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THE GEOMORPHOLOGY OF DRONNING LOUISE LAND

BY

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WITH 33 FIGURES IN THE TEXT

KØBENHAVN
C. A. REITZELS FORLAG
BIANCO LUNOS BOGTRYKKERI A/S
1957

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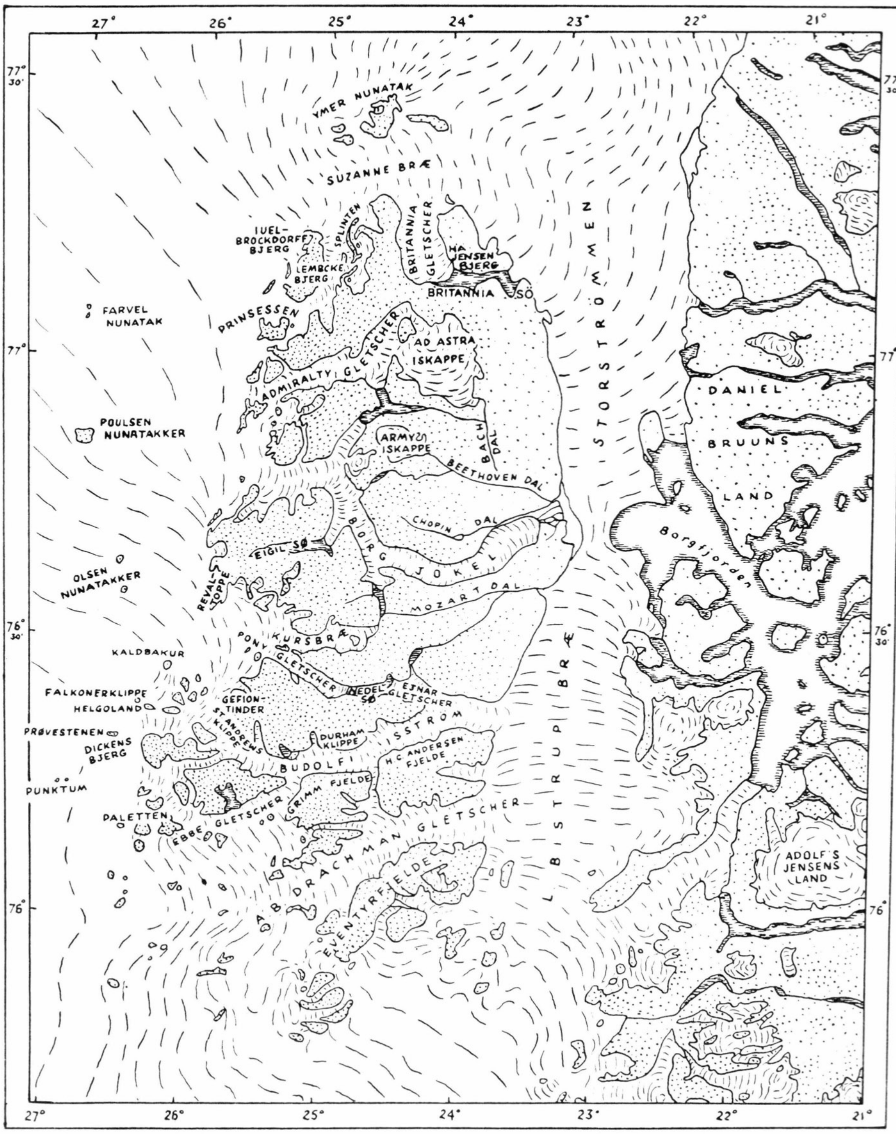

DRONNING LOUISE LAND

(from 1:1,000,000 U.S. World Aeronautical Charts)

STATUTE MILES
0 10 20

Fig. 1.

SUMMARY

The solid geology and morphology of the landscape is described and a hypothesis of the process of advance and recession of the ice is postulated. Stages of glacial recession are constructed in north Dronning Louise Land and approximate dates given to these stages.

INTRODUCTION

The completely natural landscape of Dronning Louise Land has been subjected to the action of ice on a grand scale. The features of erosion and deposition over the geologically very old rocks of the basement lend themselves to a Davisian approach. The classic treatment of the geomorphological cycle of Structure, Process, Stage has been adhered to.

ACKNOWLEDGEMENT

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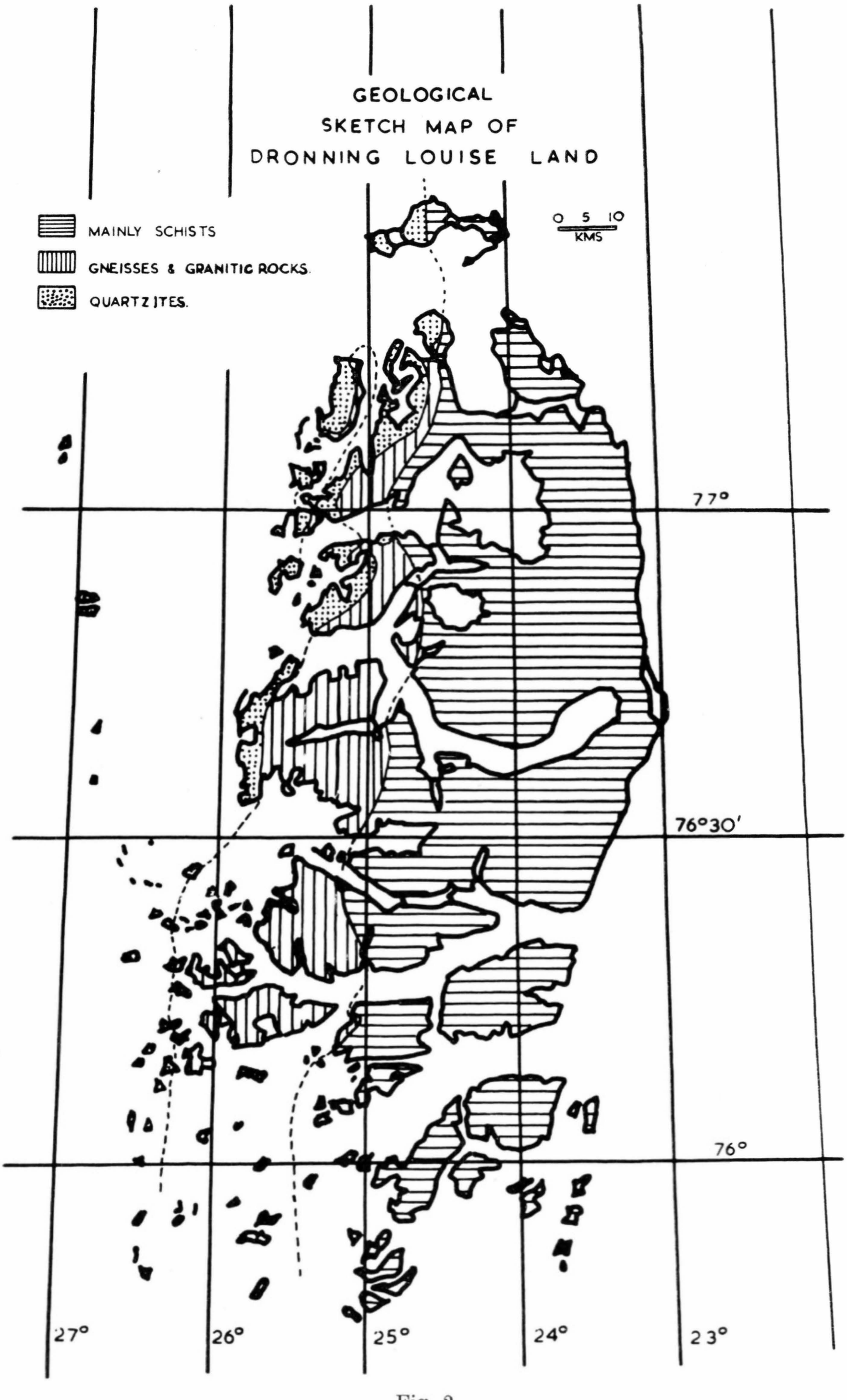

GEOLOGICAL
SKETCH MAP OF
DRONNING LOUISE LAND
MAINLY SCHISTS
GNEISSES & GRANITIC ROCKS
QUARTZITES
0 5 10
KMS
77°
76°30'
76°
27°
26°
25°
24°
23°

Fig. 2.

POSITION AND BOUNDARIES OF THE AREA INVESTIGATED

Dronning Louise Land is a deeply dissected upland near the north-east coast of Greenland between latitudes 76° N. and $77^1/_2$° N. (figure 1). The land extends approximately 160 km north to south and 60 km east to west and is isolated from Germania Land and Dove Bugt to the east by two 30 km wide glaciers of the inland ice, Storstrømmen flowing from the north and L. Bistrup Brae from the south. The Borgjökel flows approximately west to east cutting Dronning Louise Land into two halves; the southern half is slightly higher, with Alpine type mountains one of which reaches 2,700 metres. In this geomorphological study, Dronning Louise Land is considered as a whole and in relation to the glaciation of Greenland. In north Dronning Louise Land a detailed study is made of one area having characteristics typical of the whole of Dronning Louise Land which permits the reconstruction of five stages of recession.

Entity of the region.

Dronning Louise Land is a large, composite nunatak, the general surface of which rises steeply from 300 metres in the east to the fairly flat 2,000 metre summits of the north to south mountain range in the west. These mountains dam back the inland ice, and glaciers that flow between the mountains in steep sided valleys ribbon the land from west to east. The glaciers dominate the topography and with two small ice caps and many ice-dammed lakes are the principal features of this dissected upland. Scree slopes merging downwards into outwash fans, aggrading streams, and here and there tiny patches of arctic vegetation complete the picture of Dronning Louise Land.

STRUCTURE—GEOLOGY

Compositional variations.

Dronning Louise Land is composed of Precambrian rocks (figure 2) (Peacock 1956). The eastern half of the region is formed of paraschists and orthogneisses, with north—south strike and steep easterly dips; some cliff exposures show isoclinal folding. Throughout the western half of the region, there is a north—south zone of sheared gneisses, granitic rocks and migmatites, believed to be of Archean age; foliation, when present, generally dips to the east. A series of quartzites, of Greenlandian age and low metamorphic grade, lies with marked unconformity on these basement rocks and dips gently westwards beneath the ice sheet; in the north-west these slightly metamorphosed sediments have been sharply folded. The western metamorphosed sediments and the basement gneisses have been intruded by a series of wide, quartz-dolerite dykes and sills, which also strike north—south. The quartzites and granitic rocks are generally more resistant to erosion than the schists; the quartz-dolerites are yet harder.

Structures.

The dominant grain of the region has a north—south trend. The mountains, particularly the most westerly range, have a north—south direction. Strikes were not recorded throughout the region but 115 strike measurements were made in the area north of the Borgjökel. This area was arbitrarily divided into 29 approximately equal units and the calculated strike directions plotted in figure 3. Analysis of these rock strikes measured north of the Borgjökel indicates two ranges of bearings, included in which are concentrations of average strikes. This suggests that there are at least two major structural directions within the region.

Joints.

Under arctic conditions the most destructive process is rock weathering by mechanical disintegration caused by temperature fluctuations about the freezing point of water. Joints give easy access to meltwater

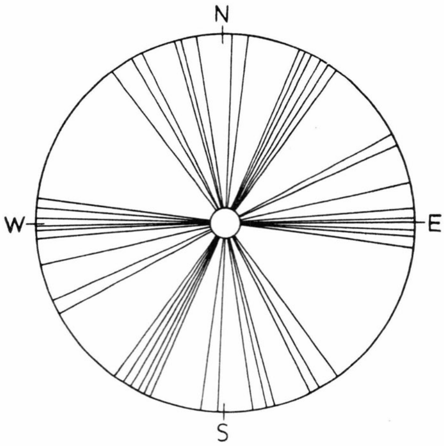


Fig. 3.
Rock strike directions in the northern half of Dronning Louise Land.

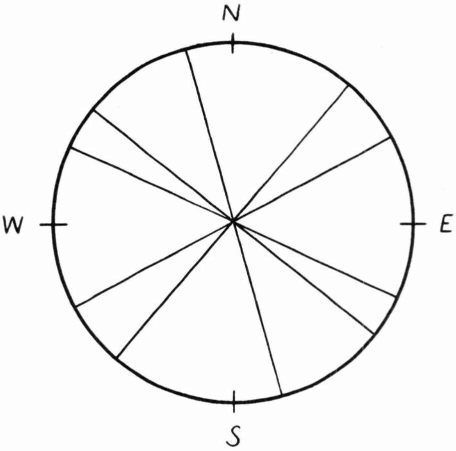


Fig. 4.
Major joints in the northern half of Dronning Louise Land.

and rock fragments are loosened by alternate freezing and thawing. Therefore the joint systems are likely to have a controlling influence on land forms. The poles of all joints measured in the northern half of Dronning Louise Land have been plotted on an equal-area net, and from it the five major joint directions have been obtained (figure 4). They are all nearly vertical.

Faults.

Since only few faults were found, each with small displacement, it is unlikely that faults have exerted much influence on the landscape. The morphological features must therefore be related to the established joint systems, structural directions and compositional variations of the rocks.

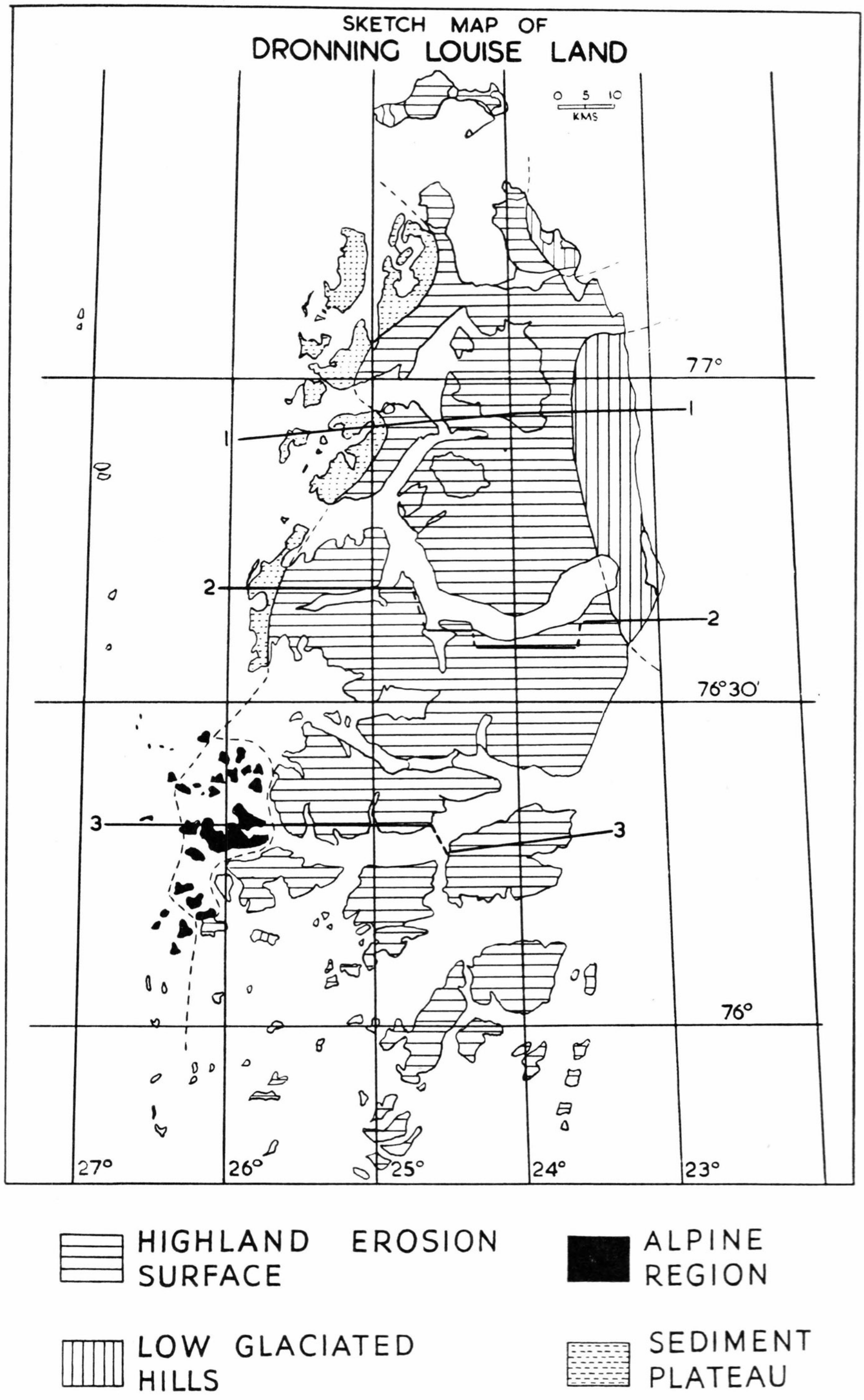


Fig. 5a. Distribution of morphological features. Cross sections 1, 2 and 3 are shown in fig. 5b.

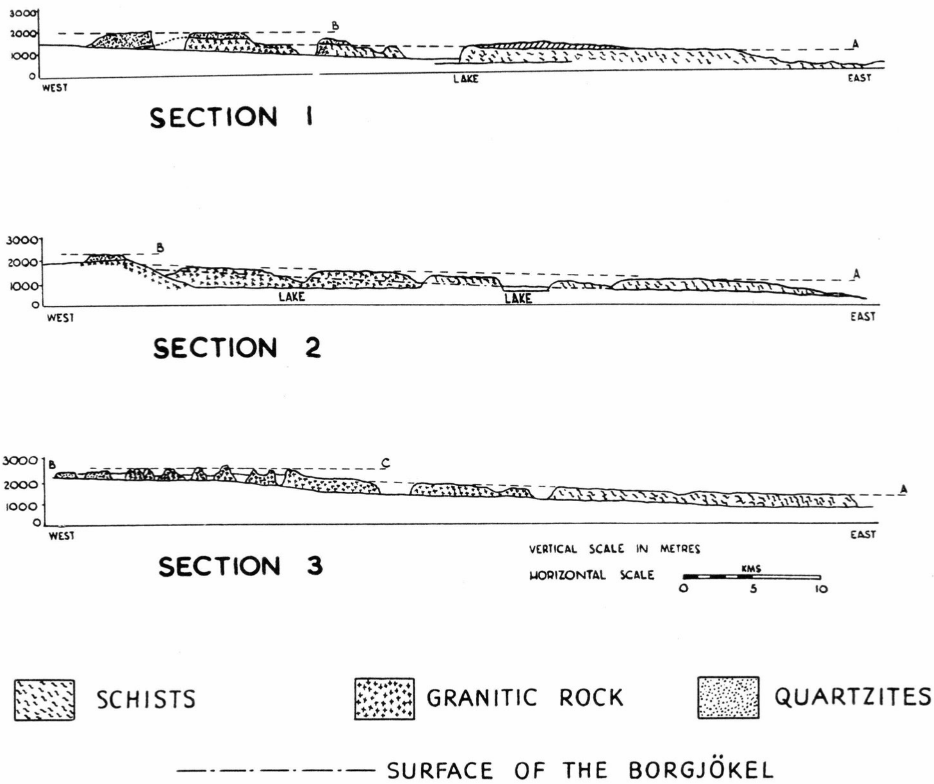


Fig. 5b. Cross sections through Dronning Louise Land (see fig. 5a).
A. Highland Erosion Surface. B. Sediment Plateau. C. Surface over Alpine Peaks.

