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PHYSIOGRAPHIC STUDIES IN NORTH WEST GREENLAND

1. PROCESSES OF DENUDATION
2. ISLAND TOPOGRAPHY
3. THE GEOMORPHOLOGICAL HISTORY OF NORTH WEST GREENLAND
4. A NIVATION THEORY OF CIRQUE FORMATION

BY

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WITH 22 FIGURES IN THE TEXT AND 18 PLATES

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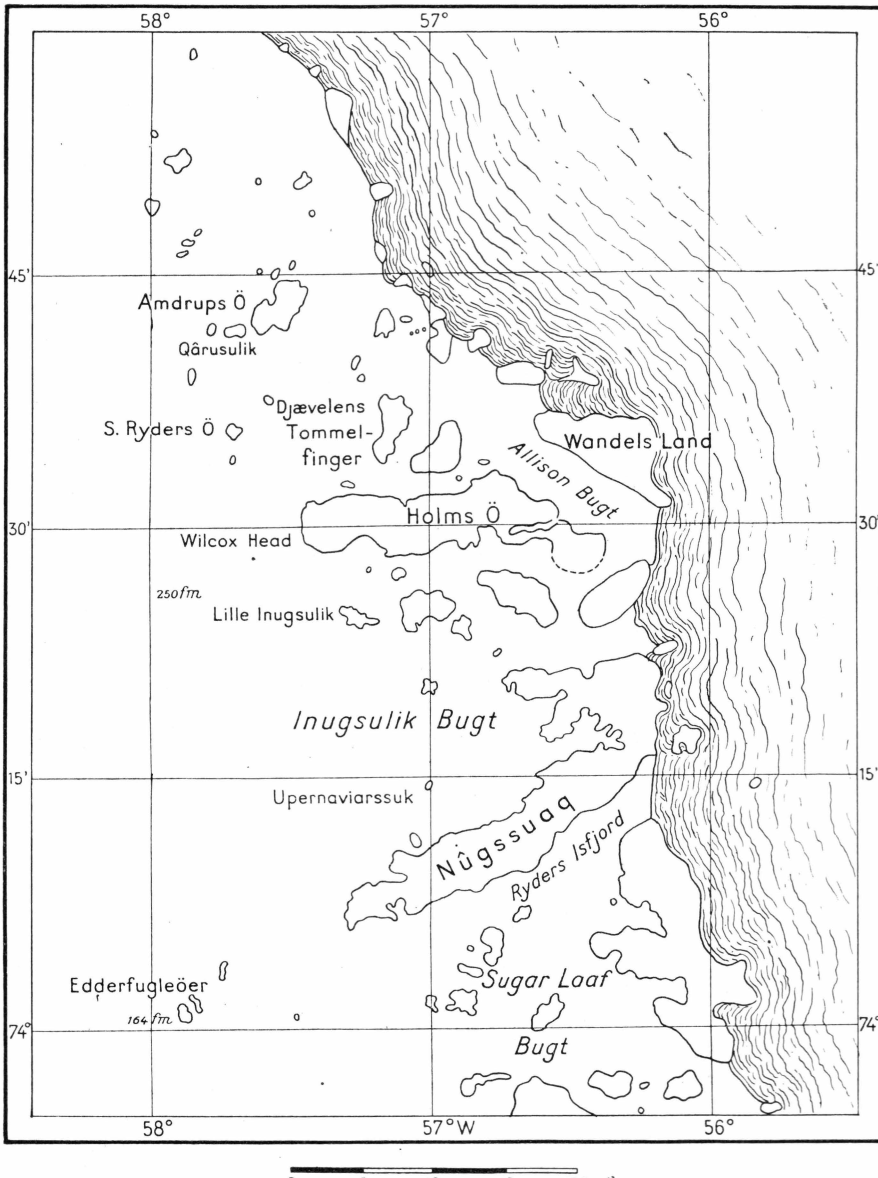

Map of region to be discussed, (after KOCH).

INTRODUCTION

In June 1934 the Wordie Arctic Expedition in the sealing vessel Heimen attempted the passage of Melville Bugt (21 — Bibliography). The ice and wind conditions were adverse, and during enforced halts among the islands of Sugar Loaf Bugt, Inugsulik Bugt and the southern part of Melville Bugt, visits of short duration to several islands became possible. The uncertainty of ice conditions generally precluded any work requiring more than a few hours, and at the longest two days, on Edderfugleøer spent mostly on survey. Intensive study of the phenomena described below was impossible but the material collected, and the experience in interpretation arising therefrom, were found of great value during physiographic surveys in other parts of the arctic on subsequent expeditions. These short studies are presented therefore in the hope that others may benefit in a similar fashion, and that the hypotheses submitted may stimulate research on the ever-fascinating problems of Greenland physiography.

The mechanics of the nivation process are fairly well understood through the experimental researches of Taber but the multifarious effects of ice-crystal growth have not been recognised to the full. Indeed a general statement can be made to the effect that subaerial denudation in the arctic regions depends almost wholly upon the growth and melting of interstitial ice crystals diurnally and annually. This somewhat sweeping generalisation is developed in the first study. It is concluded that the usual criteria for determination of former glacial action, rounded topography, striae, erratics, faceted boulders, and till, cannot always necessarily be accepted as valid, at least in a coastal region.

Dependence of the topography upon structural control and ice-crystal growth and its comparative independence of glacial action is demonstrated in the second and third studies. Undoubtedly the former extension of the Greenland ice sheet has affected major topographical features by scouring action but the most important effect is not visible, the submerged fjord system. The visible effects, U-shaped valleys, rock convexities and high fjord walls are determined in the first place by structural form and subaerial agencies. The steep fjord walls as they now stand were most likely produced by ice-crystal growth, the glacier acting essentially as a transporting agent. The ice sheet probably did not extend its border more than 20 miles farther into Baffins Bugt during the Pleistocene.

The fourth study, a short exposition of the part played by ice-crystal growth in the formation of cirques, is a logical sequent of the hypothesis developed in the first study, that nivation is a process dependent upon ice crystal pressure. Since this hypothesis was first developed my friend and colleague Mr. W. V. Lewis put forward his "melt-water hypothesis" of cirque formation. It is here contended that the most important function of melt-water is as a transporting agency for the debris produced by nivation and as providing part of the rock soaking necessary to ice crystal growth. The characteristic form of the cirque is the result of the cumulative effect of resultants of component capillary pressures determining planes of soaking—the nivation rounding of angular boulders is represented on the largest scale by the arcuate form of the cirque.

In the field I was constantly stimulated by discussion with Mr. J. M. Wordie and Dr. T. G. Longstaff to whose critical faculties I owe much clarification of ideas. Mr. P. D. Baird prepared for me two figures, Edderfugleøer, Fig. 8, and Djævelens Tommelfinger, Fig. 14, the latter figure dependent upon his observations from the top of Tommelfingeren in Dr. Longstaff's company.

I was enabled to take part in the Wordie 1934 Expedition by reason of generous financial help from my college, Trinity College, Cambridge, from Cambridge University, and from Mr. L. C. G. Clarke, to all of whom I am much indebted.

1. PROCESSES OF DENUDATION

Part 1. Description.

A. Nivation.

(i) Spheroidal nivation in the ice-foot zone.

On the western coast of Lille Inugsulik a headland is exposed to the full force of winter storms and here pack ice piles up to great thickness, so that in 1934 in late June, there remained 30 feet (Plate I). Above the ice foot the rock, to a height of another 40 feet, was free from lichen, the lower part of it showing the form of weathering here considered. This clear zone was very heavily iron-stained, probably by decomposition of ferromagnesian minerals, the rock being a garnetiferous biotite schist common along this coast. It was scaling off in thin layers or spalls, varying from $^1/_{16}$ to $^1/_2$ inch in thickness, roughly concavo-convex in section, and cutting across foliation planes at all angles.

The total result was the formation of a hummocky appearance strongly reminiscent of the spheroidal weathering in basalts. The size of these hummocks, which ranged up to two feet in diameter and were very irregular in shape, was affected and determined by barely discernible minor joints. Where jointing and banding was regular the hummocks were markedly uniform, and weathering of this nature, the spalls cutting across banding and foliation in a strongly biotitic schist, is plainly shown in Plate VIII, Middle Edderfugleø. These spalls were smaller than those on Lille Inugsulik, and crumbled more easily, due to the rapid disintegration of the biotite evident under the hand glass. Here too there was much iron staining.

At Lille Inugsulik this form of scaling became less pronounced upwards, and disappeared where lichen was growing. It is presumed that the ice-foot cannot have been much higher than that shown on the photograph (Plate I), and that the clean rock surface must have been covered by the ice-foot snow bank. The depth of this snow bank was greatest in the lower half of the zone for snow tends to pile up so as to smooth off the curve from rock to ice-foot. Thus if a gently sloping beach had a wide ice-foot there could be much snow but not of great height up the rock. Whereas on a steep coast with a large ice-foot snow would reach a great height; as on the south west coast of West Edderfugleø where pressure produces a big ice-foot against a high headland clear of lichen up to 90 feet. That the scaling was on the lower part of zone, the place where the bank was thickest and therefore lasted longest, is of some significance in interpretation of the phenomenon.

Above the limit of the ice-foot snow bank the same rock scaled off along foliation planes, though the individual laminae which peeled off were of dimensions similar to those in the ice-foot zone. This exfoliation was only prominent where the surface of the rock cut the foliation planes at a steep angle, presumably allowing easier action of frost along these planes.

(ii) Mural nivation below snow banks.

Scaling of rock below the ice-foot snow bank can also take place on a much larger scale. In the background of Plate I can be seen large slabs of rock which have broken away from the parent rock along planes parallel to the surface. These slabs were as much as one foot in thickness with irregular concavo-convex faces. The surface on some of them had been affected by spheroidal weathering at the lower levels. Plate II, from the West Edderfugleø on its southern shore, shows this scaling in a coarse gneissic rock, which had scaled off heedless of the foliation and also of the joint system in that the plane of fracture did not follow any one of the joint planes. But the slabs had broken up into smaller pieces along the joint planes, producing irregular blocks like those in the foreground. (The rounded block in the middle background is an erratic, brought there lately by solifluction). In the immediate foreground can be seen the rough and irregular character of the fracture surface unlike a smoother joint plane.

Similar scaling was seen a little south of Edderfugleøer on Uigordlerssuaq, where the rock is garnetiferous muscovite schist and gneiss. Great layers have come off sometimes as much as thirty feet across and one foot thick, parallel to the original surface. This last had been previously smoothed and rounded by glacial erosion, so that a characteristic glacial contour could be seen from a distance even though the original surface had disappeared. There were indeed no remains whatsoever in the nature of striated pavements but erratic blocks remained, some few in situ, (that is, where they were deposited), resting on a few stones supported by a shallow ledge of schist that had not slipped, though cracked and much worn. But weathered surfaces of this kind were common only on rocks where red calcitic weathering was more pronounced and on rocks, such as at Nutârmiut close by, where there was a marked biotitic increase. In adjoining areas a coarsely massive quartzite gneiss showed no mural scaling, erratics remained in situ, and glaciated surfaces had been preserved.

The mural surfaces in the ice-foot zone seldom had erratics on them except, as already noted, brought there by solifluction at a late period. BIRKET-SMITH (3) records this form of weathering,—"sometimes a peculiar form of disintegration occurs within the Precambrian area, viz. an exfoliation of large crusts sometimes only a few millimetres in thickness. This form seems more particularly to belong to rocks polished by a former ice cover". P. D. BAIRD in 1934 noted scaling of this nature on the top of the Djævelens Tommelfinger at 1500 feet. It was also widespread on the top of Wandels Land close to the ice cap, on nearly horizontal surfaces where the rock rang hollow below the boots. As a general observation it seemed that the coarser grained rocks flaked off in the mural form rather than in the spheroidal.

On Amdrups Ø a small bay on the south coast is backed by a shallow valley a third of a mile wide trending north east (see Fig. 2 A). The north side of the valley seems to run along the strike of the rock, and at the foot of the smooth strike surface, a bank of snow had collected (Plate IV). Below this bank stony debris tailed away gently in solifluction. The foot of the exposed rock slope ended abruptly in a very steep wall, about 20 feet in places, against which the bank lay and, where snow had melted, the debris was seen to butt up sharply against the wall. The rock above the snow and where the snow had cleared, had fractured along joints, and also across joints through mural and spheroidal nivation. Those pieces breaking off along joints formed angular boulders, while the smaller pieces appeared to break up still further forming the fine matrix in which the boulders were embedded, and evening out the solifluction surface.

(iii) Differential Nivation: Scaling.

On South Ryders Ø, the following phenomena were observed in a shallow gully, about 15 feet deep and 80 feet above sea level, formed by a snow bank on the south side and a low ridge on the north. The north face of the ridge was covered by a thick layer of black lichen. (Fig. 1 A). This layer extended over the top as far as the beginning of the next slope where an old fox trap had been built. Half of this trap was covered by a thick layer of lichen, the other half, on the south face of the ridge, having a much thinner covering. From this region, to a line about 10 feet lower, the rock was covered only by very scattered lichen leaving the rock grey in comparison with the thick black of the other face. The lowest part of the slope was quite free from lichen, and here much fine mural and spheroidal scaling had taken place, as well as fracturing along joint and foliation planes.

Scaling in a Rock Basin. On the same island, a few hundred yards away, a small shallow rock basin two feet deep in schist was examined (Fig. 1 B, Plate III). It was partly filled by stones derived entirely by disintegration of the rock. Along the margin spheroidal scaling in a manner similar to that in the ice-foot zone was taking place. This occurred all round the basin, and since the scaling was parallel to the surface of the rock, it cannot have been related to the foliation which

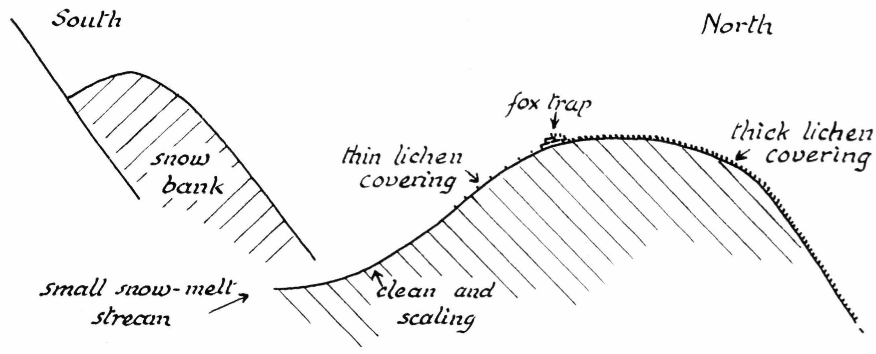

Fig. 1 A. To illustrate differential nivation — scaling in a snow-filled gully.

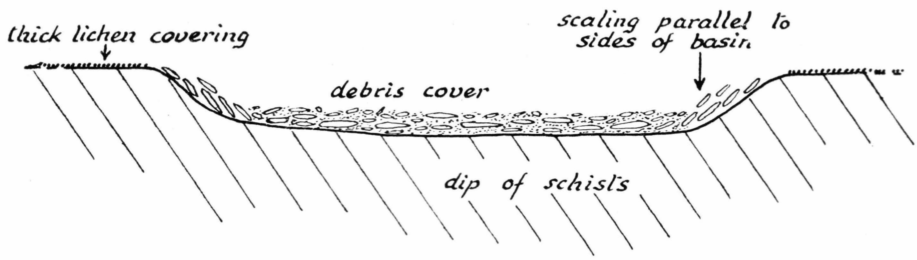

Fig. 1 B. To illustrate differential nivation — scaling in a rock basin.

was inclined at a steep angle to the surface. As well as the finer spalls there were many more massive pieces, probably derived by fracture along joints, though this may be mural scaling on a small scale. The bottom of the basin was free from rock lichen, only mosses being present, and it appeared that snow must lie here for some time.

(iv) Differential Nivation: Boulder Rounding.

Further down the valley from the site of Plate IV on Amdrups Ø the floor steepened and the valley sides converged. The fore-shore was bouldery on the north side and sandy on the south (Fig. 2 A). The boulders, entirely of local origin and cleaned by the action of the sea, were not thoroughly rounded, though in the mass they gave the impression of a storm beach. On the steep slope on the north of the bay, it was seen that the beach was being supplied by boulders pouring down as "streams" up to 50 yards across. (Plate V). Furthermore, these streams could be traced upwards to a cliff face from which angular blocks, breaking along joints, were peeling off and moving towards the shore by this form of solifluction. At high levels mud seemed to be absent but appeared at low levels where muddy ground, carrying the boulders, reached a constant slope of 5°—7° from the horizontal.

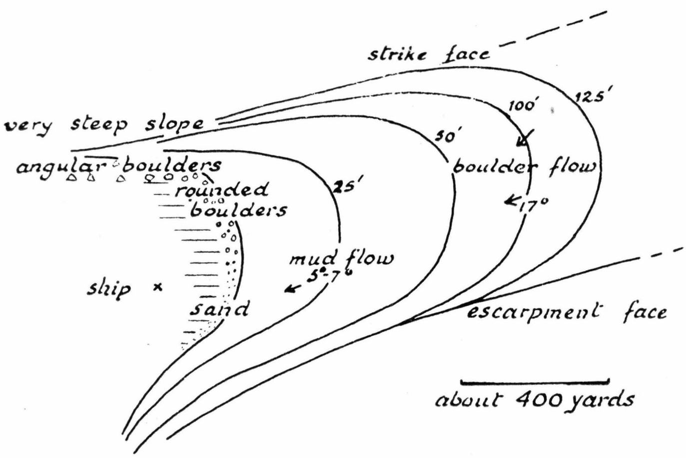

Fig. 2 *A*. Amdrups Ø. Boulder rounding and solifluction.

