I. 4. OBSERVATIONS ON THE TIME FACTOR IN INTERACTIONS OF PERMAFROST AND VEGETATION

R. E. Beschel

INTRODUCTION

During three summers in the Arctic mainly devoted to studies of plant growth in glacier forelands, the author made incidental observations concerning the relation of vegetation and frozen ground.

Numerous relations of plants and frozen ground phenomena have been summarized by Benninghoff (3). Many problems have still to be solved to understand vegetation patterns in periglacial regions of which areas with permafrost form the main part (19) and to clarify the importance of frost action as an environmental factor. Likewise, the surface structures resulting from cryopedological processes can not be adequately interpreted unless vegetation is considered as an essential modifier. The actual time of the formation of periglacial vegetation and surface patterns is only known in rare instances. Radiocarbon dating gives the best results for longer time periods. The possibilities to date changes of shorter duration will be discussed here based on personal observations.

CLOSE-UP PHOTOGRAPHS

For any future determination of changes in vegetation and surface patterns the importance of photographic documentation is self-evident. Nevertheless, most photographs are taken without adequate indications of the location and the relocation of the exact place, not necessarily by the same observer, becomes very time consuming or impossible. Vertical photographs offer better chances of measuring changes accurately but the relocation is especially difficult. If one does not have time for accurate surveying or the placing of permanent, conspicuous markers, future work is aided by combining vertical photographs with pictures of the landscape in one or more directions from the same spot. The intersection of various ridges or hills on the horizon permits a rapid orientation during a revisit. A matching of the landscape in intermediate distances finally brings the observer back to the identical place.

The second major disadvantage at present concerns the availability of photographs. Only a fraction of photographs will ever be published and their exact location is rarely given. The bulk of photographs remains scattered with the persons who have taken them. It would be in the greatest interest of geomorphologists and plant ecologists to assemble archives containing close-up photographs arranged on the basis of geographical co-ordinates. Government agencies conducting or supporting research in periglacial regions could further stipulate that prints or negatives of relevant photographs be deposited in such archives. The availability of copies for field work, especially from the vicinity of settlements and weather stations in the Arctic, would aid all studies of surface and vegetation changes greatly.

The present difficulty of finding old photographs is reflected in the rareness with which such documented changes are reported. Mattick (9) repeated in 1951 a photograph of 1938 of an elongated sorted stone ring in the vicinity of Ny-Ålesund, Spitsbergen. The structure was first thought to be active as the plant cover succeeded from the bare centre through an incompletely colonized zone of crustose earth lichens on the fines into a ring of fruticose lichens (Cetraria delisei, Stereocaulon arcticum) on the inner edge of the raised stone ring with scattered cushion plants between, and small crustose lichens on the stones. The repetition showed, however, stability of all but very few stones on the margin as well as in the centre and barely visible changes in the plant cover restricted to very few places. Mattick concluded that patterned ground in this area had formed quite rapidly in the past while colonization of the stabilized ground proceeds very slowly. Continued frost heaving in the centre of the stone ring may have hindered plant growth although further sorting did not occur.

In 1961 Anker Weidick and the author had the opportunity of taking photographs from the same locations as Steenstrup (17) had done in 1898 on the western slope of Blaesedalen in the vicinity of the three southeastern outlet glaciers of the Lyngmarksbrae on Disko Island, West Greenland (69° 18' N, 53° 30' W). Two of these photograph pairs are shown in Figures 1-4. (Copies of the old photographs were kindly provided by the Greenland Geological Survey.) The photographs were taken on 2°-10° eastward inclined basalt plateaux above the shoulder of the valley at 450 metres above sea level. The depth to frozen ground varied from 30 to 60 centimetres on July 19, 1961. Between basalt boulders of 10 to 100 cm diameter and scattered gneissic erratics the ground consists of unsorted, sandy silt. The substrata is a mixture of predominantly local ground moraine and basalt bedrock weathered in situ. Patterned ground is weakly developed in the form of scattered sorted stripes. Amorphous solifluction is not represented by lobes or terraces but could be active as a gradual creep. The plant cover consists of an open Cassiope tetragona - Salix glauca - Cetraria nivalis heath. Lichens cover only about 20% of the surfaces on boulders. The vegetation could indicate instability, especially when contrasted with the nearly complete cover on basalt ledges in the vicinity,or on the moraine, at least 1500 years old, in the middle distance of Figures 3 and 4. Changes related to the shrinkage of the glaciers are obvious. The second glacier (Figs. 1 and 2) retreated about 1 kilometre and the third glacier (Figs. 3 and 4) nearly 2 kilometres in the past 63 years. A lateral moraine of the third glacier (Figs. 3 and 4-right hand side), formed around 1850, and has decreased 3 to 5 metres in height in the last 63 years as its ice core melted. The slumping is still continuing. The flank of the old moraine outside, however, still has boulders in identical positions. Even more surprising is the stability of the terrain in the foreground during the time interval. Most stones are still in the same places. Cracks in frost-shattered stones (Figs. 1 and 2-foreground) have not widened measurably. The same Umbilicaria thalli grow on the boulders with either no measurable growth or increases up to 2.5 centimetres in diameter. In addition only a few Umbilicaria thalli less than 2.5 centimetres in size became visible and some have vanished. The vascular plant cover has altered to a higher degree. Cassiope cushions have grown anew or have expanded greatly while many willows have disappeared, but the same percentage of cover remained open. Another photograph pair with a 10°-20° south facing slope in the foreground showed, however, movement of some big boulders by several metres and the smaller stones of the foreground could not be relocated.

