provide reliable data. The lichen species described in the following paragraphs were introduced to the observers. Their usefulness in the present study is assessed, but in each new area a reassessment must be undertaken. The principal references for the determinations were Dahl (1950), Hale (1954) and Runemark (1956). The genera in this list of lichens are arranged in the sequence of the growth form of the thalli—fruticose-foliose-crustose.

Alectoria minuscula Nyl., a black, fibrous lichen, is not easily separated from the similar *Alectoria pubescens* (L.) Howe. *A. minuscula* is usually the most abundant, but no evidence could be found of a difference in growth rates between the two species. Thus the measurements were grouped, and all data used are those for *A. minuscula* s.l. In the remaining sections of the paper the two species are grouped as *A. minuscula*. These species are among the first lichens to colonize newly exposed rock surfaces in the field area, and, further, are easily recognized by the observer. *A. minuscula* is very common, and diameters of up to 140 millimeters have been found. Larger diameters have also been measured, but these thalli are often incomplete, their margins having eroded away. The senescent phase of the growth curve probably comes at 120 millimeters, there being at this point an apparent decrease in the size ratio in relation to *R. geographicum*.

FIGURE 1. *Rhizocarpon geographicum* isophyses for the northwestern margin of the Barnes Ice Cap. Also shown are the principal end moraines and former glacial-lake shorelines. The isophyses present a consistent picture of the glacial retreat and make possible a firm determination of relative chronology and a tentative decision on absolute chronology. The figure also gives an idea of the sampling network around the ice cap.



75°00'
74°00'
Rimrock Lake
Rimrock River
Isortoq River
Arenaria River
Rogan River
Eastman River
Nivalis Lake
70°30'
Flitaway Lake
Striding River
BARNES
ICE CAP
Alectoria Lake
Isortoq River
King River
Umbilicaria
130
70
18
30
Glacial lake shorelines
Shoreline of Glacial Lake Lewis (510 M.A.S.L.).
End moraines
Major lake spillways
Isophyses (lines of equal growth) of Rhizocarpon Geographicum s.l
Lichen station
Isortoq and King River terraces
Gorge
0 2 4 6 8 Mi.
0 2 4 6 8 10 Km.



Umbilicaria proboscidea (L.) Schrad. is easily recognized and presents no taxonomic problems. Although a common species, it is not always present in large enough numbers to result in 10 large thalli at each station site. A further limitation is that the thalli, particularly of old specimens (larger than 30 millimeters), are difficult to measure and that the margins of dry specimens are curled. Individuals larger than 70 millimeters were seldom seen, and the senescence point can be placed at about 50 millimeters.

Umbilicaria hyperborea (Ach.) Hoffm., although abundant, proved to be of limited use in this study. The observers too easily confused it with *Umbilicaria torrefacta* (Lightf.) Schrad. With more careful sampling, these two species could be useful for lichenometry especially when a species—*Umbilicaria proboscidea* for example—is absent or rare.

Xanthoria elegans (Link.) Th. Fr., with its bright orange thallus, is the easiest to recognize but is not suitable for lichenometry in this region because it is not always sufficiently frequent. In a transect study, for example, it may occur only at one station and is thus of little value for sequential studies. The most serious reason for criticizing its use in lichenometry is that it favors bird perches.

Rhizocarpon geographicum (L.) DC. has been divided by Runemark (1956) into 21 species and subspecies. The subunits of this group are very difficult to separate in the field, and in this paper the name *R. geographicum* has been retained in the wider sense. As the most common entity within this group is *R. tinei* (Tornab.) Runem., which grows faster or at the same rate as the other subunits (Beschel, 1961a), there seems to be little danger in this retention. Other species of yellow Rhizocarpons not of the *Geographicum* group—*R. superficiale* (Shaer.) Vain. and *R. inarense* (Vain.) Vain. (*R. chionophilum* Th. Fr.)—were collected in the study area. They are easily confused with *R. geographicum* but are not so frequent. The sampling of maximum diameters would tend to favor the selection of *R. geographicum* s.l. and especially of *R. tinei* and reduce errors in measurement.

R. geographicum is the slowest growing of the common lichens used and remains in the linear phase of the growth curve for a long period. Accordingly, it spans the longest dating range of the lichens used in this study. Although the thallus may have an upper limit of 200 millimeters in this area, it seldom reaches diameters of more than 120 millimeters. This may be attributed to a weathering of the rock surface and should not necessarily be confused with senescence.

Rhizocarpon jemtlandicum Malme is intermediate in growth rate between *A. minuscula* and *R. geographicum.* It has a greyish thallus and was sampled with *Rhizocarpon disporum* (Naeg.) Mull. Arg. and *R. grande* (Flk.) Arn. Allowance must be made for probable confusion of these grey *Rhizocarpons,* which may not have uniform growth rates. *R. rittokense* (Hellb.) Th. Fr., although not a grey *Rhizocarpon,* was sampled with the other lichens in the field and was confused with *R. jemtlandicum.* It is as common but may be easily distinguished by its peltate areoles. In central Baffin Island, *R. jemtlandicum* grows faster than *R. geographicum,* whereas on the coast of West Greenland it grows at two thirds the rate of *R. geographicum* and inland at the same rate (Beschel, 1961a). This variation illustrates that growth rates of different species are not always related in constant proportion from region to region. The growth rates of each species or their ratios must be found again for each new locality.

Other species occasionally measured were: *Umbilicaria virginis* Schaer., *Umbilicaria cylindrica* (L.) Del., *Parmelia alpicola* Th. Fr., *Parmelia incurva* (Pers.) Fr., and *Buellia moriopsis* (Mass.) Th. Fr. Data on these species are very scarce, and the authors have drawn no conclusions about their growth rate and usefulness in lichenometry.

Sampling studies

Quadrats of 8 × 8 meter size were marked out at 25-meter intervals along the proximal side of the outer lateral moraine of the Lewis Glacier. All rock surfaces in these quadrats were searched, and 50 of the largest thalli of each of four species in each quadrat were recorded, as shown in Table 2. At a later date, seven observers were sent to take samples at separate stations by the standard procedure. The stations were on the same proximal slope, but the location of the sample sites varied. The results of this study are shown in Table 3. A comparison of the two tables reveals a measure of variability, which is very large if only one species—*R. geographicum,* for example—is used. This species, however, is not so common on the moraine as *A. minuscula* and may be less valuable in a recently deglacierized area. Among the causes of variability are slumping and other earth movements. When an ice-cored moraine has slumped, a lichen value must be regarded as a minimal determinant of its age. For age determinations it is therefore

FIGURE 2. The area about the Lewis Glacier showing the position of lichen stations and the maximum values of the *Alectoria minuscula* isophyses. The isophyses show a pattern of glacial retreat that is in agreement with the geomorphological evidence. The line A–A'—A" is used as the plane of projection for Figure 3. The letters "a" to "g" indicate where willow boughs were collected, as was mentioned in the text.

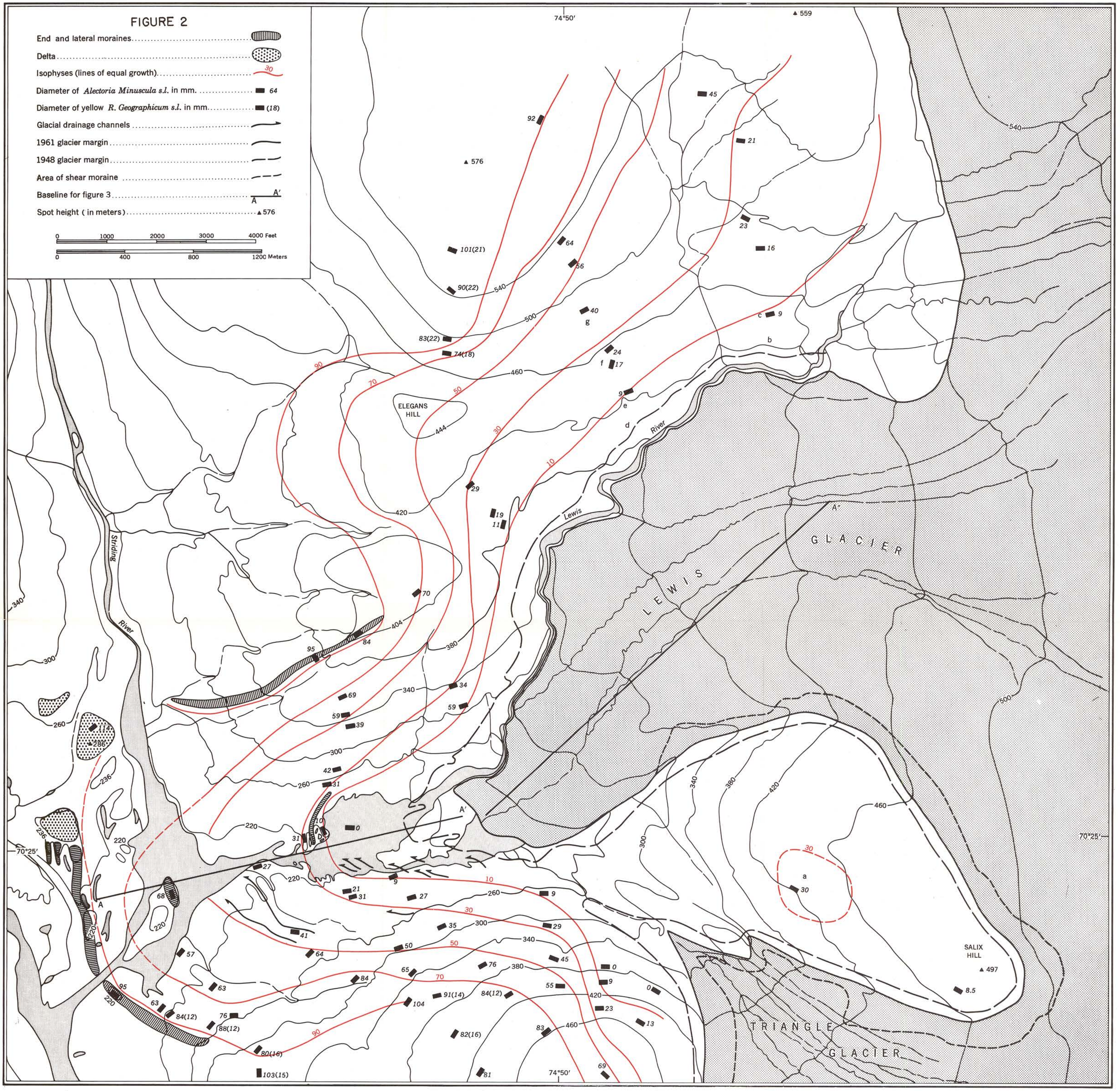


FIGURE 2
End and lateral moraines
Delta
Isophyses (lines of equal growth)
Diameter of Alectoria Minuscula s.l. in mm.
Diameter of yellow R. Geographicum s.l. in mm.
Glacial drainage channels
1961 glacier margin
1948 glacier margin
Area of shear moraine
Baseline for figure 3
Spot height (in meters)
0 1000 2000 3000 4000 Feet
0 400 800 1200 Meters
74°50′
70°25′
ELEGANS HILL
SALIX HILL
Striding River
Lewis River
LEWIS GLACIER
TRIANGLE GLACIER

important to use more than one species. Although the results of the undertaking described in this paper indicate a tendency toward undersampling, the method used can be regarded as satisfactory in view of the much larger area that would have to be sampled to increase the likelihood of finding the largest lichen.