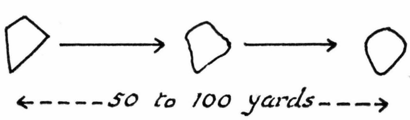

Fig. 2 *B*. Amdrups Ø. Boulder rounding and movement.

These boulders, before they had travelled fifty yards on the steep slopes had, in most cases, lost their angularity, becoming sub-angular, and finally reached a state of rounding equal to that of the boulders on the shore (Fig. 2 B). This change can be seen in Plates V and VI, where the more angular blocks are on the right and the sub-angular on the left. It was observed also that a thick covering of lichen had grown only on the boulders in the lower parts of the slopes, and these boulders were more-rounded than those of the "stone slide" at Wilcox Head, (Plate XI), where there was fast movement with no lichen growth. Where the snow had been lying or was lying in sheltered regions the boulders were more rounded than those free from snow, and had less lichen on them.

On the extreme northern curvature of the beach the ground sloped upwards very abruptly and on this steep slope the boulders were not rounded, with the result that the beach directly below was formed of angular blocks. The sand on the southern part of the beach was sub-angular and very little water worn.

Large areas of sub-angular boulders are found in other parts of the Arctic and one area here in North West Greenland can be seen on the upper slopes of Wilcox Head where, in the presence of mud, polygons are formed (see later section on this formation). When these boulders lie at low level one is liable to refer the rounding to wave action and it is only by tracing the line of flow upwards that their origin can be satisfactorily determined.

Some high level dry valleys in parts of Britain are assumed to be over-flow channels of glacial lakes, the evidence being the presence of rounded boulders. Such boulders may have been rounded in a fashion similar to those on Amdrups Ø, and are then evidence of previous arctic conditions alone.

B. Weathering along Joints.

This is probably the most important denudation process in the arctic, leading to the disruption of whole mountain sides, the establishment of enormous scree slopes and the supply of most of the material in solifluction surfaces. It is active on the very small scale and on the very largest. It supplies finely comminuted debris and blocks many thousands of tons in weight, and it is probable that the greatest part of the erosive, plucking action of glaciers is conditioned by joint features.

(i) Weathering on the small scale.

Throughout the area considered there are several joint systems, and on the Middle Edderfugleø three can be observed, the master joint 15°—20° N. of West, and secondary joints 30° W. of North, and 30° S. of West, which are shown on the small scale in Plate VII, taken when facing the camera roughly N. E. At the bottom and in the top left corner can be seen the remnants of snow covering (at the end of June), and the moisture collecting on the surface of the rock and along the joint cracks. This last situation illustrates how, at a period when the snow melts in spring, and when the temperature oscillates around the freezing point between day and night, the formation of ice crystals in these cracks, owing to the presence of this moisture, will facilitate fracture along joints. At the top of the plate there is a well marked fracture along the east and west joint direction, but scaling is there also apparent cutting across the joint fracture. This scaling is the most extensive of the fracturing processes and occurs along the foliation plane of the schist which, in this case, is parallel to the surface. To the left of the picture the scales are broken up by joint fractures as well and the result is a fairly fine detritus.

On the same island there was a prominent outcrop of garnetiferous biotite schist (Plate VIII) in which these joint features were well marked. The scaling due to spheroidal nivation cut across foliation planes, clearly visible in the foreground of the photograph, and led to rounding of the rhomboidal shapes established by the joints as already described. But weathering has proceeded more rapidly along the dip joints with their consequent deepening, and this has proceeded still further as shown in Plate IX, which is a general view of the outcrop of this biotite schist. The major dip joints have been attacked by nivation under snow banks lying along these joints (one bank is just discernible). It should be noted that the rounding on the small scale, as in Plate VIII, shows itself on the larger scale in this photograph as rounding of the blocks between each major joint. The escarpment to the right was determined by a hinge fracture. On a still larger scale these dip joints determined the topography of the neighbouring West Edderfugleø (Fig. 9).

It is important to determine the relative importance of joint weathering and spheroidal and mural nivation in such situations, for the western Edderfugleøer exhibit rounded contours which may be the result of either glacial action or sub-aerial denudation due to nivation. Moreover the situation is complicated by the fact that mural nivation preserves glacial contours though the surface itself may be removed. A rounded topography does not necessarily indicate glacial erosion therefore unless one has excluded these sub-aerial denudational processes, and in the absence of certainty about the latter the only criteria for determination of glaciation then become:

(a) striae, (provided they are not produced by floating ice),
(b) erratics, (provided they are not brought to the situation by ice floes or solifluction),
(c) faceted boulders, (provided they have not been rounded by nivation), and
(d) till, (provided it has not been dropped by sea ice, or brought into position by a solifluction which mixes up boulders, produced by joint weathering, and fine clay the result of intense fracturing).

(ii) Joint weathering on the large scale.

It has already been seen that much of the material involved in solifluction is derived from scree slopes. The production of scree is intimately connected with jointing as in other climatic regions, but under arctic conditions weathering along joints with the formation of large angular blocks is intensified, and the scree slopes can only be equalled in extent by those in high mountain ranges elsewhere. Plate X shows normal joint weathering on the western face of Sandersons Hope south of Upernavik. The big cleft in which snow still lies has formed along a major joint and is typical of the many gashes that seam the westward-facing escarpments of this region.

C. Solifluction.

Since Andersson (1) first introduced the term the phenomenon has been widely reported from arctic, sub-arctic and highland regions, and is now recognised as a major factor in geomorphological process.

(i) Stone slides.

On the south side of Wilcox Head several miles of magnificent scree slopes were traversed. On the lower parts where some vegetation had had an opportunity to root, the air was filled with the familiar scent of Erica and Cassiope which, with the general rocky character and the warm sun, reminded one of the Scottish Highlands. The likeness was accentuated by the gurgling of innumerable tiny burns of clear, ice-cold water, and only the snow and ice and the white capped mountains were of Greenland. A series of cliff-like faces, several hundred feet high, were determined by major joint faces along which shattering had led to the production of the huge boulders which dominated the screes. The scree slope was divisible into two portions, the very steep composed of freshly broken blocks moving rapidly to the lower and less steep, of about 15° from the horizontal, where movement was slow and vegetation had time to grow. On this latter portion was found the stone river described below (Plate XI).

A 35 foot wide strip of freshly exposed boulders, cut across the lichen-covered stable portion, and the line between was very well marked. The largest blocks were up to 10 feet long and 5 feet thick in the other dimensions, and interstitial material ranged down to pebbles and sandy mud. This slide could be traced up to the steep slope where the movement undoubtedly originated, and the Plate shows that the scree, so moving off the steep slope, over-rode the lower without disturbing it. There were no signs of piling up which would have resulted if the slide had moved the underlying stable material by its own forward momentum. There was no definite evidence to show whether the initial movement was produced by the pressure of freezing water or by mobility induced by the presence of much moisture, but the final turbulent result has all the appearance of being formed in the latter condition. For if the mass had moved as a solid block thrust by ice, the lichen-covered upper surface would have shown, whereas complete reorientation of the individual boulders has taken place. It is most likely that on the upper, steeper slope, owing to greater angular incidence of exposure to the sun, the interstitial ice melted before that on the lesser declivity, whence an immovable surface was presented for the slide to advance over. Later melting allowed the finer material to slip into the crevices in the subjacent layers thus reducing the apparent height of the slide. Further solifluction would lead to incorporation even of the largest boulders until the surface was uniform throughout.

Farther east from this region, much scree had collected on a low flattened divide on the shoulder of Wilcox Head. Here areas of large stone polygons, as much as 15 feet across, had formed, but where the scree fell from the shoulder down a long and steep slope, these polygons were dragged out and obliterated. At the base of the slope the scree levelled out to form a beach, lying about 5° from the horizontal. Mud polygons developed at this level.

A more striking example of soil flow was observed on the East Edderfugleø (Plate XII). From the base of a low hill and below a snow bank about which nivation was active, stretched an area of scree and clay. Blocks and fine detritus from the disintegration of the local schist and gneiss (see foreground) were mixed indiscriminately with boulders foreign to the island. This material was moving slowly seawards with the production of long lines of boulders sloping about 10° from the horizontal. The movement was accelerated by the removal of much substance through the action of the sea and ice-foot (left foreground). The mass was saturated with moisture forming a very plastic mud interstitial to the boulders. During exposure of the plate the soil began to move, beginning at that portion seen cutting the snow bank, and from there it spread upwards involving a long strip of ground. The sides of this channel then began to fall inwards, and would finally fill it up so as to produce a uniform surface. This occurred on the 6th July, a warm day with no frost. This solifluction, therefore, was probably entirely unconnected with ice thrust.

(ii) Stone stripes.

On the same island a similar stretch of soliflual material (Plate XIII) was moving towards and over the late shallow beach in the middle of the island where there was no steep drop to the sea. Here also it commenced in a smooth surface from below a snow bank at the base of a small hill. From above it showed the long streaks of stone stripes similar to those in the arctic described elsewhere, and about which there are many references in the literature. Some of these stone stripes may have been formed by the caving in of the sides of one of the runnels produced by slipping at the terminal end, as described in the paragraphs above. As the stones and mud fell in, the larger stones tended to collect towards the middle on account of their weight, and the muddiest portions were thrust below by rotational shear slip on the small scale. But those stripes commencing near the top of the slope were probably formed through another mechanism to be discussed later. A point of interest is that this whole area is smooth and not dissected by arborescent runlets gradually excavating channels. (Smoothly contoured slopes of this nature on

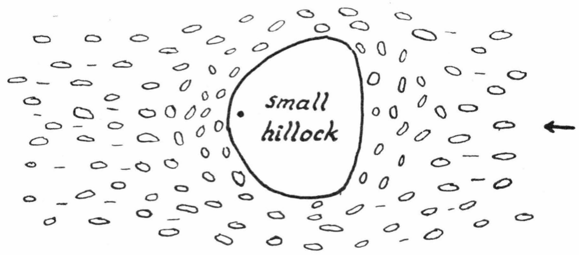

Fig. 3. Amdrups Ø. Illustrating the orientation of constituent blocks when a moving soil meets resistance.

Amdrups Ø (Plate IV), and on Wilcox Head, have been referred to already). This long, gently-sloping ground was moving steadily to beach-level where it remained at an angle of 5°—7°. The ground, composed of boulders and mud, was extremely moist and difficult to walk over, for one sank almost to knee height in this extraordinarily heterogeneous mass. The sharp break at the foot of the rock slope showed the same forms of weathering as on Middle Edderfugleø.

At one point on the right of Plate IV, on Amdrups Ø, where a small hillock of solid rock penetrated the covering of stones and mud, a flow-like arrangment of boulders had come into being (Fig. 3). It can be assumed that the boulders, to arrange themselves in such a fashion, must have been free to adjust individually to the torques produced by downhill motion acting against a fixed resistance.

There were few places where the soliflual areas had reached the stable angle of 5°, and these were all close to sea level where the action of the sea and the ice-foot, and the undermining by nivation, dispersed the lobal fronts which are commonly the result of solifluction movement. The irregularity of outline on the slope in the background of Plate II was most likely produced this way for the slope was so great that proper lobal fronts probably could not form. None of these areas shows a complete cover of vegetation except at Wilcox Head on the south side, and even there the fronts were low and obscure. This lack of vegetation, especially in the more exposed parts, is characteristic of the region exposed as it is to the winds of Melville Bugt and of the ice sheet.

D. Polygonal Structures.

(i) Mud Polygons.

(a) Small. In little rock basins found up to 1000 feet, isolated circular strips of vegetation (moss and sometimes saxifrage), three to four inches wide, enclosed flat areas of mud ranging to two feet in diameter. The mud was very plastic, almost in a liquid state, and in some cases submerged under a layer of water, only the vegetation rims being exposed. The mud, no more than about eight inches deep, carried a very large proportion of sand and pebbles (up to half an inch in diameter) of local rock. There were no larger pebbles in the rims but less clay. Apart from this, no internal arrangement was observed. Where the rock

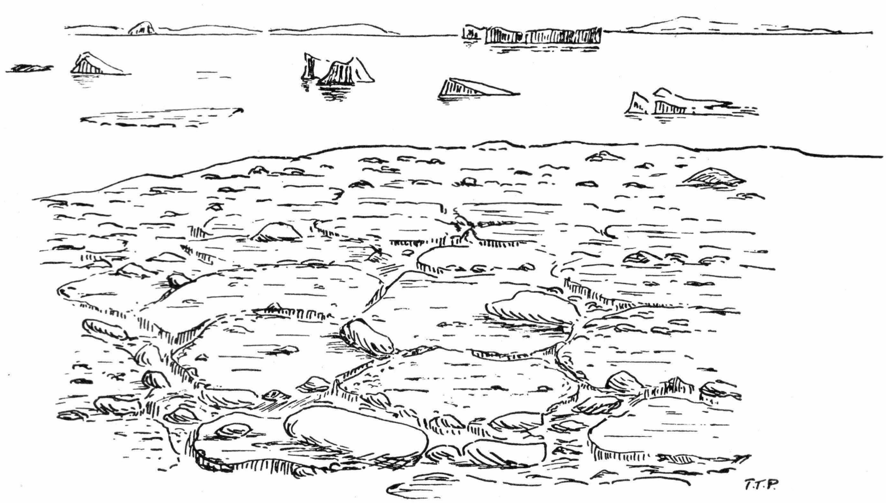

Fig. 4. West Edderfugleø. Polygon pavement in north east of island.

basins had dried up the mud was stiff on the surface and had cracked on drying, into subsidiary polygonal forms, but below, it still retained some moisture.

(b) Large. Large polygons were always associated with big pebbles and even boulders. Fig. 4 shows a terrain on the West Edderfugleø, composed of drift and scree material which had slipped from higher levels and had reached a condition of stability. The polygons, up to ten feet in diameter, were here very irregular in size and shape, and the usually vertically disposed boulders in the peripheries were at times as large as three feet across. The central muddy portion contained boulders also, but much smaller. No excavations were made.

On the flat ground of the small island of Upernaviarssuk, a short way to the south, similar but more regular, polygons were observed. Here the central portions were very stony and completely flat with the vegetation rims raised well above the surface to a height of six inches. The use of the island by eider duck as a nesting place had produced a richer soil and Alopecurus was common in the rims, presenting an aspect closely resembling the ruins of Eskimo houses. Solid rock could be reached at a depth of less than one foot and the central portion showed no arrangement of its stony and sandy constituents.

Large polygons, sometimes fifteen feet in diameter, with up-ended boulders in the rims, were seen on the flat ground of the east shoulder of Wilcox Head. The central material was a stony mud. An area of several thousands of square yards was completely occupied by these polygons in contact forming a continuous network.

(ii) Stone Polygons.

(a) Small. On Lille Inugsulik a small stone polygon was excavated. Fig. 5 shows a plan and section. The materials were wholly angular, sandy grains and pebbles derived from the local rock, with no mud. The structure occurred isolated, in a small rock basin, and the rock was encountered at about nine inches depth. Seventy-five per cent of the surface stones collected at the rim were up to 9 by 4 by 3 inches in size, and were up-ended. Generally these peripheral stones had their long axes aligned roughly perpendicular to the radial direction. There was no hummocking in the centre and all over the rock basin there was a concentration of the heavier stones on top, the bottom consisting of the finest sandy particles. In the polygon which was almost circular, the larger stones grouped at the periphery had, towards the surface, interstitial smaller stones, 1 by 1 by $^1/_2$ inch in size, all vertical. They became smaller with depth, but at the bottom there was still traceable a distinct concentration of elements larger than the adjoining finer sand. The surface breadth of the rim ranged from six to eight inches, the bottom being about two. In the centre, on the top, there was a layer of stones, $^1/_2$ by $^1/_2$ by $^1/_4$ inch in size, reaching to a depth of three inches. At deeper levels the stones became finer until sand was met with, though there was a greater depth of pebbly material in the centre.

(b) Large. Plate XIV shows a circular shingle polygon found on Qârusulik (Blochs Ø). The camera case (seven inches long), just above the centre of the photograph indicates the scale. The thin, platy stones were derived from the underlying schist, the largest piece being about about a foot across; and almost every piece was vertical and tangentially set. The centre, which was composed of a little mud, sustained a thick covering of mosses. These upright peripheral pieces rested almost directly on the underlying rock and the convex mud centre was six

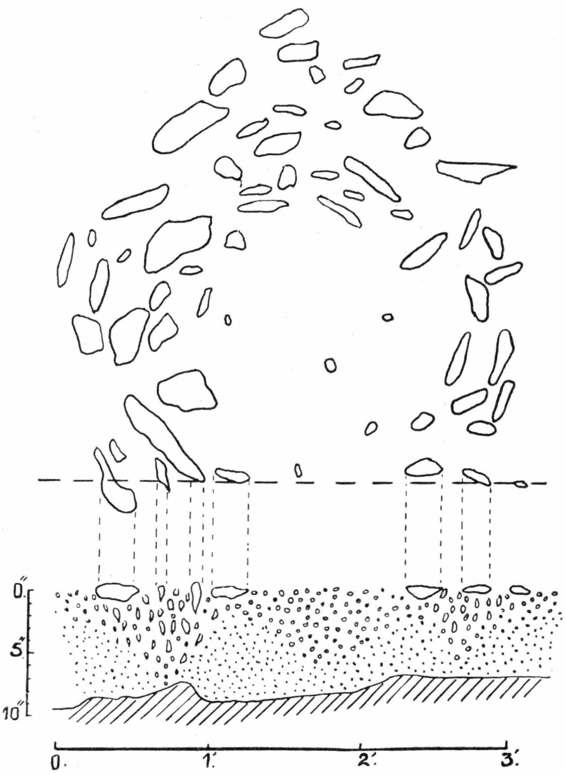

Fig. 5. Lille Inugsulik. Section and plan of stone polygon.

inches thick at the most. To the left of the photograph can be seen more upright pieces, but arranged to no definite plan.