HISTORICALLY DATED SUBSTRATES

When the position of retreating ice margins in the past is known or inferred from other evidence, the maximum time available for the formation of surface features in a glacier foreland can be ascertained. Between slumping moraines and shifting meltwater channels lie areas in which patterned ground appears to be forming particularly rapidly (20, 9). On the other hand shrinking perennial snow patches may only re-expose patterns formed long ago. Ice and snow cover have remarkably little influence on the underlying ground in the high Arctic. The advancing Crusoe Glacier on Axel Heiberg Island, N.W.T. (79° 22' N, 90° 50' W) has eroded mainly lateral meltwater channels while sod lies still undisturbed under the base of the 15 metre high lateral ice cliff. Retreating glacierets on Axel Heiberg Island expose occasionally undisturbed plant cushions at their margins (5). Under such conditions surface forms may also persist unchanged. J. D. Ives and G. Falconer of the Geographical Branch, Department of Mines and Technical Surveys, Ottawa, have observed ice-wedge polygons emerging under wasting ice masses in central Baffin Island (personal communication). Caution is therefore necessary to separate new surface forms from old ones.

Older patterns may also persist during continued sedimentation.

The formation of ice wedges at a depth of 30 metres is not necessarily related in time with the formation of permafrost as Shvetsov (14) and Taber (16) inferred. Trapping of windblown dust by open tundra vegetation may raise the soil level as well as the top of an ice wedge. Sedimentation in alluvial fans could work in a similar manner. The deposition of silt from weathering shale during snow melt and during the superficial thaw of permafrost is building a flat cone into the Colour Lake at the Base Camp of the Jacobsen - McGill Expedition on Axel Heiberg Island (79° 25'N, 90° 30'W). This alluvial fan and others in the vicinity are nevertheless patterned by large ice-wedge polygons which persist despite the sedimentation. Popov (12) gives clear evidence for this continued growth. He even claims that ice wedges increase only in conjunction with sedimentation and that they cease growing when silt and peat deposition stop on the polygons.