Basin of Glacial Lake Lewis

Table 4 shows the difference in maximum lichen diameters above and below the 510-meter shoreline of Glacial Lake Lewis at various distances from the margin of the ice cap (Figure 1). When the ice front had retreated to within 6 kilometers of the present northwestern margin, the level of this former glacial lake was finally lowered from 510 meters above sea level to a stillstand at 430 meters.

Table 2

Quadrat studies of four lichen species on proximal slope of outer moraine of Lewis Glacier
(maximum diameters in millimeters)

Quadrat 8 × 8 m	*A. minuscula*	*U. proboscidea*	*R. jemtlandicum*	*R. geographicum*
1	42	17	24	10
2	75	35	31	11
3	89	40	25	11
4	57	38	22	11
5	67	27	22	10
6	70	34	28	11
7	83	38	30	13
8	79	35	29	11
Maximum	89	40	31	13

Table 3

Maximum diameters obtained from repeated sampling on proximal slope of outer lateral moraine of Lewis Glacier
(in millimeters)

Sample number	1	2	3	4	5	6	7	Maximum diameter
A. minuscula	84	84	79	65	95	79	79.5	95
R. geographicum	6.0	9.0	14.0	9.5	8.0	14.0	11.0	14
R. jemtlandicum	—	—	25	—	25	30	21.5	30

Thus the area between these shorelines was exposed for the simultaneous development of lichens. It represents a standard time base and can be used to evaluate a possible climatic gradient away from the ice cap. In the vicinity of Rimrock Lake (Figure 1) the shoreline of Glacial Lake Lewis is readily visible owing to the difference in lichen development and density of cover, but this visual effect is less pronounced farther down the Isortoq. The steady decrease that occurs in maximum diameters above the shoreline as proximity to the ice cap increases (Table 4) is interpreted as a reflection of the progressive retreat of the proto-Barnes Ice Cap (Ives and Andrews, 1963) and in no way as the result of environmental changes occasioned by the degree of proximity. The proof of this lies in the diameters found below the shoreline, which have a maximum variability of only 3 millimeters over the three areas shown in the table. In areas less than a kilometer from the col, which upon exposure led to the drainage of the lake at 510 meters above sea level, the values above and below the shoreline are close (Table 4). These findings are of great importance in an assessment of the validity of lichenometry because they support the basic assumption that lichens on synchronously exposed substrates are about the same in maximum diameter. Thus the conclusion for the area under study is, as Table 4 suggests, that the isophyses are also isochrones. Hence, on the basis of the closeness of maximum lichen diameters, a relative chronology for this area can be sketched. Studies have also shown that what were once snowbank areas came into existence as such after the drainage of Glacial Lake Lewis. In several localities they extend below the shoreline, thus indicating that after the glacial lake was drained, climatic conditions were more severe than at present.

Table 4

Variation of maximum diameters of R. geographicum *above and below Glacial Lake Lewis shoreline (510 meters above sea level)*

(in millimeters)

Approximate distance of stations away from Barnes Ice Cap	30 km NW	12 km WNW	6 km NNW
Location	Rimrock Valley	Middle Isortoq Valley	Striding Valley
Above shoreline	130	71	44
Below shoreline	41	38	38

CALCULATION OF LICHEN GROWTH RATES

One of the main problems was to establish for the more common lichens a preliminary growth rate on which to base the first estimate of the age of the various substrates. On the revisiting of specific lichen stations in five to 10 years, the results would be checked by means of selected true-scale photographs. The growth rates make possible the conversion of relative (Figures 1 and 2) into absolute isochrones. Around the Barnes Ice Cap, the technique finds its prime application in the establishment of a relative chronology based on lichens. The calculation of growth rates for comparing the glacial history of the study area with the standard North American, European and Greenland chronologies, although important, is perhaps secondary.

Air photographs taken over the Lewis Glacier in 1948, 1959 and 1961 at scales of 1:40,000 and 1:60,000 make possible the accurate positioning of the ice margin for these years. From this, it is possible to calculate the total vertical and horizontal recession of the glacier for the period covered. Vertical profiles were carried from eight positions along the northern margin of the ice in 1963 and were surveyed by a Wild T 12 theodolite and stadia rod or an Abney level and steel tape. The profiles were taken to the 1948 limit and were then extended to the point where the first *A. minuscula* were noted. The basic data (Table 5) from which the growth rate of this species has been derived indicate that the mean vertical thinning of the glacier has been 1.5 meters a year for the 15-year period extending from 1948 to 1963, with a range of 0.84 meter. The horizontal recession has amounted to 32 meters a year, with a range of 5 meters. The division of these rates into the total distance between the 1963 margin and the point where the first lichens were observed gives, on the assumption of an approximately linear recession prior to 1948, the age of the substrate. Table 5 demonstrates that substrates of 30 to 40 years are associated with *A. minuscula* 10 millimeters or so in diameter. In estimating the growth rate, it was assumed that the lichens would not start to grow immediately upon deglacierization, and a period of 10 years was allowed for the initial colonization. Table 5 illustrates the steps involved in the calculation.

Despite the various assumptions made, the consistency of the results is encouraging. They give an optimum growth rate of 0.52 millimeter a year and an annual mean of about 0.40 millimeter. Three profiles (2, 4 and 5) were extended to include areas beyond the first lichen occurrence so as to make possible a rough check of the expected diameter. The results obtained in two instances suggest a decrease in the rate of lichen growth.

Table 5

Calculation of growth rate of A. minuscula

Location	1 Retreat since 1948 (15-yr-period)	2 Retreat (m per yr)	3 Distance from 1948 limit to first Alectoria thallus (m)	4 Diameter of Alectoria thallus (mm)	5 Age of substrate (yr)	6 Growth rate on assumption of 10 years for initial colonization (mm per yr)
		$\frac{\text{column 1}}{\text{15 yr}}$			$\frac{\text{column 3}}{\text{column 2}} + \text{15 yr}$	$\frac{\text{column 4}}{\text{column 5–10 yr}}$
		vertical	*vertical*			
Profile 1	21m/v	1.4	41	10	44	.29
Profile 2	22m/v	1.5	15	5	25	.33
" 2	"	1.5	29.5	10	34	.42
Profile 3	24.5m/v	1.6	38	10	39	.34
Profile 4	15m/v	1.0	17	9	32	.41
" 4	"	1.0	61	20	76	.30
Profile 5	24.3m/v	1.62	26	11	31	.52
" 5	"	1.62	58	19	50	.48
Profile 6	27m/v	1.8	27	10	30	.50
		$\frac{\text{column 1}}{\text{11 yr}}$				
		horizontal	*horizontal*			
Lewis snout, profile 1	('48 to '59) 370m/h	34.0	830	10	36	.38
South edge, profile 2	340m/h	31.0	820	10	37	.38
		$\frac{\text{column 1}}{\text{15 yr}}$				
Profile 3	('48 to '63) 425m/h	28.0	450	10	31	.48
Mean		1.5v, 31.0h				.39
Range		.80v, 5.0h				.23
Standard deviation						.028
Number of samples = 12						

v = vertical thinning or recession. h = horizontal recession.

NOTE: The 1948 position of the margins of the Lewis Glacier was traced by means of air photographs.

The extent to which extrapolations can be made on the basis of these results depends on the part of the lichen growth curve that is being measured by the method described in this paper. If the values pertain to the "great" period, the estimate of the age of substrates beyond this period will be too small; if they fall in the period prior to the great period, the estimate will be too large. The lack of detailed historical records within the Arctic has so far handicapped research, and the basic form of the growth-rate curve is not known. The growth rate of 0.40 millimeter a year for *A. minuscula* is comparable to the 0.56-millimeter-a-year rate for the Disko area of Greenland (Beschel 1963). In accordance with the general theory underlying the sampling of maximum-diameter lichens, a growth rate of 0.52 millimeter a year should be adopted for the northwestern margin of the ice cap. This, however, has not been used because small-scale local conditions could affect the amount of glacier recession and thus cause error. This study will therefore be based on the mean estimated growth rate. Table 6 gives the dates thus obtained for the *A. minuscula* isophyses in Figure 2. It should be noted that if the postulated error were excluded from such a date, the result would be the age of the isophyse line as calculated from a growth rate of 0.52 millimeter a year.

Table 6

Dates of isophyses of A. minuscula *in Figure 2*

Isophyse	Present Age		Date A.D.
10 mm	25	5	1940*
30 mm	75	15	1890
50 mm	125	25	1840
70 mm	175	35	1790
90 mm	225	45	1740

*All values are given to the nearest decade.

These results can be checked by comparing the known ages of willow boughs collected in selected localities with the corresponding isochrones of Figure 2. Diligent searching showed that arctic willow (*Salix arctica* Pall.) colonizes substrates within three years of the disappearance of ice from an area. The lack of a progressive increase in willow age with elevation, however, indicated that a longer period is needed for successful and continual growth. Willow burls were collected and cut into thin sections (50 microns in thickness) in the laboratory on a sliding microtome, stained with safranin and mounted between glass slides. The sections were then photographed and enlarged 10 times so that the number of rings along four radii could be easily counted. A previous study of arctic willow had shown discrepancies in the number of rings along different radii (Beschel and Webb, 1963) because of lenticular growth (Studhälter *et al.*, 1963), but the specimens from central Baffin Island did not differ in any count by more than one ring. The maximum-age willows that have been located in Figure 2 indicate the minimum age of the isophyses, but as no willow found in the area is more than 40 years old, their usefulness is restricted. Thus, at most, these willows provide a check on the estimated age of the 10-millimeter and possibly on that of the 30-millimeter *A. minuscula* isophyses. Willow "c" (Figure 2) is 20 years old and lies near the 10-millimeter line, but no willows approaching 15 years of age could be found immediately above the 1948 ice-margin position. It seems that between five and 10 years must elapse before the growth of a willow is assured. Thus an age of 25 to 30 years can be expected for the 10-millimeter isophyse or the related isochrone. This compares favorably with the age of 25 years given by a growth rate of 0.40 millimeter a year but is perhaps too near the 10-millimeter-line age based on the optimum rate of 0.52 millimeter a year. The indications are that the area bounded by this isophyse has been icefree for 20 years or less.

The willows at sites a and b (Figure 2) lie above the 30-millimeter line and have, respectively, 37 and 39 annual rings. These represent minimum ages for the area bounded by the 30-millimeter and 50-millimeter lines. Willow "a" was collected at a station where *A. minuscula* was measured at 30 millimeters. With allowance for a period of initial colonization, the minimum age for that site is between 42 and 47 years. The mean estimated growth rate dates the 30-millimeter isophyse at 1890. There is thus a 30-year discrepancy between the two estimates, the most likely reason being that the willow sampled is somewhat younger than the substrate. The discrepancy might indicate that the growth rate of *A. minuscula* increases rapidly after a diameter of 10 millimeters has been passed, but the vertical spacing between the isophyses (Figure 3, A and B), which results from the rate of glacier recession, and the variations in the lichen-growth-rate curve show no pattern that can be attributed to growth variations. The geomorphological evidence indicates, in fact, a relatively constant recession, with only a few stillstands or readvances. In short, the results of the attempt to relate isochrones to willow ages are satisfactory for the initial isochrone, which is shown to date from about 1935–40, but the results of the check on the 30-millimeter line are open to reservations.