On North Ryders Ø the floor of a gully, formed by erosion along a gabbro dyke, was covered by much angular and weathered debris, and in one portion appeared a remarkable circular formation of boulders (Plate XV). These boulders, measuring as much as two and a half feet, were generally tilted, with one of the longer dimensions vertical or nearly so, forming a closed ring about eight feet in diameter. Mixed with the larger blocks were smaller pieces, also upright. The width of the ring wall varied, in some parts being formed only by two large pieces, in others by several small. There were no large blocks in the enclosed area and the floor of this and the wall were composed of pieces of smaller dimensions, though large blocks appeared all around close to the ring. The impression obtained was of the concentration of larger blocks at the periphery pushed out from the centre. There was no mud in quantity, but a little interstitial gravelly sand and mud provided rooting for some grasses and saxifrage.

At first the structure was thought to be of Eskimo origin, but that view was rejected on these grounds:

(1) Some of the larger stones were deeply embedded among the smaller stones forming the floor and the irregularity of construction showed no human aspects:

(2) The form and size are not typical of any house, grave, meat cache or fox trap:

(3) The circle was far from the sea and about a mile from the nearest Eskimo ruin.

E. Chemical Disintegration.

That chemical weathering occurs here is strikingly confirmed by the reds, yellows and browns broadly splashed on the rocks and adding to the already colourful sea and sky. High up on Uigordlerssuaq a biotite and tremolite schist, much broken by mural scaling, formed an escarpment set back from the harder, more resistant underlying quartzose gneiss which was breaking off along joint planes. The schist was stained a deep brown and the solution from it had poured over the light grey gneiss in broad limonitic-coloured bands visible many miles away.

On Midsommer Ø a similar biotite schist had been broken down into a dark brownish-red mud intermixed with pebbles. This red denudation product in places formed mud and stone flows as much as 20 feet across and 60 feet long. They were generally ribbed by strings of larger pebbles, stone stripes, about one foot apart.

At Lille Inugsulik (it has already been noted) the spheroidally weathered portion of the ice-foot zone is heavily iron-stained, probably by wash from the vegetation-covered area above into which the staining can be traced.

The reds and browns are most obvious among rocks carrying ferromagnesian minerals such as biotite and hornblende. On Lille Inugsulik a felspathic granite with some hornblende had weathered out along crystal cleavage of the quartz and felspar, and the hornblende had disappeared entirely, leaving an appearance of a grey-white rock composed entirely of sugar lumps. On West Edderfugleø an erratic of biotite schist had disintegrated completely, Plate XVI, (probably through frost action in the first place), but the biotite crystals had disappeared and a brown staining had spread over the ground about.

Part 2. Discussion.

A. Mechanics of Nivation.

There is little heavy vegetation even at low level, except where man has lived or birds have found nesting grounds, as on the Middle Edderfugleø. Where an Eskimo house has been built close to the water the snow bank, during the occupation of the site, has been rapidly removed. This, and the presence of much refuse, has induced the growth of Alopecurus vegetation. On desertion of the site the snow bank has removed much of this vegetation and in such a way as to produce downward dragging of the grass stalks as if the snow, slipping down to the ice-foot, carried with it soaked and loosened clumps of grass and soil.

On South Ryders Ø (see Differential Nivation: Scaling), spheroidal scaling does not occur so rapidly where lichen is generally widespread. The example quoted is at such a height there can be no question of the effect of salt spray or the rise of tide; the problem is one of determining why there is a lack of scaling where lichen grows. For instance above the ice-foot zone there is much lichen, contrasting with the clean rock below, and it may be that the presence of lichen inhibits scaling, perhaps by altering the heat conductivity to such an extent that ice formation is retarded, or it decreases the area of rock whereby water can enter by reason of porosity.

Considering the situation where the fox trap is only partially covered by lichen—if the thick lichen had at one time completely covered the fox trap and the sides of the gully, subsequently to be removed by snow action, that would imply an increase of snow accumulating in the gully, and its persistence until late into the spring in years later than the building of the fox trap, which is unlikely. This argument assumes that snow removes lichen, yet it can equally well be suggested that the lichen grows at different rates owing to the presence of snow in the gully (in which case there would be no sharp line of demarkation). But in either case it follows that snow prevents growth of or removes a lichen covering, and since the winter snow is not removed from the surface generally until the spring, it seems that the persistence of the snow bank through the spring, the time when the vegetation is asserting itself, is the deciding factor. The sharp line between the thick lichen-covered rock and the thin demarks regions where snow is quickly removed in spring, and where snow lies a long time into late spring or early summer, which is here June. The thin covering is that which is establishing itself through the period of the summer when the bank is melted. So it can be assumed that where the ice-foot snow bank is concerned there is a continual advance of vegetation across the bared rock, an advance fought back and terminated by the persistence of the snow. The cleaned rock area lying above the ice foot is a measure of the size of the snow bank persisting there.

The first syllogism is therefore, that whether the lichen cover affects heat conductivity of the rock, or its area of porosity or not, the persistence of snow cover into the period of the year when lichen establishes itself prevents the extension of lichen cover and even exterminates it, thereby clearing the rock.

The ice-foot zone will be the area where lichen-free rock is most prominent, because of the presence of the ice-foot itself below the snow bank, because perhaps of the changed heat conductivity of the rock owing to cleaning by spray, because of salt water and even on account of the rubbing pressure of moving ice. Other comparable areas are those immediately fronting the ice sheet, as on Wandels Land where proximity of the glacier keeps the temperature lower than in the islands. It is on such cleaned areas that scaling of the spheroidal type is most prominent, and the difference between them and the lichen-covered areas (apart from the lichen) is the persistance of the snow beyond spring. Moreover, the part of the ice-foot zone most affected by scaling is the lower portion of the cleaned areas, that is where the snow bank has been thickest and thus persists longest after the first melting which removed the highest and thinnest layers. The second syllogism is, therefore, that the processes which lead to scaling are active during the period of spring to early summer, and after melting of the snow bank has commenced. This is the period of the year when the snow in these parts is melting by day and freezing by night, when there is oscillation about freezing point diurnally. Hence a third syllogism is that spheroidal nivation is a process conditioned by diurnal oscillation about freezing point.

The spheroidal scaling appears to be greatest in places where there is a lack of drainage. (The presence of lichen usually implies good drainage and it may be that the close contact with nearly melting snow prevents the growth of lichen in the snow bank areas). In the ice-foot zone the drainage is poor during part of the spring because the water cannot run away below owing to the freezing of the ice-foot to the rock. Nor can the melt water drain away so easily where a snow bank lies at the foot of a long rock slope (as on Amdrups Ø) where again the lower layers, protected by the bank above, remain frozen to the rock. In the rock basin on South Ryders Ø there was no possibility of drainage even by soaking for the close permafrost level would prevent it. A fourth syllogism is that there should be exposure of the rock to water during the period of diurnal oscillation around freezing point.

It has been seen that type of rock is important; rich biotite rocks show fine scaling much more frequently than coarse quartzose gneisses which break off in slabs. Rock constituents such as the ferro-magnesian minerals (biotite and hornblendes) appear to disintegrate rapidly, which is to be expected in a situation tantamount to immersion in water. But the scaling does not take place along lines of foliation, about which the biotite crystals are usually orientated, so it can be assumed that the larger spaces produced by chemical action do not form lines of weakness wherein the scaling process works. However, by increasing the permeability to water this chemical disintegration may be contributory to the scaling process. Annual soaking and drying may cause exfoliation as in lateritizing regions in the tropics, but here the scaling is confined only to a period of the year when the rock is soaked. We may take as a fifth syllogism that soaking of the rock is necessary, and since fracture takes place during the period of diurnal oscillation about freezing point, it follows that nightly freezing of the water within the interstices of the rock leads to scaling.

Taber (21) has shown how this fracturing proceeds. For instance, he demonstrates that a low temperature is not at all essential, indeed that even when the air temperature is slightly above freezing the removal of heat from cold melt-water by evaporation will produce ice crystals in the rock. He has also shown experimentally that such ice crystals produced in the interstices of the rock-base develop greatest pressure in fine-grained materials such as shales, slate, sand-stones and schists with small pore spaces. Whereas coarse textured rocks such as granites and quartzose gneisses with relatively large open spaces are most resistant to frost action. This agrees with the observations already made.

We may therefore assume, on the basis of Taber's experimental findings, that spheroidal nivation occurs during that period of the year, spring to early summer, when there is diurnal oscillation around freezing point in situations where the rock is exposed to water, and where the rock is of such a texture as to permit of soaking through the interstices. The formation of ice crystals in these interstices may be accelerated by the movement of water from lower layers in the rock (if the perma-frost level has retreated). Decomposition of the minerals in the rock probably has little effect in scaling proper since that process is one of fine comminution, and in these arctic regions low temperature inhibits the necessary speedy chemical reactions. However, what disintegration does occur assists in developing permeability.

The soaking of the rock is essential to the spheroidal character of the scaling. Planes of soaking will not conform to the angular junction of surfaces for the resultant of the component capillary pressures will establish the planes of soaking at greater depth, and consequently no angular confluence of these planes can occur. This is well illustrated by the sub-angular moulding of the boulders on Amdrups Ø.

Thus it can be assumed that this form of scaling is not dependent upon melt-water as a moving, distributive agency, but as a static, penetrating agency. As a distributive agency the melt-water becomes of importance in summer when the rapidly melting snow bank removes the products of disintegration of the previous season down the slope. If these products of disintegration are not removed a protective layer is set up which retards scaling in the next year. For instance in the South Ryders Ø rock basin the bottom is covered with the products of this weathering, and the process is active only at the sides.

This protection by debris is shown fairly clearly in the photograph Plate II of mural scaling on West Edderfugleø. The effect is probably one of raising the permafrost surface to a level higher than the rock surface. It is suggested that where the rock is exposed to melt water for some time in spring and summer the permafrost level is lowered, and in autumn ice crystals form on the surface of the permafrost giving rise to fracture along this surface, and thence to mural scaling. Where there is a protective debris cover the autumn ice forms above the rock.

A quotation from Birket-Smith already given may be repeated here, "this form (of exfoliation of large crusts) seem more particularly to belong to rocks polished by the former ice cover". It is possible that the pressure of an ice sheet disintegrates or disturbs the crystal structure of some rocks to a certain depth, and as a result such rocks are more liable to mural scaling. It would be of interest to make microscopic examination of rocks which have been subjected to such pressure. The process may account for the preservation of rounded glacial contours on mural scaling though, of course, scaling due to ice crystal formation at the permafrost surface will have the same result on the broad scale since the permafrost level will run parallel to the surface owing to uniformity of temperature gradient. It is likely, however, that on the small scale the surface resulting from ice crystal pressure and fracture will be somewhat coarse owing to the irregularity of crystal growth, compared with the rather smooth surface one would except from the uniformity of pressure applied by the ice sheet. The coarsely textured surface below mural scaling on West Edderfugleø (Plate II) indicates that the first proposition is most likely.

B. Climate and Scree.

Great scree slopes of dry, isolated stones, were not observed in this part of North West Greenland, possibly because:

(a) the islands are generally small and either low or, where high, drop steeply into deep water,

(b) and where such scree slopes are possible, as on Amdrups Ø and Wilcox Head, there is heavy comminution with the production of muddy interstitial matter and hence large solifluction slopes.

Those contrast strongly with the enormous screes of loose stones which line the fjords of north east Baffin Land across Baffin Bugt. It is possible that there, on the leeward side of the mountains, the climate is dryer in the spring the crucial time, whereas here, close to the ice sheet and on the windward side, the climate is much wetter leading to more spheroidal nivation and fine comminution.

Another aspect of this difference in climate is the comparative absence of frost heaving, common in Baffin Land and especially so in the Barren Grounds where it is still dryer. It is probable that, owing to the proximity of the ice sheet in North West Greenland, the permafrost level does not retreat annually so deeply as in Eastern Canada. There ice-needle pressure acts at depth leading to frost heave; here it acts close to the surface and along those joints open to the surface and penetrable by melt-water. On the summit of the Djævelens Tommelfinger, where it is dryer owing to exposure and isolation, there is a little frost heaving which litters this top with angular boulders. Plate XVII, East Edderfugleø, shows frost heaving of a kind, disruption of the bedding, and bending of strata until they fracture. This latter photograph demonstrates clearly that the mere thermal expansion of ice will not necessarily burst apart jointed and banded blocks since the expansion can be taken up by expulsion of air from the crevices, the system being open. It is only by postulating ice-needle pressure in this kind of open system that one can account for such a disturbance of schistose rock.

C. The Ice-Foot Effect.

This is a process which culminates in a steepening of the coast. In the first place a snow bank may slip off and carry with it the products of nivation and joint fracture, or the melt water from the snow bank washes this material on to the ice-foot which then transports it to sea on detachment. (Plate XII).

In the second place nivation steepens the shore. Consider a rock slope (Fig. 6) entering the water at an angle of say 45°, and an ice foot resting against it with a horizontal surface upon which collects a snow bank at an angle of 25°. Spheroidal scaling will then occur below this bank along a line parallel to the rock surface from the upper limit of the snow bank to the inner limit of the ice-foot (A B). In the ensuing seasons the process will continue parallel to this line (limited on the inner side by the perpendicular from the inner edge of the snow bank),

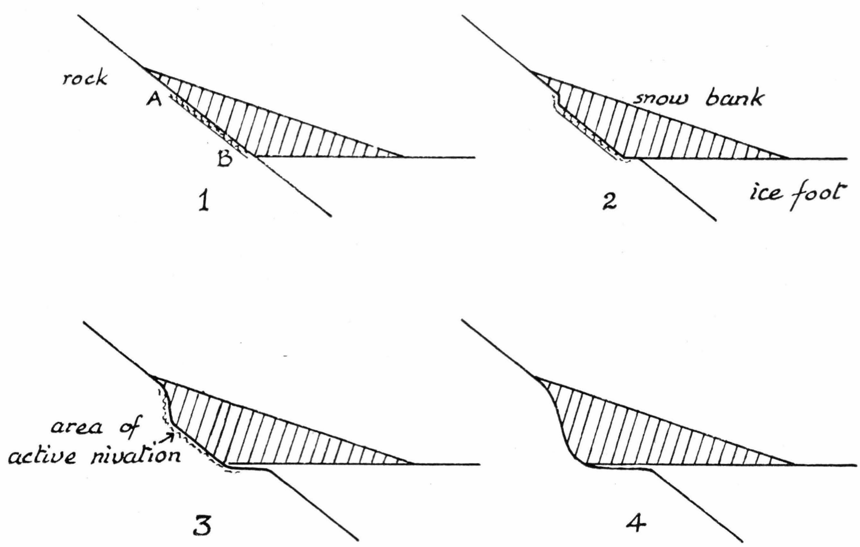

Fig. 6. Illustrating nivation theory of coast erosion (and skjaergaard development) by the ice foot.

and the process will be cumulative until, theoretically, if the snow bank does not increase, a nick will be cut into the rock, level with the original ice-foot. But since the snow bank will become progressively deeper it will last longer, the process will extend to the vertical inner wall and the final result will be a levelled ice-foot shelf meeting a sloping back, steeper than that of the original rock, in an L-shaped junction somewhat rounded. Some spheroidal nivation will take place below the bank at the end of the "fracture season" owing to increase of melting providing enough water to permeate the interface. But this scaling will be small in comparison with the scaling along the back wall.

It is such a process which Nansen (12) postulated would account for the skjaergaard in artic regions. Such a process can only be widespread if the sea remains constant in level in relation to the land over a considerable period of time. Such constancy of sea level does not hold in North West Greenland today as shown by beach levels and inundated house ruins, and therefore one cannot expect to see such a shelf being developed to any extent. But there is enough to show, as in the photographs presented (e. g. Plate XIII) that the process is active and in time would produce the shelf.

The same process will, of course, be in action wherever a snow bank lies against a rock surface, as for instance on Amdrups Ø (Plate IV). There the shelf is already forming with a well-marked back wall cut into a sloping rock face. We may assume that this 20 foot wall has been cut since the rock was bared of the ice sheet. Because we have no dating of the retreat or melting, it is impossible to make a calculation of the rate of the process.

D. Mechanics of Solifluction.

The mechanics of solifluction are still but little understood. The evidence of those examples examined in North West Greenland points to the effect of gravity on extremely moist, and therefore plastic, soils. Such an explanation has been put forward by Högbom (6), Salomon (17) and Poser (15, 16), and by various American authors (20). The process of regelation has been suggested as a more important factor. Frost heaves the stones in a direction perpendicular to the slope, and on the occurrence of thaw the action of gravity tends to displace the stones downwards from their original positions to which they would tend to return on removal of the ice support. Many of the earlier writers held this view (1), and others point out the relationship with vegetation covering (18). Beskow (2) and Passarge (14) consider that regelation is the most important factor in dry tundral country, but earth soaking gains in importance in rich marine tundra.

Two forms of solifluction can be recognised.

(a) The stone slide, which is an aggregation of stones with little mud but much water, moving downwards under the action of gravity, and of gravity alone, each element being able to adjust itself in free rotation. In the absence of water this constitutes a normal scree slope.

(b) Solifluction proper (according to the first definition of Andersson), in which a mass of stones embedded in finely comminuted muddy material, in a plastic condition, moves bodily under the influence of gravity and of the pressure of growing ice crystals.

This second form retains a stable surface upon which characteristically appear stone stripes. As a result the drainage of this surface follows the lines of stones and therefore no arborescent system is developed. The end result is a smooth, unincised surface. Water is removed by ablation as well as run-off along the stone stripes, which vary from a few inches to feet in width. It may also escape, in the late part of the season after the first slipping, between the permafrost level, (or rock level), and the solifluction mass. In summer the drainage along the stone stripes helps to clear the mud, and hence drainage and the process of stripe development become cumulative.