After disturbances, changes can be very rapid in periglacial regions. Williams observed extensive sorting and the origin of stony earth circles within one year after dwarf shrubs were removed in Rondane, Norway (22). Thermokarst often results from disturbances of the vegetation cover in areas with ground ice within a few years. Five kilometres northeast of the weather station at Eureka, N.W.T. an airstrip was constructed in 1947 by scraping the surface of a clayey silt plain at 125 metres above sea level. In 1951 this strip was abandoned. Sim mentions unfavourable cross winds for the landing and take-off of aircrafts as a reason (16). The extensive melting of ice wedges was related by station personnel to the author as another factor. This old airstrip (Fig. 5) stood out strikingly in 1960 by its much denser vegetation cover (5). P. F. Bruggemann observed this in 1953 (personal communication). There is no difference in level between the old airstrip and the surrounding area. The border has in parts a low ridge 30 centimetres high and a few metres wide which is very likely the material scraped from the runway. Ice wedges in the airstrip have melted and the polygons 20 to 30 metres in diameter are often separated by ditches 2 to 3 metres wide and 1 to 2 metres deep in contrast to the furrows outside the runway which are depressed only 20 centimetres. The new ditches possess already a well developed vegetation cover consisting mostly of Carex stans, Eriophorum scheuchzeri, Deschampsia brevifolia, and Equisetum arvense, while the only common species in the shallow furrows outside of the airstrip is Deschampsia. Colonization of a different habitat by additional species is to be expected, but the increase in plant cover on the flat polygons is surprising. Puccinellia angustata, Festuca brachyphylla, Alopecurus alpinus, Deschampsia brevifolia, and Salix arctica are much more vigorously developed on the airstrip and cover 30 to 40 per cent of the ground in sharp contrast to a scarce growth of the same dominant species covering only 5 to 10 per cent of the area outside the airstrip. Benninghoff mentions a rapid growth of cultivated plants the first year after ground above permafrost has been stripped of its original vegetation and relates it to a better water supply when the frozen ground thaws to greater depth. In later years, however, the productivity decreases (3). At Eureka the same relationship should prevail. The unexpected continuing rapid growth may be caused by the removal of accumulated salt in the top layers of the soil by scraping. Under the very arid conditions of this area salt crusts are common on bare soil and may be more disadvantageous to plant growth than the low precipitation. Water supply from melting snow and the thawing surfaces lasts over a month to keep the Eureka airstrip soft (16). Continuing thaw under the drying and hardening surface provides moisture to the deeper rooted plants for most of the growth season. Delayed thawing caused by a denser vegetation cover reduces the run-off and distributes the water supply over a longer period. The denser vegetation may also retain more snow. Whatever the interaction of the various factors may be, the old airstrip at Eureka demonstrates that minor initial changes may produce substantial alterations in a few years where permafrost and vegetation interact.

Evidence from historical information is rare and has to be supplemented with other time indications in many cases.

DENDROCHRONOLOGY

The number of whorls in spruces above the tilt in the stem resulting from caving in over thawing permafrost on lake margins permitted Wallace to estimate the recession rate of the shores (21). Palmer and Miller used the number of terminal bud scars on branches of dwarf willows to date the most recent colonization in front of a retreating glacier in the Alps (11). This method helps only to determine time spans up to 30 years because the scars become obliterated through the development of bark. In Salix arctica Beschel and Webb found further that branches are usually shed after a few decades and only the central burl, the half buried main stem of the shrub, reaches an age up to a century (6). The annual growth rings are thus age indicators for a longer time, although the rings are often discontinuous which makes counting difficult. Raup was able to use the age of dwarf willows to determine the rate of formation and regeneration of turf hummocks in Northeast Greenland (13). Growth ring studies of arctic dwarf shrubs are still very rare but give very useful results for time periods up to a century. The inferred stability of the substrate applies only for these sections of patterned or moving ground where the plants are rooted. Stability may differ greatly over a few centimetres.

LICHENOMETRY

Reindeer lichens (Cladonia subgen. Cladina) branch once a year at their tips (1, 2). The number of dichotomies from tip to base of the fruticose thallus equals the age of the living parts. Because of slow decay at the base, it is not possible to determine the total age of the plant. For a number of decades, up to a century, Cladinae can be used for dating. As the reindeer lichens establish themselves, in most cases only after a humus- or peat layer has developed, the relative stability of the substrate must have lasted for a multiple of the time these lichens are able to indicate.

Annual growth rhythms are unfortunately not expressed as distinct structures in other lichens. The diameter of circular thalli or of cushions is roughly proportional to their age (4). The rate of growth varies greatly with the climate and optimum growth rates have to be determined with the aid of otherwise dated substrates first. Growth rates differ greatly between various common species. The relationships of the largest measured diameters of different species give a multiple check of the estimated age of an undisturbed substrate within the life span of lichens and cushion plants. One of the slowest growing plants is Rhizocarpon tinei, a crust lichen of almost ubiquitous distribution in polar and alpine regions. Its optimum increase in diameter per century varies from 10 to 20 millimetres in many of the visited areas in the Arctic, with extremes of 4 to 90 millimetres in the driest parts of the Søndre Strømfjord, West Greenland, and very oceanic parts of the Alps respectively. On ground which was just at the ice margin on the first and second Lyngmarksbrae in 1898, the maximum diameters of R. tinei measured in 1961 were 8.5 millimetres. In places where less slumping occurred, the adjacent marginal moraines bear thalli of this lichen with maximum diameters of 11 millimetres. These moraines could have been colonized since about 1890. An indistinct moraine arc lies within the position of the ice margin mapped in 1912 by Mercanton (10) which bears R. tinei thalli dating back to about 1920 and having maximum diameters of 6 millimetres. Using these zones as a base and dividing the maximum diameters of common plants by the years available for colonization, the average annual diameter increments of the most rapidly developing plants can be obtained (Table I, column 1). Dividing the largest diameters of these plants in or near these glacier forelands (column 2) by the annual increments gives an approximate age of these plants until no further increase in diameter occurs (column 3). Fluctuations in the growth rates are not considered in this example. The selected plants established themselves only a few years after the ground became ice-free. These data serve only to give an idea of the range within which plant diameters can be used for dating. The growth rates vary considerably in different

