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JOHANNES KRÜGER and OLE HUMLUM

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with particular reference to Sléttjökull and Höfdabrekkujökull

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WITH ONE PLATE, A MAP 1:10.000

Summary in Danish

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ABSTRACT

I nærværende afhandling redegøres for en glacialmorfologisk ekspedition til iskappen Myrdalsjökull, Island, i 1977. Det var ekspeditionens opgave (1) at kortlægge glaciale og glaciofluviale terrænformer foran en recent gletscher med vigende isrand, (2) at beskrive de herskende deglaciationsmåder, (3) at undersøge den glaciale transport såvel som de sub- og supraglaciale aflejringsprocesser, samt (4) at studere sedimentære strukturer og teksturer i de glaciale aflejringer foran gletscheren - alt sammen med henblik på en sammenligning med det danske istidslandskab.

Undersøgelserne koncentrerede sig om to områder (fig. 1): (1) Den nordlige del af Myrdalsjökull - også kaldet Sléttjökull - der ender med sin godt 20 km lange front på en udstrakt højslette bestående af mere eller mindre permeable og deformerbare sedimenter i lighed med det nordeuropæiske isskjolds underlag i Danmark. (2) Höfdabrekkujökull - en piedmontgletscher, der er en udløber fra den sydøstlige del af Myrdalsjökull.

Geomorfologien langs Sléttjökulls rand fremgår af fig. 5, medens p1. 1 fremstiller detailmorfologien inden for en udvalgt del (Mælifell-området) af dette område. Glacialmorfologien foran Höfdabrekkujökull er vist på fig. 26.

Sléttjökull er et enestående eksempel på frontal deglaciation, hvor grænsen mellem isfrit og isdækket område er skarp; det subglacialt dannede bundmorænelandskab frilægges i takt med israndens tilbagesmeltning (fig. 11, 22, 24 og 25). Dele af Höfdabrekkujökulls randområde tjener derimod som model for areal deglaciation, hvor der optræder en bræmme af dødis og stagneret is uden for den aktive del af gletscheren (fig. 27 og 45). Resultatet af denne afsmeltningsmåde er et uregelmæssigt, småbakket landskab (fig. 28). De to undersøgelsesområder ved Mýrdalsjökull supplerer således hinanden og er velegnede til videre undersøgelser af henholdsvis subglaciale og supraglaciale aflejringsprocesser.

CONTENTS

INTRODUCTION

The last decades have seen a great increase in number of publications on glaciations and deglaciation problems within the Danish area. The main focus of attention has been the regional glacial geology, especially characterized by the contributions of workers studying the geomorphology, stratigraphy, and chronology. (Smed 1962; Krüger 1969; Berthelsen 1973; Sjørring 1973; 1977; Bahnsen et al. 1974; Rasmussen 1975; Larsen et al. 1977).

In recent years, however, there have also been considerable advances in the characterisation of glacial sediments, especially glacial tills (Krüger 1970; 1979; Marcussen 1973; 1975; Humlum 1978; 1979). This is a very important development as advances in the understanding of the environmental conditions prevailing at the time of formation of the glacial landforms depend on a reliable interpretation of the Pleistocene sediments. However, in some cases the studies of specific occurrences of tills have led to controversial ideas on the mode of deposition and this in turn has recently started another major controversy on the behaviour of the Pleistocene glaciers in Denmark (Humlum et al. 1978). This confusion largely stems from the fact that in Denmark the greatest attention has hitherto been given to a characterisation of the end-products of the work by the Pleistocene glaciers, and only in a minor degree to the mechanisms involved in till formation and the processes responsible for the glacial landforms.

It is conspicuous that many countries, e.g. the U.S.A., Canada, Britain, Sweden, and Poland, where students of Pleistocene landscapes have an almost traditional interest and activity in areas of existing glaciers, have presented valuable contributions to the understanding of till formation. The present authors are of the opinion that also among the Danish glacial geologists and glacial geomorphologists there exists a need for making comparative studies at the margin of present-day glaciers with the express purpose of attaining more reliable ideas on the past glacier behaviour within the Danish area.

During the last 5 years the Geomorphological Department of the Geographical Institute of the University of Copenhagen has organized scientific expeditions, as well as field courses and excursions for students of physical geography, to the margin of existing glaciers in the Austrian Alps, Norway, and Greenland; the expedition to Mẙrdalsjökull in Iceland in the summer of 1977 forms part of these current activities in present glaciated areas.

The object of the present paper is to give a general report on the glacial geomorphological expedition to Myrdalsjökull in 1977, while details of the work will be published in separate papers (Krüger 1979; Humlum in prep.). Furthermore, this paper is intended to lead up to more detailed investigations of the glacial geomorphology and sedimentology in the promising research areas at Mẙrdals jökull.

For financial support the authors wish to express their warm thanks to the Danish Natural Science Research Council. For most valuable assistance during the preparatory stage of the expedition thanks are due to Professor S. Thorarinsson, Reykjavik.

Students of physical geography at the University of Copenhagen, Niels Gylling Mortensen, Lisbeth Pedersen, and Henrik Højmark Thomsen assisted in the field and in the photogrammetric laboratory. The laboratory worker Winnie Eberhardt performed the granulometric analyses. Correspondent Kirsten Winther kindly improved the English of the manuscript Physician Hannah Wulffsberg acted as medical adviser. The report was typed by Annie Witte. To all these individuals the authors extend their sincere thanks.