STRUCTURE – MORPHOLOGY

Dronning Louise Land is a mountainous region surrounded by ice and traversed by several large glaciers flowing eastwards from the ice sheet (figure 1). The land rises from north-east to south-west, reaching heights of 2,700 metres above sea level. There are no higher mountains in west and north Greenland and only two mountain ranges in east Greenland have peaks rising to greater heights. Thus some of the highest mountains in the whole of Greenland are to be found in Dronning Louise Land.

Figure 5a shows the distribution of the four main morphological elements which are:—

1. The Highland Erosion Surface: a surface which extends over the greater part of the region.

2. The High Alpine Region: a relatively small area of alpine peaks and ridges in the highest land of the south-west.
3. The Sediment Plateau: this forms, in the west, a series of mountains with flat or gently rounded tops rising above the level of the highland erosion surface.
4. The Glaciers and Glacier Valleys: the upland surfaces are deeply dissected by large glaciers and glacier valleys.

The Highland Erosion Surface.

The highland erosion surface extends over large areas of the upland and slopes gently from the north-east (1000 metres above sea level) up to the south-west (1850 metres above sea level). It is remarkably level over considerable areas (figure 6) but exhibits, in many places, a rolling relief of about 100 metres. In the south-east, where the erosion surface extends to the L. Bistrup Bræ, the land is bordered by cliffs. In the north-east, this surface is replaced by low glaciated hills as the land decreases in height and passes beneath Storstrømmen (0 to 350 metres above sea level). The greater part of the erosion surface truncates the structures of the easterly dipping schists, but in its higher parts it truncates the relatively harder and more resistant granitic rocks. The general form of the surface thus appears to bear some relation to the degree of resistance to erosion of the rocks, if not specifically to geological structure. There are a few instances in the south-west where outcrops of the resistant quartz-dolerite sills and dykes are marked by low rounded ridges rising above the erosion surface. There are several empty corries cut into the surface (figure 7) and, to the south, their number increases as the surface increases in height. In the higher areas some corries are the source of small glaciers. Here, narrow ridges are occasionally produced between the headwalls of back cutting corries.

The truncation of all geological structures requires the completion of an erosion cycle; the land must have been worn down almost to sea level and then raised relative to the sea. Thus the highland erosion surface would seem to be a raised peneplain. A similar surface is present on the coast in Germania Land and in Adolf S. Jensens Land. It is probable that this uplifted erosion surface was produced at the same time as those almost identical parts, described as peneplains or highland surfaces, in many areas of east and north Greenland. R. F. Flint (1948, p. 92) has reviewed the relevant literature and states that "the time of formation of this late-mature surface has not been definitely determined". There is no evidence in Dronning Louise Land on which to date the surface.

Fig. 6. The highland erosion surface in South-east Dronning Louise Land. View northwards from the Budolfi Isstrøm.

Fig. 7. Large, almost empty corrie on the north side of the Budolfi Isstrøm.

The surface slopes gently north of east. The easterly component, calculated from the cross sections in figure 5b is 1.5 ‰; the northerly component is about 0.5 ‰.

The High Alpine Region.

The highest mountains (2,700 metres), formed of the granitic rocks in the south-west, have been subjected to more intense corrie erosion which has produced jagged peaks and serrated ridges of alpine type (as figure 7). The highland erosion surface, rising gently from the east, slopes sharply upwards just before the alpine peaks are reached (figure 8). On some of the mountain tops within the alpine area, there are small remnants of an almost level surface. Thus it appears that before intense erosion by ice, a high level surface extended over the alpine peaks and was separated from the highland erosion surface by abrupt slopes. Most of the evidence of this higher surface has been destroyed by corrie action. The existence of two surfaces at different heights may be explained by one of the following hypotheses:—

(a) The higher surface could have resulted from differential erosion. Geologically, it is an area of granitic rocks, and the highland erosion surface always lies somewhat higher in such areas, but the slopes separating the two surfaces do not follow a lithological boundary, and steep slopes are not usually present around such areas. Thus, it is unlikely that the two surfaces are due to differential erosion alone.

(b) It is conceivable that there has been differential uplift of the granitic rocks in relation to the schists, but without more geological evidence, correlation of accurate heights, etc., it is not justifiable to discuss this as a plausible hypothesis.

(c) The surface over the alpine peaks could be a remnant of a peneplain formed during an earlier erosion cycle. This would seem to be the most plausible hypothesis.

After being uplifted, the earlier peneplain was almost destroyed by the formation of the highland erosion surface during the next erosion cycle, and by recent glacial erosion.

The Sediment Plateau.

The western mountains rising above the highland erosion surface are capped everywhere by sediments. The low westerly dips of these sediments appear to be conformable with and responsible for the approximately flat tops of the mountains, but where the sediments are folded, the plateau truncates the geological structures. The line of nunataks protruding above the ice about 25 km from the western mountains (figure 1) represents the peaks of a buried mountain range. These too

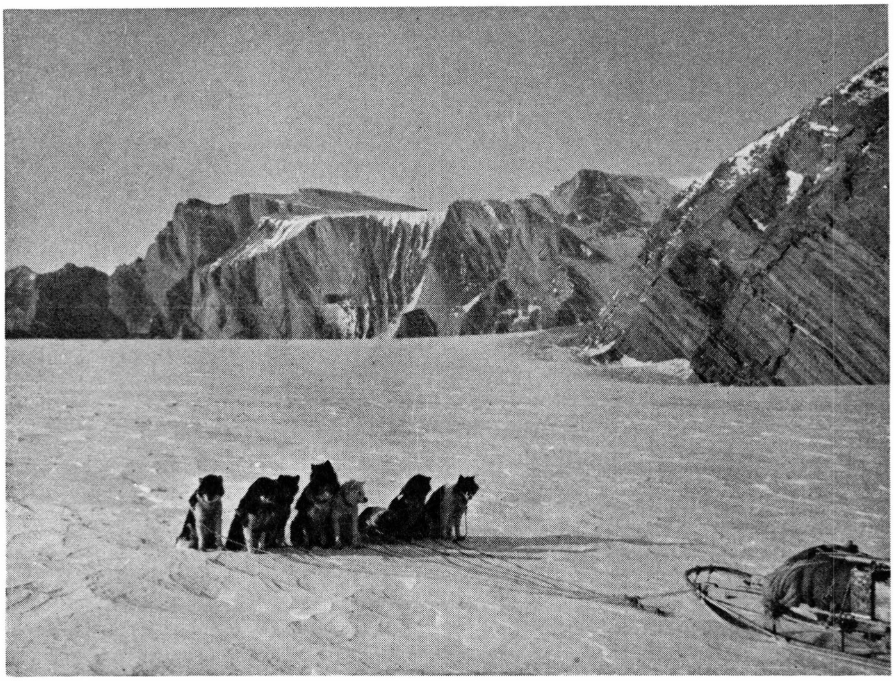


Fig. 8. View north-west from Budolfi Isstrøm. St. Andrews Klippe. Note the near vertical cliffs, the upwards slope of the highland erosion surface in the background, and the large facet (in the background) bevelling the edge between the highland erosion surface and the cliffs (see also fig. 17d).

are composed of westerly dipping sediments. The line trends east of south and joins Dronning Louise Land in the south-west.

Lauge Koch (1928, p. 495) has examined the Precambrian sandstones in north and west Greenland and refers to the "Great Sediment Plain" of north Greenland. He considers that the sediments on the gneiss plateau around the ice sheet form part of a continuous plateau beneath the ice. The sandstones and quartzites of Dronning Louise Land form a plateau and pass beneath the ice, so this evidence in north-east Greenland supports L. Koch's hypothesis.

The sediment plateau is separated from the alpine peaks by a plane of unconformity passing west of the alpine region (figure 5a). It extends northwards and southwards from the alpine peaks, and slopes westwards from them (figure 9a). It is usually higher than the highland erosion surface and is separated from it by an abrupt slope (figure 9b), but in the north, where the sediments are folded, the two surfaces merge almost imperceptibly (figure 9c).

The difference in level of the sediment plateau and the highland erosion surface could be explained by:—

(a) Differential erosion. The quartzites are harder and more resistant to erosion than the schists.

(b) The operation of successive erosion cycles.

The sediment plateau dips away evenly from the alpine peaks, so here it must be related to the earlier cycle of erosion (figure 9a). Therefore it can also be related to the earlier cycle where it is higher than the highland erosion surface (figure 9b). But when the sediment plateau and highland erosion surface are at the same level (figure 9c) the sedi-

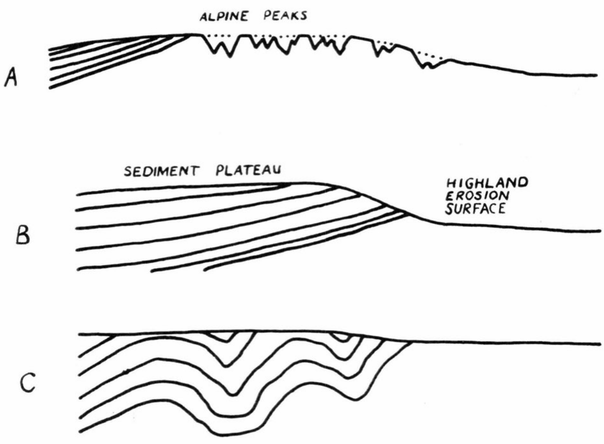


Fig. 9. Relations between erosion surfaces (and solid geology).

ment plateau must be related to the second erosion cycle. This suggests that preservation of the earlier peneplain in the sediment plateau is due to differential erosion: during the second cycle, the flat-lying quartzites resisted base-levelling, but the folded ones did not.

Differential erosion may also be invoked to explain the preservation of the earlier peneplain over the alpine peaks. The region is well within the zone of hard granitic rocks and might be expected to resist base levelling longer than the rocks around it.

From the mutual relations of the three surfaces, we have recognized the operation of two erosion cycles separated by uplift of the land relative to sea level. The second peneplanation was followed by a second uplift raising the surfaces to their present heights. Then the rivers, rejuvenated by the uplift, began to wear down the land in a third cycle of erosion. Subsequent glaciation formed the deep valleys dissecting the raised surfaces, which constitute the fourth morphological element.

Fig. 10. Aerial view to the south east in south eastern Dronning Louise Land. The glacier on the left is the Budolfi Isstrøm. Note the gulleys and buttresses on the cliffs.

The Glaciers and Glacier Valleys.

Most of the major valleys owe their form to ice erosion, and most of them are occupied by glaciers. The sculpturing effect of the large, eastward flowing glaciers is impressively displayed in a magnificent series of marginal cliffs (figure 10) some of which rise almost vertically to heights as much as 900 m above ice level. Large joint blocks are riven from the cliff faces by thaw-freeze processes and joints parallel to the cliff faces appear to control their form.

During an arctic summer, the temperature in higher areas rises above freezing point for a shorter period than in lower areas and there is less water present in the higher areas. Therefore, one would expect less activity of thaw-freeze processes in the higher areas. The number of frost-riven blocks below the cliffs is a measure of this activity. Using the amount of rock debris below cliffs as a basis, valley walls can be classified into four main types.

(i) In the high areas of the west, the cliffs generally pass beneath the ice level without modification of their verticality. Few joint blocks are scattered on the glaciers below the cliffs.

(ii) Rock debris accumulating below the cliffs at intermediate heights sometimes forms small scree slopes, but more often forms a ridge of lateral moraine overlying a core of ice. This ice melts more slowly than the unprotected ice around it because much of the heat from the sun's rays is absorbed by the rocks covering it.

(iii) In the lower eastern areas, the cliffs are less steep and scree slopes below them are more common. There is usually a gap between the margin of the glaciers and the cliffs.

(iv) The ice has receded from many of the lowest valleys leaving large, generally U-shaped trenches, often occupied by lakes. On the slopes bordering the valleys there is considerable development of scree generally mixed with, or underlain by, morainic material deposited by the glaciers. The small rock faces rising above the screes are rarely vertical.

Thus, there is a reciprocal relation between the amount of rock debris accumulated below the cliffs and the height of the mountains above them. It appears that the slower action of thaw-freeze processes in the higher areas has not yet produced screes.

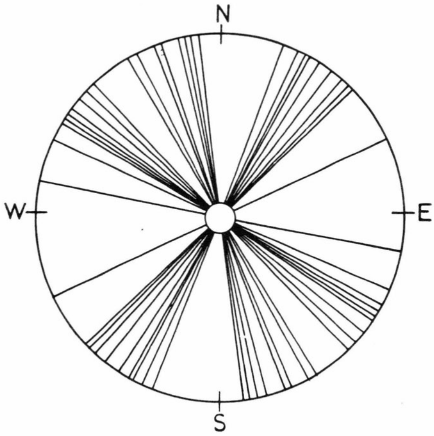


Fig. 11. Flow directions of glaciers in the northern half of Dronning Louise Land.

Towards the east, the lower cliffs are often ribbed by a series of parallel gullies and buttresses (figure 10). Their faces are developed along joint planes, and are probably formed by melt water flowing into, and freezing within, joints at the tops of the cliffs. The absence of such features in the cliffs of higher areas is also due to the shorter period of freeze-thaw, and the lack of water.

The map shows the angulate pattern of the glaciers which flow in directions approximately north—south and east—west (figure 1). Cer-

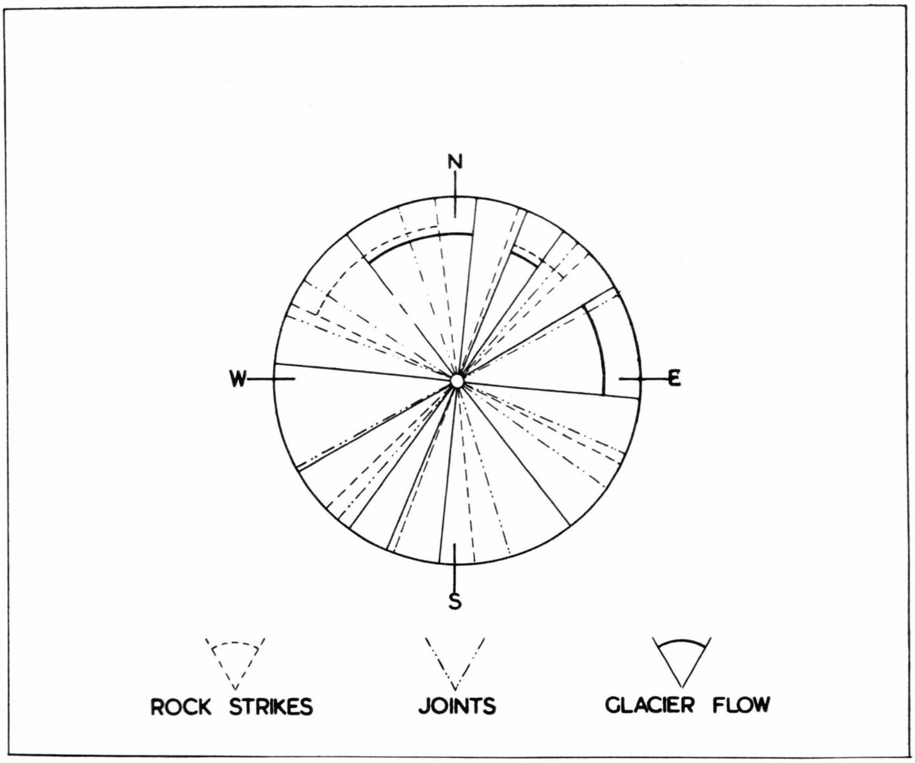


Fig. 12. Average rock strikes, major joints, and glacier flow directions in the northern half of Dronning Louise Land.

tain directions of flow are repeated frequently in different places. The directions of flow of every glacier north of the Borgjökel are plotted on a circular diagram (figure 11). Since the large Borgjökel flows through four distinct straight portions from the ice sheet to its snout, four directions have been plotted for it. Similarly two directions have been plotted for the Admiralty Gletscher. No distinction has been made between glaciers of different sizes since direction is the concern here.

The directions of flow fall into three well defined ranges. Such a definite pattern implies that valley erosion was structurally controlled. To discover what degree of control is exerted by the structural elements, figure 12 compares the directions of glacier flow, the structural directions of the rocks and the regional joint pattern. The two northerly directions of flow correspond closely to the major structural directions. The joint planes bear no special relation to the glacier flow directions and this suggests that the joint system has not played a significant part in the development of the main valleys. The glaciers flowing north of east have no discernible structural control. They are directed down the regional slopes of the highland erosion surface.

Though joints have exerted no influence on the development of the main valleys, yet the faces of the cliffs bordering the valleys are controlled by joints. It is necessary to reconcile these facts. The trend of the cliffs is approximately parallel to the direction of glacier flow, but only rarely do cliff faces exactly parallel these directions. They are normally aligned at small angles to the directions of flow and may even form a series of oblique faces (figure 10). Once the direction of a valley has been established, the architecture of the cliffs is created not by the glacier but by other agents of erosion; in particular, mechanical disintegration by thaw-freeze processes. The form of the cliffs is thus controlled by joint planes which give easy access to melt water.

Some of the joints may have been produced by exfoliation, resulting from release of pressure as the glaciers exposed rocks once deeply buried. W. V. Lewis (1954, p. 420) has discussed the function of such pressure release in connection with glacial erosion, and he concludes that within rock which consolidated at depth, stresses result from the gradual removal of the overburden. With the final release of the superincumbent load the internal stresses exceed the yield stress of the rock, which bursts up in layers parallel to its surface. If this process had been important here, the joints which were measured alongside the glaciers should show some correspondence with the directions of glacier flow, but only two of the five major joints determined lie within the ranges of glacier flow directions. Thus the form of the cliffs is due to a normal joint system independent of the glaciers.

From the evidence cited above, it may be inferred that:—

1. The factors controlling the directions of ice flow were the slope of the highland erosion surface and the regionally developed directions and planes of weakness in the underlying rock structures.
2. The factor controlling the form of the individual cliffs is weathering along normal joint planes.

Superficial deposits.

The four morphological elements described constitute the framework of the scenery; detail is provided by the effects of ice erosion and the superficial deposits.

All high level surfaces are covered with frost shattered blocks; fine material is rarely seen, the smaller particles having been washed away during the thaw periods or blown away by strong winds from the ice sheet. The relative antiquity of the high level surfaces is indicated by the scarcity of denudation products from cliffs bordering the glacier.

Fig. 13. Large stone polygons formed in till. View from a mountain in south-west Dronning Louise Land. The polygons are about 2000 m above sea level.

Erratics of quartzite, carried from the west, are frequently found on the erosion surface. They indicate movement over the erosion surface of ice from the west. Extensive glacial deposits occur in the relatively lower parts, e. g. in the north. Here, most of the high ground is covered by glacial deposits. The till on the erosion surface contains a high proportion of rounded and semi-rounded blocks of quartzitic sandstone and quartz-dolerite (both carried from the west). Fine material is not common in the high level deposits, except in moraines. Stone and soil polygons and stripes are often developed in the deposits of ground moraine, both at high and low levels (figure 13). Their occurrence is limited, but the factors controlling their distribution have not here been established.

Fluvio-glacial deposits are not extensive. Only three glaciers (the Borgjökel, the Admiralty Gletscher, and the Sunderland Gletscher), have their snouts on land; the others either end in lakes or form tributaries to the L. Bistrup Bræ. Aerial photographs show fluvio-glacial deposits between the snout of the Borgjökel and Storstrømmen, but these have not been examined. Støvdal, the low-lying area between the Admiralty Gletscher and the Britannia Gletscher, is filled with terminal and ground moraine, with fluvial and aeolian deposits. Similar deposits occur on the outwash plain to the east of Ad Astra Iskappe and in Stranddal (through which flows the river from Britannia Sø to the margin of Storstrømmen).