The mechanics of polygon formation as studied on this expedition, have been previously examined (PATERSON, 13). A most instructive situation relating polygon formation to solifluction was that on the eastern shoulder of Wilcox Head where a large polygonal area extended laterally on to a fairly steep slope showing strongly marked solifluction stripes and stone slides. An angle of rest between 5° and 7° from the horizontal was finally attained, and here again polygon formation was prominent. The first conclusion is that polygons do not form on a surface steeper than this base level. A second conclusion, though not so certain, is that the stone stripes were initiated at the top of the solifluction slope by movement of the polygons over the edge, the borders of the polygons parallel to the direction of flow being accentuated, and those athwart the flow being obliterated by the movement downwards. These stone stripes did not penetrate deeply into the soliflual mass and were separated by bands of very muddy material, slightly convex. HAY (5) has shown that in Cumberland the convexity is produced by the growth of ice crystals between the permafrost level and the thawed ground, this layer of crystals being thicker below the mud and thinner below the stones, presumably because of the circulation of air among the stones. HAY suggests that the stones are brought upwards by the constant action of crystal formation and thaw and, on reaching the surface of the mud dome, they move sideways being concentrated in the stripes. This is but a development of Low's convection hypothesis (11) of the formation of polygons, but it does not show how the differentiation between mud and stones was first achieved. Such a differentiation would come about from the movement of polygons into the solifluction slope as suggested above. But it is not necessary to assume this convection to account for the further development of the stripe.

Ice thrusting radially from a centre of freezing and thawing will act on the solifluction surface as well as on the polygon, but the centre, instead of being symmetrical, will be elongated by gravity in one direction, that is downwards, and therefore those sides parallel to this elongated central mass will develop more than the smaller portions of the perimeters on the upslope and downslope sides. These will be obliterated by the movement of mud, in the first place from the elongated polygon centre above it, and secondly by movement of the centre itself, downwards.

The importance of solifluction flow, whether in the form of streams of incoherent boulders and stones, or of coherent, plastic masses of boulders, stones and interstitial mud, lies in:

(a) its capacity for removal of detritus produced by processes of rock shattering and

(b) the moulding of many topographical features.

The removal of detritus is particularly evident at the base of rock slopes where nivation is very active (see Plate IV). It is also important close to the shore, bringing the detrital products of nivation on to the ice-foot which, breaking away, transports it southwards. The nivation process at the ice-foot is active in the late spring and early summer and precedes the flow of detritus on to the ice-foot during the late summer when thaw is considerably advanced. Brown (4, p. 49) has described this before:

> "As the spring and summer-thaws proceed, land-slips occur, and earth, gravel, and avalanches of stones come thundering down on the ice-foot, there to remain until it breaks off from the coast, and floats out to sea with its raft-like load of land-debris . . . I have known the ice-foot, laden with debris, to be driven up by the wind and high-tides on to low-lying islands, spits and shores, piling them with the load thus carried from distant localities . . ."

The action of soliflual removal of detritus in the ice-foot zone results in an over-steepening of the shore, particularly well shown on Plates II and XII.

Smoothing of contours.

It has already been shown that mural nivation preserves the original glaciated contour, but soliflual distribution of the debris may smooth the contours even further as demonstrated in the classic works of Davis and Baulig. Normally the surface would be dissected by an arborescent drainage system which, on development, would lead to gully formation and reentrants. But by solifluction the debris is distributed laterally as well as vertically and the drainage during the wet season takes place along the stone stripes and at the rock or permafrost level. The result will be tilted planes or smoothly rounded slopes which impart a convexity of outline easily mistaken for the effect of glaciation. Such forms are common throughout the arctic and in the highland areas of northern Europe. Their symmetry of outline, hardly possible as the result of unidirectional glacier movement, leads, occasionally to naming illustrative of their mammiform character. Where such slopes approach sea level and are subjected to the action of ice-foot transport, they are convex as against the concave of the fluvial contours, (Plate II).

Where the solifluction slope does not reach the ice-foot transport level it will flatten out to a base level between 5° and 7° being slightly concave at the beginning of the flattening. Such slopes on West Edderfugleø and Wilcox Head have been described, and the background to Plate XVI illustrates the upper part of one of these slopes, dried by

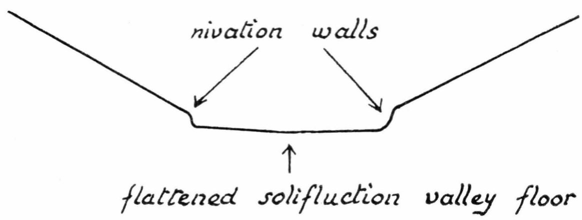

Fig. 7. Cross section of valley near watershed in North West Greenland.

ablation, smooth and unfurrowed. Below it passes into the polygonal area of Fig. 4.

A similar smoothly contoured surface is that of the valley on Amdrups Ø, (Plate IV). On either hand the valley sides terminate abruptly in nivation-sapped walls, and the valley floor dips therefrom gently towards the middle, and more steeply down-valley, Fig. 7. It is unlikely that in temperate regions, where such forms may have been developed during Pleistocene times, they will be preserved for a fluvial drainage system would rapidly destroy them especially during the postglacial melt-water stage.

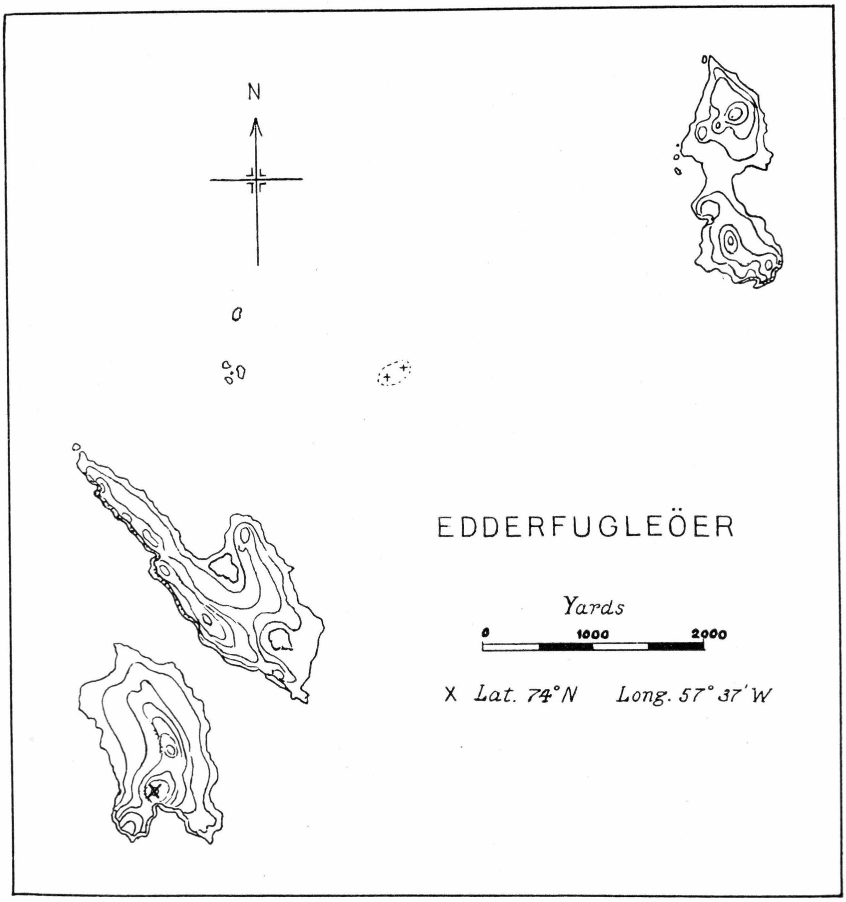

Fig. 8. The Edderfugleøer: survey by P. D. Baird.

2. ISLAND TOPOGRAPHY

A. Edderfugleøer.

These islands, three in number, lie some eight miles off-shore in latitude 74° N. (Fig. 8). The two in the south-west, here called the West and Middle Islands, lie close together separated only by a narrow and shallow channel. The third, East Island, lies two miles to the northeast.

The rocks belong to an Archaean gneissic complex of which the most prominent member is a grey quartzose gneiss. Biotitic and garnetiferous bands appear and a striking rock is a dark biotite-garnet schist, especially well developed on the Middle Island, (Plate VIII). This complex has been invaded by a series of basic intrusives prior to the main folding, which has produced a general dip of 30° to the N.E. on the two westerly islands, though on the East Island it has swung to the west. Later acid pegmatites traverse these rocks and are intimately associated with the the strike of the major joints, that is, they follow the E.—W., and the N.W.—S.E. series of the mainland.

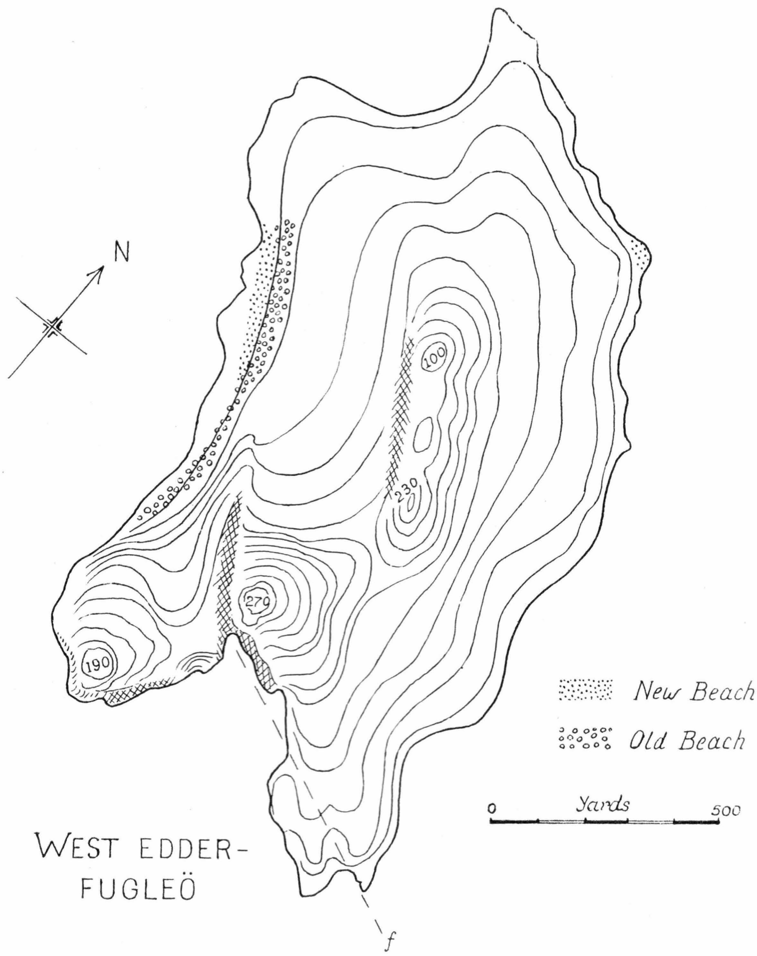

Fig. 9. West Edderfugleø: sketch by the author.

The West and Middle Islands (Fig. 9, Fig. 10, Fig. 11).

A high headland on the south-west of the West Island forms the most prominent feature. Here went the whalers to look out on the ice conditions to the north. It is bounded on the south side by a sheer cliff to water, but slopes fairly gently to the north-east, separated in that quarter by a shallow depression from a ridge divided into four blocks. The western extremity is formed by a rounded knoll, 190

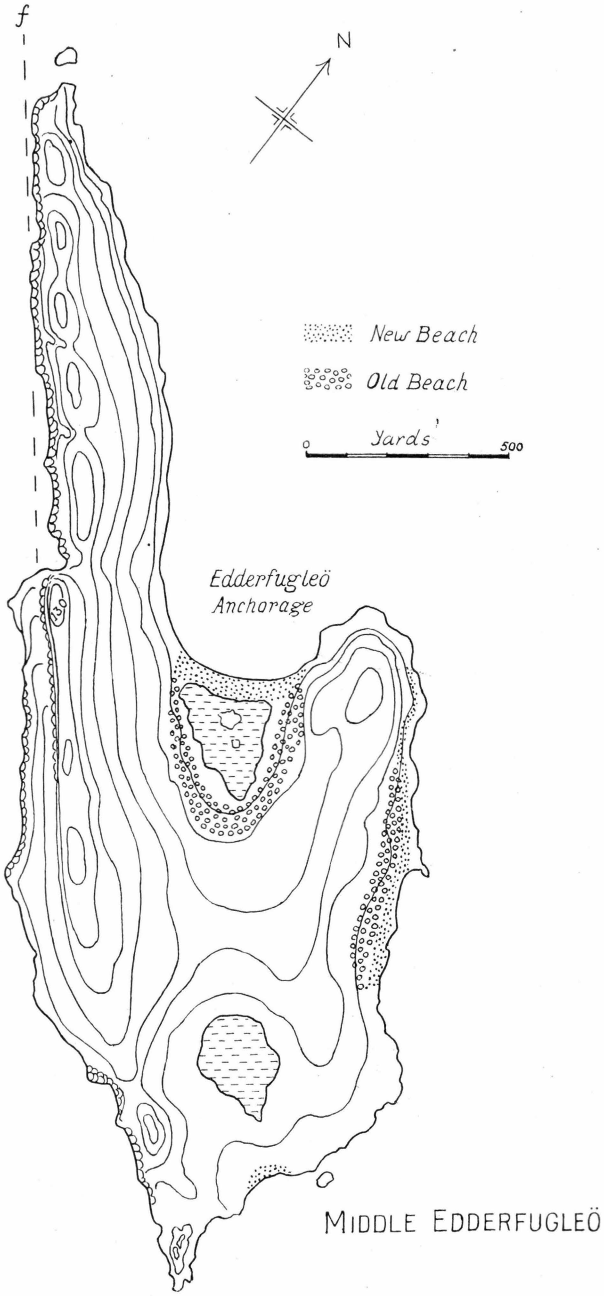

Fig. 10. Middle Edderfugleø: sketch by the author.

feet high, weathered and roughened by exposure to the full force of storms.

All three heights are bounded on the south-west by escarpment cliffs running in a direction corresponding to the general strike of the rock. The escarpments are determined by a hard, resistant, grey garnetiferous gneiss which also forms the headlands that fringe the island. The two points on the north are in line of strike of the escarpment cliffs of the two hills, while a small skerry off the west coast is in line

Fig. 11 *A*. West Edderfugleø.

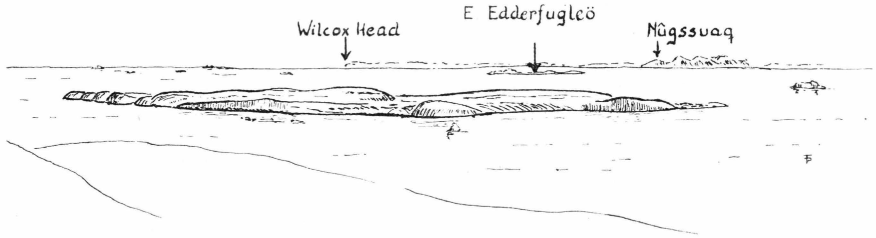

Fig. 11 *B*. Middle Edderfugleø.

with the westerly headland. The same rock has been collected along each main strike escarpment so that it recurs three times, but there are no signs of thrusting or overfolding. The very steep cliff on the south side of the main hill is due to a minor fault running W.N.W. along its face; it also produces a small cliff 20 feet high on the southern point running in the line of the fault and crossing the strike of the rock, hence the irregularities in the form lines there.

On the Middle Island (Fig. 10), the main features again conform to the strike of the rock. There are two low ridges running almost N.W.—S.E., separated by a rather broad and shallow depression in which lie two small lakes. The westerly ridge is the higher and in the north-west end is broken up into blocks while the escarpment there falls into the sea. This cliff face is continued towards the south where it is separated from the sea by a shelf, 30 yards wide, sloping upwards and to the south, merging with the top of the cliff at the south-west end. A strike fault hinging at its southern end determines this shelf, which is covered with stony clay. The fault probably belongs to the same group as that on the south of West Island.

On the low ground scree and drift material have accumulated and, under the action of solifluction, is now distributed as gently sloping ground, streaked and patterned by stone stripes and polygonal structures. The largest area is on the north-east of West Island (Fig. 4). The lowest angle of slope is 5°.

The blocking of east hill, West Island, and of the west ridge, Middle Island, is due to jointing. The master joints run E. and W., cutting across the strike, and secondary joints are parallel to the strike. These blocks are all rounded by a process of nivation already described. On Middle Island the gullies have been so denuded that the highest parts lie well back from the edge of the cliff, and along one joint close to the Anchorage nivation has cut the island almost in two. The depth of the gullies suggests stream erosion, but since they cannot be traced outwards, it must be presumed that nivation alone produced them.

Post-glacial material consists chiefly of scree slopes of angular and sometimes very large stone blocks from the cliff escarpments, the result of mural nivation and joint weathering which can be seen in action on most faces. Mural nivation simulates strike fracture on the west side of the S. W. headland of the West Island. Even on the highest point this shattering has occurred, but the pieces are not so big; and since fracture along cleavage planes becomes prominent there, the stones are more flattened.

There are two beaches. Apart from difference in height the newer can generally be easily recognised since all the boulders are well rounded, whereas the older, at a higher level has a greater quantity of angular blocks. The newer beach rises to about 8 feet and is presumably washed by storms. The older is 25 feet above sea level and sometimes part is cleared away by ice-foot denudation. A large strip of this old beach lines the west coast of West Island being especially well marked in front of the main hill. On the new beach lies an erratic of gabbro, 20 × 20 × 10 feet. On the north-west headland of the same island a large patch of rock between the ice foot and this beach has been cleared of vegetation, and scaling has occurred later than the formation of the beach.