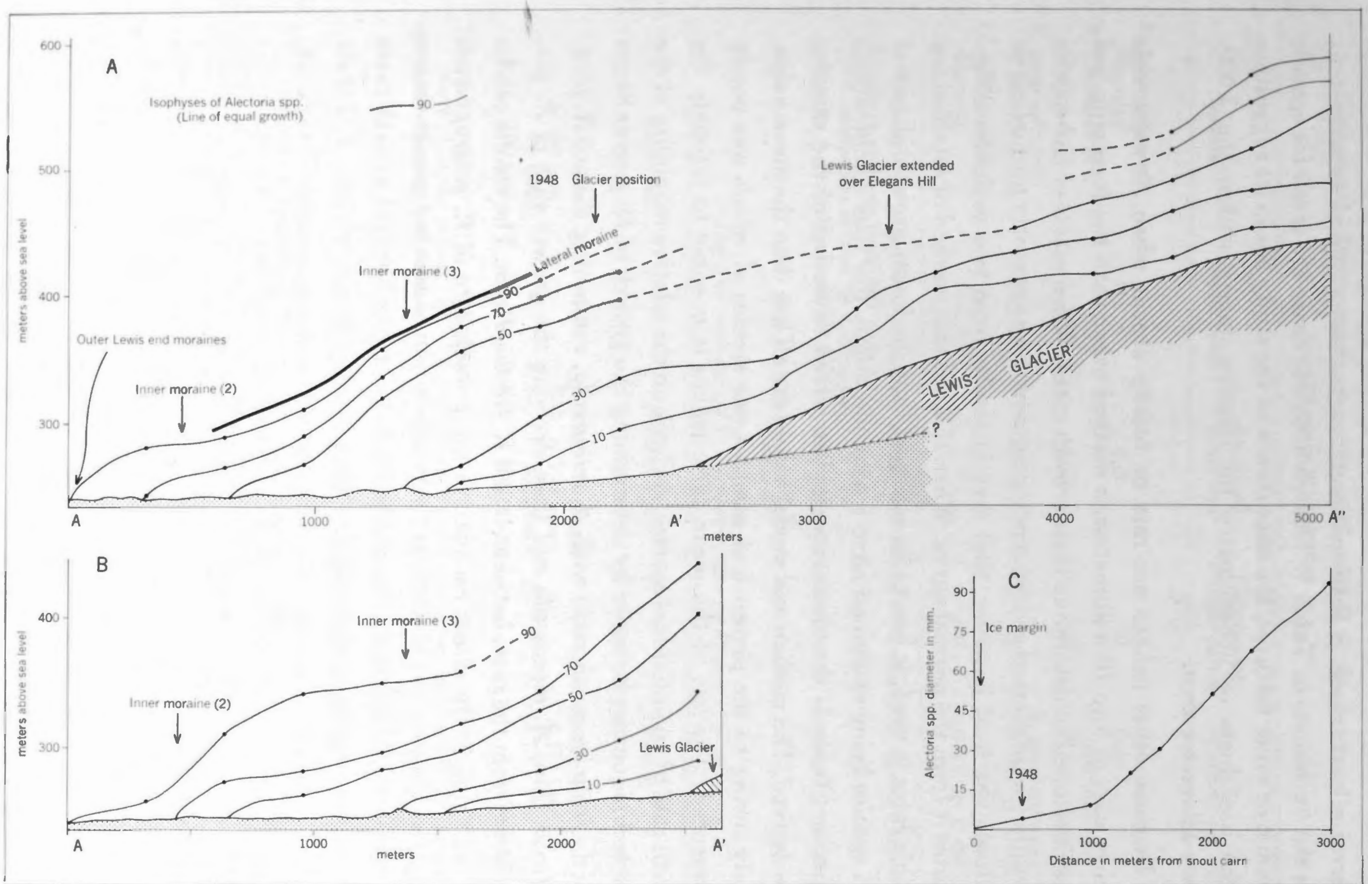


FIGURE 3. Drawn from the data in Figure 2, this represents a cross-section down the centre of the Lewis Valley with isophyses included. The gradient along these, shown in parts A and B, is similar to the gradients of such marginal features as lateral moraines and glacial drainage channels. Part C indicates distance from the present snout in meters plotted against the *A. minuscula* maximum diameters.

With the use of the 0.40-millimeter-a-year growth rate in this study, an error allowance of ± 0.10 millimeter a year is proposed as consistent with the variations in Table 5. Though absolute dates are given for specific morainic or other features, the importance of the study lies in its suggestion of the usefulness of lichenometry for relative dating within the 2,800-square-kilometer area.

Because other lichens are rare or totally absent when *A. minuscula* reaches sizes of 5 to 10 millimeters, a method other than the foregoing had to be developed to determine their growth rates, When ratios of one species to another were plotted as frequency diagrams, an apparently normal curve resulted. The fact, however, that a ratio results from two variables differentiates it from the normal curve. When this indirect method of establishing growth rates is used, it has to be assumed that the linear growth phases of both species being examined have a common origin. For four combinations of species (Table 7) the mean ratio and standard deviation of the samples were derived. The median and modal values are all less than the mean value, largely owing to the presence of samples one species of which was poorly represented. The use of the mean ratio makes it possible to estimate the growth rate of an individual species. A check on the relative reliability of the ratio technique can be made by determining the growth of *R. geographicum* directly from its mean ratio with *A. minuscula*, computing that of *R. jemtlandicum* from *A. minuscula* and then deriving the growth rate of *R. geographicum* from the ratio between it and *R. jemtlandicum*. The results can be seen in Table 7. By direct calculation the growth rate of *R. geographicum* is 0.057 millimeter a year whereas the interposition of another species makes the rate 0.067 millimeter. The similarity in the two estimated growth rates indicates the measure of confidence that can be placed in them. For their absolute veracity, of course, they still depend on the determined rate for *A. minuscula*, and thus their accuracy is relative. On the basis of the variations within the sample ratios, confidence limits can be set up; these have been taken from the internal variation within each frequency distribution and are not standard errors of estimate. The suggested ranges of error can be seen in Table 7 and Table 8. The latter lists the estimated age of each of the *R. geographicum* isophyses of Figure 1. Further investigations after an interval of perhaps 10 years will probably result in modifications to Table 8, but the relative chronology will stand.

Table 7

Data used to calculate growth rates of R. geographicum, R. jemtlandicum *and* Umbilicaria proboscidea

Species	Mean ratio	Standard deviation	Number of sample ratios	Growth per yr
R. geographicum:				*R. geographicum*
Alectoria[1]	1:7.0	2.8	97	0.057 ± 0.02
R. jemtlandicum:				*R. jemtlandicum*
Alectoria[2]	1:2.98	1.01	105	0.135 ± 0.04
R. geographicum:				*R. geographicum*
R. jemtlandicum	1:2.00	1.06	122	0.067 ± 0.02
U proboscidea:				*U. proboscidea*
Alectoria	1:2.78	1.1	131	0.17 ± 0.07

[1]The ratio is based on samples in which the *Alectoria* diameter is greater than 60 millimeters and less than 120 millimeters.

[2]*A. minuscula* is over 30 millimeters.

NOTE: A growth rate of 0.4 millimeter a year is assumed for *A. minuscula.*

Table 8

Dates of isophyses of R. geographicum *in Figure 1*

Isophyse	Present age	Date
18 mm	315 ± 90 years	A.D. 1645
30 mm	530 ± 150 years	A.D. 1440
70 mm	1,200 ± 360 years	A.D. 750
130 mm	2,300 ± 650 years	350 B.C.

NOTE: For the period 1400–1960, values are given to the nearest decade. Older values are to the nearest half century.

RECENT HISTORY OF LEWIS GLACIER

The intensive sampling done in the environs of the Lewis Glacier enables a series of vertical and horizontal profiles of the former glacier to be drawn (Figures 2 and 3). Observations were spaced at increments of between 25 and 50 meters. The maximum diameters of *A. minuscula* were plotted on a contour map of the area at an original scale of 1:12,000, and isophyses were drawn by joining points of equal maximum diameters (Figure 2). These lines represent a time picture of the Lewis Glacier during five successive phases represented by the diameters of 90, 70, 50, 30 and 10 millimeters. The regular pattern of the isophyses about the present glacier suggests that they accurately portray the historical Lewis Glacier. Additional confirmation of this is the similarity between the gradients of the marginal and submarginal glacial drainage channels and the isophyses. The picture presented by the 90-millimeter isophyse (A.D. 1740±45 years) is that of the Lewis and Triangle glaciers lying combined immediately behind the outer end moraines and frontal delta, upon which *A. minuscula* reaches a maximum of 114 millimeters (A.D. 1680±60 years). Recession, indicated by the progressively smaller lichen diameters downslope and upvalley, seems to have been fairly constant (Figure 3). Figure 3 (C) indicates the rate of horizontal recession. From A.D. 1680 to A.D. 1938 the glacier seems to have retreated at a linear rate of about 10 meters a year, but from 1938 to the present day this figure increased to 43 meters a year. This marked increase, however, is due not so much to climatic factors as to the initiation of the marginal Flitaway Lake drainage, which must have led to considerable undercutting and collapse of the northern margin and snout.

Figure 3 (A and B) illustrates the gradient of the isophyses for both the northern and the southern slopes of the Lewis Valley. The isophyses have been constructed by projecting points to a line A-A' along the centre of the valley and A'-A" along the crest of the glacier. A most noticeable point is the parallelism between the present glacier surface and margin on the one hand and the various isophyses on the other. Both gradients average 1:15. Figure 3 (A), which represents the northern side of the valley, shows very clearly the effects of the small lobe of the Lewis that pushed over Elegans Hill toward the Striding River valley (Figure 2) and did not leave completely until after the 50-millimeter phase. Figure 3(A) also suggests that between the 50- and 30-millimeter phases there was a period of rapid vertical recession that ended with a series of small stillstands, which led, in their turn, to the formation of three end moraines. The period is dated as extending from A.D. 1840 to A.D. 1890, with the stillstand at the latter date. The isophyses from the southern side of the valley (Figure 3, B) have gradients similar to those of their counterparts to the north but are marked by a noticeable inflexion where the margin of the Triangle Glacier and the ice cap was contained by the hill immediately west of the glacier.