There are lateral moraines high above the present valley bottoms in several of the glacier valleys, and on the hillsides of the lower lying areas in the north. These are described in the discussion on stages of recession.

PROCESS OF GLACIAL ADVANCE

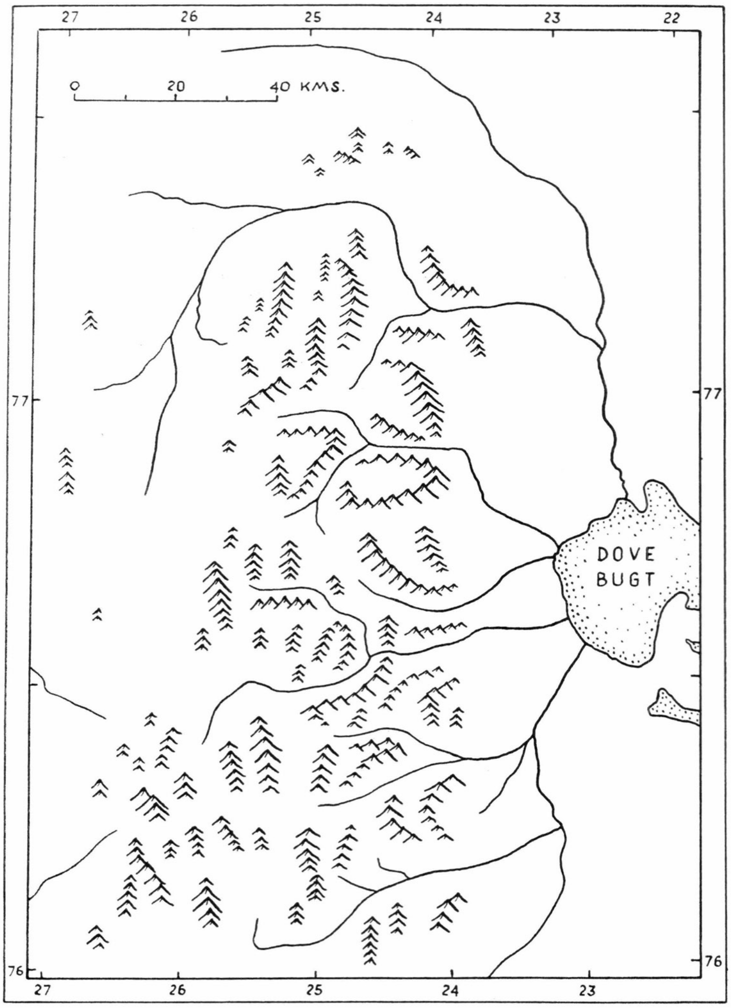
The initial glaciation of the sub-continent of Greenland is generally believed to have been by snow accumulation on a high central plateau, thickening and flowing outwards. Pioneers in trans-Greenland exploration discovered, along an approximately north—south centre line, two domes of ice which were thought to reflect the underlying topography. COLEMAN (1926, p. 28) says, "There appear to be two centres of glaciation which have become confluent."

The marked absence of nunataks projecting through the inland ice suggested that the ice thickness was very great. Before WEGENER's first seismic soundings in 1931, many writers on the subject quoted MEINARDUS (1926, p. 99) who gave 1,400 metres as a probable mean thickness of the Greenland ice. Recent seismic soundings (HOLTZSHERER, 1953, p. 52) shows that 2,000 metres is more correct but this early figure was a very good estimate.

The absence of mountains in the central area of Greenland tends to disprove KAYSER (1928, p. 366) and KOCH (1928, p. 445) who favoured the idea of the Greenland ice growing from central areas and invading the periphery. BROOKS (1923, p. 453) and most recently CAILLEUX (1952, p. 10) postulate the accretion of ice first on the high mountain ranges of the periphery of Greenland; next flowing out and forming piedmonts, then thickening and "when their rising level reaches the snowline, they bear firn, bulge and grow to ice-cap or inland ice". CAILLEUX calls this a hypothesis of altitudinal autocatalysis (1952, p. 1).

Isostatic equilibrium.

Gravity anomaly is the difference between the measured value of gravity at a point on the earth's surface and the value calculated for the latitude and altitude of the point. The extent of this anomaly and its sign (plus or minus) indicates whether there is a mass surplus or deficit. This is based on the assumption that any two cones subtending equal solid angles at the centre of the earth have the same mass or will tend to have the same mass, given time for balance to be achieved.



PROBABLE PRE-GLACIAL DRAINAGE PATTERN
IN DRONNING LOUISE LAND

Fig. 14.

This theory of isostasy indicates that if there is no gravity anomaly over an ice sheet, then the ice has pushed down the rocks, replacing the mass of the rock by an equivalent mass of ice. Bull (1956) found that the central region of Greenland is in isostatic equilibrium, which means that we may substitute a mass of rock of a mean specific gravity, say 2.7, for the present mass of ice of specific gravity 0.9. The resulting height of the rock plateau in North Greenland would be 500 to 1000 metres above sea level.

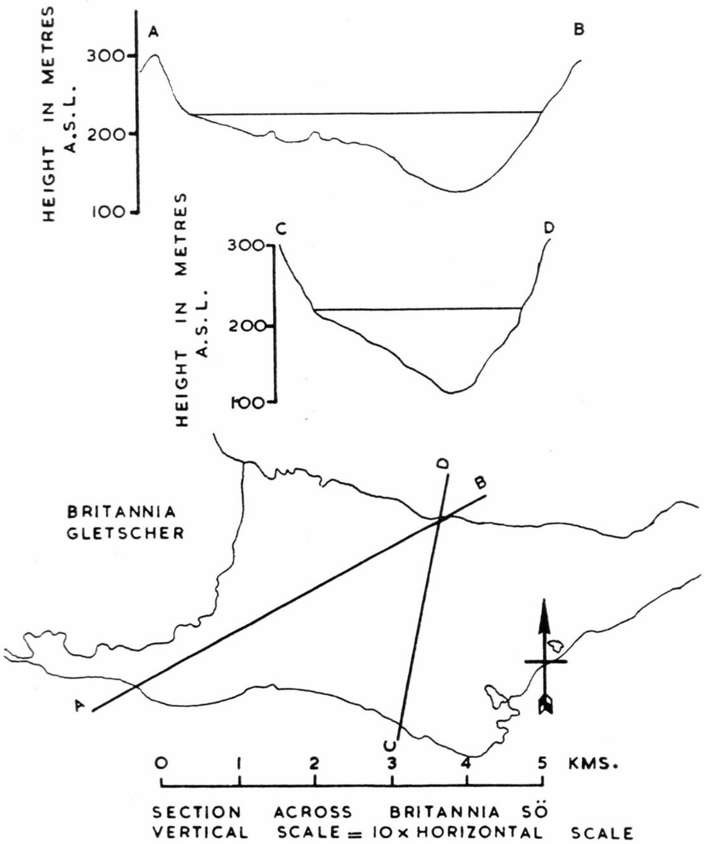


Fig. 15.

Pre-Glacial drainage.

The drainage of the central Greenland plateau required the cutting of troughs through the mountain rim of Greenland. Dronning Louise Land is part of this mountainous border of East Greenland, breached to the north and south by river valleys that carried eastwards the drainage of the extensive rock plateau inferred from the gravity measurements.

In Dronning Louise Land, the pre-glacial drainage pattern may be deduced from the morphology and structure of the region. The north to south watershed along the west of Dronning Louise Land initiated main drainage to the east, and shorter, steeper streams to the west. These consequent streams flowed eastwards down the highland erosion surface and westwards down the sediment plateau (figure 5a). Subsequent streams followed the two regionally developed directions of weakness in the rock structure (figure 12) with an approximate north—south direction. Figure 14 shows the probable pre-glacial drainage pat-

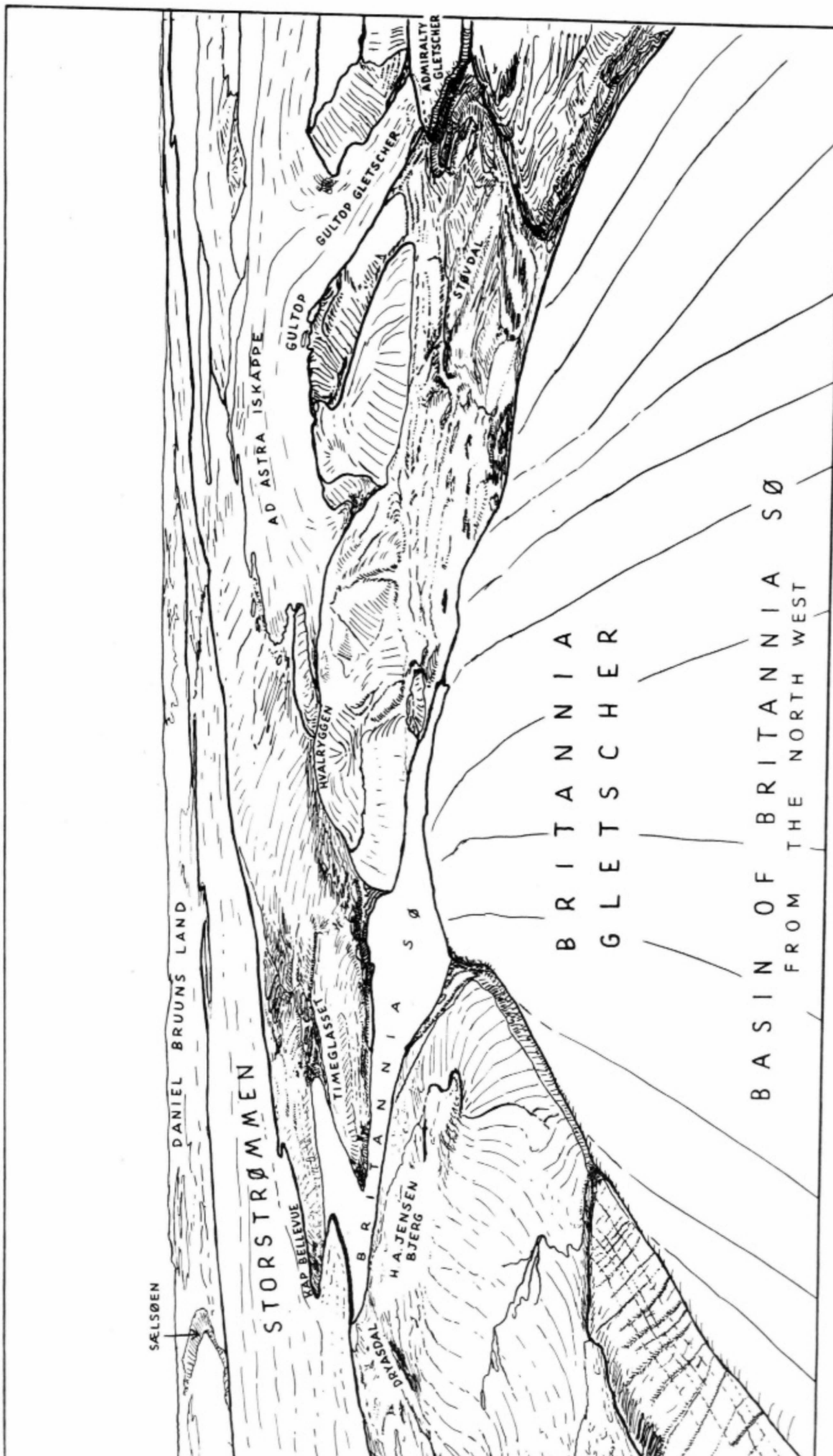

SÆLSØEN
DANIEL BRUUNS LAND
STORSTRØMMEN
KAP BELLEVUE
TIMEGLASSET
HVALRYGGEN
AD ASTRA ISKAPPE
GULTOP
GULTOP GLETSCHER
ADMIRALTY GLETSCHER
STØVDAL
BRITANNIA SØ
H. A. JENSEN BJERG
DRYASDAL
BRITANNIA GLETSCHER
BASIN OF BRITANNIA SØ
FROM THE NORTH WEST

Fig. 16.

tern with the main structurally controlled rivers occupying north—south valleys, particularly in the east and west of the region. The alpine region in the south-west is a focus of this drainage. In the north-west the subsequent stream in the broad north—south valley, collected many consequent streams and flowed to the north of the region, turning south along the valley of the Britannia Gletscher and east through the basin of Britannia Sø, to the wide, mature valley of Storstrømmen. The submarine contours of Britannia Sø (from a gravity survey made by Bull over the lake ice) show a typical river cross section (figure 15) in spite of subsequent glacier invasion. On the eastern side of the wide Storstrøm valley, opposite the Britannia Sø, is a breach in the mountain wall (figure 16) with the fjord lake Sælsøen continuing east to Dove Bugt. The river postulated in the valley of Storstrømmen would seem to have captured a river that once flowed eastwards through the valley of Britannia Sø and Sælsøen. Annekssøen, to the north of Sælsøen, is a possible second river capture.

Initiation of glaciation of North Greenland.

Since the land surface of the north central region of Greenland can scarcely have been as much as half the height of the mountain rim (see above) we may expect that the greatest precipitation fell on these flanking mountains. At present in Dronning Louise Land, most of the precipitation falls with easterly geostrophic winds, associated with depressions off the east coast (Hamilton, private communication and Flint 1947, p. 43). At the foot of the west facing mountain slopes, snow drift from off the inland ice contributes a large part of the snow accumulation.

In pre-glacial times the zone of westerly winds probably extended much further north than now (Brooks 1949, p. 53) and so one would expect at that time that moisture bearing, westerly winds would blow across the lower central parts of Greenland and cause precipitation on the higher eastern mountains. This process does not now occur owing to the build up of the ice sheet and the southward movement of the zone of westerly winds.

Corrie glaciation.

A polar diagram of corrie directions shows almost a full circle but most of those corries with deep back walls face westward. Their floors are at or below the present ice level, but the rate of flow of ice in these corries would seem to be very slow indeed, there being very few coalescing corries giving rise to medial moraines, and bergschrunds if present are only feeble cracks. Many corries now contain dwarfed, mis-fit glaciers, and moraine from corries is in some cases cut off by subsequent valley glaciers. It would seem that corries are not now being carved but are the product of the onset of the ice, as is postulated by Mannerfelt in Norway and Sweden (1945, p. 227). Cotton (1947, p. 173) assembles various authorities postulating corries as a product of early glaciation but sometimes deepened and sharpened after re-emergence. East and West Greenland have many deeply cut, sharp edged corries. These are cited by Cotton as examples of corries that have sapped mountain flanks after an ice sheet has removed all residual weathered rock debris. No specific examples of this were found in Dronning Louise Land, though such a re-invigorating of corries may be possible, given sufficient snow accumulation.

Valley glaciation.

The Sunderland Gletscher is an example of the coalescing of glaciers fed from corries. Here, four corries, in the westward facing valley wall, enclose lobes of the present glacier, but most probably contributed a major part of the ice which initially flowed along this valley. Valley head amphitheatres and head-wall sapping to an advanced stage of dissection, where mountain divides are thinned to fretted ridges and peaks, is achieved only in the south-west of Dronning Louise Land and on the high mountain Prinsessen.

If the mountain rim of Greenland supplied ice sufficient to cover the central basin of Greenland, the amount of accumulation and ice flow must have been very great and the consequent glacial erosion quite intensive. Yet the mountains of Dronning Louise Land now exposed from under the ice and thus offering a bared surface for renewed sharpening and fretting, are not subdued mountains of a glacial landscape in old age (Davis 1900, p. 665). Thus we may infer that while the ice was coalescing in the wide north—south valleys, there was ice accumulating in the central Greenland basin to the west and hence there were snow bearing winds from the west.

Ice sheet glaciation.

Flint (1947, p. 233) assumes that westerly and southerly winds crossed much of the North American continent and deposited snow from which spread the Laurentide Ice Sheet. A similar mechanism may be postulated for Greenland save that, instead of accumulation initially along the mountains of Ellesmere Land, Baffin Land and Labrador, with subsequent shift of the ice shed to the west, there would seem to have been, in Greenland, accumulation along the mountainous periphery from which the iceshed moved to an approximate north—south centre line.

The flow of glaciers into the basin of Greenland would greatly encourage the deposition and growth of snow and ice in the basin. C. E. P. Brooks (1949, p. 128) has shown by calculation how land covered by ice or snow reflects much more of the incoming solar energy than did the rock which is now covered and thus creates colder conditions, which encourage further ice accretion.

The shift of the ice shed from the Greenland mountains to the centre had the effect of changing the direction of flow of ice on the inland facing mountain slopes. In Dronning Louise Land the valley glaciers flowing westwards, as tributaries to the main south to north valley glaciers, were overcome by the higher ice to the west. These glaciers now thickened and flowed eastwards as distributary glaciers of the ice sheet, breaching the lower parts of the north—south mountain ridges and reversing the slope and direction of flow of many of the earlier westward flowing glaciers. The rising ice to the west would flow through any available gap in the mountain wall on the east. This bifurcating of the ice streams and overrunning of glacier divides, called by A. Penck, diffluence and transfluence respectively, was enacted on a grand scale, as is still evident by the many branched glaciers in west and south Dronning Louise Land (e. g. figure 10). Hobbs (1911, p. 44) classifies these glaciers "transection type", one of the important results of which is the lowering and subsequent retreating of the divide in the direction from which the overflowing ice has come. As detailed by Linton (1949, p. 2 et seq.), glacial diffluence is an important mechanism in the modification of the fluvial drainage pattern and hence has been considered in the reconstruction above of the pre-glacial drainage. The Hastings Gletscher and the Sunderland Gletscher, east of Prinsessen with the distributary of the Admiralty Gletscher south east into Trefork Sø and the overridden corrie into the Carlsberg Gletscher are but four of the many examples of this breaching of mountain divides by glacial diffluence.

The rounded summits of north Dronning Louise Land, the smoothing of the more easterly corries and particularly the glacial deposition on some of the flatter mountain tops above 1000 metres, is evidence of the ice having been more than 300 metres thicker than it is today and covering all but the highest peaks in the south west of the region. Antevs (1928, p. 78) claims with much support in the literature that the ice was 200 to 600 metres higher and concludes that the narrow coastal plain, now ice free, probably had a 400 metres thick layer of ice and the interior of Greenland probably had, on the average, 100 to 200 metres more than today. The gravity anomaly found by Bull (1956) near the edges of the ice sheet at Dronning Louise Land, suggests that there is not isostatic equilibrium. To achieve a balance, a mass of ice more than 300 metres thicker than that shown by the present profile is required. Though there is much uncertainty about the greater thickness of the ice sheet in the centre of Greenland, all the evidence at the eastern margin of the ice about the 77° N. latitude here considered, suggests that there was once 300 to 600 metres more ice than there is at present. The altitude of the ice surface decreases to the north, but it is not easy to understand how mountains in Peary Land, now capped by ice or housing valley glaciers (Fristrup 1951, p. 188), once held back the ice completely. Lauge Koch concluded, after extensive travel and observation in northernmost Greenland, that "the inland ice during the maximum of the glaciation did not cover the northern part of Peary Land, but was checked by the Caledonides" (1925, p. 283). As outlined above, the possible displacing northwards of the easterly winds that brought precipation to Greenland early in its glaciation may be a contributory factor to the dearth of snow accumulation in the extreme north of the sub-continent.