On the Middle Island these beaches play a more important topographical part. The old beach flanks all the eastern coast of the east ridge up to a height of 30 feet, and fringes the triangular shaped lagoon immediately south of the Anchorage. The lagoon is separated from the Anchorage by a bar, about 30 yards wide and 200 yards long, formed by the shingle of the new beach, in which ice blocks are stranded. The swampy lake to the south is circular rather than triangular, and at a higher level, 20 feet. The shape seems to be associated with its formation for it is rather a shallow depression in the mud-filled stony clay. Both stretches of water are being gradually filled up with mud washed from the surrounding slopes and already an island has appeared in the northerly lagoon.

The origin of the stony clay that is found on the lower parts of these islands is not certain. A great number of the boulders are erratic, the nearest known site of two being at least 20 miles away on Lille Inugsulik and the Ryders Øer, all lying to the north-east. Many boulders are very rounded and evidently water worn, but some are faceted, of true boulder clay type. No striations were seen. The largest erratics are confined to the lower slopes and the solifluction areas or the beaches, but smaller foreign boulders are seen at over 200 feet elevation. Boulder clay fills some of the joint gullies on the Middle Island but not those of the heights of the West Island. Many perched erratics are to be seen on the Middle Island.

The East Island. Fig. 12.

This island is divided into two parts, a northern and southern, joined by a low-lying marshy waste. The northern part (Plate XIII), has three escarpments, the principal being that in the west where a cliff, 100 feet high, overhangs the sea. These escarpments run to the north-east where they form points or blunt, steep headlands. Drift partly obscures the hollows between escarpments, lessening declivities and filling up gullies. The southern part has also three escarpments, corresponding to the two easterly on the northern part and the eastern headland on the north side of the bay. There is no blocking of the escarpment by joints as in the other islands, but two series are prominent. The first runs N.E.—S.W., and is more pronounced in the south where numerous little gullies are cut into the coast. To this series belongs a very deep gully now filled up with drift and cutting off the southern part from the low marshy ground. The second and subsidiary series is perpendicular to the first and is best developed on the east coast of the northern part. Since the strike differs from that in the other islands by almost 45° this second series corresponds to the major joints of the Middle and West Islands, and there are no E.—W. joints at all. The cause of the change of direction of strike and jointing may be faulting between the islands, and such faulting must lie between the East Island and the skerry near Middle Island; for on that skerry the joints and strike correspond to those of the latter island.

A new beach fronts the west cliff on the northern part of the island, and lines on either side the low connecting land where the old beach is best seen, though now partly obscured by overflowing solifluction material, well shown as striped ground in the forefront of Plate XIII.

Drift similar to that on the other islands, and carrying the same erratics, covers even the higher ground. It is probable that before the time of the formation of the old beach the two parts of the island were separated and the intervening area filled with drift.

Remarks: It has been seen that the major physiographic features of these islands are determined by the strike of rock, joints and soli-

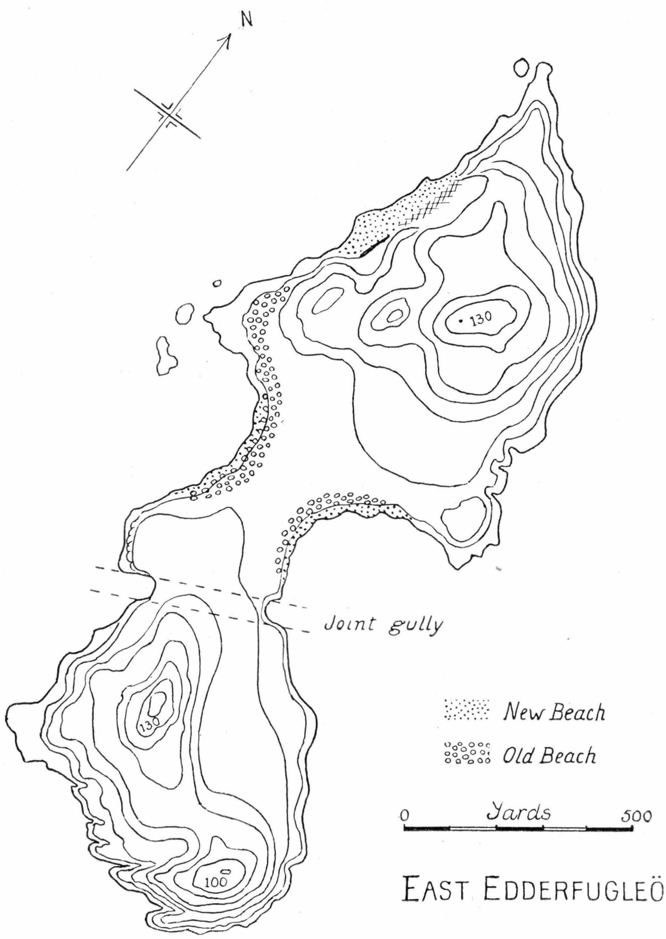

Fig. 12 East Edderfugleø: sketch by the author.

fluction slopes, but the occurrence of drift and erratics sets the question of the exact role ice has played in modifying these features, and the condition of the ice transporting the drift.

The big erratics are all congregated on the beaches and lower parts and are not found at heights. Nor does the highest region of the West Island bear erratics. Striations are absent though that may be the result of later sub-aerial erosion. The rounded contours may well be due this latter process also and it can be pointed out that even when the strike of the rock changes, as it does in the East Island, the escarpment face and opposing strike slope are defined by the rock structure alone. If land ice had moved from the north-east, as the erratics might indicate, then the contours would have shown signs of such, for later sub-aerial erosion would not have removed superimposed glaciated forms but preserved them. Moreover the enclosed boulders are not all glacier-transported; though some are faceted a great number are thoroughly rounded, water worn. The angular boulders and clay could quite well be derived from nivation processes and transported by sea ice.

If sea-ice has been the transporting agent the low-level large erratics are easily explained; but for the higher smaller ones and the drift on the Middle and East Islands a further assumption must be made that the sea level was over 200 feet higher at one time. There is plenty of evidence of such in the high level beaches in West Greenland. Moreover ice floating from the north-east, as it does today, would bring the types of erratics here encountered, and since the water would buoy up the ice no moutonnée forms would be produced. The studies on nivation led to the conclusion that the joint gullies on Middle Edderfugleø had been subaerially denuded. Some are now filled with a boulder clay which might have been glacier transported but was just as probably brought by sea- ice (though floating glacier remnants as small icebergs may have done the same). Hence these gullies were exposed before submergence either by ice or sea. If they are pre-glacial then the ice sheet, if it reached this distance, cannot have been very powerful for the rock is soft, disintegrates easily and would have reacted at once to glacial erosion.

The conclusion is that Middle Edderfuglø was not glaciated, and that therefore the Greenland Ice Sheet, in these parts did not extend 30 miles beyond its present limit.

B. South Ryders Ø. Fig. 13.

This island, which is the largest of the Ryder Group, lies to the north-east of Edderfugleøer in latitude 74°36′ N., much closer to the ice-cap front, since in that region the Melville Bugt Glacier, beginning north of Wandels Land, curves towards the north-west. The island is triangular in shape with east, south, and north-west coasts. The greatest length is about two miles and the highest point 480 feet, on the north-west coast.

The rocks belong to the same Archaean complex as those of Edderfugleøer but grey granitic gneisses are prominent as against the garnetiferous gneiss of these latter islands. In the south-west several large bodies of epidiorite, caught up by the same folding that has contorted the gneisses, run east and west conforming to the general strike, the dip being steep and variable. The subsequent geological history indicates the development of major jointing running 40° E. of N. with secondary jointing at right angles to that and a third, subsidiary, associated with the strike. Later the island was affected by a major fault running due north and south cutting it almost in half. The throw was

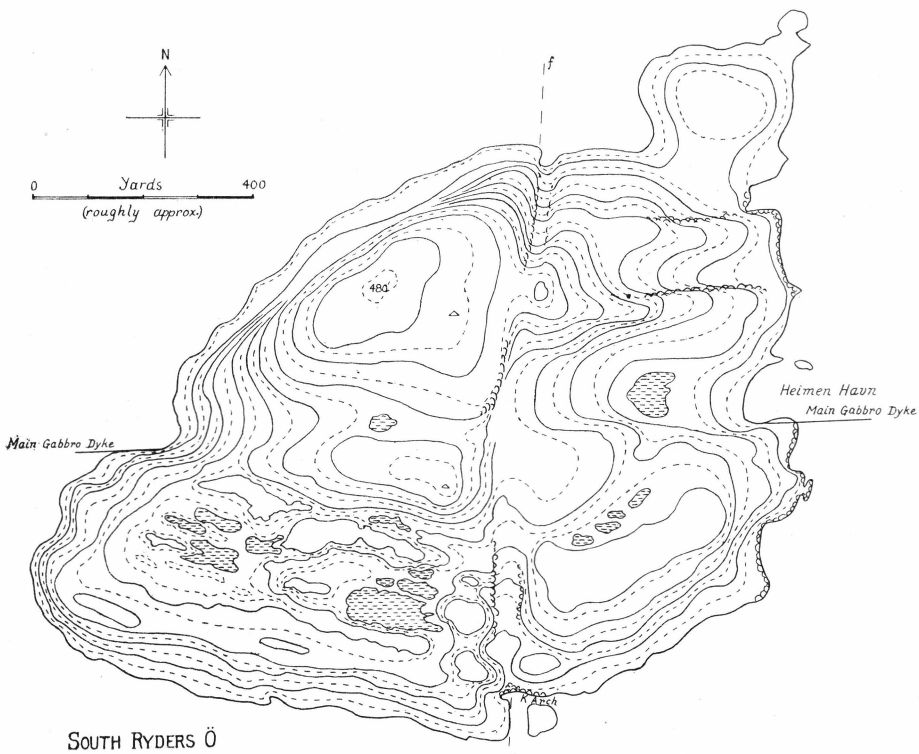

Fig. 13. South Ryders Ø: sketch by the author.

sufficient to cut off the continuation of the epidiorities from the south-west into the south-east. This faulting was associated with the intrusion of gabbro dykes, which preceded and followed the faulting. The most prominent is a dyke passing from east to west, the general line of intrusion, and bisecting the island at right angles to the fault. Probably the last stage of this tectonic phase is the intrusion of a series of E. W. pegmatite dykes well developed on the east coast.

By reason of the fault and the main gabbro dyke the island can be divided into four regions, and each has distinct physiographic peculiarities. The north-east sector in the northern part is low and rounded, and there much denudation has taken place. The ground rises farther south into two E. W. strike escarpments which, continued to the coast, form prominent cliff fronts. From the southerly escarpment the ground slopes to the widest valley on the island opening to the sea as a shallow bay, Heimen Havn. From the beach the ground slopes up fairly rapidly over a ridge made of large boulders, behind which a small heart-shaped tarn has formed in a rock basin. Behind the tarn the rock climbs upwards all round forming an amphitheatre. The appearance is typical of a corrie with fronting moraine and ridge damming the lake.

The south-east sector has a smooth coastline on the south due to the strike coincidence, but it is broken where the strike ridge forming the backbone meets the sea on the east. The rock slopes gently away southwards under water as stranded icebergs indicate. North of the main ridge hollows have been formed in the rock, and several pools have collected in a line parallel to the ridge. On the south coast, next to the fault gully, a natural rock arch has formed, defined by a resistant band of gneiss.

The fault gully on the north and south is U-shaped, about 40 yards across. Where the fault has cut across the bands, in which the corrie has been eroded, a steep cliff face has formed running north and south emphasising the corrie topography. Along the main gabbro dyke erosion has not been so strong, but a shallow longitudinal depression traverses the island from Heimen Havn to a little bay on the west coast.

The south-west sector has an aspect totally different from the others. The coast-line is smooth except for some gullies along N. W.—S. E. joints, and rises to a ridge bounding the epidiorite area. The lenses of epidiorite are strung out along east and west lines and have been denuded much more quickly than the surrounding gneisses. At the same time the gabbro dykes are eroded to a similar extent. In the hollows so produced, long lakes have formed out of which stand the sharp and jagged remains of dykes and intervening gneisses. The rock surfaces are covered with scree and flat angular scaling fragments. This rough and coarse scenery, not unlike parts of Skye, contrasts strongly with the rounded and smoothened character of other sectors, and the contrast is heightened by the vegetation which is much more luxuriant. On this area alone does Campanula, Arnica and Chamaemerium latifolium grow, probably due to the intense degradation with the production of a finer and more alkaline soil.

The north-west sector is the highest. The ground rises rapidly from all other parts of the island and the surface is rounded, free from erratics. Jointing is only seen on a minor scale but on the north-west side a cliff drops sheer over 400 feet to a narrow beach. This cliff runs parallel to the major joint series, N. E.—S. W., and no fault line, or glaciated features could be seen. It is suggested that this cliff and the direction of this coast-line cutting across the strike, can only be due to weathering along a major joint. Land ice moving from a north-east direction, could have accentuated this joint feature. (It is unlikely that the island represents a crag-and-tail form consequent on ice moving from the south east). The rapid scaling on this cliff, and the beach scree

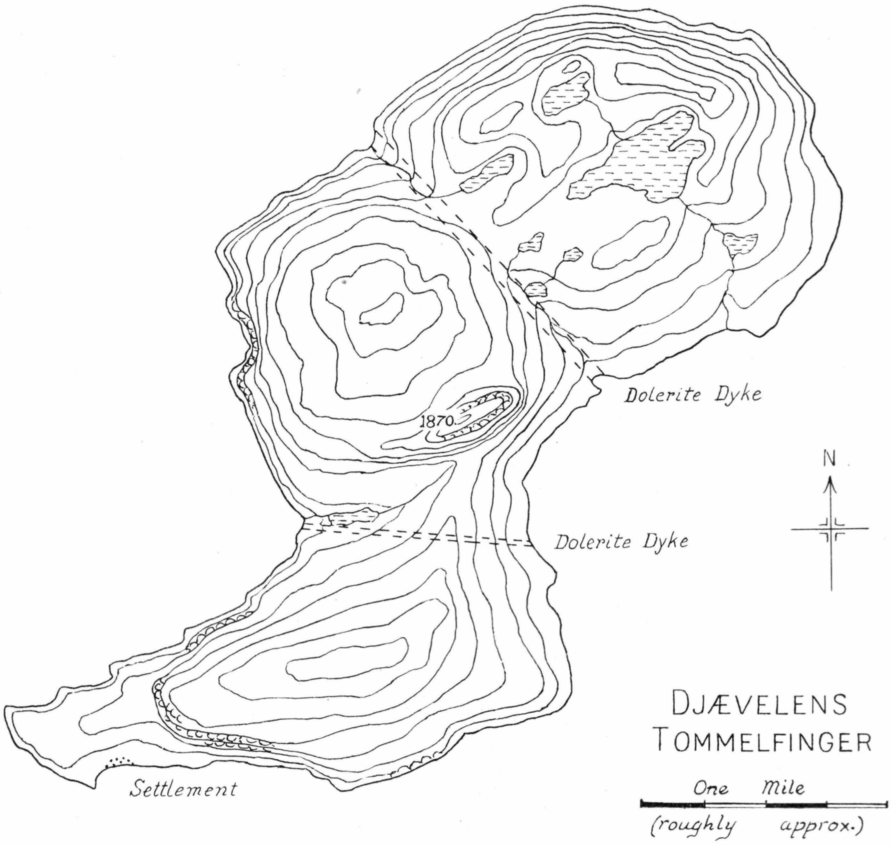

Fig. 14. Djævelens Tommelfinger: sketch by P. D. Baird.

of large blocks derived therefrom, is further evidence for erosion along a line of weakness.

There is no beach older than the present.

C. Djævelens Tommelfinger. (Fig. 14).

This is a landmark well known to the whalers of last century. It is outstanding as a stumpy projection clearly seen against the ice-cap from seaward where the view is end on (Fig. 17), but from the side it is much more broad. It is composed of gneiss similar to the shoulder on which it stands with no fault or break where the shoulder passes up into the higher pinnacle.

The island itself is made up almost completely of a resistant grey gneiss striking in a general N. E.—S. W. direction. It is traversed by two dolerite dykes on either side of the Thumb, the larger dyke being to the east, where erosion has produced a hollow passing from one side of the island to another. Along this gully-like depression nicks are produced where joint planes cross the dyke. The dykes are believed to be of an age with the gabbros of South Ryders Ø. The strike of rock determines the ridging of the island and on the north-eastern sector little lakes have congregated along the hollows in a N. E.—S. W. line.

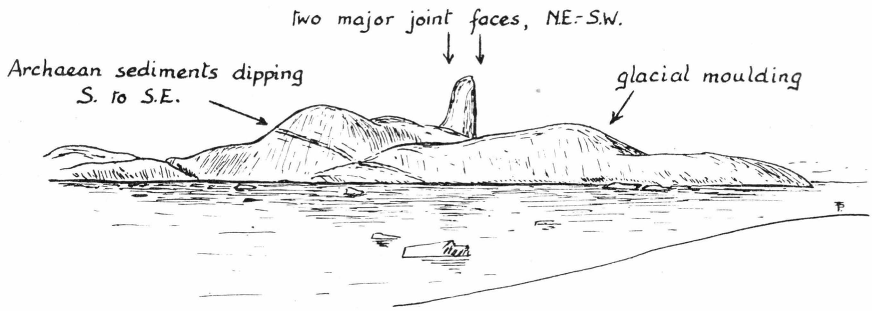

Fig. 15. Djævelens Tommelfinger from the South.