TABLE I

Growth of common plants in the forelands of the first and second outlet glacier of the Lyngmarksbrae, Disko Island

Species	Average annual diameter increase of optimally developed plants in mm	Diameter of largest plants in and near the forelands in cm	Possible maximum duration of diameter increase in years
On soil			
Salix glauca	45.5	320	70
Saxifraga tricuspidata	6.7	65	97
Silene acaulis	7.1	40	56
Stereocaulon alpinum	3.4	26	75
Peltigera rufescens	15.8	33	21
On boulders			
Physcia caesia	1.0	7.0	70
Xanthoria elegans	0.75	8.2	110
Placodium melanophthalmum	0.26	2.6	100
Umbilicaria virginis	0.82	11.4	140
Umbilicaria hyperborea	0.44	6.5	150
Umbilicaria proboscidea	0.50	5.2	105
Alectoria pubescens	0.56	15.5	275
Aspicilia cf. arctica	0.30	15.3	510
Lecidea cf. lapicida	0.35	33.0	940
Rhizocarpon tinei	0.15	21.7	1550

climates and remain only roughly proportionate among themselves. The observed maximum diameters fluctuate also. Under more adverse microclimatic conditions, growth may be very much slower. Many of these plants may also retain a constant final diameter for a long time because of inherent characteristics or if they are in competition with other plants. The age estimates are thus conservative, but nothing can be said about the duration of persistence with unchanged size. Stone surfaces, completely covered with slow growing crust lichens and diameters of individual thalli of several centimetres, indicate stability of the surface for at least many centuries. More extensive nivation in the last centuries has killed this old cover in local depressions as remnants of large lichen thalli often indicate. Even then, these lichen corpses denote a stable position of the boulders. Limestones, dolomites, shales, soft sandstones, and soft schists do not possess an old lichen cover because of their fast weathering. Lichen crusts on bare soil seem to be fast growing and have not been used for dating thus far. Lichenometry is useful in interpreting the rate of surface changes if hard rocks are present. The time interval for which the method can be applied exceeds dendrochronology in the arctic by an order of magnitude. The accuracy is lower, however, especially when dating of areas below 100 metres square is desired.

SUCCESSION AND TOTAL PLANT COVER

A rough indication of the activity of patterned ground and solifluction is generally gained from the degree of plant cover on soil. Successions for the formation of non-sorted patterns are interpreted only with very crude time estimates (8). Zoned vegetation on many types of patterned ground or on solifluction lobes simulates successions. This is not necessarily the case because the various zones are also influenced by different microclimates, different length of snow cover, great differences in soil structure and water supply, besides the commonly assumed differences in stability of the surfaces. Other factors contribute at least to accentuate a pattern related to frost action. Vegetation may in turn preserve the patterns and even be responsible for their origin. Freezing and thawing cycles progress at rates which vary with the type and amount of vegetation cover. These differences produce instability and maintain it in turf hummocks and tussock rings. Patterns, whose development extends over decades to centuries, may change at a fairly constant rate which preserve the overall pattern for millennia without the development of vegetation to a complete and homogeneous cover as Sigafoos has shown (15). Trends towards uniformity cannot be used to give a time estimate because frost action may cause the plant cover to become more diversified.

Ice-wedge polygons on the higher parts of the flood plain of the Expedition River on Axel Heiberg Island vary in diameter from 10 to 30 metres. The separating furrows are shallow trenches between the raised edges of the polygons, which are about 20 centimetres high. A few points have been raised up to 60 centimetres above the centres of the polygons. The base of these hills consists of fine silt. Their bulk is made of raw humus, a dense tangle of rhizomes, roots, and partly decayed mosses. The hills have become perches for long-tailed jaegers and snowy owls as regurgitated pellets and bird manure indicate. Excess fertilization permitted a better development of plants. The dead plant parts and the raw humus act as an excellent insulator of the frozen ground after the outer few centimetres have thawed. The permafrost table rose in the hummock preserving its shape. The birds became more attracted by the hummocks rising highest which permitted still better growth on these.