RECENT HISTORY OF NORTHWESTERN MARGINS OF BARNES ICE CAP

The margin of the Barnes Ice Cap was studied from Umbilicaria Lake to the Lewis Glacier and then northward to a point 4 kilometers east of the upper Striding River. Figure 1 shows the location and extent of the principal end moraines and former glacial lakes. The drawing of the 130-millimeter isophyse of *R. geographicum* was difficult because of the weathering of rock surfaces. There is thus less probability of finding increasingly larger thalli with increasingly older substrates after the first 80-millimeter thallus has been encountered in a transect. The 130-millimeter line was drawn on lichenometrical and geomorphological evidence. On the plateau surface, west of Umbilicaria Lake and 12.5 kilometers from the present ice margin, there is a massive end moraine upon which *R. geographicum* reaches 133 millimeters. At the lower end of the lake section of the King River there is a series of large end moraines, the outer one being associated with a high outwash terrace, which at present is 16 meters above river level. Lichen stations established on the moraine and on the terrace had maximum readings of 85 millimeters, but the occurrence of maximum values of 89, 98 and 100 millimeters at three sites 10 kilometers to the east indicates that the outer moraine is at least older than the 100-millimeter lichen and is probably contemporaneous with the 130-millimeter isophyse. Similarly, it is possible to map on the air photographs the extension of the outer King River moraines across the interfluve into the Isortoq Valley. Here, a conspicuous end moraine at the junction of the King and Isortoq rivers is associated with an elevated outwash terrace 32 meters above the Isortoq and 16 meters above the King River. The maximum *R. geographicum* measurement obtained on the Isortoq end moraine was 100 millimeters. The correlation of the terrace systems, however, supports the theory that the outer King River moraine and the Isortoq moraine are, in fact, contemporaneous. The latter moraine lies 31 kilometers from the Lewis Glacier. There has been no field investigation in the area between the Isortoq moraines and Rimrock Lake, and the 130-millimeter isophyse is sketched from air-photograph interpretation. In the Rimrock Lake area it seems possible that the 555-meter col was being used as a lake spillway, but there is no evidence to suggest that the Glacial Lake Lewis spillway had been exposed.

The 130-millimeter isophyse corresponds to the age of 2,300 years (Table 8). This date places the large end moraines associated with this phase within the Sub-Atlantic climatic period.

The 70-millimeter isophyse of *R. geographicum*, estimated as marking the late-eighth-century ice-cap margin, is not significant in the glacial history of the ice cap although a significant stillstand and moraine-construction period seems to have antedated it by about 100 years. Toward the north, the lichen stations indicate that the Glacial Lake Lewis spillway was in use and that ice-dammed lakes were forming between the retreating ice margin and the watershed of the Isortoq and Striding rivers at the head of Arenaria Valley.

The 30-millimeter (A.D. 1440 ± 150 years) line marks the margin of the Barnes Ice Cap as it was immediately after the drainage of Glacial Lake Lewis. By this time the ice-cap margin near the present Umbilicaria Lake must have been very close to the present ice-cored moraines, but near the Lewis Glacier it was 5 kilometers from the present margin (Figure 4). Over the last 500 years the retreat of the ice cap has therefore been progressively more extensive on the north and northwest.

FIGURE 4. The western margin of the Barnes Ice Cap 4 kilometers south of the King River fronting an ice-dammed lake at 392 meters above sea level. On the left, at 404 meters above sea level, is a former glacial-lake shoreline. This feature is apparent in the field only because of the change in lichen cover and development above and below the shoreline. The sparseness of the cover can be seen in the foreground, where the record shows the maximum diameter of *A. minuscula* to be 36 millimeters (A.D. 1870). Above the shoreline the diameter of this species was 95 millimeters and *R. geographicum* reached 20 millimeters. The lichen stations were established on the slope in the middle ground of the photograph. Photo: JTA–62–68–1, August 17, 1962.

The outer moraine of the Lewis Glacier has a series of associated end moraines indicating an important stillstand that occurred about A.D. 1680 ± 60 years (120-millimeter *A. minuscula*). There are well-defined end moraines at the head of King Valley (Figure 5), and the ice-cored moraines that front the present ice-cap margin to the south appear to have a similar age. The growth of the small ice caps north of the Barnes Ice Cap were also affected by the climatic deterioration. Additional evidence for a deterioration of climate on Baffin Island in the seventeenth century has been noted by G. Falconer, of the Geographical Branch. The age of mosses exposed by the recession of a small ice slab 200 kilometers northwest of the Barnes Ice Cap has been given as 330 ± 75 years (I–1204, GF–63–V–80). The exposure occurred in 1961 (G. Falconer: personal communication, 1964).

FIGURE 5. A northward view over the head of King Valley with the King lobe of the Barnes Ice Cap visible on the right. On the far side of the valley is a distinct color change associated with a large 45-meter end moraine just visible in the left centre that is damming a lake in the valley. At lichen stations established by Andrews in 1962 and by Beschel in 1963 it was found that *R. geographicum* reaches 17 millimeters and *A. minuscula* 122 millimeters. Thus the site is comparable in age to the outer Lewis complex. Photo: JTA–62–69–5, August 17, 1962.

The computed ages of the main end-moraine systems are presented in Table 9, where they are compared with readvances or stillstands on Baffin Island (Hale, in Ward, 1952; Thompson, 1954) and Greenland (Weidick, 1959 and 1963; Beschel, 1958). There is close agreement between the records of glacial fluctuations in southwest Greenland and those of the recent moraines of the northwestern margins of the Barnes Ice Cap. The date A.D. 1890, ascribed to the third inner Lewis moraine (Figure 2), is of special significance: it seems to have been the date of a world-wide glacier stillstand (Ahlmann, 1953) recognizable in nearly all areas. The date 1920, assigned to the innermost moraine, is also critical, the records indicating a sharp rise in Arctic temperatures after that year (Mitchell, 1961; Ahlmann, 1953).

Table 9

Suggested moraine dates for Baffin Island and Greenland

Baffin Island			Greenland	
Barnes Ice Cap (N and NW)	Barnes Ice Cap (SE, Hale, 1952; Sim, 1961)	Pangnirtung Pass (Thompson, 1954)	(SW, Weidick, 1959 and 1963)	(SW, Beschel, 1961a)
A.D. 1920				A.D. 1920–25
A.D. 1905				A.D. 1890–95
				A.D. 1870–80
A.D. 1890		A.D. 1883 ?	A.D. 1890	A.D. 1850
	A.D. 1825	A.D. 1820 ?		A.D. 1820
			A.D. 1800	A.D. 1770–80
A.D. 1740			A.D. 1750	A.D. 1740–50
				A.D. 1680
A.D. 1650				A.D. 1600
A.D. 1300				
A.D. 950				
A.D. 650	A.D. 710			800–500 B.C.
	A.D. 200			>2000 B.C.
450 B.C.			Sub-Atlantic	Readvances after thermal optimum

The dates determined by Harrison (1964) for end moraines in the Bruce Mountains of Baffin Island indicate similarities between the date pattern of the Barnes Ice Cap and that historically substantiated for Greenland. Lichen studies made by Hale (Ward, 1952) at the southeastern end of the ice cap and by Sim (personal communication, 1961) indicate that the two ends differ greatly in the history of fluctuations. Sim, in measuring the maximum diameters of 100 *R. geographicum* above and below the prominent former glacial-lake shoreline in the Generator Lake basin near the present glacier margin, found a maximum diameter of 73 millimeters below the shoreline and 100 millimeters above it. This suggests that the lake was drained at 700 A.D. ± 350 years (if a growth rate of 0.057 mm/year is used), at which time the ice margin could have been only 6 kilometers from its present position. Hale's evidence, since the outer moraine with 50-millimeter *A. minuscula* abuts against a zone of mature lichen colonization, suggests that the southeastern margin had readvanced. Recalculation of his suggested lichen growth rate in keeping with the growth rates established in this paper points to A.D. 1830 as the date of this moraine. In contrast, the western and northwestern margins have been retreating steadily inland since 5,000 years ago, when the Baffin ice may still have reached the inner parts of bays leading into Foxe Basin (Ives, 1964). The margin has responded to climatic fluctuations during which end moraines have been formed, some dating from A.D. 550–850, when glaciers were less extensive in Europe than they are today. There are Alaskan moraines, however, that date from this period (Heusser and Marcus, 1964). Thus the history of the western and northwestern margins is one of linear recession with no major readvances but with stillstands. The southeastern margin, on the other hand, seems to have readvanced extensively at the beginning of the nineteenth century.

ASSESSMENT

In the vicinity of the ice cap the topography is subdued, its maximum relief being 300 meters and often much less. The valleys are broad and open and the area has no extreme topographical irregularities, which through insolation or other effects could cause marked differences in lichen growth. Because of these factors and the presence of the former Glacial Lake Lewis drainage basin, which extends north and south from near the ice cap for more than 36 kilometers, the technique of lichenometry could be appraised. The results were very encouraging: three widely separate areas within the Glacial Lake Lewis basin showed no difference in the maximum diameter of *R. geographicum*, and the steady decrease in diameter above the shoreline could be interpreted as a reflection of ice recession. The large number of stations has made it possible to draw a series of isophyses, which represent relative isochrones and permit the correlation of events along the northwestern margin. Absolute isochrones still await firm establishment, but the suggested dates for the principal phases do correlate with Greenland chronologies. At the very least, it has been established that the 'little ice age' maximum occurred during the seventeenth century or perhaps early in the eighteenth. The fluctuations have been imposed on a general pattern of marginal retreat that has been going on for between 5,000 and 7,000 years, with intermittent stillstands or readvances.

The writers suggest that geomorphologists can have great success in using lichenometry for the relative dating of recent glacial events in areas that lack datable organic material for the time span involved. For future research the stations will be extended right around the margin of the ice cap.

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POSTGLACIAL MARINE SUBMERGENCE AND EMERGENCE OF MELVILLE ISLAND, N.W.T.

W. E. S. Henoch

ABSTRACT: This paper presents some of the results of a detailed investigation of emerged features on Melville Island that was carried out during the summer of 1962. Extensive coverage of the area was made possible by aircraft support.

The writer sums up previous observations on the evidence of glaciation and, on these and his own observations, postulates a multiple glaciation. He describes postglacial emerged features and the difficulties encountered in correlating them.

He discusses the significance of seven radiocarbon dates of samples collected on the island and uses them to construct a preliminary uplift curve. This curve indicates that over the last 2,000 years uplift has been negligible and that Melville Island is near isostatic equilibrium. This comparatively early regression of postglacial sea from its coast is also corroborated by recent permafrost research at Winter Harbour.

RÉSUMÉ: La présente étude donne une partie des résultats d'une investigation fouillée poursuivie au cours de l'été 1962, à l'aide d'un aéronef, sur des formes de terrain émergées dans l'île Melville.

L'auteur résume des observations déja faites sur les preuves de glaciation. En y ajoutant ses propres observations, il conclut à l'existence de plusieurs glaciations successives. Il décrit des formes de terrain émergées après la période glaciaire et explique pourquoi il lui a été difficile de les rattacher les unes aux autres.

Il parle de la valeur de sept radiodatations au carbone 14 de plusieurs échantillons prélevés sur l'île et trace, à l'aide de cette méthode, une courbe préliminaire du relèvement isostatique, montrant que ce phénomène est infinitésimal depuis 2,000 ans et que l'équilibre isostatique de l'île est presque rétabli. Cette régression ancienne d'une mer postglaciaire, à partir de ses côtes, est corroborée aussi par des études récentes faites sur le pergélisol à Winter Harbour.

INTRODUCTION

Melville Island lies north of McClure Strait and Viscount Melville Sound between latitudes 74° 25' and 76° 55' N and between longitudes 105° 21' and 117° 38' W. It forms one of the northwesterly group of the Queen Elizabeth Islands, which are believed to have remained along the northernmost fringe of the Wisconsin continental ice sheet. Its glacial history is still relatively unknown, although Fyles (personal communication, 1963) suspects that a morainic belt running along the south coast may represent

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the outermost position of the Wisconsin continental ice sheet. The co-existence of a local ice cap, or ice caps, is also suspected, and the present-day occurrence of small plateau ice caps between Murray Inlet and Ibbett Bay lends credence to this.