The main joint planes coincide with the strike and it is such coincidence which probably led to the production of the Thumb. This N. E.—S. W. main jointing, it should be noted, is the same as on South Ryders Ø a few miles to the west. On the south side of the Thumb the largest joint has produced a cliff face almost 1100 feet high and erosion has continued in this line so that the island is constricted and lowest there. The next master joint has happened to approach the first on the north side of the Thumb and fan jointing (the result of confluence), assisted in steepening the ends, by producing a tilting effect at right angles to both master joints, the result being the peculiar shape of has this rock mass. Seen from the sea in the north west, the strike slope of the northern coast is continous with the top of the Thumb. The pinnacle is therefore defined by denudation of a strike surface along two joint lines of weakness.

Erratics are found on the lower parts of the island and, because of proximity to the ice-cap, it is assumed that land ice passed over the island. If so, the Thumb was protected by the main island mass to the east and the ice would pass on either side of the Thumb and accentuate, rather than obliterate, its peculiarities. There is a suggestion of crag-and-tail form in the southerly part with a lee cliff just north of the settlement. It cannot be seen how ice alone could have eroded out such a rock as the Thumb unless previous weathering along these master joints had already proceeded far enough to block out the essential form.

D. Remarks.

The geomorphology of South Ryders Ø and of Djævelens Tommelfinger corroborates one of the conclusions on the Edderfugleøer—the scenery is conditioned almost wholly by sub-aerial denudation processes along lines of weakness such as joint planes and faults, along strike, and by differential weathering of various rocks. But whereas it was concluded that the Edderfugleøer were not covered by the ice sheet, here, closer to the present front, the possibilities of glaciation are greater.

On South Ryders Ø the north eastern part is rounded and the contours are glacial, (though its surface is not necessarily the original pavement), and it is most likely that though the first weathering of the Thumb master joints led to its formation, the major part of the definition was glacial, ice passing along the lines of these joint planes from the N. E. If this is the case then the stoss-and-lee form of the southern half of Djævelens Tommelfinger, unconformable as it is with strike direction, can be accepted as glacial. But the northern half, and the form of South Ryders Ø with its main wall on the north west and subsidiary walls facing east, cannot have been moulded in the same fashion by the same ice sheet. The most satisfactory way of explaining all these phenomena is to assume that firstly these walls were determined by sub-aerial denudation along major joint and other structural weaknesses, and that secondly glacial movement along the line of those faces accentuated their wall-like character.

Nivation and joint fracture, after retreat or melting of the ice sheet, has so affected the surface that on South Ryders Ø there is no certain vestige of glacial action except some perched boulders (not necessarily erratics) on the eastern shore, and the contours of the N. E. coast. On Djævelens Tommelfinger there are pavements and perched boulders.

On neither island were boulder-clay-like deposits found, as on Edderfugleøer; nor are there any beach levels older than the present. This suggests, though of course it cannot be certain, that when the ice sheet was over-riding the inner islands, the submerged Edderfugleøer were being inundated with debris brought by floating ice; then later, after emergence to the 25 foot beach level, the inner islands were still protected by ice the greater part of the year. After final retreat of the ice sheet from these inner islands to the present situation the newly emerged surfaces would therefore show little or no covering of massive transported debris, and now the debris-laden ice breaking away from the sheet, deposits its material off-shore.

3. THE GEOMORPHOLOGICAL HISTORY OF NORTH WEST GREENLAND

The pre-Cambrian rocks are of two series, one sedimentary, chiefly of biotite schists and quartzites reminiscent of the Algonkian, the other igneous, of grey quartzose gneisses and biotite gneisses. A group of acid granites has been intruded into both, and the whole has been altered and folded by some major tectonic movements; no thrusting was seen, but in this direction the investigation was limited. On Wandels Land, these gneisses and schists dip steeply towards the south (Fig. 16).

At Upernavik some erratics of slate and mudstone, similar to the Dalradian of Scotland, were collected. They may have been brought by sea-ice from the sedimentary area north of Melville Bugt but this

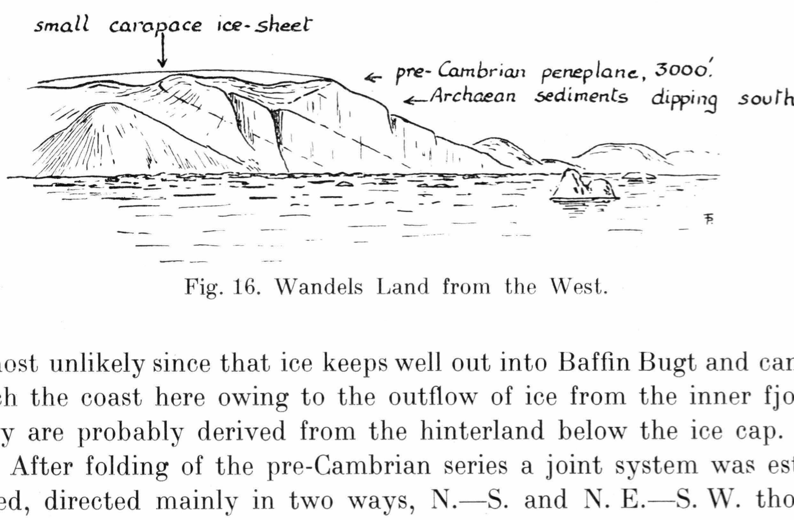

Fig. 16. Wandels Land from the West.

is most unlikely since that ice keeps well out into Baffin Bugt and cannot reach the coast here owing to the outflow of ice from the inner fjords. They are probably derived from the hinterland below the ice cap.

After folding of the pre-Cambrian series a joint system was established, directed mainly in two ways, N.—S. and N. E.—S. W. though minor jointing occurs at right angles to both and locally may be dominant as on the Edderfugleøer. Later faulting disturbed these trends as shown in the difference between East Edderfugleø and the two westerly islands. Strings of acid pegmatites seem to follow the main lines of weakness established by the jointing, but these pegmatites are themselves sometimes folded, though not so severely as the earlier pre-Cambrian.

The faulting mentioned appears to be associated with the late intrusion of relatively undisturbed gabbro and dolerite dykes and, on analogy with similar forms in the Tertiary province further south, it is suggested that they are of the same age—Tertiary.

The morphological history commences with the development of a peneplane of erosion of the pre-Cambrian series, subsequent to their folding and the intrusion of the pegmatites. The remains of this peneplane form small isolated plateau remnants on the highest islands and peninsulae at a general height of about 2000—3000 feet (Fig. 16, Wandels Land shows this erosion plane cutting across the strike of the pre-

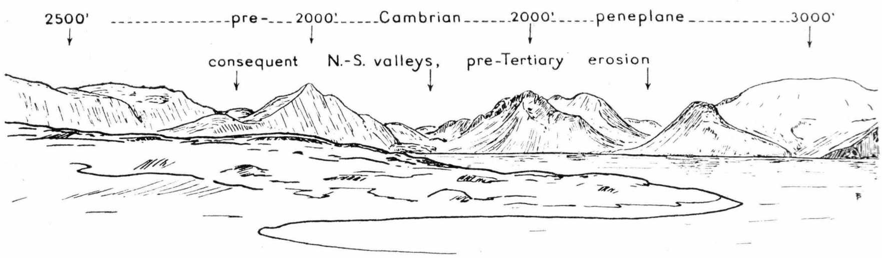

Fig. 17. Nûgssuaq Peninsula from Upernaviarssuk.

Cambrian). Southabout in West Greenland this plane of erosion, 150 miles away, is more extensively developed as a mature, gently rolling surface at a higher level, about 3500 feet. Northabout this peneplane seems to tilt, passing under the Paleozoic sediments of the Kap York province. The age of this tilting will be discussed later. (Fig. 21).

On the other side of Baffin Bugt, in North East Baffin Land, this peneplane was examined during the same Expedition. Around Eglinton Fjord and Clyde Inlet it forms small plateau fragments at 3000 feet, dropping southwards to 2000 feet at Kap Dier and rising northwards in the mountainous area of Ponds Inlet—a reversal of the Greenland configuration. The Baffin Land surface can be traced westwards as part of the great Laurentian peneplane of Northern Canada. There, as in Greenland (apart from the Paleozoic formations in the Arctic basin), there has been no sedimentation until Tertiary times.

Prior to the onset of the great Tertiary diastrophism a recrudescence of erosion of the pre-Cambrian peneplane seems to have occurred. The evidence for this lies outside the district under review, suffice to say that the Tertiary volcanics in West Greenland have been laid against this new surface which is incised into the old peneplane. This can be strikingly seen from the sea, where the Tertiary formation of Svartenhuk Peninsula passes north into the Archaean of Upernavik.

The dissection proceeded along lines of weakness determined mainly by the master joints. The result was a major valley system, with intervening highlands, generally aligned along S. W. axes, Ryders Isfjord and Nûgssuaq Peninsula being good examples of the orientation of many fjords and peninsulae to the south. Along the N. W.—S. E. system of minor joints at right angles to this, consequently valleys were eroded, for instance those illustrated in Fig. 17, of Nûgssuaq Peninsula from Upernaviarssuk just to the north. Holms Ø lies approximately on an E. and W. axis, but this is due to differential erosion (Fig. 19). It is composed of three main blocks lined, N. E.—S. W., joined by lower

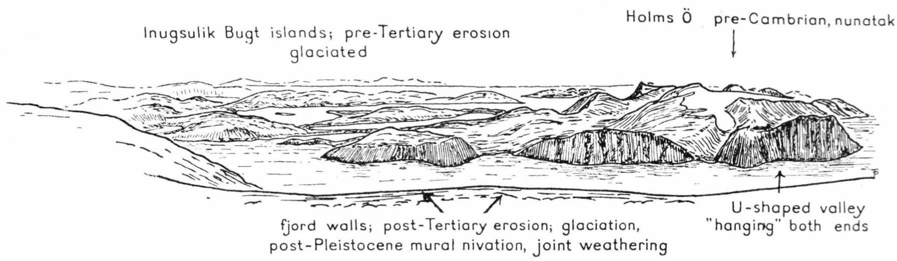

Fig. 18. Holms Ø and Inugsulik Bugt from Wandels Land.

waists running N. W.—S. E., relic consequent valleys at high level. The walls on the Melville Bugt side face nearly N. W. and close by, the main N. E.—S. W. jointing is well in evidence on Djævelens Tommelfinger and South Ryders Ø.

This pre-Tertiary dissection, which did not reach maturity, cut to about present sea level as shown by the consequent valleys of Nûgssuaq, which, being athwart the line of ice-sheet extension, were not excavated much further by glacial erosion. In some cases however, e. g. Allison Bugt, they have been further excavated, presumably by river capture during a succeeding Tertiary phase of erosion, and on glaciation and submergence have formed N. W.—S. E. fjords usually much shorter than the main N. E.—S. W. fjords. The islands of Inugsulik Bugt, apart from a few very small remains of the older surface, form part of this immature erosional surface (Fig. 21).

After extrusion of the volcanics of Svartenhuk and Disko, a renewal of denudation cut through thousands of feet of these Tertiary formations and quickly deepened the pre-Tertiary valley system. This post-Tertiary uplift must have been fairly rapid for the valleys are not widened. It was probably accompanied by increased precipitation, itself the result perhaps of elevation. Such elevation cannot have been contemporaneous with the Tertiary volcanism, since the whole formation of that period had time to consolidate and be eroded, and the gabbro and doleritic dykes, believed to be Tertiary, though not certainly so, are all eroded even where the ice-sheet did not pass. It is a possibility, indeed a likelihood, that this elevation and increase of precipitation may have been associated with the onset of the Pleistocene, and were responsible for the formation of the Greenland Ice Cap.

With the onset of glaciation the ice-sheet extended into and along these valleys. It submerged the islands of Inugsulik Bugt imposing upon them a rounding which contrasts with the angularity of the high ground of Holms Ø and Nûgssuaq (Fig. 18). It can be said that the

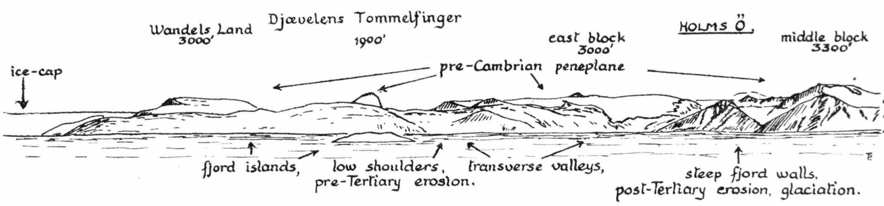

Fig. 19 A.

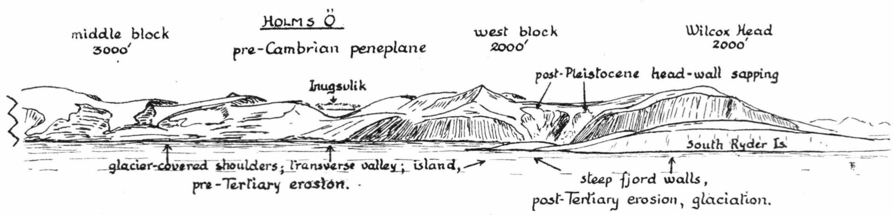

Fig. 19 B.

Fig. 19. Panorama East to South from North Ryders Ø.

pre-Cambrian surfaces, in this district at any rate, were generally left as nunataks or were covered by small carapace sheets like that of Wandels Land today, while the pre-Tertiary and post-Tertiary surfaces were glaciated. The figures 17, 18 and 19 show how the top of Djævelens Tommelfinger, Wilcox Head, the three major heights in the east of Holms Ø, and the western end of Nûgssuaq are not smoothed off. The rounded character of the 3000 foot pre-Cambrian peneplane on Nûgssuaq peninsula (Fig. 17) is most likely the result of carapace sheet protection and peripheral, subaerial nivation and solifluction. Ice probably lay over the shoulder of Wilcox Head as a carapace sheet falling to the main sheet lying in the fjord below. Plate XVIII shows the two inner blocks of Holms Ø, still covered by small carapace sheets, retaining the original plateau form while the walls of the pre-Tertiary erosion valleys in the northwest face are steeply eroded. Figure 18 shows a U-shaped valley high above Allison Bugt on the north side of the inner block of Holms Ø. It is likely that the topmost layers of the main ice-sheet here met the carapace sheet of the block and were diverted, scouring out this "hanging valley", peculiar in that it "hangs" at both ends.

Passing down into already deepened valleys the glacier excavated them even further, and was especially active in steepening valley walls (Fig. 21). Those valleys of N.—S. strike lying athwart the main flow were submerged but little affected. Joint faces were cleaned and scree rapidly removed as can be observed today around the nunataks of Melville Bay. Joint weathering was especially active above the surface of the sheet where it came alongside steep valley walls, the end result being huge palisade faces, of which the best examples are Sandersons

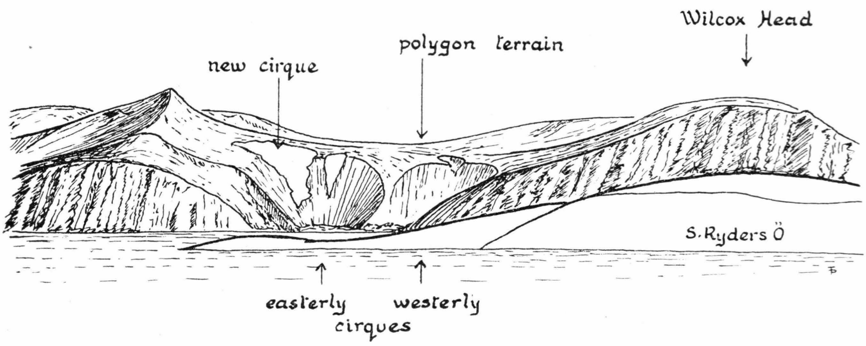

Fig. 20. Cirque forms on Wilcox Head, (1937).

Hope, and Kap Shackleton (Plate 10), both over 2000 feet sheer from the sea. Mural jointing with its annual scaling was also probably very active.

The extension of the ice-sheet cannot certainly be defined. It did not reach west as far as Edderfugleøer, but it covered the Inugsulik Bugt islands and possibly South Ryders Ø. From this limit it calved its many icebergs which carried morainic debris to be deposited on the sea floor further south or locally on Edderfugleøer, then submerged. This debris contained rounded as well as glacially-faceted boulders so it may be assumed that exposed land lay to the north east where nivation was active. There is further evidence for this exposure of land.