The possible horizontal extent of an ice mass may be found from Nye's formula which relates ice thickness to surface slope for a shear stress of one bar for ice over rock (1952, p. 529). From Dronning Louise Land the ice cannot extend much further eastwards over rock. The east coast of Greenland lies approximately 90 km east of this region but Dove Bugt brings the sea much nearer and this would permit the ice to spread eastwards as an ice shelf. A strand line at an altitude of 500 metres on Store Koldewey, 100 km east of Dronning Louise Land indicates that water dammed by ice, and hence the ice itself, was at least at such a height.

The greater mass of ice over Greenland probably joined on the western side with the Laurentide ice flowing from the mountains of Ellesmere and Baffin Island, and perhaps the hundreds of metres depth of sediment on the bed of the North Atlantic are a product of this huge ice mass (Swallow, 1954, p. 259). Cores sampled in the North Atlantic have never been more than a few metres long but, even so, south of latitude 46° N. these cores represent thousands of years. Four zones of glacial marine sediments were found in deep sea cores less than three metres long by Bramlette and Bradley who suggest that these zones represent sub-stages of the Wisconsin glaciation (1942, p. 11) and that at greater depth there are probably greater thicknesses of glacial marine sediments.

The firn line.

The process of glaciation outlined above implies a depression of the firn line of this region from a height of approximately 1000 metres to somewhere near sea level. The 1000 metre height is the accordance level of many of the corrie basins in the north west of the region; only minor corries can be seen below this height. It is possible for corries to form below the firn line, but the process of formation will be more restricted than in corries above the firn line.

The early stages of deglaciation in Greenland, have, with fluctuations, been progressing for possibly the last 5,000 years. This implies a rise in the firn line, which has now returned, in Dronning Louise Land, to a height of 1000 metres though there are local anomalies such as on the corrie glacier that forms a tributary to the Admiralty Gletscher. This corrie is favourably sited for accumulation and the ice flows at the foot of the clifis of the composite Admiralty Gletscher, marked off from the ice of this glacier by a wide moraine. The boulders on the ice and the lee provided by the cliffs each facilitate snow accumulation with the result that here the firn line is at 900 metres.

At the present time very much of Dronning Louise Land lies below the firn line but the mass of the inland ice above the firn line pushes the long glaciers across and round the whole region and gives an ice cover which belies the amount of local snow accumulation.

Multiple glaciation.

There is some evidence of multiple glaciation. The slopes of the mountains on the south side of the Budolfi Isstrøm suggest the presence of a high-level, broad, shallow, U-shaped valley. On some mountains the slope dips almost uniformly towards the glacier (figures 17a and 18). To infer that these slopes are the remains of a glaciated valley is unjustified on this evidence alone, but their probable glacial origin is made more clear by the reconstruction of complete profiles (figure 17b). In one place, however, a more typical glaciated profile remains (figures 17c and 19). The Budolfi Isstrøm is not centrally placed in the floor of this former glaciated valley, and for this reason the floor is preserved. Further east there are, at the tops of the cliffs, small facets which bevel the normally rectangular edge between the cliffs and the highland erosion surface (figures 17d and 8). The field evidence suggests that the slopes and facets could have formed part of a single, broad, shallow, U-shaped valley, with walls becoming steeper to the east. They are covered with frost-shattered blocks, confirming that they are older than the bare rock surfaces produced in this area by the present glacier system. The presence of a high level glaciated valley suggests that the ice advanced over the region in two distinct stages. It is not clear whether these were (a) the local glaciation and (b) ice flowing in from the Greenland plateau. The pattern of the present ice is different from that of a possible

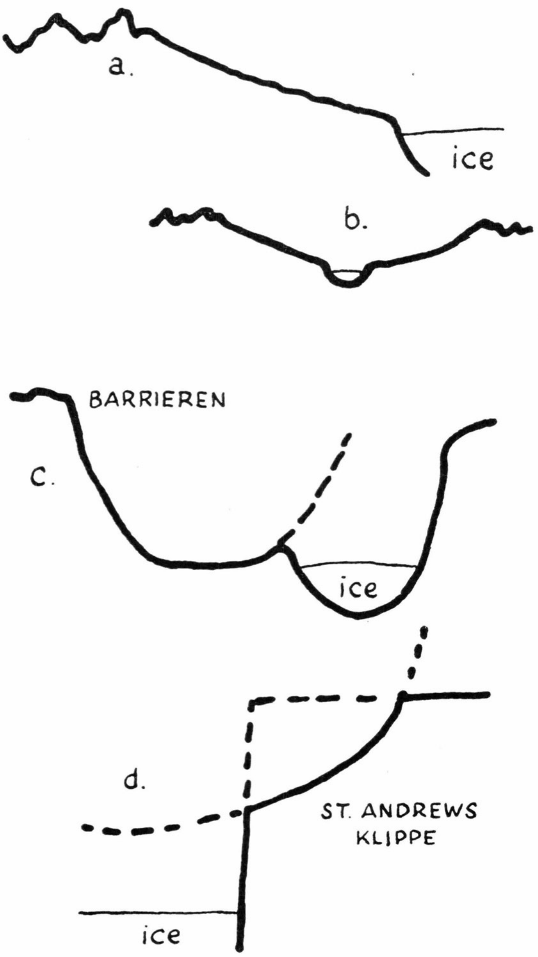


Fig. 17. Valley slopes as evidence of multiple glaciation.

earlier glaciation as described above. This difference suggests a period of ice recession between the two ice advances.

R. F. Flint (1948, p. 153) cites evidence from the Fjord Region of east Greenland constituting "more than a strong suggestion that multiple glaciation has occurred during Pleistocene time". The slopes of the high level glaciated valleys which he uses as illustrations are as gentle as the slopes occurring on the south side of the upper Budolfi Isstrøm (figure 18) but the probable glacial origin of the fairly uniform slopes

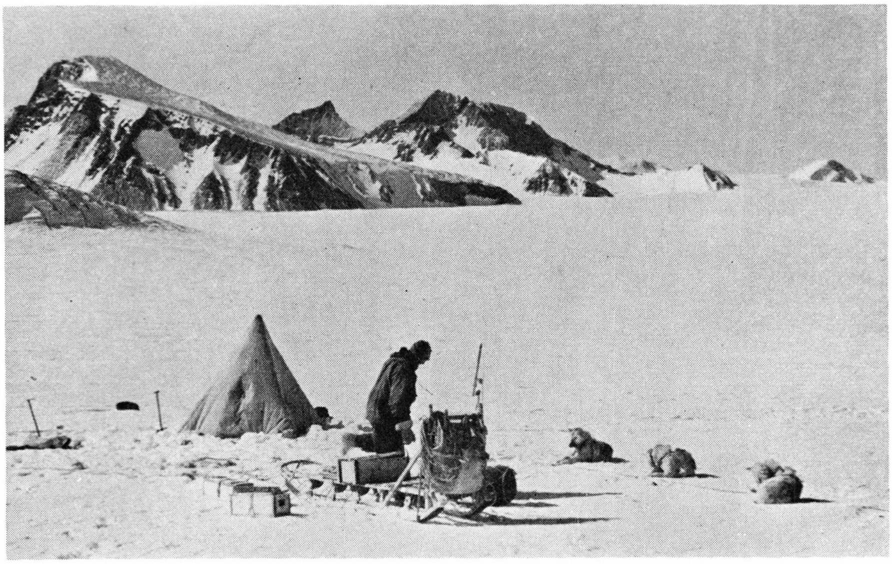


Fig. 18. View to the west along the south side of the upper Budolfi Isstrøm. Note the fairly even slope on the nearest mountain. See also fig. 17a and 17b.

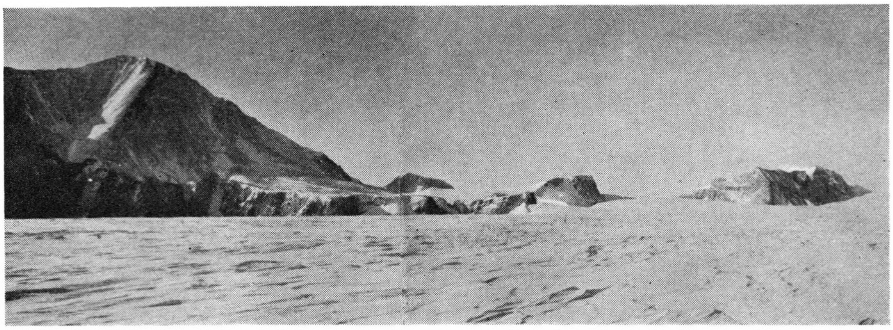


Fig. 19. View westwards up the Budolfi Isstrøm. The glacier flows through the gap at the right of the figure. Note the U-valley bordering the mountain Barrieren, on the left. See also fig. 17c.

on either side of the valley is made clear in his examples by the preservation of complete profiles (figures 17b). Pre-glacial and inter-glacial features will be preserved only in favourable localities; it would seem that generally they will be destroyed by subsequent glacial erosion. Therefore, it is only in the highest parts that evidence suggesting multiple glaciation has been preserved and surfaces, similar to those described above, occur beside smaller glaciers in the high mountains south of the Budolfi Isstrøm.

PROCESS OF GLACIAL RECESSION

Evidence of ice recession is clearer than that of ice advance. Erratics on the highland erosion surface prove that, at one time, ice covered almost the whole of the region. Many of the glaciated valleys dissecting the upland surfaces are now occupied by lakes; corrie glaciers are often reduced to small lobes of ice occupying deep excavations (figure 7), and many corries are now empty (figure 16); the fact that Ymer Nunatak, to the north of the main land mass, is covered by a layer of till is evidence that the ice sheet here was once at least 500 metres thicker than it is now. Thus, glaciers have receded and the ice sheet has decreased in height.

There are many nunataks within and around Dronning Louise Land. By studying these, it is possible to deduce the probable order of emergence of the mountains of Dronning Louise Land from the cover of ice.

Emergence of nunataks.

Nunataks of two types have been recognised. Some result from exposure of the rock floor of the ice sheet; others are high mountain peaks emerging from a thick cover of ice.

Figure 20 illustrates six observed stages in the process of emergence of the rock floor of the ice sheet.

(a) A smoothly rounded and regularly crevassed ice hill forms on the surface, reflecting the contours of the underlying bedrock. There are numerous examples of such hills on the edge of the ice sheet, particularly in the north.

(b) The down-flow slope of the ice hill becomes steeper, and is so irregularly crevassed that it is almost an ice fall. Good examples were noted extending northward from Dronning Louise Land.

(c) The emergence of irregular heaps of englacial moraine at the foot of such an ice fall was recorded in the south. This occurs when the ice becomes thin enough for englacial debris carried near the base of the ice sheet to melt out.

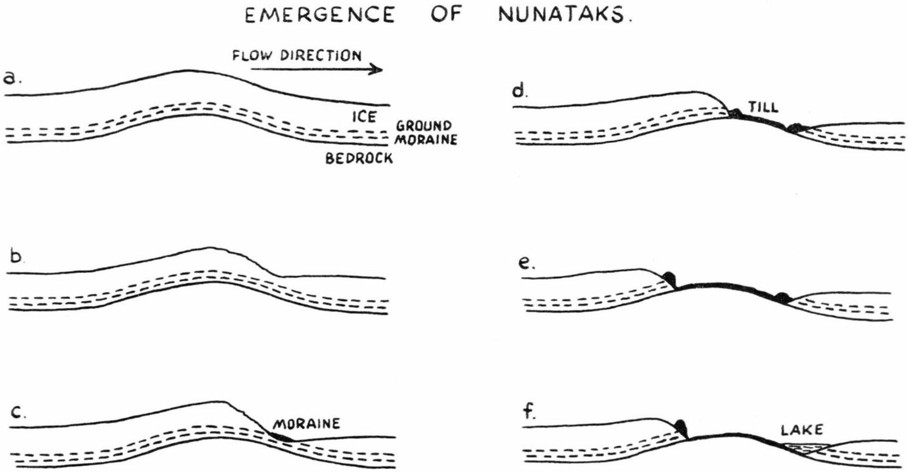


Fig. 20. Six observed stages in the process of emergence of the rock floor of ice sheet.

(d) If this period is of sufficient duration, a line of moraine develops at the foot of the ice slope, i. e. on the down-flow side of the emergent nunatak. Eventually the ice retreats across the bedrock, leaving a deposit of till on the nunatak. The thickness of the till depends upon the rate of recession and the amount of englacial moraine carried by the ice.

(e) Once the crest of the buried hill has been uncovered, there is an increasing thickness of ice above the rock on the up-flow side. There is a temporary equilibrium when the rate of ablation is balanced by the fresh supply of ice being carried across the nunatak. The presence of large horse-shoe moraines on the up-flow sides of many nunataks shows that a state of near-equilibrium has been attained. On the down-flow side, however, the ice must continue to retreat, despite the thickness increasing away from the nunatak, because the melted ice is only partly replaced by ice flowing round the sides of the nunatak.

(f) Many nunataks were observed with two moraines but more often the ice on the down-flow side of the nunatak rises gently from a lake. It seems probable that a ridge of moraine is present beneath such lakes.

Many of these nunataks are lower than the surrounding ice. Invariably the horse-shoe moraines are perched on the ice sloping down to the nunatak.

The till forming the moraines and covering the nunataks is composed of a variety of rock types. Many of them must have been carried within the ice sheet for great distances. The blocks vary in size from more than 3 metres down to the finest particles, and in shape from sub-angular to rounded. There can be no suggestion that the horse-shoe moraines are derived entirely from local bedrock as is suggested for the terminal moraines of the Barnes ice cap (Goldthwaite, 1951, p. 567).

The second type of nunatak (produced by emergence of mountain peaks) may be distinguished from the first by the rock types composing moraines near them. These are derived only from the nunataks, because the englacial material is too far below the ice surface to melt out (figure 21). Mountain peaks emerging from the ice sheet must ob-

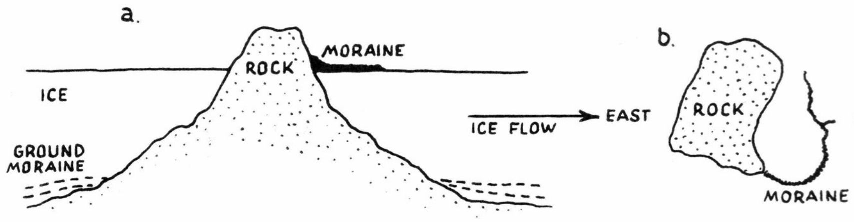


Fig. 21. Kaldbakur. A nunatak formed by the emergence of a high mountain peak. a. Profile. b. Plan.

struct the outward flow of ice. Near some nunataks, the sinuous course of a moraine indicates an eddy in the ice flowing around an obstructing nunatak.

Emergence of Dronning Louise Land.

Figure 22 shows three stages of this process.

(a) The thinning of the ice sheet which must have accompanied the last deglaciation resulted first in the emergence of the high western mountains (the second class of nunatak).

(b) Eventually, the section of the ice sheet above the highland erosion surface was separated from the main ice sheet by the western mountains. Glaciers flowed through passes in the mountains and dissected the upland surfaces.

(c) The ice on the highland erosion surface slowly melted, leaving the englacial moraine on the surface. With further thinning of the ice sheet, many of the glaciers flowing through the region were cut off from the ice sheet by emerging rock thresholds.

Effect of rock thresholds.

Climatic changes (increase in mean annual temperature; decrease in amount of precipitation) are the main causes of glacial recession. The high rock thresholds in the western mountains, over which the larger glaciers in Dronning Louise Land flow eastward from the ice sheet, introduce another limiting factor in the supply of ice. Thinning of the ice sheet margin would cause the thresholds to emerge and separate the glaciers from their source of supply. This would speed the process of recession. The application of this argument to Dronning Louise Land becomes more evident on the map (figure 1).

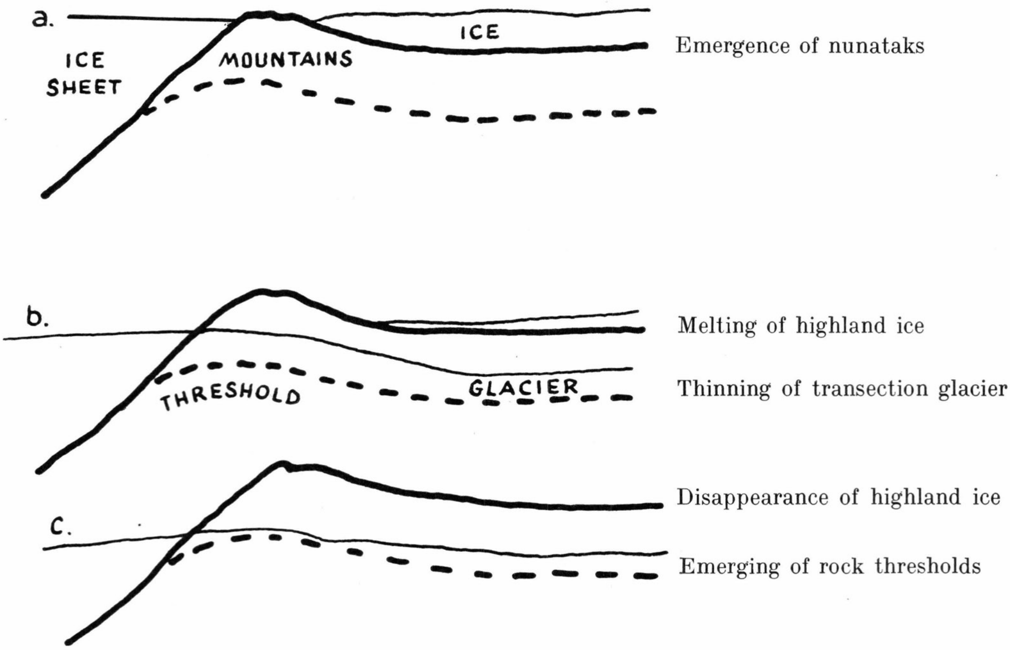


Fig. 22. Stages in the process of emergence of Dronning Louise Land.

Along a front of over 150 km the western mountain range presents to the ice a barrier that is breached by only three major glaciers; the Admiralty Gletscher, the Borgjökel and the Budolfi Isstrøm. The wide Suzanne Bræ sweeps eastwards around the north of Dronning Louise Land. The line of ice hills and steep ice slopes extending northwards from the north-west corner of the land indicates that this glacier passes over a prominant threshold in the west. South of the alpine area, the mountain range continues as a line of nunataks and steep ice slopes (indicating buried peaks) which divide the ice sheet proper from a lower expanse of ice. Two glaciers flow from this area (the Ebbe Gletscher and the A. B. Drachmann Gletscher), but neither of them extends westwards through the mountain range. Thus, there is an almost continuous mountain barrier extending from north to south along the western margin of the region. The line of outlying nunataks represents the peaks of a buried mountain range which must reduce the quantity of ice reaching the mountains of Dronning Louise Land. Seismic soundings confirm the presence of this buried mountain range (BULL 1956). These mountain barriers are undoubtedly the main reason for the existence, within the margin of the ice sheet, of the large area of ice-free land which forms Dronning Louise Land.

The large outflow glaciers of west Greenland (e. g. the Umiámáko Isbræ, the Rink Gletscher and the Jakobshavn Isbræ) extend far into the ice sheet as high discharge ice streams occupying deep sub-glacial trenches (BAUER, 1954, p. 52). The three glaciers which breach the western mountain barrier of Dronning Louise Land show no signs of similar subglacial trenches extending into the ice sheet. The large glaciers passing between the high cliffs are soon lost among the low ridges, hills and valleys forming the surface of the ice sheet. This fact strongly suggests that even the major glaciers pass over relatively high rock thresholds. A small decrease in the amount of ice supplied from the west would probably cause them to shrink markedly.