Many of the early explorers observed the emerged features of Melville Island and measured their altitude barometrically. The observations are summarized by Tozer and Thorsteinsson in Geological Survey Memoir 332, on the western Queen Elizabeth Islands. These authors investigated the island in 1955, during "Operation Franklin." Bedrock geology was their main concern, but they also studied the glacial features and made many observations on the upper marine limit. This paper concerns mainly the lower raised marine shore features—the determination of their height, horizontal correlation and possible tilt—rather than the upper marine limit.

Mollusc shells found by Tozer at 175 feet (53.3 meters) on the east shore of Weatherall Bay were at the highest altitude of any of the evidence that supported marine submergence and yielded a radiocarbon age of 8,275 $\pm$ 320 years (Craig and Fyles, 1960). Reference to the Glacial Map of Canada (1958) and to Farrand and Gajda (1962) indicates maximum submergences of about 60 meters in the northwest and 85 meters in the southeast. North American isobases drawn by Farrand and Gajda yield a very simple linear pattern for the entire northwestern and central parts of the Queen Elizabeth Islands. They trend from west-southwest to east-northeast, are widely spaced and suggest that the region lay close to the northern limit of continental glaciation. This reasoning and the available radiocarbon dates imply relatively early deglaciation, which would give an early start for completion of the process of glacio-isostatic recovery. Such a hypothesis, however, together with the trend of the isobases, must be regarded with extreme caution. The lines on Farrand and Gajda's map are not true isobases in that they do not connect features of equal age; thus the drawing of isobases on the existing evidence is not realistic. Yet, when the glaciation of North America as a whole is considered in relation to the position of Melville Island, it can be seen that the island is situated on the outer fringe of the area of glacio-isostatic fluctuations. This is in contrast to areas such as Foxe Basin (Sim, 1960, 1961; Ives, 1963; Ives and Andrews, 1963) and Hudson Bay (Lee, 1960), which were situated much closer to the centre of continental glaciation and emerged from the ice sheet 2,000 or 3,000 years later.

The work described here was intended to provide more detail on the problems of late-glacial and postglacial marine submergence and subsequent isostatic recovery. Aircraft support facilitated detailed investigation of much of the perimeter of the island. The initial objective was the precise levelling of the heights of the marine limit and all prominent raised marine shore features so that specific strandlines could be identified and dated by radiocarbon methods. As much of the coastal area was formed of soft, horizontal sedimentary rocks, and as the depositional marine features had a high clay and silt content, extensive postglacial solifluction prevented positive identification of many raised shore features. Structurally controlled benches occur along many sections of the coast and further complicate reliable interpretation. Instead of geomorphic forms, the highest marine features in many localities were molluscs, which afford only a minimum estimate of the height of the marine limit. The progress made, however, resulted in a much greater abundance of data than was hitherto available. A series of radiocarbon dates, from molluscs, peat and driftwood, ranging in elevation from 1.6 meters to 71.5 meters, make it possible to construct a provisional uplift curve and prompt the conclusion that little, if any, isostatic uplift has occurred in the last 2,000 years.

EVIDENCE OF GLACIATION

Crescentic hills, conical hills and hills in the shape of table mountains, rising from 20 to 40 meters above the uplands, are found on the main water divide of Dundas Peninsula (Figure 1) and south of it, as well as north of Bridport Inlet and Skene Bay and on the eastern side of Sabine Peninsula. They are composed of gravel, silt and some boulders. The last-mentioned include soft sedimentary rocks from the bedrock of the island, exotic rocks of gneiss, schist and quartz and igneous varieties. These deposits are considered by Thorsteinsson and Tozer (1959, page 9) to be till. Although no proof of their glacial origin has been found, this possibility has to be taken into consideration.

On the basis of topographic and tonal contrasts evident on air photographs, Fyles (personal communication, 1963) has identified a belt of fresh, young-looking moraine ridges extending along the south coast of Dundas Peninsula for about 80 kilometers and bordered on the northern (inland) side by much-older-looking drift. Another area of glacial drift lies above the marine limit along the south shore of Liddon Gulf.

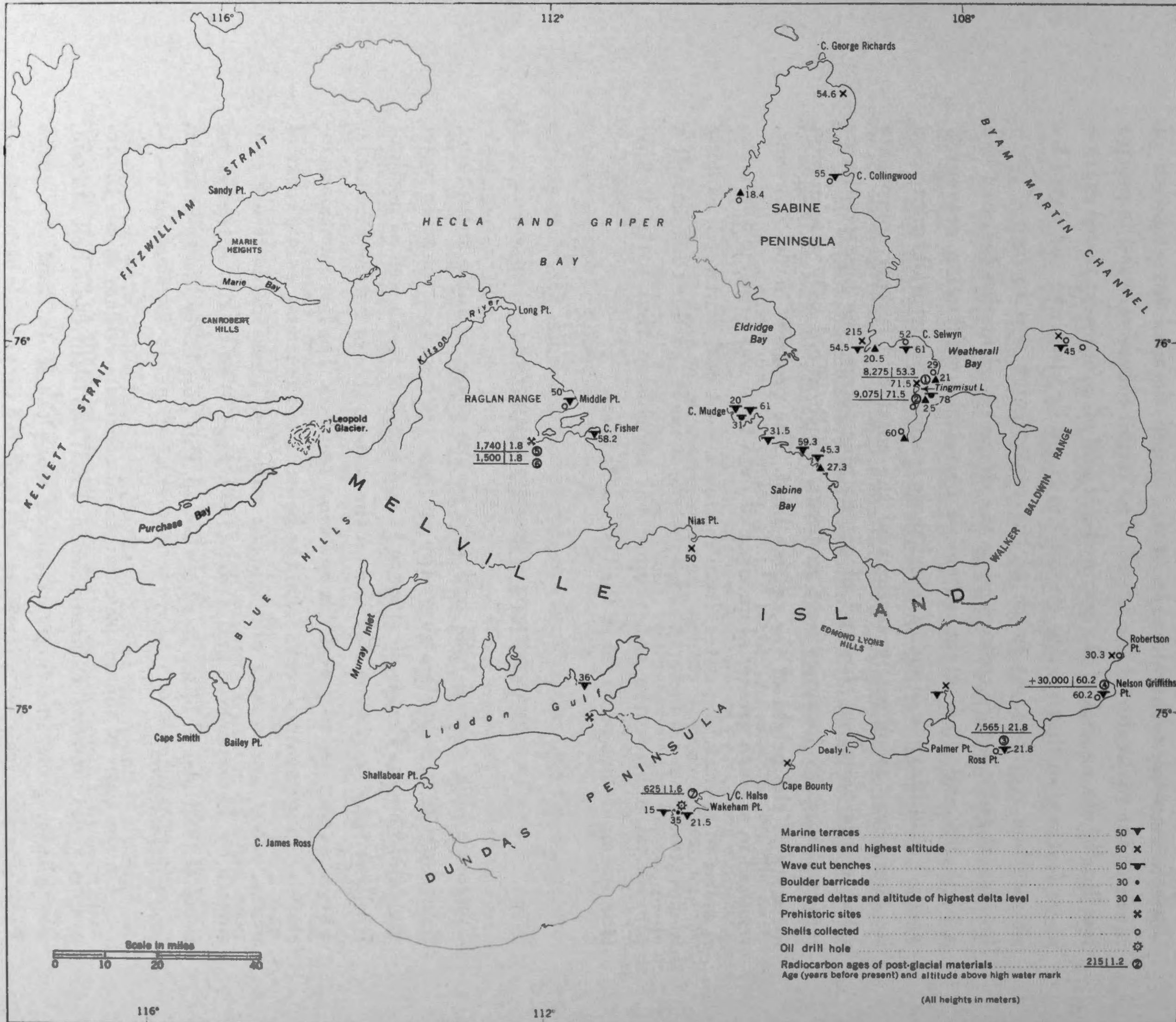

FIGURE 1. Location map.

Erratics of crystalline and igneous rocks are ubiquitous on Melville Island. As they are found up to 700 meters above sea level (high above the maximum height of marine submergence), they cannot have been ice-rafted. Their distribution seems to indicate glaciation of the entire island.

Among the erosional features that may have resulted from glacial action are the many fiord-like bays that deeply indent the coast. Although it is evident that the river system proposed by Fortier and Morley (1956) has been the main agent in the formation of the valleys now drowned to form the embayments, the possibility that they were reshaped into fiords by glacial action cannot be rejected. Tozer (1956, page 9) suggested that the embayments "represent stream valleys that have been enlarged by tongues extending from an ice cap similar to that present on Devon Island today."

The only striations so far discovered on the island are those at the head of Liddon Gulf that were identified by McMillan (McMillan, in Bernier, 1910, pages 411 and 461), who assumed that they had been formed by westward-moving ice.

Other evidence of glaciation includes ground-moraine topography, small lakes scattered throughout the island (for example, east of the east arm of Weatherall Bay), glacial drainage channels not related to the present ice caps, and postglacial emergence from the sea.

EMERGED MARINE SHORE FEATURES

The emerged shore features of Melville Island investigated during 1962 include beaches, bars and spits, boulder barricades and deltas. A careful search was made for marine macro- and microfossils, stranded driftwood and terrestrial organic deposits associated with specific levels below the marine limit, the dating of which would give a minimum time lapse since emergence.

A Zeiss N-2 automatic level was employed for the most important occurrences; for the others, use was made of two Wallace and Tiernan surveying altimeters FA-181, calibrated at 10-foot intervals to 7,000 feet and connected for temperature and pressure change whenever possible. The altimeters were used primarily for preliminary estimations. Although some of the traverses made with the Zeiss level were closed with an accuracy of 2 centimeters, the final results were rounded to 0.5 meter.

As there were no data for accurate calculation of the sea level around Melville Island, heights were measured from the high tide mark. This mark can be traced as a break in the slope of unconsolidated materials. The high tide mark was used as a reference point only where it could be traced for some 25 meters and where it could be distinguished from ice-pushed ridges and storm-wave marks. All heights given are relative to high water-mark, not to mean sea level. The following subsections describe the forms identified and surveyed at the various locations indicated on the map (Figure 1).

Emerged shore features of Hecla and Griper Bay

At Cape Mudge, surrounding a flat-topped peninsula at about 20 meters, there is a broad terrace. Above it, 5 kilometers inland, two terraces were identified at heights of 22.5 and 37 meters. There is also a terrace on the north side of Sabine Bay, east of Cape Mudge; this occurs at 21.5 meters and appears as a continuation of the Cape Mudge terrace. Higher emerged shore features in this vicinity have probably been destroyed by mass movement.

A distinct terrace runs parallel to the south shore of Hecla and Griper Bay, separating rock detritus above from a sandy plain below; it lies south of Nias Point at 50 meters and was traced eastward for 22 kilometers. It appears to be a beach representing the marine limit in this area, but surface materials taken from above and below the terrace were barren of foraminifera.