In Figure 20 are shown two cirques in the north face of Wilcox Head. The head walls are steep, the form circular (except where later sapping on the top of the wall has commenced) and the floor grades to about 2—300 feet above sea level. In the easterly a large snow bank lies on the S. E. part of the wall and appears to have worked its way back as a subsidiary cirque into the old carapace ground behind. In the westerly cirque erosion from the carapace ground has cut into the wall near its middle, and in this fluvial hollow a snow bank appears to be working back, though not so far as the easterly. It should be noted that most of the snow banks on Holms Ø face eastward and northward and those which do face westward and southward are generally smaller. Yet it is the westward facing bank in the eastern cirque which appears

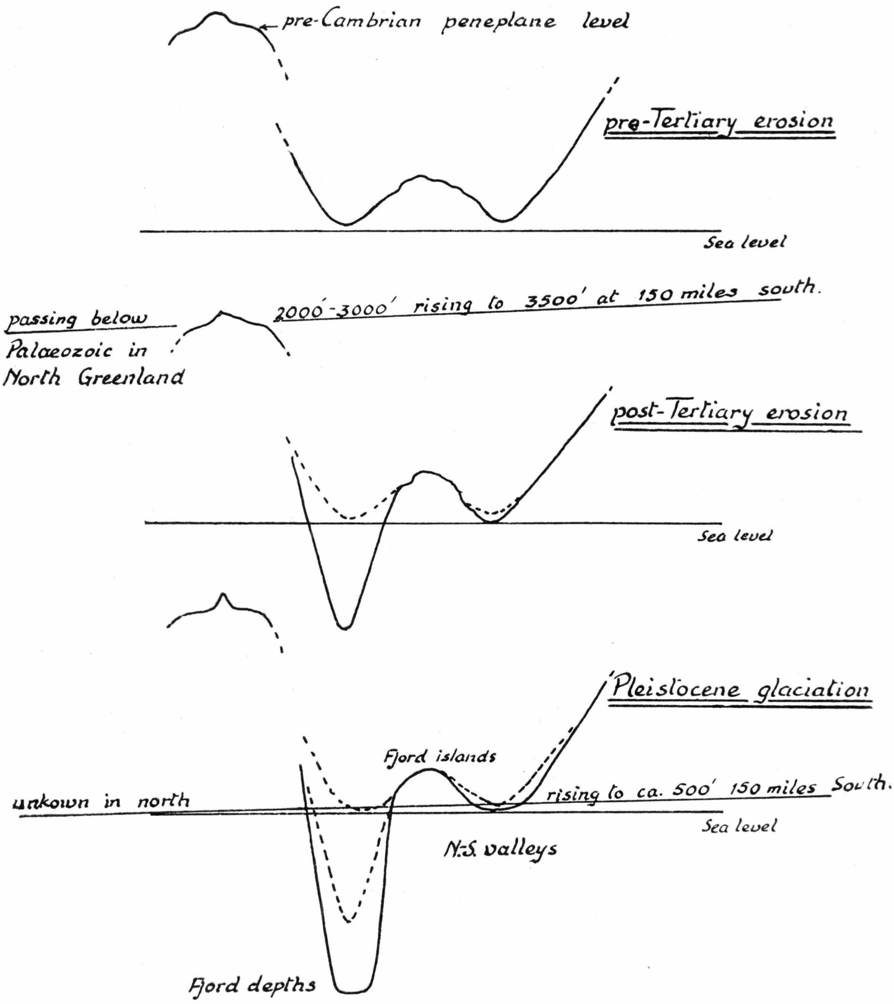

Fig. 21. Sequence of Denudational Cycles.

to be more active in rock sapping. A tentative conclusion is that in this latitude the westward facing banks commence melting earlier than the eastward and therefore the spring-early summer nivation process may be more extensive in time.

A second point is the existence of the wall between the cirques, which are themselves flanked by big palisade faces, presumably steepened by former expansion of the ice sheet. It is surprising that this inter-cirque wall should be unaffected by the same ice sheet. It may be that both cirques have been formed in post-glacial times. If this is so, then more cirques would have been developed in other parts of Holms Ø. They are developing at present on the flanks of the mountain top to the immediate S.E. but not nearly to the same extent; for the active snow banks are much in the same stage of wall sapping as the secondary cirque bank above the easterly of the sea level cirques. Whether these sea level cirques were formed during glacial extension or in preglacial times the presence of the inter-cirque wall suggests that the ice sheet did not submerge the cirques. Therefore land must have been exposed during the maximum ice sheet extension which cannot have been of great magnitude, for at the longitude of the cirques the sheet was less than 200 feet thick.

If the assumption is correct that these cirques were formed during the period of extension of the ice sheet, that is when the Edderfugleøer were submerged, then cirque formation was proceeding at sea level. If however the cirques were formed in pre-glacial times (the intervening wall being unaffected by the low level limit of the ice sheet during glacial times) then it must be assumed that the land stood higher than the present, and this would account for the rapid post-Tertiary erosion cycle. Such a process would also account for the great cirques at low level which can be found in most west Norwegian fjords, for instance opposite Vadheim in Sogne Fjord. They were first developed during a pre-Pleistocene period of low marine level, then extended during the Pleistocene at those times when they were not ice-submerged.

If the top layers of the ice sheet at maximum extension formed the double hanging valley at the innermost end of Holms Ø, and sloped to nearly present sea-level at the eastern end of Holms Ø, the gradient of the surface would not be much different from that of the present sheet in Melville Bugt. This distribution would thus account for the deeply cut northern walls of the middle block of Holms Ø, (Plate XVIII), which show glacial action on the lower part and subaerial denudation in the upper. The same photograph shows how nivation and joint weathering have cut out angular mountain tops from the pre-Cambrian peneplane.

The small carapace sheet on Wandels Land is surrounded by a field of boulders derived from the local rock, and where solifluction on the slope has removed this cover mural jointing is active. It is likely that the great boulder field on the shoulder of Wilcox Head above the cirques, is the product of a similar carapace sheet which lay there, and that subsequent nivation has led to comminution, mud formation and finally polygons. These fields are also common fringing similar carapace sheets on Baffin Land, and where one meets these high level boulder fields now free from snow or ice it may be assumed that here at one time lay a carapace sheet, either an original isolated sheet by itself, or the remnant of former extension of a main ice sheet. It is suggested that the great expanses of "head" in southern England fringing the limits of the Pleistocene ice-sheet, are the products of similar carapace sheets acting upon soft sediments and flint. The presence of these carapaces would also account for radial drainage by coombes on several Chalk areas, as for example at Royston in Hertfordshire.

On retreat of the ice the land was elevated. The pre-Tertiary erosion surfaces, now about sea level or a little above, appear to rise southward in West Greenland where the N.—S. cross-valley bottoms are higher and of the order of somewhat less than 500 feet. This is not such great tilting as that of the pre-Cambrian surface, therefore it must be supposed that the tilting commenced in pre-Tertiary times, possibly associated with the elevation that led to dissection of the peneplane, and continued in post-Tertiary times, most likely into the Pleistocene. These are tentative opinions, and would require for verification much investigation of land forms which would be impossible until the Greenland coast has been completely mapped on the new 1 : 250,000 scale.

It may be that the tilting is due to differential isostatic recovery and that the ice load in this latitude is greater than in West Greenland. In this latter area there are several raised beaches to a height of over 500 feet. Here in the north only one beach, the 25 foot, has been noticed so far. It may be of course that elevation has been rapid and the lack of sediments and soft materials did not allow recording of any stadia of retreat. Ice foot nivation has not been able to form beaches. The uplift continued until the 17th century at least and, at a time subsequent to that, there has been a downward movement, for a 17th century house ruin on South Ryders Ø is now being washed by waves. Since the removal of the ice joint-shattering and solifluction have been rapidly denuding the exposed rock, as demonstrated in the previous study. The glacial moulding is preserved by nivation and the oversteepening on palisade walls is continued by joint fracture.

4. A NIVATION THEORY OF CIRQUE FORMATION

The preceding studies have demonstrated the importance of the phenomenon of nivation which, despite the origin of the word, is essentially a process concerned with the growth and melting of ice crystals within rock interstices, and as such has little to do with snow itself except in that the snow-bank provides part of the water from which the ice crystals are developed. Most of the water providing ice crystals comes by hydrostatic movement from a deeper frozen level in the rock, the permafrost layer, the water moving outwards to the region of freezing and thawing and forming crystals perpendicular to the surface due to cooling from that direction.

The action of this process in developing rock steepening in the ice-foot zone has been demonstrated theoretically in the discussion of Figure 6. The importance of this process in a consideration of the cirques on the northern flanks of Wilcox Head, Figure 20, becomes immediately apparent. There, two large cirques with their bases at low level are free from snow and ice but in the upper parts of their head walls, which are about 1,000′ high, snow banks have established themselves and have cut back producing arcuate hollows which appear to be the beginnings of cirques at a new, and higher level. To put it roughly we see here the result of a climatic change, the heightening of the level of cirque excavation. The hollow in the westerly of the main cirques was fi:st excavated by fluvial erosion of the cirque rim so it is assumed that the snow banks in the eastern cirque were able to establish themselves in comparable hollows. Presumably the run-off from the northerly aspect of the shoulder of Wilcox Head has found the descent into these cirques as the only possible escape route. It is most likely that the two main cirques also commenced by excavation of fluvial hollows the result of drainage of that shoulder at a previous, perhaps pre-glacial, period. In other words the process is repeating itself in this apparently post-glacial phase.

Nivation under snow banks, as shown on Amdrups Ø, will take place wherever an interruption in the profile of the valley side allows of snow lying into the summer period. Such hollows and interruptions of the profile may be developed by differences in the rock structure (and therefore differential weathering) as shown particularly in this region by the long lines of snow banks along the strike of the Archaean sediments.

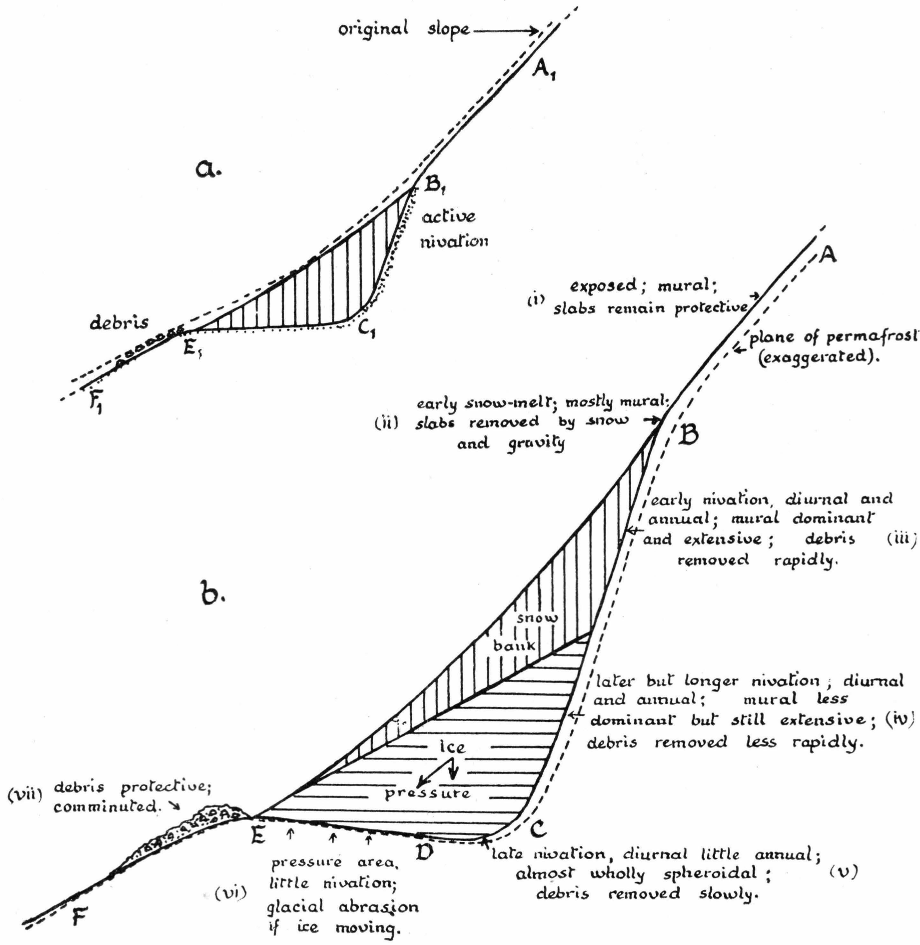

Fig. 22. Illustrating the Nivation Theory of Cirque Formation.

On Djævelens Tommelfinger and its neighbour to the east some slopes have the appearance of a striped football jersey for there nivation, proceeding in the same fashion as that on Amdrups Ø, has accentuated the outcrop of the sediments.

A nick in the profile is usually produced by headward fluvial erosion and the level at which the snow banks form is dependent upon the position of the snow line. For purposes of discussion we may assume in Figure 22a that in such a profile nick, or rock hollow, nivation has proceeded as far as stage 4 in Figure 6. During early spring the snow melts quickly in the region A_1 to B_1 exposing the rock to solar radiation. Nivation is therefore early and, since the water supply on the surface is reduced, spheroidal nivation is small in extent. But water can be derived from the permafrost level and annual nivation will produce mural disintegration, as can be observed where the rocks ring hollow to the boots. These slabs however remain in position and protect the rock from further disintegration except where penetration along joint cracks leads to major frost heave of these slabs, sometimes a foot or more, when the process is accelerated. As in Figure 6 spheroidal and mural nivation but principally spheroidal will develop in the region B_1 to C_1. If the snow bank is not too large and therefore heavy, the melt water at the snow-rock interface will be able to penetrate below the bank and emerge beyond E_1. Therefore nivation can take place in the area C_1 to E_1, but since the pressure of the snow will close the route outwards and tend to preserve the temperature close to freezing point and thus inhibit melting of the rock water to any depth, there will be no nivation other than spheroidal.

The debris so produced, either falling from the rock face above the bank or incorporated into the snow bank and washed away by melting, will tend to collect in front of the snow bank as a low ridge of fine material. This debris cover serves to protect the rock at that point since the melting does not penetrate far; and nivation will act further in comminuting the rock spalls almost to a mud which often can be seen pouring away from the mound of snow bank debris.

Where this type of nivation hollow is still further developed, Figure 22b, and in a climate which is conducive to preservation of the snow-bank throughout the year, ice will form as permanent glacier ice on the floor of this L-shaped excavation. During the winter snow will pile up upon this ice and extend far up on the mountain side, lasting longer into the summer on account of the absorption of latent heat by the subjacent ice. The angle of slope of the ice is probably no more than 30° according to observations of the very few cirques to be seen on Baffin Land in the same latitude, and of the cirques in Ellesmere Land. The angle of rest of the snow-bank in early spring, according to photographs of Greenland and of these above mentioned regions, can vary up to as much as 70°. The steep slopes of snow-plastered rock walls in the Himalaya, the Alps and the Jotunheimen are more generally known.

As in Figure 22a the region AB loses its snow cover early and is subjected to little spheroidal nivation but to some mural, being protected by the debris so produced. Towards point B this debris in slabs and scales is removed rapidly by gravity owing to the steeping of the declivity and the lubricant effect of deeper snow in the melting season. Therefore below B the denudation will quickly increase and becomes extensive in the region B to C.

In the upper part of B and C, against which snow alone lies during part of the year, nivation will commence early owing to the melting of the snow, to the passage of this meltwater at the snow-rock interface, and to circulation of warmer air against the rock. During the day the latent heat of the meltwater is absorbed by the rock thus leading to melting of interstitial ice. At night this freezes and, especially during the beginning of the season, spheroidal nivation takes place. Towards the end of the spring nivation period the latent heat supplied to the rock is greater and penetration therefore deeper, leading to mural nivation. In the autumn the first freezings will draw water towards the surface away from the permafrost level and mural nivation will again occur. The scales, blocks and slabs so produced will fall on to the ice below and down into the bergschrund there to be incorporated into the ice and thus transported away. This accounts for the fact that there are two seasons of the year when rock falls are commonest, in the spring after melting of the snow banks, and in the autumn during the first freezings, though the latter is less extensive and its effects are partly shown in next spring's discharge.

In that part of the region BC against which the ice rests much the same process will occur. However, owing to the greater amount of heat required to melt the ice, and its protection by the snow-bank, the nivation will commence at a later period. Although melt water in percolating downward assists in thawing the outer layers of the rock, protection by the snow and ice does not permit of the circulation of warmer air, nor of exposure to the sun, as in the region A to B. Nevertheless by reason of this protection the process of diurnal nivation will proceed for a longer period during the annual season. It would be expected therefore that mural nivation is not so prominent here as it is in the upper part A B, though this does not imply that the process is any the less active throughout the total season. Indeed it may be more active and cut back more rapidly, on account of the longer period during which nivation is active. Air can also circulate down the bergschrund more easily during this later period, and the near presence of ice will assist the night time cooling by the atmosphere. Annual fracture leading to mural nivation will also be prominent and more extensive in its final effect than spheroidal nivation. The blocks and slabs so produced fall off and freeze into the ice across the bergschrund or, during winter in closing of the bergschrund and with snow passing into ice, the shattered rock will be plucked away by the ice thus exposing more of the rock to the next year's nivation. Hence it follows that denudation will be much more rapid along BC than along AB. These steep head walls of cirques, sometimes as much as 2,000′ high, break off in large slabs, as observed in Baffin Land and in a magnificent cirque east of Godhavn on Disko in West Greenland.

Some of the melt water on the ice-rock interface will be able to penetrate during the summer between the ice and the rock on the floor at the region CD. Here pressure of the ice keeps the temperature of the rock surface about 0° C., and the penetration of some melt water will lead to thawing of the rock face (the absorptivity of the rock is greater than that of ice) and hence spheroidal nivation will occur. But owing to the relatively limited period during which this can happen, and also because there will be little or no annual variation, the amount of disintegration is small. Moreover gravity cannot assist in removal of the debris and the amount of transport by the ice at this part is a minimum. Hence the rock surface will be protected to some extend by the fractured rock.

Beyond D towards E meltwater, should it penetrate, freezes immediately and therefore we would except that no nivation will occur in some regions between D and E. However, if the ice pressure is increased water will melt below the ice and other meltwater be circulated; and if the pressure is then released the water will freeze at once. This process of freeze and thaw will lead to slight spheroidal nivation of no great consequence since the pressure changes due to movement are small, and those due to excess of snow are annual, and being slow there is sufficient time for adjustment of the temperature-pressure relation and the ice-water equilibrium.

The debris resulting from nivation on the steep head wall and removed by the ice, will collect at the snout of the cirque glacier on the region E to F. This is a very frequent phenomenon and can be said to be part of the cirque structure. As on West Edderfugleø where debris has protected the rock from ice-foot nivation so this cirque-debris protects the rock from disintegration. The amount of penetration by meltwater, or of melting of interstitial ice, might be such that the solid rock is not attacked at all, but that nivation will act upon the debris itself reducing it in coarseness. Towards F the debris will be thinner and the rock will be more strongly attacked by nivation. If the cirque is providing a moving glacier, passing over the lip E to F and proceeding down the valley, the surface will be protected in the same fashion as in D to E. But there denudation will take place on account of abrasion assisted by the inclusion of angular debris in the base of the ice.