The presence of high rock thresholds must constantly restrict the quantity of ice flowing eastwards from the ice sheet, but their effect will only become marked when the thickness of the ice flowing over the thresholds is reduced to the same order as that of the glaciers. Any further decrease in height of the ice sheet, and therefore of the thickness of ice flowing over the thresholds, must then be reflected in a more rapid recession of the glaciers (figure 22).

All stages of this process have been observed. Most of the smaller glaciers in the west clearly originated as ice streams spilling from the ice sheet through mountain passes. In many places they exist at a higher level than the margin of the ice sheet and are therefore cut off from their supply of ice. These glaciers are now receding as they are supplied only by local precipitation, which is insufficient to maintain them under present conditions. South of the alpine peaks there are several U-shaped valleys, high in the mountains, showing the positions of glacially deepened passes which are now ice-free.

A more striking example is offered by Eigil Sø. The surface of the lake lies in a deep trench, 700 metres above sea level, where the highland erosion surface is about 1500 metres high. It extends westwards for 20 km almost to the foot of Revaltoppe, a mountain range rising to an altitude of 2500 metres above sea level. This deep valley was carved by a large glacier which was fed by tributaries from north and south as well as from the west. No glaciers reach the valley at present since the source of supply of ice has been cut off by the high mountains around the valley as the ice sheet decreased in height.

The Pony Gletscher illustrates an intermediate stage in this process of recession resulting from starvation. Between the Revaltoppe and the alpine peaks, the ice sheet extends eastwards at a high altitude (about 1850 metres above sea level). From this tongue of ice the Pony Gletscher flows into Vedel Sø, a lake dammed at its east end by the Ejnar Gletscher. Entry to the glacier from the west is down a series of steep ice slopes which give way quite sharply to a normal glacier tongue, and the snout of the glacier passes into the lake by way of a steep, smoothly convex slope. There are no signs of calving from the snout, and, when the glacier was visited in April 1954, there were no pressure ridges formed in the lake ice next to the snout. Thus, there had been no movement of the glacier during the preceding winter. In contrast, winter movement of the Ejnar Gletscher at the other end of the lake had produced such a confusion of pressure ridges in the lake ice that it was difficult to find a route through them. The steep slopes at the head of the Pony Gletscher suggest the presence of a glacially modified corrie beneath the ice. The sides, head wall and floor of the corrie, merging into the tongue of the glacier, are clearly reflected in the surface contours of the ice sheet. The probable history of the glacier is readily deduced. With the onset of glaciation a corrie formed in the high mountains. This was the source of an eastward flowing glacier. As the ice sheet expanded and grew it flowed across the divide south of the Revaltoppe, augmenting the supply of ice to the relatively small corrie glacier. The glacier was then fed directly by the ice sheet, and formed a tributary of the large Budolfi Isstrøm. Decrease in the level of the ice sheet has virtually cut off the supply of ice from the west; the glacier is now a stagnant remnant occupying a valley too large for it. Lateral moraines high on the sides of the lake are evidence of a much greater glacier which once flowed through this valley.

These three phenomena (the shrinkage of the Pony Gletscher, the disappearance of the glacier which formerly flowed through the valley containing Eigil Sø and the disappearance of the glaciers which once flowed through the glaciated passes high in the mountains) are due primarily to thinning of ice over the high thresholds of the western mountain barrier. The evidence outlined suggests that the recession of the glaciers here is controlled, near the final stages, by thinning of the ice sheet, and the consequent emergence of rock thresholds.

STAGES OF ICE RECESSION IN NORTH DRONNING LOUISE LAND

Ice recession did not proceed continuously. Halt stages are indicated by depositional features and to a lesser extent by erosional features. It is only in the relatively low-lying areas of north Dronning Louise Land that there is sufficient evidence to permit the reconstruction of the separate stages of ice recession. The land was studied directly in the field and indirectly from oblique photographs taken by the Geodetisk Institutet and from a mosaic of vertical photographs taken by the R.A.F. in summer 1954.

Round the basin of Britannia Sø, five stages of glacier recession have been reconstructed and plotted on a map prepared from R.A.F. verticals. The map of the area includes only the largest depositional forms.

Britannia Sø, one of the many ice-dammed lakes that form a dominant feature of Dronning Louise Land, occupies most of a steep sided valley between H.A. Jensen Bjerg to the north and Hvalryggen and Timeglasset to the south (figure 16). The Britannia Gletscher, Støvdal and the snout of the Admiralty Gletscher, border the lake environs in the west and the huge glacier, Storstrømmen, bounds this type-area to the east. These morphological units may best be described as separate localities of the basin of Britannia Sø. The separate morphological units are:—

(a) The area north of Britannia Sø between the Britannia Gletscher and Storstrømmen.

(b) Støvdal, the snout of the Admiralty Gletscher and junction with it of the Gultop Gletscher.

(c) Hvalryggen and the northern edge of Ad Astra Iskappe.

(d) Timeglasset and Dryasdal.

The evidence is detailed stage by stage for the recession of the ice across the area (a), north of Britannia Sø. This area forms the most complete unit for delimiting the stages of ice recession since the area is bounded by the two large glaciers from the inland ice and by Britan-

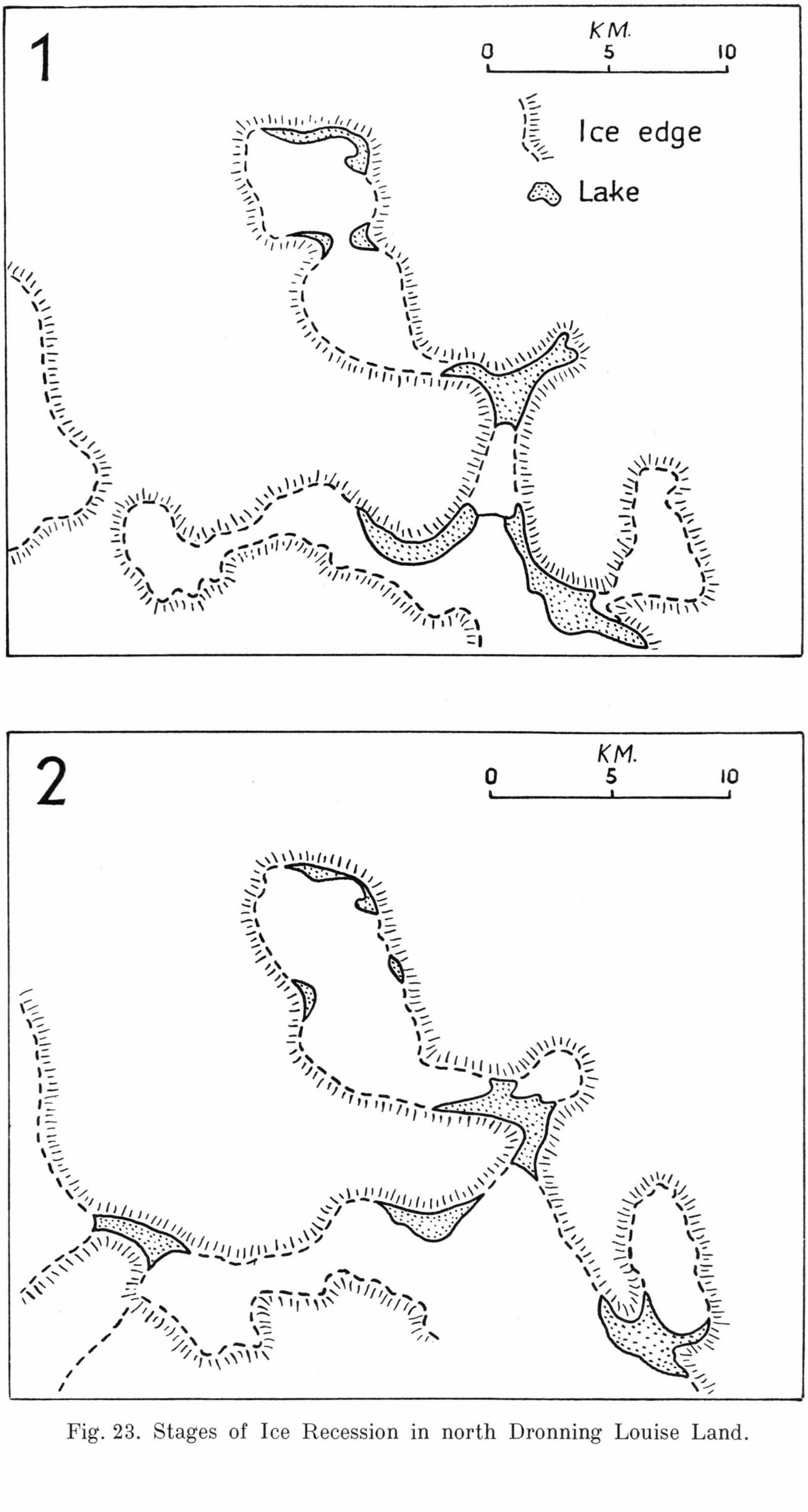


Fig. 23. Stages of Ice Recession in north Dronning Louise Land.

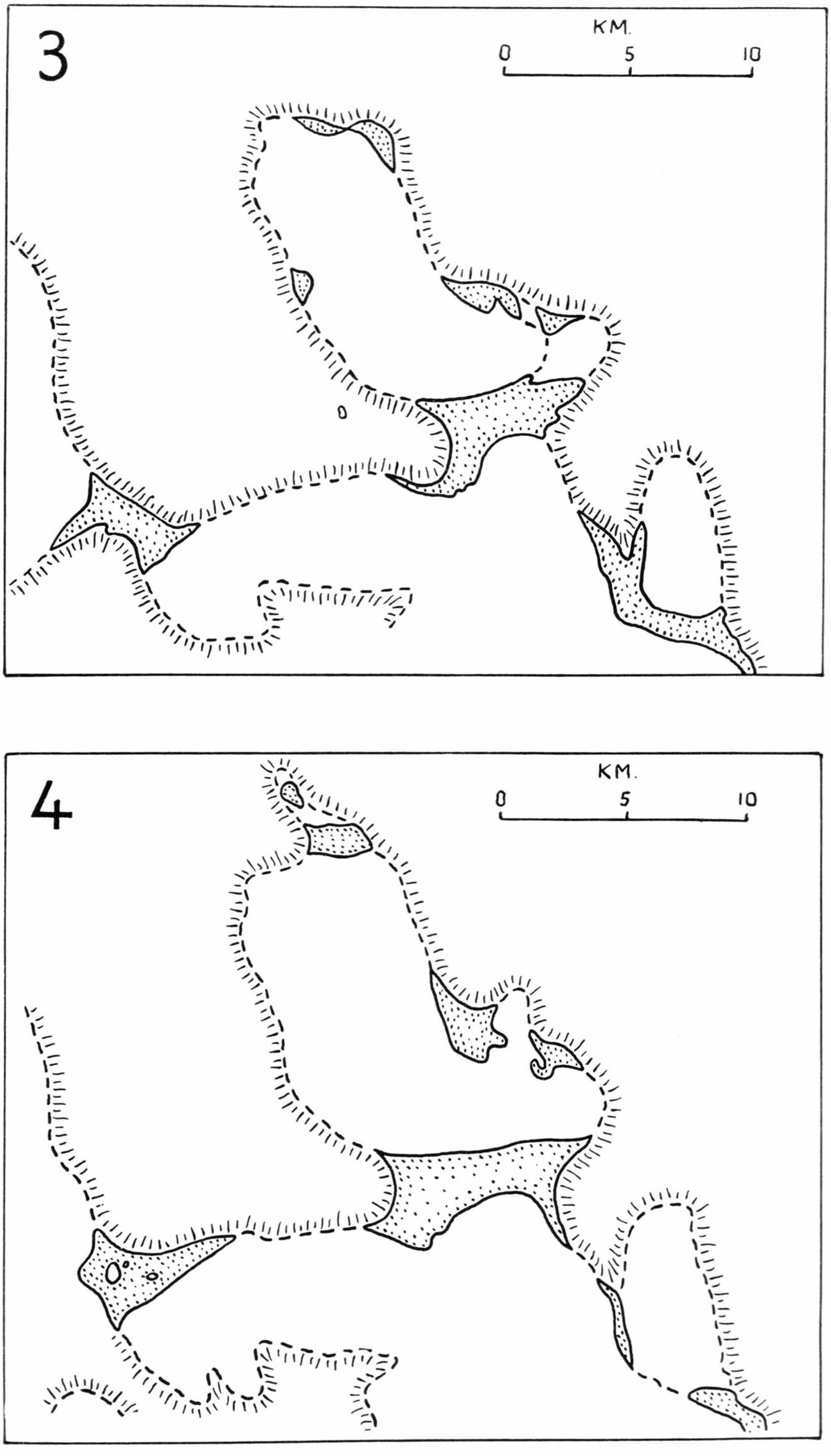


Fig. 23. Stages of Ice Recession in north Dronning Louise Land.

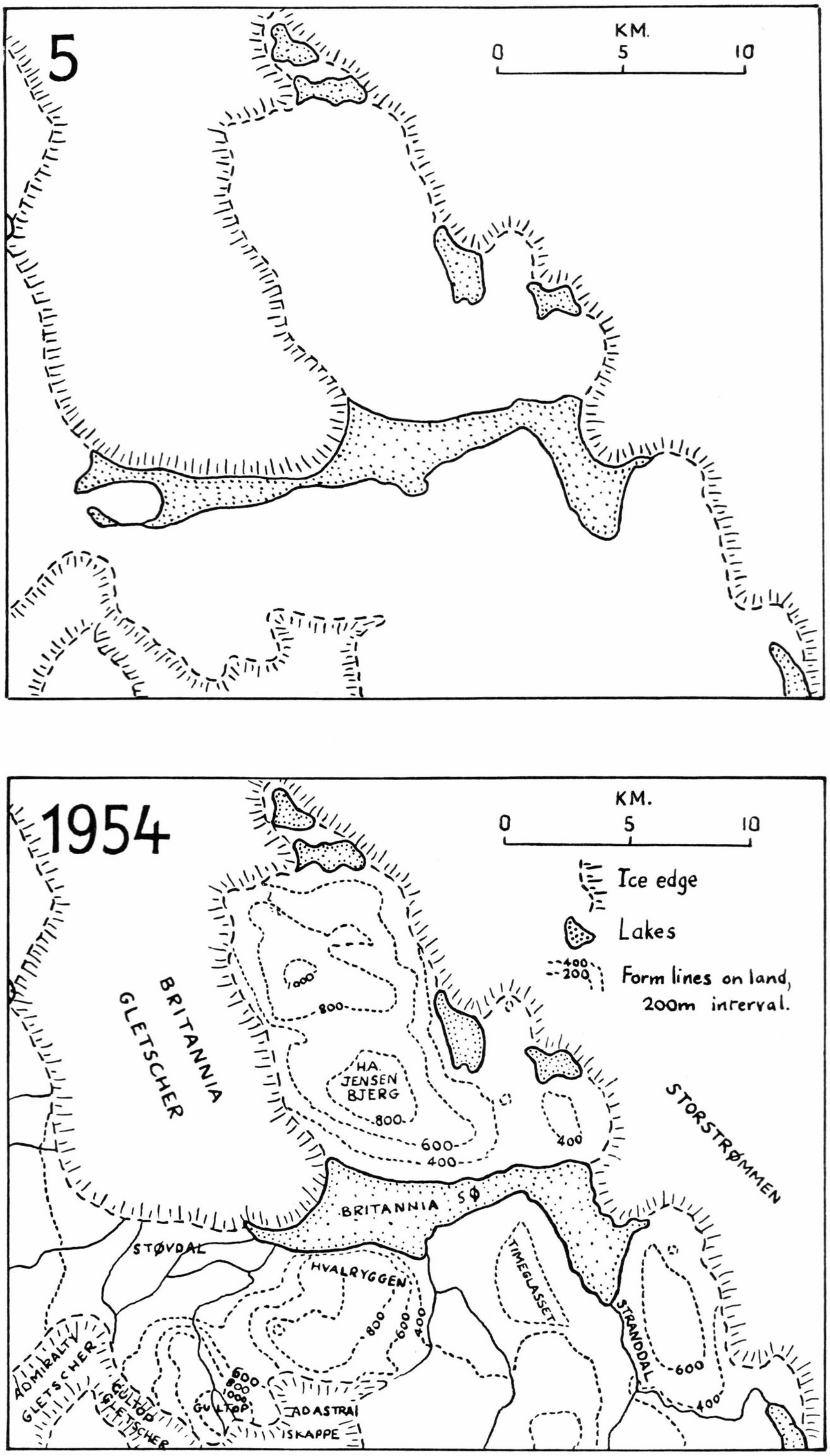


Fig. 23. Stages of Ice Recession in north Dronning Louise Land.

nia Sø. The areas south and west of Britannia Sø are not isolated morphological units and are complicated by Ad Astra Iskappe. These areas have been described as evidence of the mechanisms of the receding ice. The main evidence of stages of recession has been briefly outlined since to detail all the evidence, stage by stage, and across each area would be too lengthy to be included here. The whole area provides a most intriguing study of the development of ice dammed lakes. These, with the principal halt stages in the five periods of recession and an outline of the present day ice and lakes are shown in figure 23.

The area north of Britannia Sø.

The area north of Britannia Sø covers approximately 50 square km. It is bounded in the west by Britannia Gletscher, in the south by Britannia Sø, and in the north and east by Storstrømmen (figure 1). The mountains rising to 1000 metres above sea level in the western half of the area form part of the highland erosion surface; they present steep slopes or cliffs to Britannia Gletscher. The eastern half of the area falls well below the level of the erosion surface and passes beneath Storstrømmen (fig. 5). The high western mass is divided by an east-west, U-shaped valley, lying almost 250 metres above present ice level. It appears that this valley carried ice eastwards from the Britannia Gletscher. The western end of the valley overlooks Britannia Gletscher (figure 16) and rises gently eastwards to a barrier of moraine ridges blocking its eastern end. The most northerly land consists of two small nunataks lying below the level of the Britannia Gletscher and the Suzanne Bræ. They are separated from the main land mass by the Søstersøer, two ice-dammed lakes.

A uniform layer of till covers most of the area, but there are numerous ridges of moraine, marking halts in the recession of the ice.

Stage 1. The presence of till over the whole area is evidence that even the highest parts were covered by ice. Since supraglacial moraine is rarely present on the glaciers of Dronning Louise Land, it seems likely that the till was englacial moraine and that the cover of ice must have been of considerable thickness to deposit englacial moraine in such large quantities.

There appears to have been an almost continuous recession from the time of exposure of the highest mountains to the position of the ice margin delimited in figure 23 as stage 1; the highest halt stage.

A large, well-preserved, lateral moraine on the hill-side north of the narrowest part of Britannia Sø marks the position of the Britannia Gletscher snout at this stage. The moraine extends westwards for approximately 2 km, rising from about 50 metres above present lake level at its eastern end to almost 200 metres above lake level at its western end. Westwards from the moraine the hill-side becomes much steeper, and no other traces of the moraine are present. This is probably due to the observed increase in the combined action of slumping, solifluction and melt wash on the steeper hill-side.