A part of the polygons mentioned above has been undercut by the outbreak of ice-dammed lakes (5). Although the most recent disturbances caused splitting and collapsing of polygons on the shore of the river, earlier erosion resulted in a differential melting of ground ice and ice wedges. The bulk of each polygon has maintained its height because a dry carpet of moss peat on the surface permits only a seasonal thaw to 20 centimetres in contrast to the ground in inorganic or wet organic soil which thaws usually to 70 centimetres in the vicinity. Instead of shallow furrows the polygons are separated, however, by gullies up to 5 metres wide and 4 metres deep with flat bottoms. The gullies decrease gradually in size away from the river and continue into the normal shallow furrows about 100 metres from the shore. In contrast to the sparse and xeric vegetation on top of the marginal polygons the gullies possess dense mats of sedges and mosses. The presence of ice wedges together with the insulating effect of the dry moss layer could produce these intense relief forms. Slumping continues on the edges of the polygons but the presence of organic layers below the surface maintains the steep sided walls of the gullies. Organic matter at depths of 130 to 140 centimetres gave a radiocarbon date of 2900 ± 120 years (7). Sedimentation must have continued many centuries until the gullying began. The erosion probably proceeded rapidly at first and has now approached an equilibrium. The erosion may have lasted for centuries but the rapid colonization as shown in the ditches of the old airstrip at Eureka makes it rather futile to look for evidences of the lapsed time period in the stage of succession.

SUMMARY

In the complicated interaction of vegetation and frozen ground phenomena the time scale of changes is rarely known. Surface forms may change rapidly within a few years or may persist practically unchanged for many centuries. Repetition of photographs will provide the best evidence in the future. Frequently, vegetation provides useful time indications and can be used through dendrochronology or lichenometry for a better understanding of the processes. Rock surfaces are colonized very slowly but the succession on soil is a much less reliable time indicator as great changes in the total cover of plants can occur within a few years, while the same patterns of incomplete cover may last for centuries under the limiting conditions of the arctic environment. Local differences of the environment persist over long periods and the vegetation is not able to change the environment towards more mesic conditions. Contrarily, differences in the environment may be accentuated through the vegetation. Trends towards a climax cannot be observed in regions with permafrost.

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Discussion

T. A. Harwood asked how lichens are used for dating to which the author replied that in a glacial foreland, for example, the diameters of the largest and fastest growing plants are measured. The later and slower growing plants are not considered. The growth rates of different species of established lichens must be related for dating purposes. It is possible then to compare growth rates in different moraine areas.

In replying to a further question by T. A. Harwood asking if any rock glaciers have been excavated, the author stated that none had been excavated and it was possible to say only how long the surface had been stable.

G. H. Johnston requested information on the rate of deposition of sedimentary material on the ice wedge polygons. The author remarked that as much as 4 metres of sediments have been observed overlying ice wedge polygons. C-14 dates gave an age of 4,000 years at a depth of 2 1/2 metres and 2,900 years at a depth of 1 metre indicating a very slow rate of accumulation of material. T. A. Harwood commented that the dating of areas can be facilitated with the use of aerial photographs. The National Air Photo Library has photographs taken in 1949 on which young polygons are visible. Now, 13 years later, it is possible to examine present photographs and therefore follow the changes in these polygons.

Fig. 1 Blaesedalen, Disko Island, West Greenland; 2nd outlet glacier of Lyngmarksbrae seen from south; August 1898.

Fig. 2 As Fig. 1; July 1961.