Cape Fisher is a terrace of sand and silt rising to 58 meters and surmounted by a small ridge 4.5 meters high that has the appearance of an emerged bar. The slopes of the cape are notched by wave-cut beaches at 17, 28, 30.5 and 44 meters. Ice-pushed ridges were found in association with the 17-meter beach, but are otherwise confined to altitudes below 8 meters.

Middle Point, north of McCormick Inlet, is a sandy promontory rising steeply to 50 meters, with a gentle slope extending inland to the foot of the Raglan Range. On the point, marine molluscs were collected at 50 meters, but, owing to extensive slope wash at the foot of the range, it was not possible to determine the marine limit.

Thus in Hecla and Griper Bay, former marine submergence is indicated by (1) molluscs found at 50 meters at Middle Point, (2) a raised beach at 50 meters running east of Nias Point, (3) an offshore bar at 62.5 meters, above Cape Fisher, and (4) numerous other emerged shore features at lower levels. In addition, many localities show extensive depositional terraces varying in height between 58 (Cape Fisher) and 61 meters (Mudge Point), the origin of which is uncertain. The terraces are often as much as 3 kilometers wide and run along the coast for a considerable distance; molluscs and marine shore features are frequently found on their surface, but it is believed that the terraces themselves date from an earlier period.

Emerged shore features of east coast

On the northern slopes of the gypsum dome at Cape Colquhoun wave-cut terraces were formed at 54.5, 21.5 and 16 meters and molluscs were collected at 50 meters. Mass movement above 54.5 meters made it impossible to determine the maximum height of submergence. Farther south, at Cape Collingwood, there is an extensive constructional terrace at 55 meters. Small mollusc-shell fragments were found on the terrace, which extends far inland. It seems that the greater part of Sabine Peninsula was submerged.

East of Cape Selwyn well-developed beaches occur, the most pronounced lying at 51.5, 34, 30, 23.5, 18 and 13.5 meters. None could be followed horizontally for more than about 30 meters, and numerous intermediate levels merged with them. Shell fragments were found at 61 meters.

The highest evidence of marine submergence on the entire island was found at Tingmisut Lake, west of Weatherall Bay. Here molluscs were collected at 71.5 meters and yielded a radiocarbon age of 9,075 $\pm$ 275 years (I-730)(Figure 2). These data thus increase by 18 meters the height of submergence as determined by Tozer (Craig and Fyles, 1960, page 12) and indicate that deglaciation occurred about 1,000 years earlier.

Robertson Point provided the finest development of raised beaches on the east coast. They occur as a densely spaced flight of terraces below 30.5 meters, the most prominent lying at 18, 14.5, 10.5, 7 and 4.5 meters.

Emerged shore features of south coast

At Nelson Griffiths Point, only 18 kilometers from Robertson Point, the highest shore features lie at 60 meters. Shells were collected from the uppermost beach, which at this level yielded a radiocarbon age of 34,050 $^{+2,650}_{-1,990}$ years (GSC–154), the significance of which is uncertain. The shells of this age may have been redeposited remnants of pre-Wisconsin materials, but the absence of beaches above 30.5 meters at Robertson Point may be due to original lack of formation of such features or to their subsequent destruction by mass movement.

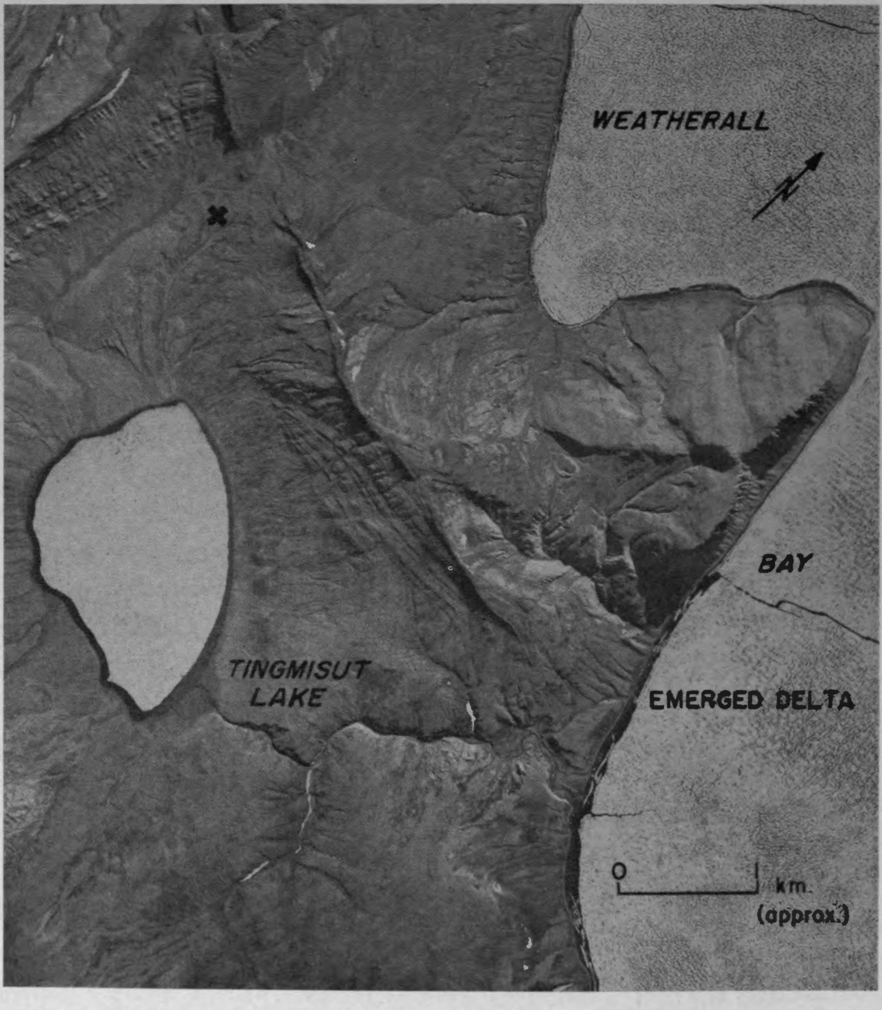

FIGURE 2. The Tingmisut Lake area. The cross indicates where marine shells were collected 71.5 meters above high tide mark. The radiocarbon age of these shells is 9,075 ± 275 years (I–730). The prominent ridge east of Tingmisut Lake trending north is a gabbro dike. Note the raised delta shown in the ground photograph (Figure 3). Photo: RCAF vertical A–16763–55.

A well-developed sandy terrace occurs at Ross Point 22 meters above sea level. Marine molluscs collected from the terrace surface gave a radiocarbon age of 7,565 ± 235 years (I–841). Below the terrace, many raised shore features were apparent in the air photographs, but they were so difficult to identify on the ground that they could not be surveyed. Above the terrace a prominent bench composed of silt, sand and gravels that are barren of marine microfossils occurs at 83 meters. Its true significance could not be determined.

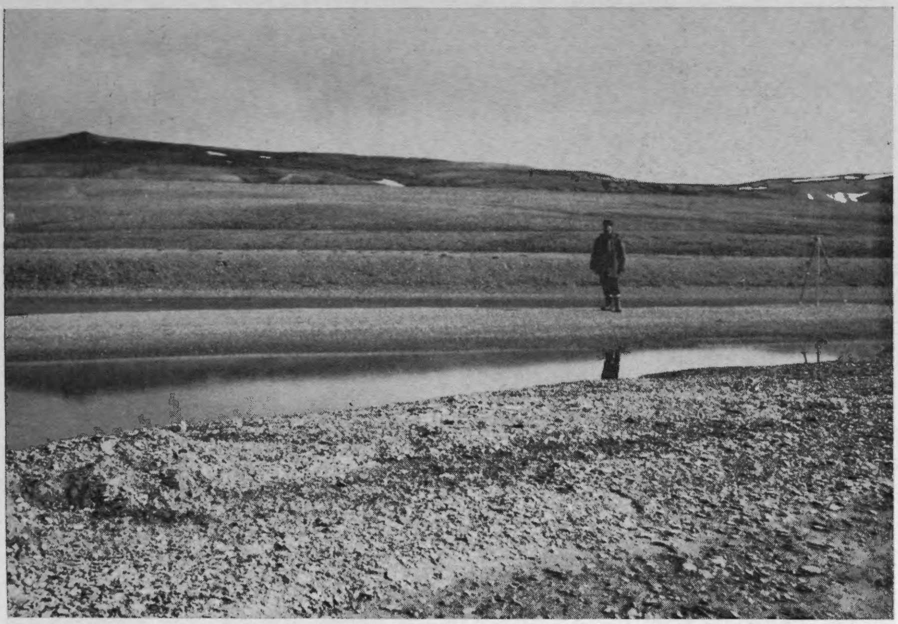

FIGURE 3. Raised beaches on an emerged delta dissected by a river flowing from Tingmisut Lake.

The bay north of Wakeham Point (Figure 4) contains a flight of closely spaced marine beaches below 15 meters. Although evidence of greater submergence is lacking, comparison with other points along the south coast shows that submergence exceeding 15 meters undoubtedly occurred. Of special interest was the discovery of a piece of driftwood 1.2 meters long by 0.3 meters thick at 1.6 meters above high watermark in the northwest corner of the bay. Partly buried in sand and protected from wave action by a low peninsula, it lay 14 meters inland from high watermark. Thus sheltered, it would not be pushed by ice or thrown by storm waves for any considerable distance. Its radiocarbon age was 625 $\pm$ 100 years (I–842), and it seems likely that at the beginning of that period the high watermark was approximately at this level.

A pronounced terrace lies to the east of Winter Harbour at 21.5 meters, and the most prominent wave-cut terraces below it lie at 1.0, 7.5 and 17.5 meters. Benches occur on the main terrace rise, but bedrock exposures

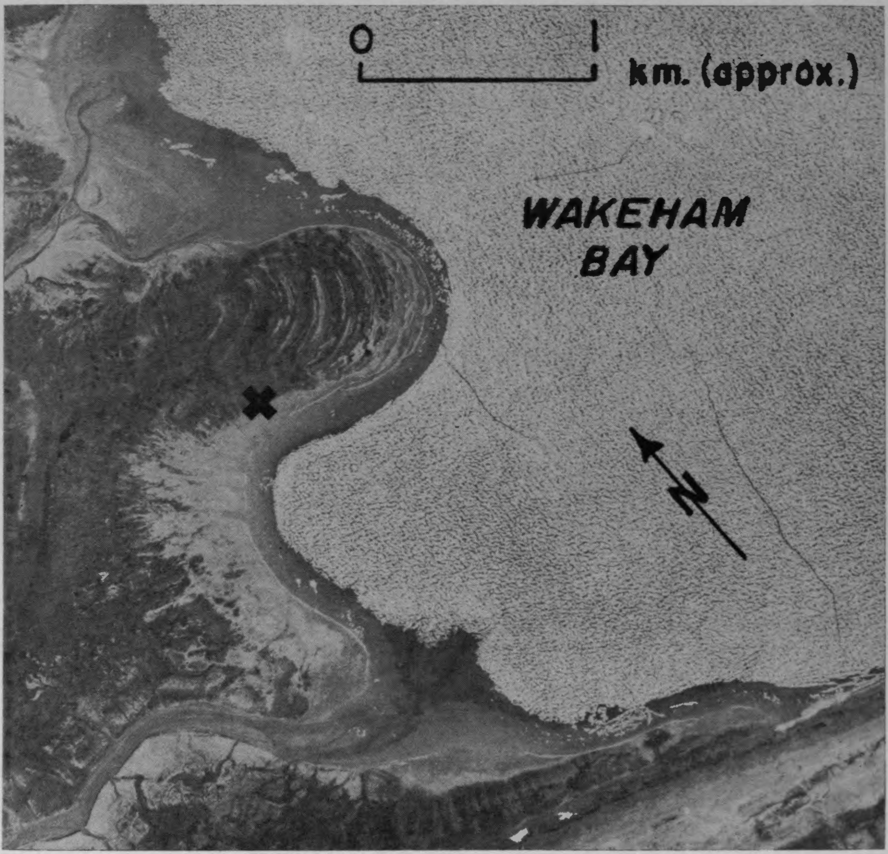

FIGURE 4. The cross marks where the driftwood was collected. Photo: RCAF vertical A–17719–103.