The corresponding position of the Storstrøm margin is well marked north of Britannia Sø by an east-west ridge of moraine on the crest of the hill north-west of the Britannia Gletscher moraine. The ridge rises from a height of 300 metres above lake level at its eastern end to more than 400 metres above lake level 2 km further west. Here, it merges into the general cover of till. Although the well-defined moraine ridge ceases here, the continuation of the highest limit of terminal and lateral moraines left by the retreating Storstrøm may be traced, sweeping northwards around the hill-side. It joins the moraine (750 metres above sea level) forming the wall at the east end of the high-level U-shaped valley. There are no other moraines marking the end of this stage elsewhere. The absence of well-defined lateral moraines in the north may be attributed to the presence, at the end of the first stage, of ice-dammed lakes similar to Søstersøer (about 850 metres above sea level). A terrace around the small hill (height 886 metres) in the north of the area, and two small overflow channels (800 metres above sea level) north-east of the U-shaped dividing valley are due to erosion by melt water. The prominant terrace around the hilltop is fairly level and composed of boulders, gravel and sand. There are many boulders up to 2 metres in diameter, but they rarely stand out more than 50 cm above the surrounding finer material. The larger boulders outline ill-defined polygons. At the end of the first period of recession, the ice probably passed east of this hill (about 850 metres above sea level), damming back a marginal lake (figure 23). The overflow southwards from this lake was by way of two channels, probably successive streams marginal to Storstrømmen, which have stripped the till from the bedrock not far south of the terraced hill.

The Britannia Gletscher, and not Storstrømmen, probably sent a tongue of ice eastwards through the U-shaped valley. Although the snout of the Britannia Gletscher was more than 100 metres lower than the neighbouring Storstrømmen, it appears that the Britannia Gletscher then had a steeper gradient than Storstrømmen, just as it has at the present time.

Stage 2. Several small ridges of moraine are distributed irregularly between the old Britannia Gletscher moraine and Britannia Sø. They indicate recession of the Britannia Gletscher from its position at the first stage, but there is no clear evidence of the ice front at the second and third stages of recession on the northern shore of Britannia Sø.

The hill-side is covered by resorted till. If any lateral moraines were left by the retreating glacier, no trace of them remains today. A series of terraces indicate successive heights of an ice-dammed lake.

Storstrømmen, however, has left evidence of these stages on the north and east facing slopes of the area. A few small, sub-parallel ridges close to the high first-stage moraine probably correspond to the irregular heaps of moraine below the Britannia Gletscher moraine of the first stage. This evidence may indicate intermittent recession for a short period at the beginning of the second period of ice retreat. A broad expanse of till, about 300 metres wide, slopes gently northwards from the sub-parallel ridges to a second continuous moraine. This ridge, slightly smaller than the large moraine on the crest of the hill, marks the second stage of recession. It curves around the hill-side to the north, gaining height slowly, and remaining about 100 metres below the limit of the first stage. Further north, the steeper hill-side facing east is covered by numerous ridges and heaps of moraine. When the distinct moraine marking the end of the second stage reaches this steeper hill-side its position is no longer distinguishable. Looking northward across the mass of deposits, faint traces of remnant ridges were distinguished, approximately contouring the hill-side, but close examination failed to reveal any definite lines to mark the end of the second stage of recession. In the north, there is a large lateral moraine on the low ground south of the terraced hill (77°14′ N. 23°40′ W.). This prominent ridge marks the second stage. It is about 100 metres below the ice margin at the end of the first stage, which is consistent with evidence from further south. The ice-dammed lakes present in the north at the first stage of recession would seem to have persisted during the second stage.

At the western end of the U-shaped valley that cuts into H. A. Jensen Bjerg there is a small lateral moraine more than 600 metres above sea level; this is consistent with the ice margin at the second stage of recession of Britannia Gletscher. Figure 23 shows a reconstruction of the glacier margins and lakes at stage 2.

Stage 3. Extending for 2 km, in the extreme north-west, there is a large curving moraine, its sharp crest rising to 650 metres above sea level. A short distance to the west, a low ridge is a continuation of this moraine. The moraine is about 100 metres below the position of the ice margin at the second stage of recession and therefore marks a third stage. There is no other evidence of this stage in the north of the area, but lake terraces and overflow channels in Dryasdal indicate a fairly well-defined halt. The low-lying area north of Dryasdal contains many low, glaciated hillocks, generally somewhat elongated in a north-south direction. Associated with the hillocks is a series of short moraine ridges, trending north—south and east—west. The rectangular distribution of the moraines here is readily explained by comparison with present processes at the adjacent margin of Storstrømmen. The ice moving southwards appears to mould the hillocks and becomes highly crevassed above them. Glacial streams find easy access to the glacier floor through the crevasses, and the short north—south moraines are probably formed by concentration of debris either in the subglacial streams, or where they leave the ice. The east-west moraines would seem to be produced by the melting out of englacial debris, particularly evident at the base of the glacier. Parallel moraines are forming now where Storstrømmen terminates on land between the two marginal lakes. During the third period of recession there were probably two ice-dammed lakes, similar in form to those present today north of Dryasdal. A large terrace, 375 metres above sea level and at least 100 metres in diameter, is evidence of the westerly lake. The overflow from the easterly lake was partly southwards through the overflow channel in Dryasdal, and partly around the margin of Storstrømmen. The Dryasdal channel, 30 metres wide and 30 to 50 metres deep, is steep-sided. It cuts through the great quantities of till deposited over this area during the earlier periods of recession; the till is at least 30 metres thick, since bedrock is nowhere exposed in the overflow channel. A well-defined notch, on the eastern side of the hill between Dryasdal and Storstrømmen, marks the position of the stream, marginal to Storstrømmen at the third stage.

There must have been extensive lakes in the north, because the till within the arc of the northern moraine has been levelled. A high proportion of fines is present in contrast to the massive boulder pavements found on the higher ground (which has never been beneath water). Small soil polygons, divided by narrow lines of coarser material, cover the flat areas of the surface.

The position of the ice margins at the third stage of recession, as inferred from the evidence detailed above, is shown in figure 23.

Stage 4. On the north central shore of Britannia Sø, on the resorted till, there are no moraines with which to mark a halt in the recession until the fourth stage. This is clearly defined by a large lateral moraine entering the lake 3 km to the east of the present Britannia Gletscher snout. The moraine (30 metres high in places) extends westward and upwards on the hillside to a point almost opposite the snout of the glacier, 100 metres above lake level. Here, it is much reduced in size. The moraine is bordered on its north side by an old river bed, 50 metres wide, composed of well sorted gravel and boulders. The regular, resorted till on the north shore of the lake slopes to the edge of this old river bed. The abrupt occurrence of the large moraine against resorted and stabilised till strongly suggests that the end of the fourth period of ice recession was marked by a period of equilibrium, possibly following a re-advance. The period of equilibrium is indicated by (1) the large size of the moraine, and (2) the width of the lateral river which flowed while the glacier was in this position. The old river bed is almost 10 metres above present lake level where it reaches the lake; this suggests that Britannia Sø, at the end of the fourth stage, was 10 metres higher than it is at present. This is confirmed by lake terraces found on the south shores of Britannia Sø.

Lateral moraines have not been preserved on the steep hill-sides west of H. A. Jensen Bjerg, but the upper limit of the ice at the end of the fourth stage is defined by a sharp line between the fresh grey-coloured rocks and scree below the line, and the more deeply coloured rocks above it. Beyond where the lateral moraine ceases to exist as a ridge, the line continues westwards in the steepening hill-side. It extends to the south of the U-shaped valley, where it is only 50 metres above the present ice margin. It would seem that, higher up the Britannia Gletscher, there can be no great difference between the position of the ice margin at the fourth stage, and that at the present time. This very small recession of the upper glacier is also suggested by the balance between the rate of flow and of ablation as measured, 1952—54 (Lister 1956, p. 234).

Between the limit of Storstrømmen at the end of the third stage and the present glacier margin, there are many moraines, but none is more pronounced than the rest. The line in figure 23 showing the margin of Storstrømmen at the fourth stage of recession has been estimated by comparison with the inferred position of the Britannia Gletscher snout at this time. The ice-dammed lakes north of Dryasdal probably continued to drain southwards through the overflow channel for part of this fourth recession period, until the receding margin of Storstrømmen allowed the level of the easterly lake to fall below the outlet channel. The recession may have been relatively rapid during this stage, because downcutting of the overflow through the till was unable to keep pace with the fall in level of the dammed lake. On the steep hill-side (77°10′ N. 23°20′ W.) overlooking Storstrømmen, there are several notches cut by lateral streams that followed the ice edge as it receded.

Stage 5. The fifth and sixth periods of recession have continued to the present day with little evidence, in the northern area, of a halt stage. On the north-west shore of Britannia Sø there is a succession of sub-parallel moraines between the large moraine described above, and the margin of the glacier. The fine material has been washed out of these deposits. Many of these moraines cover a core of dead ice. The ice cores, and the fresh grey colour typical of the deposits of the fifth stage around Britannia Gletscher indicate that the fifth period of recession is quite recent.

The fifth stage is the line between the coarse material and the fresh, grey coloured material, much of which contains dead ice. Stage 5 would seem to be comparatively close in time to stage 4. The present position of the ice cannot yet be called a halt stage since a slow recession is still in progress.

Small glaciers are more susceptible to minor changes in the supply of ice than are large glaciers and it may be that a halt stage or even a re-advance of the Britannia Gletscher was caused by a minor change in its regime. The larger Storstrøm glacier, being less susceptible to small changes in conditions, does not show evidence of a recent halt stage.

Støvdal, the snout of the Admiralty Gletscher and junction with it of the Gultop Gletscher.

The wide almost flat-floored valley of the lower Admiralty Gletscher separates the steep sided mountain to the north-west from the cliff sided Gultop and the corrie arm chair of Hvalryggen mountain to the south-east (figure 16). The lower, northern end of the valley is blocked by the snout of the Britannia Gletscher which fans out in piedmont form though now much reduced. The snout of the Admiralty Gletscher presents a ten to twenty metres vertical cliff across the valley in the south-west. Meltwater from lateral streams of this glacier follows a braided pattern in a half mile wide stone and gravel trough which widens and shallows as it merges with the floor of Støvdal. Glaciofluvial deposits and the remains of successively eroded outwash terraces and moraines fringe three shallow lakes that empty into this river after it joins the lateral stream of the Britannia Gletscher. The river then follows the three to ten metre ice cliff of the Britannia Gletscher and discharges into the western arm of Britannia Sø over nearly vertical strata of quartzites that form rapids and establish a local base level that is little more than one metre above lake level (figure 24).

Three successively higher dry valleys can be traced across the widely terraced south-east corner of the exposed valley floor. The lowest of these dry valleys connects three amphitheatres initiated by river meanders in the deep lacustrine sands that here and there preserve ripple marks. The fairly steep (concave upwards) walls of these sandy arenas have at their foot, patches of fine sand more grey in colour and with aeolian ripple marks since these patches seem to be deposited by the frequent dust spirals that can be seen in the basin in summer;

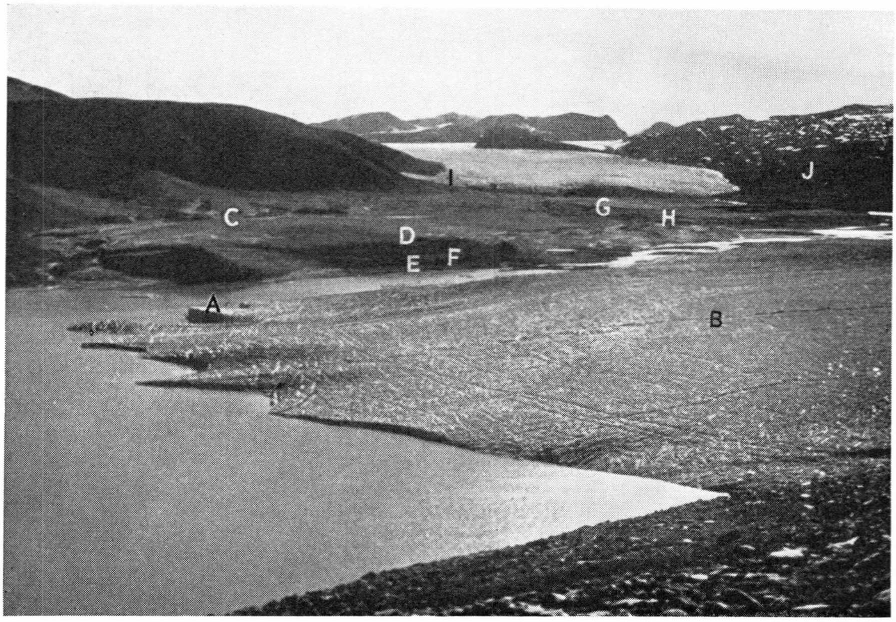


Fig. 24. Britannia Gletscher flowing into Britannia Sø with Støvdal (Dust Bowl) and Admiralty Gletscher beyond.

Note: A Sixty metre ice cliff where snout of Britannia Gletscher is aground.
B Principal surface melt-streams on lower Britannia Gletscher.
C, D, E Successive outlet channels from Støvdal.
F Bare quartzite with striations.
G, H Large terraces and moraine in Støvdal.
I Junction of Gultop Gletscher with Admiralty Gletscher.
J Successive lateral drainage channels and kame terraces.

hence the name Støvdal (Dust Bowl). The three main terrace levels have a cover of fairly rounded stones and boulders, some of these being split and shattered by frost action though this is more obvious on the scattered boulders in the firmly bedded sand.

The north-west valley wall has a perfect series of lateral drainage channels and narrow terraces now breached by two steep 'V'-shaped meltwater gullies from the permanently snow-capped mountain summit. Towards the foot of these north-west slopes the almost parallel lines of the lateral drainage channels give place to a broad cover of outwash material now quite brown in colour.

The whole basin is of a brownish colour except the lowest terrace, the channel of the aggrading river and a broad arc round the south-westerly bulge in the snout of the Britannia Gletscher, all of which are grey. These grey areas have no vegetation and the land near the Britannia Gletscher has boulders that still retain a broken veneer of the pasty glacial mud. This would seem to corroborate not only that here the ice has recently receded but that the annual snow accumulation here is very small indeed, or summer melting and run off would have removed such exposed glacial muds.

The exit for Støvdal into Britannia Sø is quite narrow, between some low, bare rock hills and Britannia Gletscher (figure 24). Probably less than twenty years ago, since there is almost no plant or lichen to be found here, the exit was through a now dry gorge to the south of the recently exposed rocky hillocks. The terrace heights with the heights of the now dry channels give a picture of the successive ice-dammed lakes in Støvdal (figure 25b).

The snout of the Admiralty Gletscher. Approaching the snout of the Admiralty Gletscher the floor of Støvdal rises in three successive terrace levels to the glacier cliff which reaches 20 metres in height where the lateral streams have eroded the terrace, but at the centre rises 10 metres from the terrace level (figure 25a). A fourth terrace along the valley side is as high as the ice surface of the glacier snout. Small, lateral moraines of the Admiralty Gletscher are found only where the mountain wall dips gently to the highest terrace. A few hollows are the only suggestion of kettles formed by slumping in the terrace, due to melting of the contained ice.

The lateral stream along the foot of the highest terrace has cut a gorge 15 metres wide (figure 25b) and now floored, apart from the actual stream bed, by ice which has a thin cover of coarsely bedded sand with scattered, half rounded stones. Falls of debris from the terrace sides have produced many hummocks on top of this ice, the height of these being accentuated by the differential melting. The uppermost ice is in layers, some of which have between them air gaps up to 5 cm. An examination of the crystal form revealed vertical columns (candles) of lake ice. This ice formation seemed most remarkable until subsequent visits during the year revealed that some water flowed along the river channel near the centre of the glacier, even in February and with an air temperature of—34° C. The water sometimes reached as far as 100 metres from the glacier cliff before freezing on the surface of the river. Before the summer melt began, this part of the river was built up more than a metre above the level of the frozen river, further along the Støvdal.

A sledge travelling unwittingly over this layered ice, broke through and revealed water flowing between some of the layers even above ice layers apparently with only air between them. Snow seemed to evaporate from this section of the river ice but large feathery flakes of hoar grew on the surface. The outpouring of water at negative air temperatures

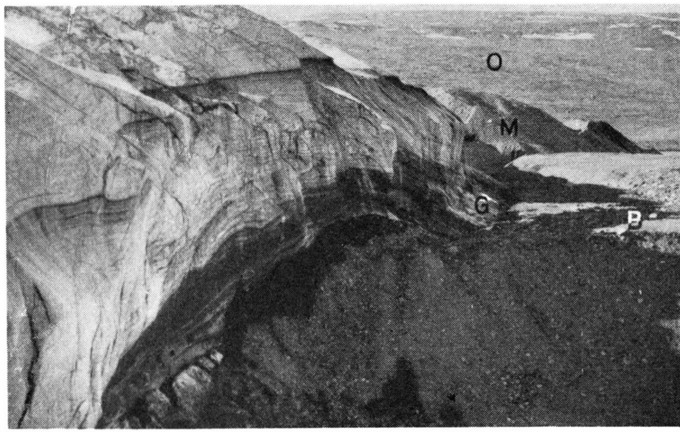


Fig. 25 a. 'Chinese Wall' cliff of Admiralty Gletscher now advancing over terrace B. Darker ice of lower strata of the glacier contrast with the cleaner, white ice of the upper strata. Note: Débris covered ice apron at G; Moraines at M; Kames and old moraines at O.

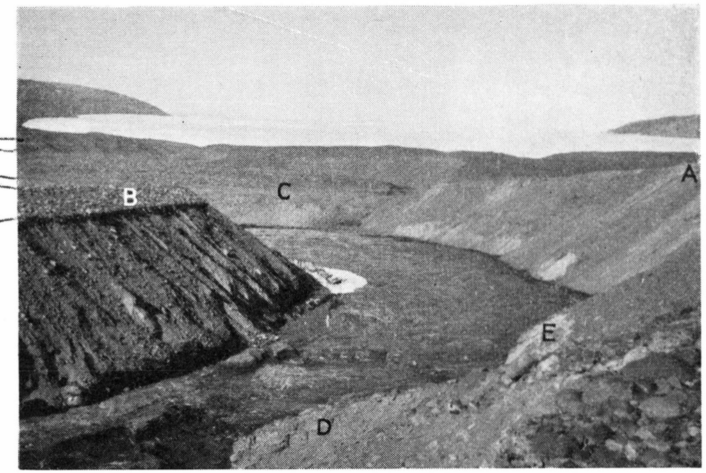


Fig. 25 b. Three successive terraces, A, B, C. Dead ice melting from under A and B. Lake ice of refrozen melt-water floors the 30 metre wide gorge. Lateral drainage from the Admiralty Gletscher is now eroding the foot of terrace B. Vertical sections of D and E shown in fig. 26. Britannia Gletscher in background.