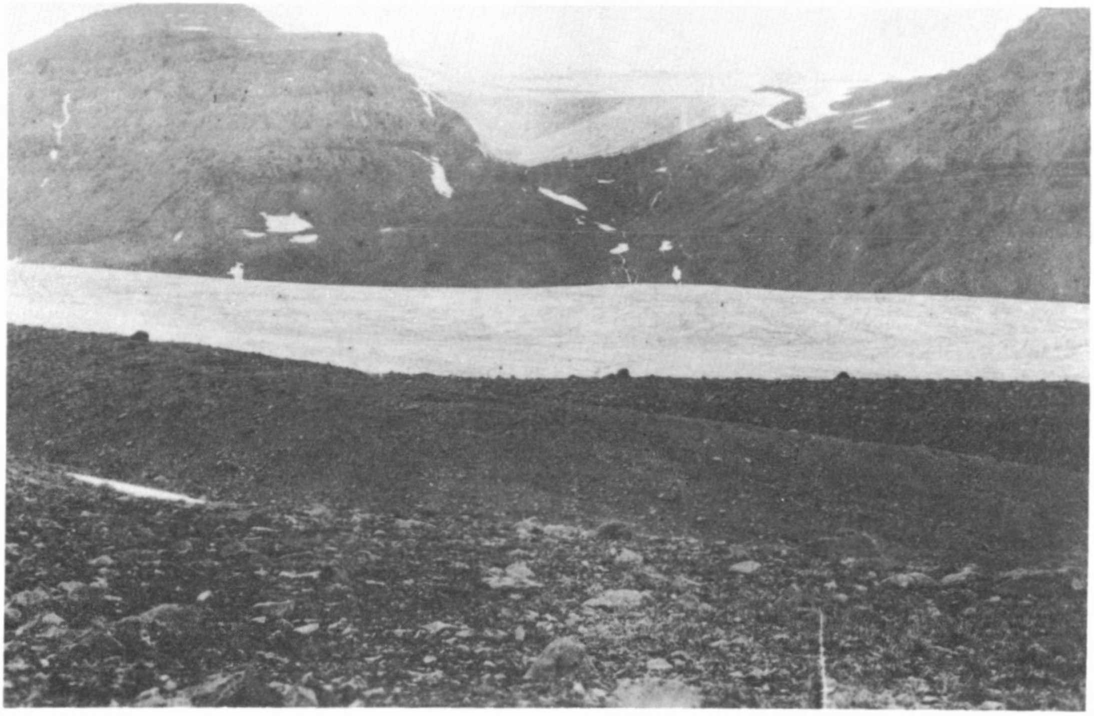

Fig. 3 Blaesedalen, Disko Island, West Greenland; 3rd and 4th outlet glaciers of Lyngmarksbrae seen from south; August 1898.

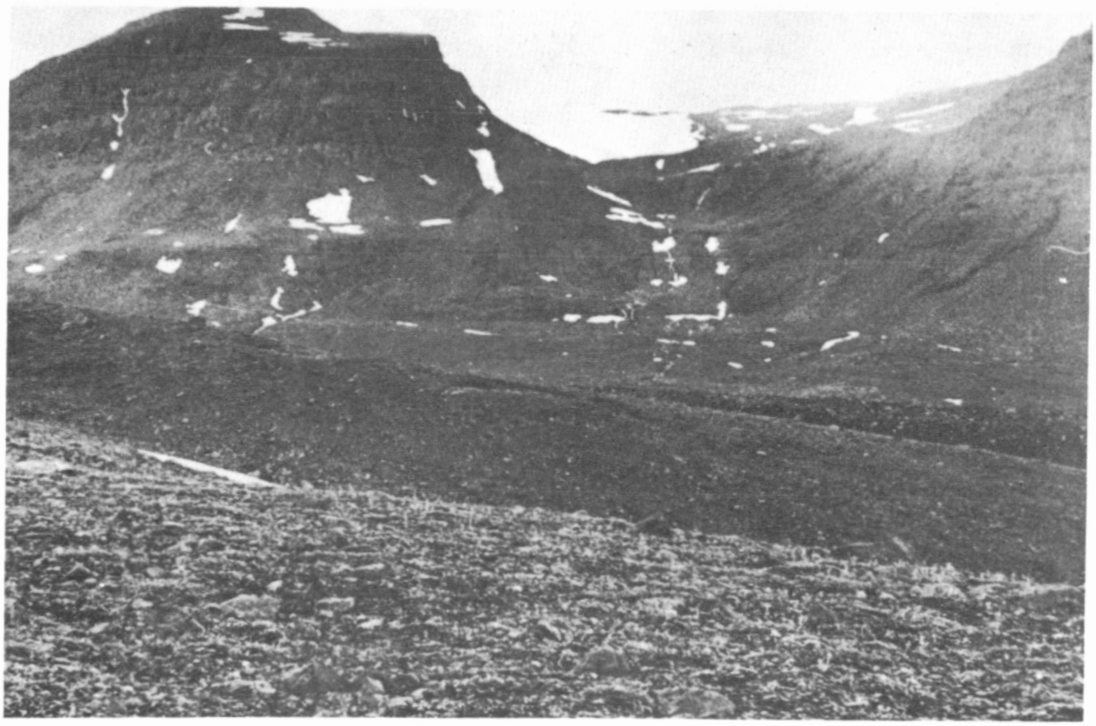

Fig. 4 As Fig. 3; July 1961.

Fig. 5 Eureka, Ellesmere Island, N. W. T.; dense plant cover on the 1951 abandoned airstrip on the left.