FIGURE 5. A boulder barricade indicating the upper marine limit at 35 meters above high tide mark.

imply structural control. Parry Rock stands at 15 meters on a terrace that broadens southward and continues for 3 kilometers beyond Hearne Point, where it is covered with lagoonal lakes trending parallel to the coast and separated by shingle bars. Northeast of Winter Harbour a boulder barricade was found at 35 meters (Figure 5). This was the highest raised shore feature discovered on this sector of the coast and may represent the marine limit. Samples of fines taken from above and below the boulder barricade again proved to be barren of foraminifera.

Emerged shore features of Liddon Gulf

Only three localities could be investigated in Liddon Gulf. These gave no positive results but illustrated the problems of interpretation of raised shore features. Several features were surveyed barometrically west of Peddie Point, but a rapid change that took place in atmospheric pressure during the survey made the results unsatisfactory. Raised shore features occur to about 15 meters. Higher features are probably structural benches.

At Bushnan Cove, shore features were surveyed up to 18 meters, although here, also, structural influences could not be eliminated. West of the cove a flat-topped peninsula composed of waterworn pebbles and cobbles rises to 35.5 meters. Some of the cobbles were of erratic crystalline material, but no molluscs or foraminifera were discovered. While not definite, the 35.5-meter terrace may well prove to be the highest raised shore feature of Liddon Gulf.

Emerged deltas

Some of the most striking features in the configuration of the coast of Melville Island are emerged river deltas, which continue to extend seaward under the present environmental conditions. These deltas are essentially of the bird's foot type and have many special characteristics. They vary up to 1.5 kilometers in width and 8 to 10 kilometers in length and are composed of six to eight alluvial deltaic fans rising inland as a flight of terraces. The highest do not exceed 50 meters. The largest deltas on Melville Island have been formed by rivers draining the eastern slopes of Sabine Peninsula and flowing into Hecla and Griper Bay. Smaller deltas have formed on the southeast coast (south of Robertson Point), but those on the south and west are poorly developed. More appear on the north coast. Cape Bray is located on a delta tip. Two other deltas have formed on the southern shore of Marie Bay.

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The apparent periodicity in the deposition of delta fans may have been caused by changes in factors governing deposition in the river basin or by relative changes in sea level. The profiles of six of the best-developed deltas were precisely surveyed in the hope of correlating certain points in their longitudinal profiles with other emerged features along the coast and relating these points to the former sea levels. The complex structure of the fans, however, sometimes made it difficult to recognize levels of the same origin. Correlation was further complicated by distance, and the coincidence shown by some of the levels may have been incidental. As no other reliable method was found, the relations between these points and the former sea levels could not be determined.

ATTEMPTED CORRELATION OF RAISED SHORE FEATURES OF MELVILLE ISLAND AND SUMMARY OF DATA OBTAINED

The coasts of Melville Island, except the west coast between Liddon Gulf and Cape Scott, were examined at frequent intervals for raised shore features. Not all levelled features, but only the more prominent or more significant, have been described under the foregoing subheadings. The table contains all the assembled radiocarbon data.

An attempt was made to correlate raised shore features by constructing equidistance diagrams. When the results had been plotted on these diagrams, however, it was apparent that raised shore features in different parts of the island could not be correlated.

A general picture of the extent of the isostatic adjustment to deglaciation can nevertheless be formed, even if it is based only on the interpretation of air photographs, field observation of emerged features and consideration of the altitude of the highest observed features. These may not, of course, represent the upper marine limit in their particular locality.

The highest observed raised shore features were found at 71 meters near Tingmisut Lake, on Sabine Peninsula, at 50 to 60 meters around Hecla and Griper Bay and at similar altitudes on the east coast of the island. The heights diminish westward along the south coast, where a boulder barricade, found at 35 meters near Winter Harbour, might indicate the upper marine limit. The highest observed raised shore features on the west shore of Dundas Peninsula appear to be at even lower elevations but rise again in Liddon Gulf to about 35 meters.

Once accepted that emergence results from rebound of the crust unburdened by deglaciation and that, given the geophysical characteristics of the crust, the amount of emergence is in proportion to the dimension of the ice cover and the time it was in existence, it follows logically that the ice cover was of the greatest thickness over Sabine Peninsula and Hecla and Griper Bay and never attained the same thickness over the southeastern part of the island; and that it thinned out considerably toward the southwestern coast of Dundas Peninsula. Daly (1938, page 182) indicated that an ice cap must have a minimum diameter of 500 kilometers and a minimum thickness of 1,000 meters before it will depress the crust. It is possible that Sabine Peninsula was depressed by an ice cap approximately of these dimensions that covered the Parry Islands and had its centre (or one of its centres) in the general area of that peninsula.

The evidence of emerged features and the glacial deposits on the south coast of Melville Island and along the coasts of Liddon Gulf suggests that the depression of the south coast was caused by ice lobes occupying the adjacent straits and sounds and originating in the continental ice sheet to the south.

INTERPRETATION OF RADIOCARBON DATES

From the many types of terrestrial and marine organic material collected from Melville Island, six samples were selected for radiocarbon dating. Together with the single date on shells collected by Tozer (Craig and Fyles, 1960), they provide seven absolute dates related directly or indirectly to the problem of determining the relation between sea level and the rising land. The seven samples are listed in the table, which also gives the relevant data on the site and on the dating laboratory. The seventh sample is very old and cannot be used in the following discussion, which is concerned primarily with the postglacial emergence of the land. Finally, the fifth, while adding to the degree of reliability of the fourth and sixth, cannot properly be used in the construction of an uplift curve (Figure 6), because it relates to human occupancy. The samples will be discussed individually in some detail before being considered as a group. They will be described in chronological order, from the oldest and highest to the youngest and lowest.

Sample 1: Tingmisut Lake—I-730

Marine molluscs were collected from the surface material at a height of 71.5 meters above high watermark. The site was a broad terrace extending into

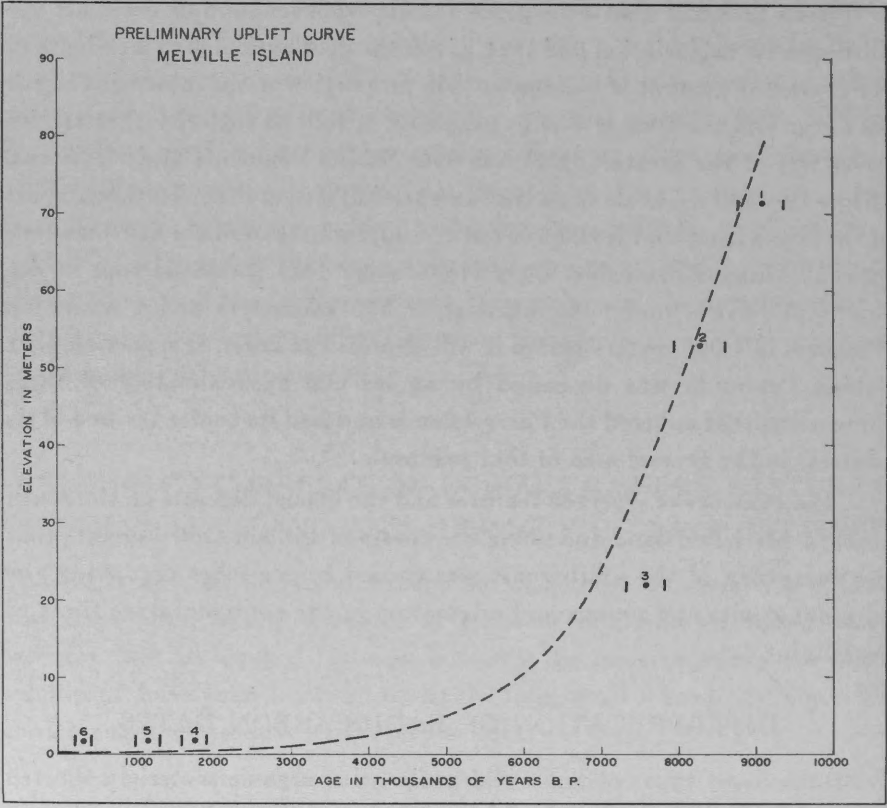

FIGURE 6. Preliminary uplift curve, Melville Island.

a wind gap in the immediate vicinity. While the shells could not be related to any specific sea level, the possibility of their redeposition by downslope movement can be ruled out. They are the highest recorded evidence of marine submergence on the entire island, although it must be understood that the relevant sea level stood higher than the shells themselves. Isotopes Incorporated recorded the age of these shells as 9,075 ± 275 years (I-730). This is probably their minimum age and represents the earliest known date at which this part of the coast was free of land ice.

Sample 2: Tingmisut Lake—I(GSC)-21

This was collected from the surface material on a marine terrace at a height of 53.5 meters some 400 meters from the site of Sample 1. The marine shells of which it consists showed a radiocarbon age of 8,275 ± 320 years. The heights and related ages of this and the preceding sample are complementary. Although neither sample provides evidence of the age of a particular marine stage, the data are internally consistent.

Sample 3: Ross Point—I-841

Ross Point lies 115 kilometers south-by-east, from Tingmisut Lake. The sample is composed of molluscs collected from the surface material of a well-developed sandy terrace at 22 meters. The foot of the landward slope is between 300 and 500 meters north, and it seems unlikely that solifluction of the surface material has occurred (Figure 1). Redeposition by wave action, however, is a possibility, and the shells cannot be related to a specific sea level. Their age, 7,565 ± 235 years (I-841), implies that about 7,600 years ago the sea level stood more than 22 meters higher, relative to the land, than it does today.

Samples 4 and 5: McCormick Inlet—I-840 and I(GSC)-148

The ruins of a dwelling situated 1.8 meters above high watermark was discovered at McCormick Inlet on the west coast of Hecla and Griper Bay (Figure 7), and Map (Figure 1). Artifacts collected from the site have been identified by W. E. Taylor of the National Museum of Canada as related to Dorset culture. The dwelling stood on a gravelly beach, which in 1962 was almost completely devoid of vegetation. Dead moss discovered under the flagstone pavement within the dwelling was collected as Sample 4 (Table 1), and its radiocarbon age was found to be 1,740 ± 190 years (I-840). Burnt peat remains were also found in the fireplace. These were collected as Sample 5 (Table 1) and dated as 1,150 ± 160 years old (I(GSC)-148).