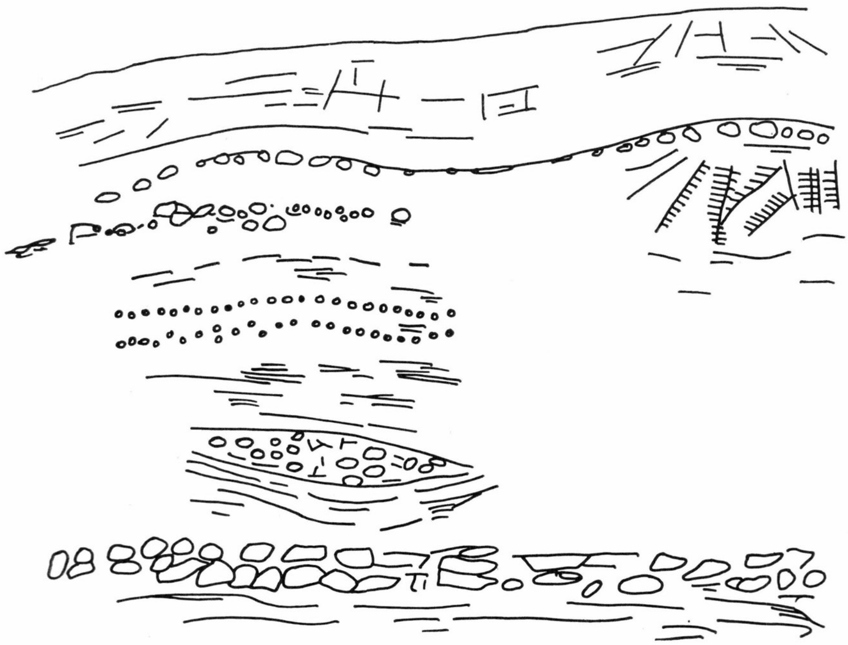


Fig. 26. 40 metres from the shout of the Admiralty Gletscher two vertical sections of the highest terrace revealed the striking layered features above. The terrace is 15 m above the floor of the gorge, see figure 25b.

has been reported in Alaska and in Young Sund, East Greenland, from under Wordie Gletscher (Ahlmann 1946, p. 244).

This winter ice formation explained the debris-covered lake ice, but within the debris of the terraces were enclosed large masses of dead glacier ice. At some of the places where discolouration of the steep sides of the terraces indicated percolating meltwater, digging revealed glacier ice more than 2 metres thick. Falling debris prevented more detailed examination of the ice and its extent but dead ice seemed to be present behind much of the terrace walls.

Within 40 metres of the glacier snout, two vertical sections of the highest terrace were free from fallen debris and revealed most striking layered features. At this site the terrace comprised 10 metres of boulder clay with a mantle of 5 metres of coarse sand and rounded gravel with occasional boulders. Within the clay was much dead ice, melting out where it was sufficiently close to the terrace wall.

The stratification of the two exposures (figure 26) was as follows:—

30 cm from top of boulder clay	— A line of large pebbles.
60 cm from top of boulder clay	— A band of coarse gravel, some rounded, some angular. This layer is a little folded on the side 'down glacier' and merges to all clay.

2 metres from top of boulder clay —	A double line of small pebbles.
4 metres from top of boulder clay —	Stratification in boulder clay becomes more marked, but is not perfectly regular and dips slightly 'up glacier'. Coarse angular stones generally lying flat are set between some of the stratified clay.
$4^1/_2$ metres from top of boulder clay —	A lense of coarse gravel, some rounded, some angular, resting on a bed of finely stratified clay, bent to concave upwards.
7 metres from top of boulder clay —	A 60 cm bed of large gravel and small boulders slightly rounded.
$7^1/_2$ metres from top of boulder clay —	Very dark till with dead ice up to $1^1/_2$ metres thick.

The second exposure nearer the glacier cliff:

At top of boulder clay —	Finely stratified clay.
30 cm from top of boulder clay —	A line of large rounded pebbles.
30–100 cm from top of boulder clay —	Five columns of clay, three nearly vertical and two tilted, one to nearly 45 degrees. The columns were 10 to 15 cm diameter, the one most tilted being conical in shape. The columns were varyingly stratified and had a fairly loose sand infilling between them.
7 metres from top of boulder clay —	A 60 cm bed of large gravel as in first exposure (above).
$7^1/_2$ metres from top of boulder clay —	Very dark till as in first exposure (above).

Between the two exposures and continuous with much of the second exposure, the boulder clay was fairly homogeneous save for intermittent stratification, dipping 'up glacier' and merging with the consolidated, unstratified mass. The 60 cm thick bed of large gravel and small boulders was continuous as far as it could be traced, to the present glacier.

The story told by these remarkable exposures is not very obvious. If we presume that glaciofluvial action has laid down the till we would expect some suggestion of seasonal stratification with a decrease in size of particles from bottom to top, concordant with a reduced carrying power in the stream as the glacier front receded. There is a general reduction in the amount of debris of a specific particle size from bottom to top but the falling off in particle size is very irregular. There is only very poor cyclical arrangement in the stratification and few real varves. The marked horizontal change in the exposures in a very short distance and the absence of grading from one layer to another, remove the possibility of the deposits being laid down by river action. The slumping, folding and infilling suggests that the deposits are not lacustrine. The contained dead ice suggests that settling of the whole is still continuing and that the stratification is very probably due to the position of englacial and supra-glacial debris. The possibility of meltwater reworking the debris here described still exists but the mechanism responsible for the deposition in its present form would seem to be the slow melting of dead ice, depositing its contained debris in situ (Carruthers 1946, p. 45), with perhaps some interference at times by streams or small lakes.

The proximity of the towering cliffs of the Admiralty Gletscher to such great depths of glacial deposit and dead ice, and the pushing forward of moraines at the centre of the glacier snout suggest a re-advance of this glacier. The measured forward movement of a point midway up the cliff face of this glacier was 11 metres in the 3 months of autumn. Subsequent measurement was foiled by the calving of slabs of ice from off the glacier cliff, removing the measuring marks and presenting a different shape of cliff front. The re-advance is probably fairly recent but would not seem to be a major advance. Current advance of the ice seems to be compensated by calving and melting and measurements over the length of the glacier surface show ablation to be greater than accumulation by an average of 90 cm of water equivalent (Lister 1956, p. 233).

The vertical cliffs are not evidence of current advance, but are common to all these glaciers. This is, perhaps, in part due to the low angle of radiation, the more rapid melting of the dark, dirt laden ice of the lower layers and possibly due to fairly rapid movement of the upper layers over the lower layers loaded with sediment (Odell 1937, p. 112). The last two reasons seem more probable. At two places, pins separated 2 metres vertically showed movement of the upper pins of 12 and 16 cm in 8 weeks. This differential movement helps to compensate for melting of the ice cliff. Widespread evidence from which differential movement may be inferred, is the loss of ice, not so much due to melting but by the calving of great vertical slabs from the upper layers of the snout of the glacier and to a lesser extent from the sides of the glacier. The extent of cliff overhang, in places like the "Chinese Wall" front, first so called by Greeley (Chamberlin 1895, p. 568), facilitates this calving. The "Chinese Wall" front is a near vertical cliff with a reverse slope or overhanging bulge in the upper part.

Gultop Gletscher. The Gultop Gletscher from Ad Astra Iskappe flows north-west down a steep-sided valley and ends abruptly in the side of the Admiralty Gletscher which it meets almost at right angles (figure 16). The ice surface is steep and in its lower reaches is very hummocky though not quite the same as the fairly flat surface of the Admiralty Gletscher which has rounded hummocks whereas the steep Gultop Gletscher has many pointed hummocks, cones and ridges. This increased

Fig. 27. Along the N.E. side of the Gultop Gletscher is a series of lateral moraines, M, and Kames, K. On the glacier margin is a line of rafted debris. It is probable that the trough, T, will become a lateral drainage channel cutting off the line of rock debris and thus forming the next lateral moraine.

sharpness is probably due to the greater downcutting of the faster flowing meltwater over the more steeply inclined glacier surface.

Lateral moraines up to forty feet high are visible at places each side of the glacier, particularly on the north-east side (figure 27). Marginal rivers have separated these moraines from the parent glacier but on the moving ice is a lateral moraine of glacial clay, some boulders and many angular stones. Superimposed on these are blocks of rafted moraine material with contorted muds and more rounded stones (figure 28).

Between the side of the Admiralty Gletscher and the adjoining snout of the Gultop Gletscher a gorge, 5 metres wide, has been cut by the marginal river, apparently eroding along a weakness at the junction of the two glaciers. During the winter, this river dried up and the slight forward movement of the Gultop Gletscher nearly closed the gorge at its middle and highest point. The erosion of the sides of the gorge by meltwater seems now to be just keeping pace with the forward movement of the glacier.

Where the Admiralty Gletscher meets the shoulder of the mountain, the lateral stream has cut a deep channel and courses through an area of dead ice in a corner formed between the two glaciers. This stream joins the marginal stream of the Gultop Gletscher and continues through the gorge described above. In one year the changes in this dead ice corner were most marked. Marginal thinning of the Gultop Gletscher had caused the emptying of many small lakes leaving planed-off debris heaps, narrow benches and some higher dirt cones. The lowest terraces displayed

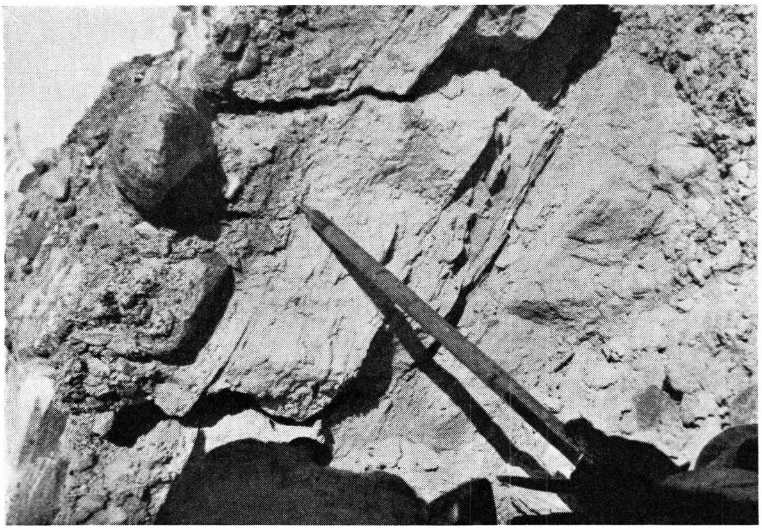


Fig. 28. Varves in the rafted debris (fig. 27) of a lateral moraine. The ice axe points to the smallest measurable layers, above which is the unsorted boulder clay.

some stratification, were more grey in colour and of finer material than that in the higher deposits.

About 10 metres above this composite terrace were broad flats, pock-marked by small kettle holes and pools sinking into the dead glacier ice which almost everywhere could be seen underlying the debris-covered surface. Sand was the dominant material, sometimes current-bedded, with coarse pebbles and boulders strewn on top.

From these broad flats rose a series of benches with from 2 to 6 metres vertically between them. About 20 metres above the present river level was a broader composite bench and nearly 30 metres higher again was a similar terrace but of coarser material and tilting slightly from west to east. Minor terraces were intermittent between these more dominant levels. Above these glaciofluvial deposits was the bare, abraded rock exposure of gneiss and amphibolite with only a small amount of scree filling the vertical gullies.

On some of the broad benches were stone stripes and stone polygons but these were not well developed.

Conclusion. In Støvdal the great depths of glaciofluvial deposit, the dominance of fine debris, the steep terrace sides and the deeply incised meander scars in terrace faces suggest a long period of slow ice recession with a limited outlet for the products of melting. The terrace levels and associated spillways indicate phases (stages 2 to 5) in the lowering of the glacier ice, damming the exits to Britannia Sø (figure 25).

Near Gultop Gletscher the chief evidence of ice recession is in the form of lateral moraines with kame terraces at higher levels along the mountain walls. There were no concave faces of kame terraces showing their formation in contact with glacier ice but the outwash terraces of sand and gravel in the lower valley show some fluviatile bedding and erosional faces (FLINT 1929, p. 257).

The deposits in the corner between the two glaciers and the mountain wall appeared as a newer and smaller example of the deposits in Støvdal. In both areas the masses of debris covered dead ice, the paired lakes, the flights of terraces and associated spillways, the streams graded with respect to the lowest lake, the dearth of purely recessional deposits all suggest down-wasting as opposed to the moving back of glacier recession (FLINT 1929, pp. 259—263). The presence of moving glaciers higher up the valleys quite firmly indicates frontal retreat of glacier recession. Hence it would not seem to be possible to separate these different mechanisms of ice disappearance if we consider only a small area. Indeed, frontal recession and down-wasting may be mutually interdependent, a contention much debated in the literature (JOHNSON 1941, p. 23).

Hvalryggen and the northern edge of Ad Astra Iskappe.

Rising very steeply from the Britannia Sø, the mountain Hvalryggen, of gneiss and quartzite, reaches 900 metres above sea level. The flat summit is covered with slightly rounded stones, many bedded in a flat pavement and many on slight slopes, in raised, crescent-shaped forms, some of which have snow patches throughout the year. In the flat mountain top are three shallow troughs, partly snow-filled and bounded by boulder and stone strewn ridges. The mountain falls steeply southwards to the margin of the Ad Astra Iskappe which seems to cover a rather flat mountain dome reaching 1,300 metres height and is 10 km in diameter. This mountain is probably part of the highland erosion surface (p. 4). The whole of this ice cap becomes coarse firn and ice in summer and is runnelled by melt water channels that increase to small trenches near the ice edge. Sections near the top of this glacier revealed the stratification of blue, with bubbly white ice (and coarse firn), indicating the mechanism of accumulation which BAIRD (1951, p. 194) has detailed on the Barnes Ice Cap and for which he suggests the name "Baffin type" of glacier. The light precipitation of the long, cold winter becoming superimposed ice during the short, cool summer due to the glacier being below the firn line for the region, are the principal conditions requisite for such "Baffin type" glaciers. The firn line at this latitude was found to be at 1000 metres on the edge of the inland ice, but the Ad Astra Iskappe is nearer the sea and is almost surrounded by exposed rock which increases the summer temperature and thus raises the firn line in this locality.

Two small glacier tongues of the Ad Astra Iskappe dip steeply towards Britannia Sø, one to the east and one to the west of Hvalryggen. The snout of the north-west glacier has a thin, dirt cover washed into lines and arranged into the typical horse-shoe patterns by glacier movement. Short steep hummocks of moraine irregularly aligned round the thinning snout are reduced or even removed, at the very front of the snout, by meltwater. The mechanism of moraine formation is not like that at the snout of the Admiralty Gletscher but is very similar to glaciers in Iceland (i. e. temperate glaciers), the ice being thin and much cut by surface streams, some of which cut through to the glacier bed. Melting under the ice edge has revealed water-logged heaps of coarse debris, some of which surround ice broken off the edge of the snout (Lister 1953, p. 30). The lateral moraines are not so different from those on other glaciers, the steep mountain wall shedding debris onto the glacier periphery, large sections of which are cut off by meltwater, to become dead ice within the very little sorted, coarse debris of the lateral moraine. From this north-west glacier of Ad Astra Iskappe meltwater reaches Britannia Sø, aggrading as it follows many channels through the reworked material of end moraine, cutting deeply in its middle course, revealing graded outwash and then meandering over the old lake bed as it nears Britannia Sø.

The north-east outlet glacier is (figure 29) a narrow, fairly steep tongue of the Ad Astra Iskappe with meltwater channels closely set and flowing straight down the glacier. The surface, dirty from downwashed debris, is smoother than the surface higher on the ice cap. The more even dirt cover seems to have increased ablation uniformly and where meltwater streams cut through to the glacier bed, small, rounded boulders and coarse, rounded gravel can be seen both under the ice and included in the glacier sole. Rock falls onto the sides of the glacier and some slides down to the snout. The isolation of many of these areas by stream action has left dead ice, the melting out of which is producing temporary kettles and hummocks but the debris is so loose that further melting causes many changes in the minor topography. There is little definite moraine but simply hummocks of loose till, some of which have coalesced and fanned out in their fall down the steep mountain sides. Higher up the sides of this narrow col are small cirques and some landslip hollows, many occupied by snow patches. These seem to give rise to further soil-slip, marked by finer debris, some being simply sludge hollows in cuspate form. The river from the glacier is deeply incised in the short valley which has one dominant terrace level, the lowest of a

Fig. 29. North east glacier from Ad Astra Iskappe. Note the range of depositional features in the valley middle ground and the erosional features on the high ground and steep slopes.

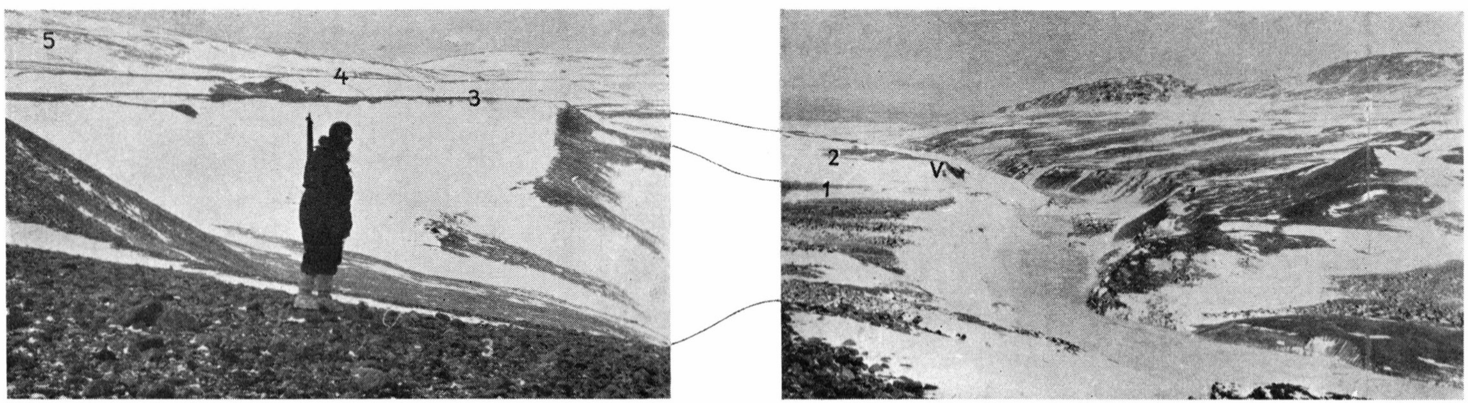


Fig. 30a. Fig. 30b.

Looking N. up Stranddal. Numbers indicate successive heights of main terraces. V indicates site of varves.

series on each side (figured 29). The terrace rises slightly in steps, up to the loose debris of the end moraine, each terrace edge, particularly on the northern side, being a little higher than the platform area of the terrace. The small platforms of the terrace are quite rounded so that the raised edge may be due to the ice contact face but is more likely to be the product of deposition by the marginal stream of the earlier advanced glacier and the shallow lake that bordered the ice here and secondly to drying out, which often produces hollows in terraces of fine-grained material. The terrace sides of fine, sorted debris dip steeply to the narrow floor of the small valley along which the glacial river is cutting a gorge, here and there, through fluvial gravels. Above the terrace, some lateral moraines and many kame terraces ribbon the mountain side to the south, while to the north the steeper slopes have little moraine but have scars of land-slip, normal to the steep mountain side and are severed by steep gullies which have very small debris fans from their foot.

Conclusion. Both erosional and depositional forms left by the Ad Astra Iskappe so correspond with the evidence seen in association with the inland ice that recession of both appears to have been contemporaneous and hence the Ad Astra Iskappe would seem to be a remnant from the last glaciation of North Dronning Louise Land.

Retreat of the ice due to excess of melting over alimentation is suggested by:—

1. The recessional moraines channeled and re-worked by proglacial streams;
2. outwash terraces of sand and gravel with profile concave upwards due to aggrading streams;
3. prolonged erosion by these streams at the lower ends of the valleys; and
4. kame terraces retaining a suggestion of an ice contact face.

This is in good accord with FLINT's (1929, p. 256) requirements for evidence of recession as opposed to down-wasting. The preservation of a well-defined ice front is not so definite, much of the present ice edge being quite obscure due to debris cover and separation of dead ice, which are considered down-wasting phenomena. However, the persistence of an ice cap (rather than the appearance of a nunatak and ice recession from it) and the recessional deposits may be considered good evidence of horizontal recession of the ice though much vertical thinning has accompanied this and would seem to be an inseparable part of the mechanism of recession.