The above considerations may be looked at from a different point of view, the movement of the plane of permafrost. During the winter months and those periods of the day when the air temperature is below freezing point the permafrost level will move towards the surface. If the rock is sufficiently exposed to water the permafrost plane will be coincident with the surface. Consider the interrupted line in Figure 22b which illustrates in an exaggerated fashion the relative position of the permafrost plane at the periods of most active nivation for the particular region of the rock profile given. Thus the position for the region AB will be reached earlier than that for BC and CD. Therefore the position of the interrupted line is not simultaneous throughout its length but is valid for purposes of discussion.

In early spring the rock face AB will be exposed to solar radiation during the day time and the permafrost level will retreat. Since there is also exposure to circulating air and a good run-off the rock surface will be comparatively dry, hence on night cooling the water forming ice crystals will be in the major part derived from the permafrost level which has been driven fairly deep. At a later part of the season, and due to percolation of the run-off from AB, the permafrost plane behind the snowbank and the ice retreats, earlier in the upper regions owing to earlier exposure, but on the whole sufficiently deep to allow of mural nivation. Progressively lower, towards the point C, the permafrost plane will be less deep and spheroidal nivation will be more active though as a result of bergschrund deepening, and therefore greater circulation of water and air, the permafrost level recedes sufficiently to allow mural nivation. This is the lowest limit of the mural effect.

If D be the point of furthest limit of percolation of melt water, that is, where the melt water refreezes, then between C and D the permafrost plane will approach the surface of the rock and spheroidal nivation will be the only form of denudation. If the cirque ice is large and thick the bergschrund may not penetrate to the level of the lowest limit of the ice. In such a case circulation of air will be inhibited and finally stop, and only meltwater will penetrate to the base of the ice. Therefore downwards mural nivation will decrease more rapidly the thicker the ice. In such a case the form of the wall will be different from that drawn in the figure since the head wall at the bottom will not be sapped so rapidly as that further up, and the final result will be a much wider concave base to the L of the profile. It is in this manner that the bergschrund controls the formation of part of the cirque and otherwise has only a contributory effect in the total process of head wall erosion.

At point B there tends to develop an angular contact between the two regions of differential nivation AB and BC. But since the ice crystals grow perpendicular to the surface there will be, in the vicinity of B, a component set of capillary pressures set up by junction of the two regional planes of cooling, and hence the surface of the permafrost and of ice crystal formation above it will be arcuate. This will off-set the tendency to angular junction and will produce a smooth profile of the back wall passing into the line of the original surface above.

Since the pressure of the ice or bank keeps the temperature at 0° on the floor of the cirque permafrost will be coincident with the rock surface between D and E. Any oscillation around this temperature (owing to decrease of pressure for example) will be slight, the permafrost level will move very little and nivation will be at a minimum.

Beyond the limits of the cirque ice the mound of debris ejected by the ice may be of such thickness that the plane of permafrost may actually lie beyond the rock surface, and in the debris itself. However, if the debris is loose and water can percolate, then in the later part of the season it is likely that the plane of the permafrost will recede and allow of some spheroidal nivation, but not mural. If the seasonal variation in the extent of the ice is large it is possible that the debris cover is pushed further downhill or even washed away exposing the rock, in which case mural nivation will take place.

Since the region of minimum nivation lies between points D and E a ridge of rock will be the result with a hollow on the floor on the inner side between the ridge and the head wall. The importance of the pressure of the ice or snow in determining this region of minimum nivation brings up the question of the point at which the pressure will be a maximum. It would be expected that the region immediately below the centre of gravity would be this point, and if the gradient of cirque ice is no more more than say 30° (an observation on cirques in other parts of the Arctic) then this point will not be far out on the basal limb of the L. However, because of the heterogeneous distribution of the ice about this centre of gravity there will be a component of pressure directed outwards which in fact shows itself in arcuate planes within the ice, the upper layers tending to slide over the lower layers as the former move outwards (see arrows in Figure 22b). Owing to the rising sill beneath, these arcuate glide planes will in the end be directed upwards and outwards at the limits of the ice.

The pressure will be increased by weight of the snow-bank during the early part of the season, and therefore during this period will be directed on to a point outwards from that immediately below the centre of gravity. Hence as the season proceeds meltwater penetrating further below the ice will be frozen and halted progressively nearer to the head wall for, as the pressure of the snow bank is removed, the component vertically directed from the centre of gravity becomes greater. Beyond a certain thickness of ice in the cirque it is doubtful whether arcuate glide planes can develop and the ice, under the extra weight of snow, will tend to move as a whole and therefore scour the surface of the rock base, aided by the embedded debris from the nivation process.

The total result will be a steep head wall scaling rapidly backwards into the mountain side, passing downwards in an open L-shape into a hollow, "down at the heel" form (according to JOHNSON) then rising into a sill, the hollow representing the total downward effect of nivation —and also of glacial scouring if the ice has reached sufficient thickness. In other words the cirque cuts backwards but very little downwards. It is possible that during a period of retreat of the snow level, when the precipitation cannot replace the annual ablation, a small snow bank or ice remnant in the hollow at the base of the back wall will tend to deepen the hollow still further.

The cirque may have begun in a hollow of irregular outline, but as a result of the summation of the process described under the section on boulder rounding (Study No. 1), these irregularities will be evened out, angles will be destroyed and the final form must approach the circular as being the optimum for distribution of the plane of perma-frost and of capillary pressures within the rock. Therefore it does not matter much in what form the cirque has begun it will end, provided it is given sufficient time, in the arcuate. In this it differs from the nivation hollow of the ice-foot zone which must necessarily be longitudinal because of the annual recurrent longitudinal distribution of the ice-foot.

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PLATES

Plate I.

Lille Inugsulik. Spheroidal nivation in the ice-foot zone in the foreground. Mural nivation left centre.

Plate II.

West Edderfugleø. Mural nivation in the ice-foot zone. To the right protection by debris raising the permafrost level and inhibiting nivation. Foreground roughening of the surface the result of ice crystal growth in mural nivation.

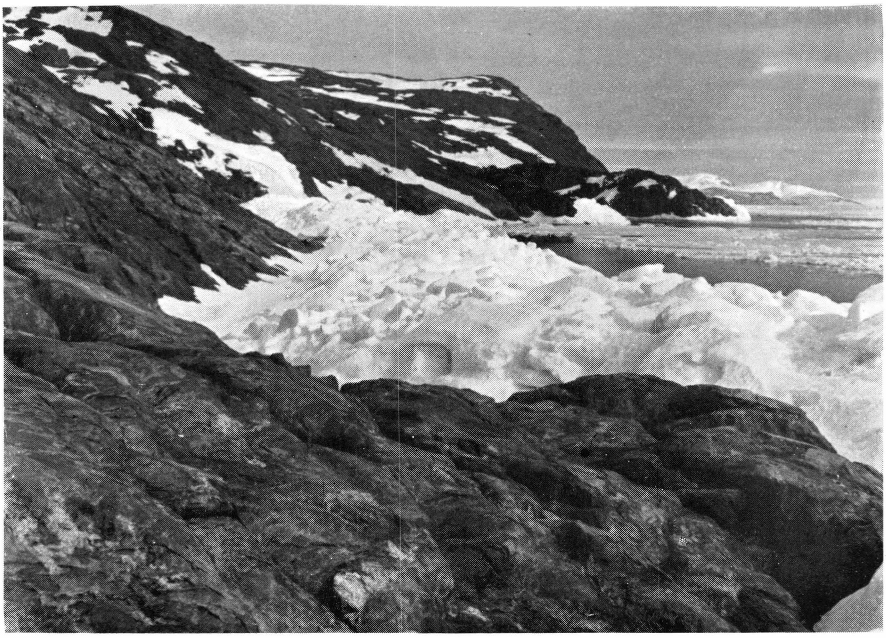

Plate II

Plate III.

South Ryders Ø. Rock basin scaling parallel to the rock surface on the left; protective debris covering on the bottom. Note absence of debris on surrounding rocks.

Plate IV.

Amdrups Ø. A 20′ wall in a strike face cut by mural and spheroidal nivation and by joint weathering. Large smooth solifluction slope with stone stripes and no arborescent channeling.

Plate III.

Plate IV.

Plate V.

Amdrups Ø. Boulder rounding; snow still lying on a steep scree slope; angular boulders to right, sub-angular to left.

Plate VI.

Amdrups Ø. Boulder rounding, angular to right, sub-angular to left, solifluction towards the shore.

PLATE V.

PLATE VI.

Plate VII.

Middle Edderfugleø. Joint system, 15° N. of W., 30° W. of N. and 30° S. of N. Melt water collecting along joint cracks; scaling along E.—W. joints at top; foliation scaling with joint fracture to left producing fine debris.

Plate VIII.

Middle Edderfugleø. Spheroidal nivation and joint weathering in a biotite schist. Most rapid weathering along dip joints.

Plate VII.

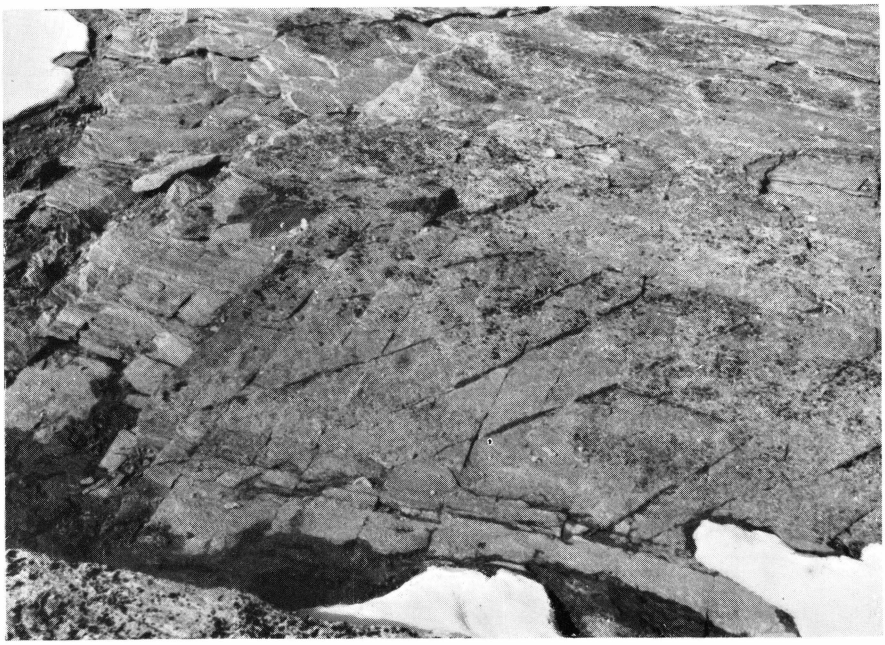

Plate VIII.

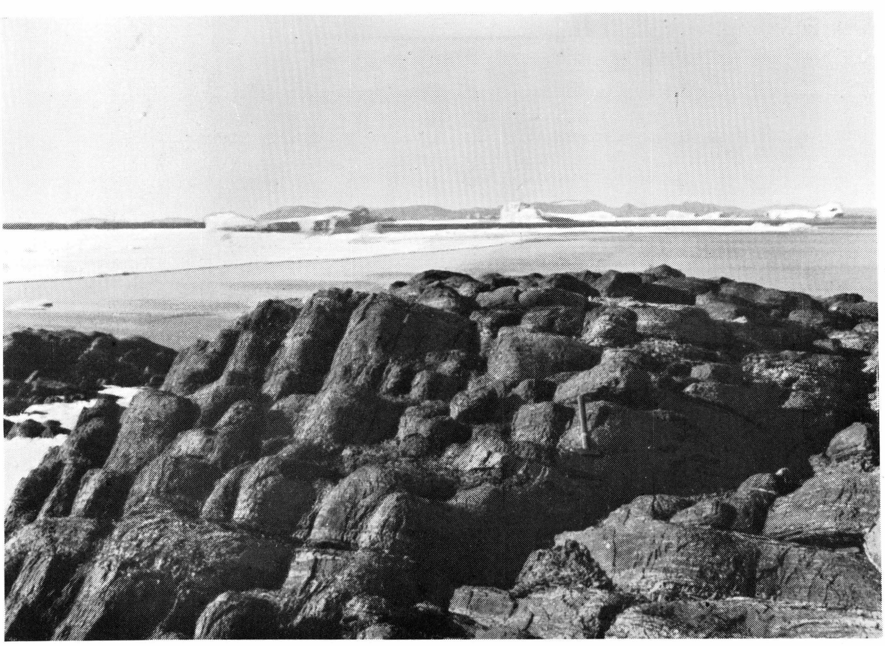

Plate IX.

Middle Edderfugleø. Biotite schist of Plate VIII; extension of dip joint weathering into five major blocks, facilitated by nivation under snow banks in the dip joint crevices.

Plate X.

Sandersons Hope. Joint weathering on a large scale, most extensive along a major joint extended by preservation of a snow bank therein and consequent nivation.

PLATE IX.

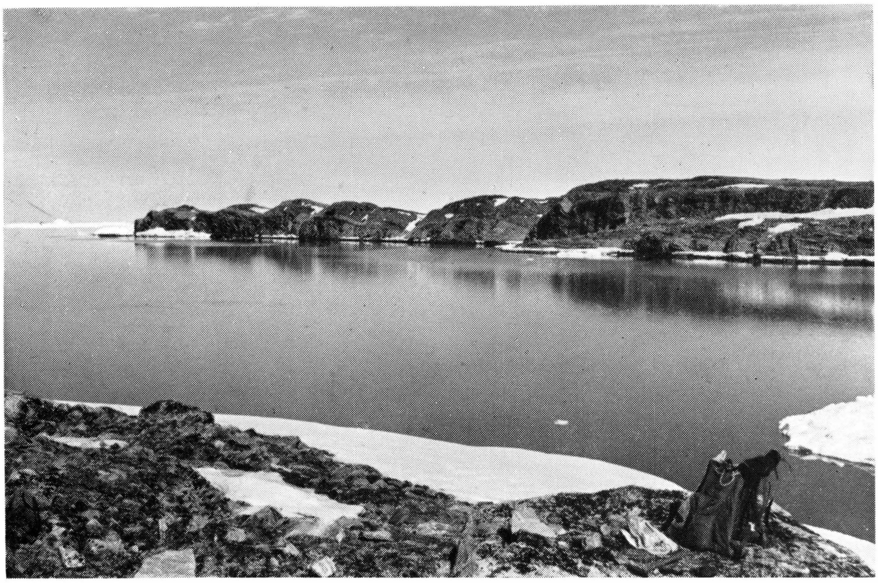

PLATE X.

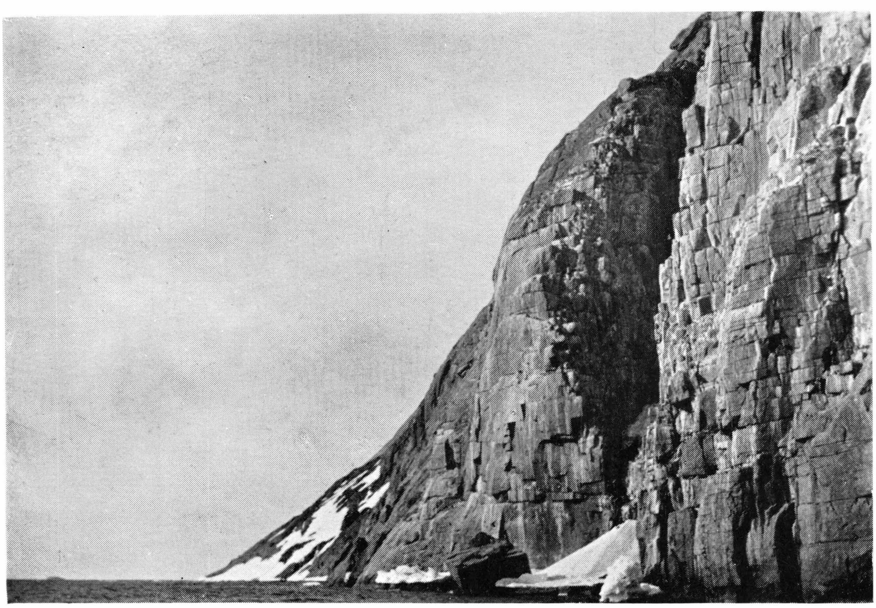

Plate XI.

Wilcox Head, Holms Ø. Stone slide on the southern scree slope showing the junction of stable lichen-covered scree and the fresh, freely-rotated boulders of the slide.

Plate XII.

East Edderfugleø. Showing stone stripes, removal by ice foot action, and to the left of centre, a mass of mud and stones actually sliding on to the ice-foot snow bank.

PLATE XI.

PLATE XII.

Plate XIII.

East Edderfugleø. Solifluction slope showing stone stripes moving on to the beach connecting the two halves of the island. Ice-foot steepening is well marked on the northerly coasts.

Plate XIV.

Qârusulik. Circular shingle polygon. Camera case just above the centre is 7″ long.

PLATE XIII.

PLATE XIV.

Plate XV.

North Ryders Ø. Large stone polygon. In the background joint weathering of gabbro and spheroidal nivation of the angular corners. Boulders embedded in fine detritus. The rule is 1′ long.

Plate XVI.

West Edderfugleø. Remains of a frost-shattered and chemically disintegrated boulder of biotite schist. The slope in the background is a good example of smooth contouring of a dry solifluction surface.

Plate XV.

Plate XVI.

Plate XVII.

East Edderfugleø. Frost heaving in the foreground showing disruption of bedding and bending of strata. In the background snow bank nivation steepening rock walls.

Plate XVIII.

Holms Ø from South Ryders Ø showing small carapace sheets and steepened northward facing walls. (1937).

PLATE XVII.

PLATE XVIII.