Since it is unlikely that a dwelling would be built much closer to high water than 1.8 meters (the present height of the site), it is assumed that knowledge of the age of the moss collected from beneath the flagstones is indispensable for a good estimate of the amount of land uplift over the past 1,700 years. The conclusion is that uplift relative to world sea level, if any occurred, was appreciably less than 1.8 meters. Assuming that the true dates (Dyck and Fyles, 1963) of Samples I-840 and I(GSC)-148 fall within the specified range, the dwelling was probably seasonally reoccupied between 1,150 and 1,740 years ago. These two dates are internally consistent and can be used to provide a figure for the maximum possible amount of land emergence for the last one and a half millenia, which is appreciably less than 1.8 meters.

Radiocarbon dates from Melville Island

No.	Locality	Laboratory no.	Age in years	Elevation[1]	Occurrence	Material	Collector
1	Tingmisut Lake	WEH 62–55[2] I–730[3]	9,075 ± 275	71.5 m	surface material	marine shells (Hiatella Arctica Linné)[4]	W. E. S. Henoch
2	Tingmisut Lake	WEH 62–105 I(GSC)–21[5]	8,275 ± 320	53.5 m	surface material	marine shells (Hiatella Arctica)	E. T. Tozer
3	Ross Point	WEH 62–8P I–841	7,565 ± 235	22 m	surface material	marine shells	W. E. S. Henoch
4	McCormick Inlet	WEH 62–28P I–840	1,740 ± 190	1.8 m	archaeological site	peat under floor of Dorset dwelling	W. E. S. Henoch
5	McCormick Inlet	WEH 62–3W I(GSC)–148	1,150 ± 160	1.8 m	archaeological site	charred peat from hearth	W. E. S. Henoch
6	Bay north of Wakeham Point	I–842	625 ± 100	1.6 m	raised beach 14m inland from high tide mark	driftwood	W. E. S. Henoch
7	Nelson Griffiths Point	I(GSC)–154	34,050 + 2650 − 1990	60 m	surface material	marine shells	W. E. S. Henoch

[1]Elevation above high tide mark.

[2]Geographical Branch sample number.

[3]I, Isotopes Incorporated laboratory.

[4]GSC Report P1–9–63 F.J.E.W.

[5]GSC Geological Survey of Canada radiocarbon laboratory.

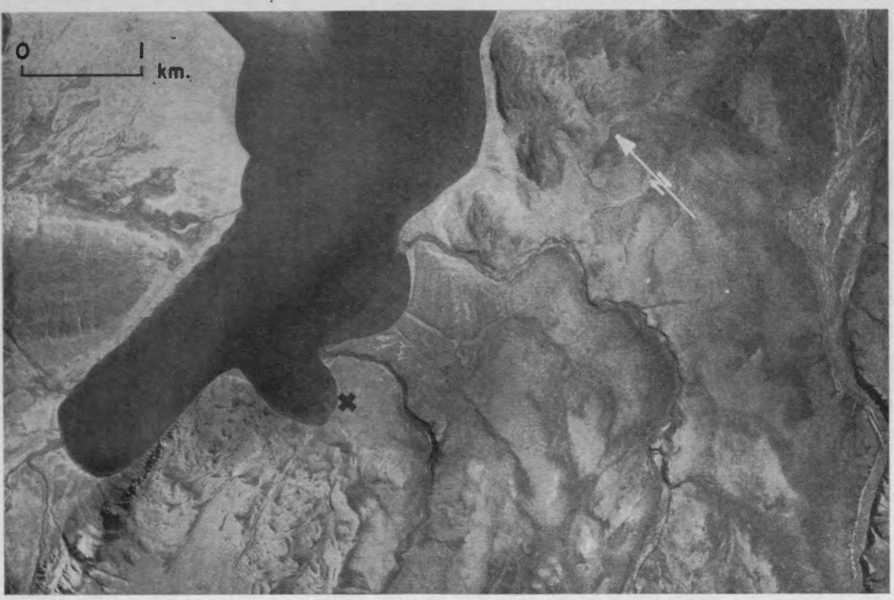

FIGURE 7. The cross marks the Dorset prehistoric site, at McCormick Inlet, on the west shore of Hecla and Griper Bay. Photo: RCAF vertical A–17721–125.

Sample 6: unnamed bay north of Wakeham Point—I–842

The piece of driftwood mentioned on page 113 was discovered on the shore of the bay between Cape Halse and Wakeham Point some 8 kilometers northeast of Winter Harbour. Its height above high watermark (1.6 meters) represents the maximum amount of uplift that could have occurred since its deposition. The age of the sample—625 ± 100 years, including the time during which it was drifting from its point of origin—does not absolutely sustain the conclusions drawn from Samples 4 and 5, but it does constitute important corroborative evidence for the thesis that uplift over the past thousand years or more has been slight.

Sample 7: Nelson Griffiths Point—I(GSC)–154

This sample consists of shells collected from the surface of a storm beach at 60 meters above high watermark on the extreme southeast point of the island. As the shells lie in the altitudinal range between Samples 1 and 2, they were dated in the expectation that they would provide further information on the early postglacial phases of land uplift. Since the radiocarbon analysis gave a very great age, the result could not be used in the intended manner but served to show something of the complicated nature of the glacial history of Melville Island. It is significant that the shells are of a "pre-classical" Wisconsin age and that they were found in beach deposits rather than in till or other obviously glacial material. Their occurrence could mean that the upper beaches in the area date from this earlier period. It seems more likely, however, that all the beaches are postglacial in age but include reworked shells that could have been derived from one of two sources: (1) glacially transported materials pushed up from lower levels or (2) old beach deposits more or less *in situ*, that were slightly modified by glacial action and subsequently reworked into postglacial beaches. This sample adds further to the list of pre-classical Wisconsin materials that are being found in increasing abundance throughout the Canadian Arctic (Christie, 1962; Craig and Fyles, 1960; Dyck and Fyles, 1963; Ives, 1963; Sim, 1961).

POSTGLACIAL EMERGENCE

The problems of interpretation of radiocarbon dates based upon marine molluscs have been indicated by Olsson and Blake (1962). These problems, inherent in the present discussion, are further aggravated by the small number of datings available and the wide dispersion of their localities.

In plotting the five main points and drawing a tentative curve through them (Figure 6) full allowance must be made for the limitations of both the method and the data. It has already been shown that among the various localities on the island wide differences exist in the maximum amount of marine submergence. Thus the island's response to isostatic recovery was almost certainly not uniform, the lack of uniformity resulting presumably from marked regional differences in the thickness and duration of the ice masses. Despite these limitations the age-versus-height plot has been constructed as a graphical method of comparing the radiocarbon data. Because of the limitations, however, no allowance is made for eustatic changes in sea level. Provided the results are treated with discretion, the data in Figure 6 should be of value to an understanding of the late-glacial and postglacial history of the coastlines of an important part of the western Queen Elizabeth Islands.

To the five main points through which the curve is drawn, a point representing the burnt moss at McCormick Inlet is added for completeness. The greatest weakness in the curve is the lack of data between points 4 and 3—that is, between 1,700 and 7,500 years. This gap is particularly critical because the lower points that indicate the most recent dates are based on terrestrial material while the three upper points are based on marine molluscs, which could have been deposited at various depths beneath their contemporaneous sea levels. Since the curve represents the sea level of the time, it must therefore pass beneath the lower points but above or to the left of the three upper points. This means that a fairly wide variety of curves could be drawn through the five points. It is apparent, however, that any such curve would be encouragingly similar to curves drawn for other localities (Blake, 1961b; Farrand, 1962; Ives, 1964; Lee, 1960, 1962; Olsson and Blake, 1961–62; Washburn and Stuiver, 1962). Important differences between uplift curves can be detected, but the shapes are generally much alike. The similarity indicates that, as in other areas of northern Canada, initial uplift was very rapid and was followed by a rapid deceleration that varied in time from one locality to another. The last few thousand years show relatively slight uplift, especially on Melville Island. A number of problems immediately emerge from a consideration of the uplift curve.

First, the age of 9,000 years established for the highest sample implies that this section of Melville Island has been free from glacier ice for about that time. Fyles (personal communications, 1963) has pointed out that this age is later than those related to the southeasterly withdrawal of the northern margin of the last inland ice sheet on Victoria Island and does not coincide with the general pattern of deglaciation. Fyles (personal communication, 1964) indicates that the classical Wisconsin ice margin must have withdrawn from the southern shore of Viscount Melville Sound more than 12,400 years ago. This discrepancy of some 3,000 years can be explained by assuming either that higher and older molluscs yet remain to be discovered on Melville Island or that the island was at least partly submerged beneath an ice cap covering several of the Queen Elizabeth Islands for some 3,000 years after the opening of the south shore of Viscount Melville Sound.

It is also possible that the marine transgression that left molluscs on northern Melville Island about 9,000 years ago resulted from land depression caused by an ice sheet that advanced on Melville Island from a centre located somewhere in the east of the Queen Elizabeth Islands.

A second problem is the uncertainty about the extent and type of the "classical" Wisconsin glaciers of Melville Island. As isostatic depression to the extent of 72 meters is significant and as isostatic recovery would begin before the opening of the coastline to marine transgression, the actual maximum of such depression, although unknown, is certainly greater than that recorded. This raises the question whether purely local ice would be adequate to make the depression so extensive, or whether massive inundation by the continental ice sheet from the south must be considered. This problem pertains to the whole of the Queen Elizabeth Islands.

One positive conclusion is that uplift over the past 2,000 years has been negligible; this implies that Melville Island is very close to isostatic equilibrium. Important corroborative evidence has been provided by Dr. George Jacobsen of the Tower Construction Company, Montreal. In a preliminary attempt to analyze the temperature gradient recorded from a thermistor installation sunk to a depth of 650 meters at Winter Harbour, difficulty was encountered in correcting the ensuing curve for the effect of sea water that was assumed to have covered the site of the drill hole (Figure 1) until a relatively recent time. The drill hole is 20 meters above high tide mark. That such an effect was not noticeable on the curve seems to support the conclusion recorded here, that the site itself has been above sea level for several thousand years, at least long enough to permit the establishment of a degree of thermal equilibrium.

The flatness of the left-hand side of the uplift curve, which implies negligible positive relative movement of the land with respect to sea level over the past 2,000 to 4,000 years, makes an interesting contrast with results obtained elsewhere in northern Canada by Lee (1960, 1962) and Ives (1964). Lee and Ives provide evidence, for Hudson Bay and Foxe Basin respectively, that appreciable uplift is occurring today. These two areas and Melville Island must be considered in relation to the data available on the extent and thickness of the Wisconsin ice sheet and the history of its dissipation. Since both Foxe Baxin and Hudson Bay seem to have been glaciated early in the Pleistocene and covered by very thick ice, and then deglaciated in relatively recent times, incomplete isostatic adjustment is to be expected. Melville Island, however, probably lay on the northern fringe of the main continental ice sheet and, apart from the complication of a local ice sheet, which may have existed to within 10,000 years ago, was free of ice relatively early. The Melville Island data compare closely with results obtained from Spitsbergen and commented on by Blake (1961a, page 109) as follows: "If a slow isostatic uplift of the land is occurring, it is certainly balanced by the present eustatic rise of sea level."

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