The recession of the ice cap up the steep mountain sides appears to have been fairly rapid, the reduced size and increased spacing of the moraines marginal to the ice cap suggest that the rate of recession has been increasing during the last few decades. This is in accordance with the evidence on the north-west shore of Britannia Sø (p. 37). The containing hummocks and mountain walls that now surround much of the ice cap appear to have arrested the rapid recession though some change in the weather may be responsible for this. The slight evidence of the possible recent development is somewhat shrouded in the changes of land slope and form round the ice cap.

East of the Ad Astra Iskappe and Timerlasset.

East of the Ad Astra Iskappe is a broad valley which opens north to Britannia Sø. From the lobate eastern edge of the ice cap a broad flat ridge of rounded boulders tops the steep mountain side that has a series of almost continuous, coarse, stone moraines, some with quite steep slopes. A number of shallow basins are rimmed by arcs of subangular stones and floored by a pavement of gravel and pebbles. Many of these basins are occupied by the snow patches which formed them. Drainage channels from snow patches cut the moraines and are yet more evenly paved with medium rounded gravel (figure 31). The valley bottom is a broad, fairly flat trough with many streams aggrading their beds, finding new channels and then coalescing as they approach Britannia Sø. Going down the valley, the typical lakes, hummocks and channels of old, dead ice topography give place to a more horizontal valley floor with much levelled and reworked till and finally lacustrine terraces. These terraces have four distinct accordance levels which may be correlated with four outlet channels, the lowest one being the present river outlet and the highest one a dry gorge which provided an earlier outlet to the east.

On each side of the 50 metres wide and 30 metres deep gorge of the present river outlet to Britannia Sø can be traced four lines of moraine. Under Hvalryggen these moraines, rising steeply, tail off to a cliff that drops abruptly into the lake save where a 10 metres wide terrace of rounded boulders hugs the mountain foot. The four moraines further east round the lake are bigger and composed of much smaller debris; they reach 10 metres in height, are up to 20 metres apart and are concave to the north-west. Round the hillside, a little higher than the moraine, runs an ill-defined trough above which outcrops the slightly scoured bed rock. The lowest moraines, which extend the furthest round the lake, end rather abruptly at a wide slope of coarse gravel with some small boulders. A little glaciofluvial debris further east along the lake shore is in small terraces beyond which another slope of coarse gravel fans out and merges with an irregular and steeper slope of gravel and

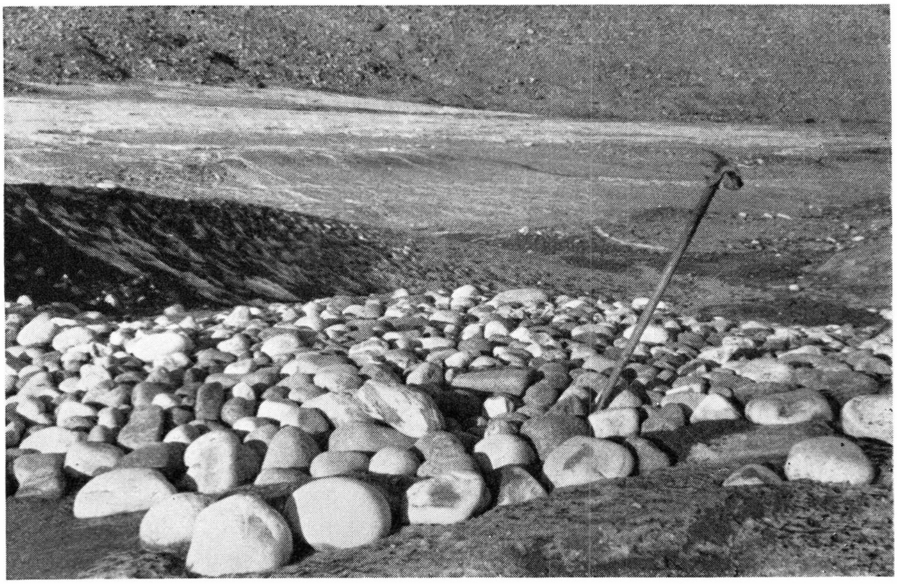


Fig. 31. Pavement of rounded gravel with snow patch middle left. Note dirt cover and uniform angle of snow pinnacles formed by radiation.

boulders, with frost-shattered bare rock outcropping here and there. Two deep gorges, each about 10 metres square cross section are cut in the well-jointed country rock and lead down towards the lake. One gorge divides into two, apparently due to water eroding along a line of weakness in the gneiss of the country rock.

A little further east along this southern shore of the lake are three broad terraces of coarse gravel and boulders at approximate heights above the lake surface of 18 metres, 25 metres and 65 metres. Rock falls from the mountain above the highest terrace are mixed with rounded stones and a small amount of fines all of which at first sight look like re-worked moraine. The terrace levels across this neck in Britannia Sø suggest the lake level at stages 4, 3 and 2 respectively.

Nearly cutting Britannia Sø into two and forming these 'narrows' is a broad, hogback mountain called Timeglasset that forms the eastern side of the wide, north-south valley described above. On the western side of Timeglasset, opposite the north-east glacier from Ad Astra Iskappe, a short stretch of glaciofluvial gravels in broad, closely set hummocks, as of dead ice formation, appears to mark the extent of the Britannia Gletscher at the first halt stage. Any other terminal deposits in this valley marking the further recession of the Britannia Gletscher have been re-worked and present only low hummocks, some of which are bent in right angles, possibly by ice blocks, grounded bergs, or channeled water between them and give no indication of direction or rate of glacier movement.

A dry gorge that cuts west to east across Timeglasset has a reversed delta leading up to a rounded-off, though rather narrow, entrance from which the gorge falls rapidly, reaching 80 metres wide and 30 metres deep. Bare rock exposures along the sides of the gorge are covered in places by rock falls of the frost-shattered gneiss that now presents a surface broken along its mural jointing. The exit of the gorge has a broad outwash fan of coarse gravel and large stones and is lead up to, in the gorge, by increasing size of boulders.

Conclusion. The Ad Astra Iskappe extended eastwards and the Britannia Gletscher south east into the north—south valley. The isolation of large blocks of dead ice with down-wasting was probably equal in importance to ice front recession in the mechanism of ice wastage in this valley. This may be readily appreciated since the Britannia Gletscher was possibly afloat across Britannia Sø. Frontal recession was dominant as the Ad Astra Iskappe receded up the valley side which is marked by the long continuous moraines along the eastern mountain flank of the ice cap. The Britannia Gletscher, fed by the inland ice, persisted after marginal retreat of the Ad Astra Iskappe and dammed back successive lakes, four stages of which can be reconstructed. The highest and most extensive lake found an outlet eastwards through the gorge across Timeglasset which pushes out into Britannia Sø and also bears evidence on its northerly point of successive lake levels. Some of the higher lakes at this narrow part of Britannia Sø were connected by a series of drainage channels round the front of the Britannia Gletscher to the lakes in the valley east of the Ad Astra Iskappe. The direction of flow was from the latter to the former, the south western lakes to the lakes at the neck of Britannia Sø.

East Britannia Sø and Stranddal.

The western side of Storstrømmen dams the eastern arm of Britannia Sø (figure 16). A short distributary glacier from Storstrømmen flows into the lake and in winter folds and shears the lake ice in front of the snout. Polished and scoured, bare rock with north—south striae can be seen high on the side of the northerly point of Kap Bellevue which borders Storstrømmen to the east and Britannia Sø to the west. In line with the flow direction of the distributary of Storstrømmen but on the opposite shore of the lake, smoothed gneiss with striations, chatter marks and a few cuspate hollows credited to rock plucking, indicate an earlier advanced position of the glacier.

On each side of the north—south valley are intermittent lines of narrow terraces marking lateral drainage channels and nearer the lake level some strand lines can be seen, well marked in the few places where there is little debris cover. South of the lake the rising floor of the valley is covered with knob and kettle forms and low moraines. Coarse gravel and stones form the moraines, the fine material, having been washed out, is spread between them. The river outlet for the lake is through a gorge which deepens further south where it flows close under the eastern mountain wall of the valley called Stranddal (figure 30). In broad arcs across the valley, wide terraces reach a height of 410 metres. Along a line across the contours and up the side of Kap Bellevue is end moraine, water-worn into hummocks, some with tops terraced like truncated cones (figure 30b). This line of moraine marks the first dominant halt stage. South of the delta where the deep dry gorge enters to the south of Timeglasset, two 'V' shaped channels enter the valley but at slightly greater heights. These smaller channels were spillways for a lake to the west, formed prior to the first major halt of the ice at stage 1. The principal terrace heights are 410 metres, 350 metres, 280 metres, 250 metres and 225 metres (figure 30) and indicate the heights of the successive lakes dammed by the ice at stages 1, 2, 3, 4 and 5 respectively. Smaller terraces, at heights between these, indicate fluctuations in the lake level. These are particularly evident between stages 3 and 4. The possibility of a small advance of the ice has already been suggested for this fourth period of recession, discussed in the analysis of stages of ice recession north of Britannia Sø.

The Strandelv turns east round the south side of Kap Bellevue, cutting a yet deeper trench between the mountain side and a second group of three terrace levels at lower heights than the terraces further north, nearer Britannia Sø,

Conclusions. The striae on high outcrops indicate that ice flowed from north to south over Kap Bellevue. After a period of ice recession the north—south valley of the eastern arm of Britannia Sø, which probably contained a pre-glacial river flowing north and then east into the valley of Storstrømmen, was occupied by two distributary glaciers from Storstrømmen, one flowing south and one north round Kap Bellevue. Since these glaciers were fed by Storstrømmen, they maintained an ice front during the recession and dammed meltwater between them. The lake thus formed was added to by the discharge through the gorge west to east across Timeglasset. Recession of the southerly glacier, which had at its greatest extent turned nearly 180° to the direction of flow of the parent glacier, permitted a lowering of the ice-dammed lake and its extension in ribbon form along the western margin of Storstrømmen.

On a small scale this can be seen today when Storstrømmen dams a marginal lake as it had done prior to 1951 when it emptied, but began to reform in 1954. Recession northwards of the northerly distributary from the parent Storstrøm glacier permitted a proglacial lake between the glacier front and the higher valley, since this glacier was flowing up the valley in the reverse direction from that of the pre-glacial river.

The Britannia Sø began as several separate lakes and ice recession permitted the coalescing of the lakes dammed on each side of the ice.

SUMMARY OF STAGES OF RECESSION AND ESTIMATE OF DATES

From a complete cover of ice over north Dronning Louise Land, to the appearance of nunataks and accompanying formation of lakes dammed by the ice, was probably the longest period of recession. The first halt stage which can be reconstructed is shown in figure 23 as stage 1. A similar mechanism is today in process at Ymer Nunatak (north of the area detailed here). The ice-margin at the second stage in the recession of the ice is approximately 100 metres lower than the first and is characterised by the ice forming a pattern of valley glaciers. The third stage is again approximately 100 metres below the second stage. At this stage is found the greatest number of ice-dammed lakes and development of spillways. The difference in altitude of the border of the ice between the third and the fourth stages of recession varies from 25 to nearly 100 metres. This is in part due to the retreat of glacier tongues along the valleys resulting in comparatively small vertical changes of the ice edge. A further reason for the reduced vertical recession is possibly the great thickness of ice in the valleys providing a more persistent glacier cover than the thinner ice over the mountain slopes that were covered until the earlier stages. This change in thickness from hill covering ice to valley ice did not occur uniformly at any one period of recession and for this reason would be a cause of variation in the amount of vertical retreat of the glacier margins. An advance of one glacier would have the greatest effect in causing this variation in the amount of recession. A small advance, or at least a more prolonged halt of the Britannia Gletscher, seems possible since its recession across Britannia Sø would be expected to be accelerated by the presence of the large lake. The long and high moraine on the north shore of Britannia Sø is good evidence of the fourth stage being prolonged. Hence it is not possible to assume that a smaller average retreat of the ice is necessarily indicative of a shorter time interval between stages. The fifth stage is scarcely a halt in the process of recession since there is little evidence of this, but it is here considered a stage in the (apparently almost continuous) recession from stage four. The characteristics of this fifth and last stage of recession are:—

(i) the large area of Britannia Sø formed by the coalescing of the ice-dammed lakes;

(ii) the opening of the exit to Støvdal by the retreating Britannia Gletscher;

(iii) the small re-advance of the Admiralty Gletscher.

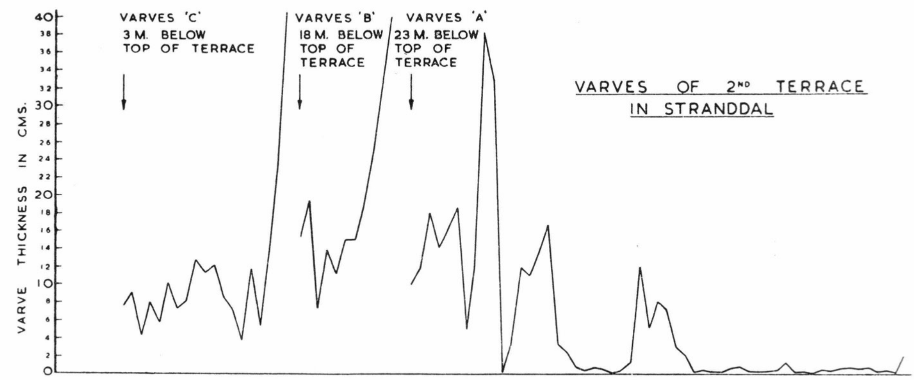


Fig. 32.

In all these successive stages of recession, the margins of the glaciers from the inland ice lose altitude, but the margins of the Ad Astra Iskappe gain in altitude.

Close inspection of some of the fluvial terraces revealed sharply defined layers, each with a graded deposit, of which the finest particles were at the top. In Stranddal, where there are the greatest number of terraces, three exposures of varves were measured at one site in the second terrace (figure 30b) and the thickness of the layers plotted (figure 32). The thickness of the bands varied from a maximum of 46 cm to less than a millimetre. It was not possible to measure these smallest layers. Adjacent terrace cliffs were examined to find a continuation of the sequence of layers but without success. The best examples of the varves were in the river gorge which was difficult of access in summer and buried by snow in winter. Some sections were destroyed in attempts to reach a position from which measurements could be made. The varve thicknesses plotted in figure 32 are representative of the top, middle and bottom of the cliff and give mean values of 12.5 cm, 19.0 cm, and 4.2 cm respectively. There is not a steady decrease in the thickness of the layer nor is there a steady decrease in the average particle size from the bottom to the top of the terrace. Hence it is doubtful whether it

Table 1. Approximate dates of Glaciofluvial Terraces.

Stage	Terrace	Height a. s. l.	Approx. Interval		Date
			metres	years	
1	5	410	60	500	300
2	4	350	70	600	800
3	3	280	30	250	1400
4	2	250	25	200	1650
5	1	225	10	100	1850
Present					1950

is possible here to assume that the distance of the ice from the deposit is inversely proportional both to the varve thickness and to the particle size. The second terrace corresponds to the fourth period of ice recession

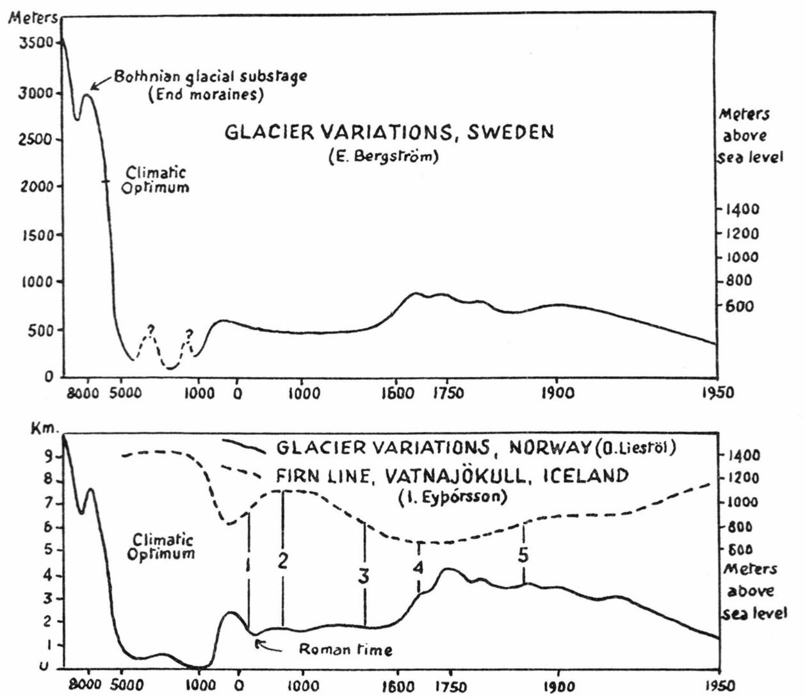


Fig. 33.

(table 1) in which a possibility of ice advance and the probability of a marked change in the rate of recession has been discussed. The variation in varve thickness may be related to these fluctuations of the ice front. As an approximation, the mean varve thickness of the three suites examined is 11.9 cm and the heights of the terrace cliff 30 metres, which gives a period of 250 years as the approximate time for deposition of the stratified deposits in the cliff.

The highest of the large terraces in Stranddal is at an altitude of 410 metres (p. 65) and there is an almost continuous series of fluvial deposits through the 190 metres from the river gorge. Extending the very approximate treatment l. c. of dividing the depths of deposit in each terrace by the thickness of the mean (annual) layer, gives a quotient which is the time required for building the terrace. These are shown in table 1. Figure 33 from AHLMANN (1953, p. 36), shows the approxii-mate dates of glacier variations in Sweden, Iceland and Norway. The approximate dates of the stages of ice recession as found from the depths of the terraces, have been added. Since the method adopted in finding these dates is so very approximate, the good agreement of the recession in Dronning Louise Land with that in North Europe can only be considered fortuitous. From the morphological evidence the pattern of recession in Dronning Louise Land seems to be very similar to that in North Europe.

CONCLUSION

The ice over Dronning Louise Land has been receding for the past 2,000 to 3,000 years. Five halt stages can be traced, the last being quite a minor one. Re-advance also seems to be of rather small importance, though there is a suggestion of re-advance ending the fourth period of recession in the eighteenth century. This is coincident with the recent maximum extent of ice in north Europe.

Most of the glaciers of Dronning Louise Land are below the firn line which is at 1,000 metres. The net loss from the surface of the glaciers is nearly one metre of water equivalent per year but flow from the ice sheet about compensates for much of this ablation. The rate of recession is thus much reduced but where a glacier flows across a rock threshold in a mountain divide, continued lowering of its surface by ablation reduces the cross sectional area of ice at the threshold and the restricted flow becomes insufficient to compensate for ablation. Recession is then much more rapid. This is the reason for the deeper valleys in Dronning Louise Land being occupied by ice while large areas at greater altitudes are ice free.

Most of the glaciers occupy pre-glacial river valleys which they have deepened and have carved vertical cliffs in the hard crystalline Pre-Cambrian rocks. The highland erosion surface of a raised peneplain is the dominant morphological unit and is probably contemporaneous with similar extensive features in east and north Greenland. The highland surfaces between the glacier valleys are not deeply dissected. The channelled ice of valley glaciers seems to be a powerful erosive agent but the extensive ice cover of a 'cap' or 'sheet' leaves far less evidence of great erosion. Though coarse till is fairly uniformly spread it is only exceedingly thick where a halt stage or fluvial action is evident. This cover of till continues to protect extensive areas after the ice has receded.

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