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ORGANIZATION OF THE EXPEDITION

The plan of undertaking an expedition to Iceland in the summer of 1977 originated in the Geomorphological Department in Copenhagen. Recent studies of the glacial geomorphology and sedimentology carried out by the authors on selected localities in Zealand, Denmark, had called the attention to phenomena important for the interpretation of processes involved in till deposition by pleistocene glaciers. Therefore, the reason for the expedition to Iceland was a wish for making comparative studies of landforms and deposits adjacent to present-day glaciers. But the authors also took inspiration from the Nordic Geo-excursions to Iceland in 1969 and 1975 under the stimulating guidance of Professor Sigurdur Thórarinsson and Dr. Thorleifur Einarsson, Division of Geosciences, University of Iceland, Reykjavik.

OBJECTS

From the beginning the main objects of the expedition were: 1) to study and map geomorphological features in a recently deglaciated area, 2) to obtain information about modes of deglaciation, 3) to obtain information about types of glacial transportation, 4) to make a special study of the mechanisms involved in subglacial and supraglacial deposition, and 5) to study the textures and structures in the sedimentary end-products in the forefield of the glaciers considered.

The northern and eastern Mýrdalsjökull forefield was selected for the research work because of the following features:

1) The northern part of the ice-cap, which is called Sléttjökull (Rist 1967), has an almost 21 km long glacier front terminating in a landscape of very low relief. 2) At present this part of the glacier undergoes a distinct frontal retreat, leaving extensive areas of ground moraine and associated landforms. 3) Mýrdalsjökull is a temperate glacier and the-

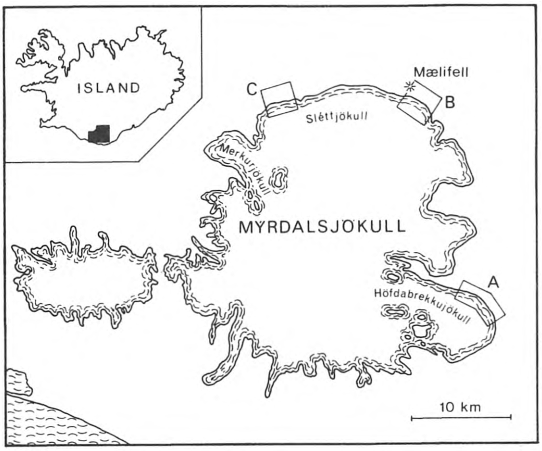


Fig. 1. Map showing the Mýrdalsjökull and the location of the planned research areas of the 1977-expedition. (A) Höfdabrekkujökull, (B) the northeastern margin of Sléttjökull (the Mælifell area), and (C) the northwestern margin of Sléttjökull. During the field work, however, only the two first-named areas were studied.

Fig. 1. Kort over Mýrdalsjökull med angivelse af 1977-ekspeditionens planlagte arbejdsområder. (A) Höfdabrekkujökull, (B) Sléttjökulls nordøstrand (Mælifellområdet), og (C) Sléttjökulls nordvestrand. Under ekspeditionen blev dog kun de to førstnævnte områder studeret.

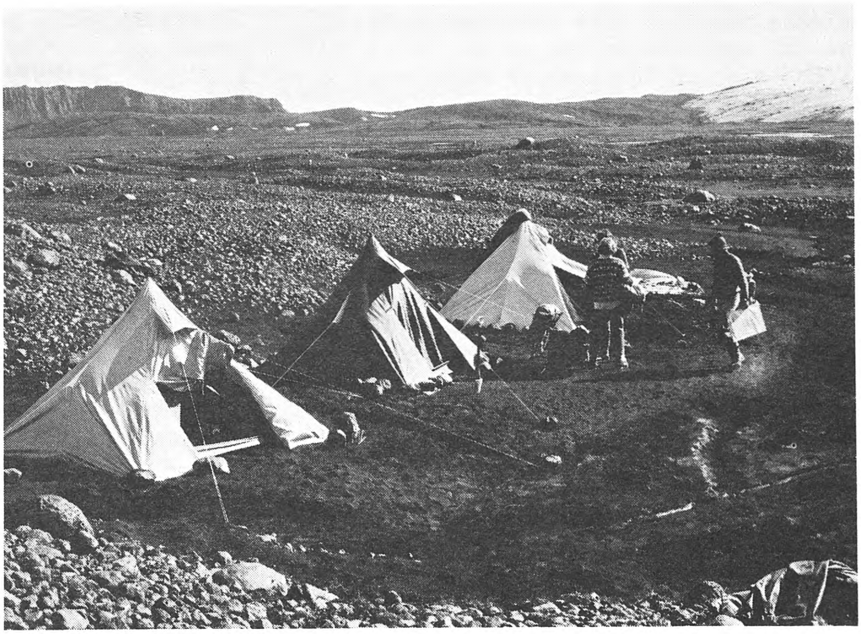


Fig. 2.
The base camp in the forefield of Sléttjökull southeast of Maelifell. In the background the northern margin of the glacier is visible.

Fig. 2.
Basislejren foran Sléttjökull, sydøst for Mælifell. I baggrunden ses gletscherens nordrand.

refore offers conditions suitable for the operation of subglacial till deposition. 4) Contrary to the northern margin of Mýrdalsjökull the Höfdabrekkujökull, which is a piedmont-like outlet glacier extending from the eastern part of Mýrdalsjökull, has a dirty surface with conditions favouring flowage processes and areal down-wasting.

The planned research area of the 1977-expedition to Mýrdalsjökull is shown on fig. 1.

PERSONNEL

Members of the expedition were the following: Niels Gylling Mortensen (assistant), Lisbeth Pedersen (assistant) , Henrik Højmark Thomsen,(assistant) , Ole Humlum (scientific collaborator) , and Johannes Krüger (leader of the expedition). Furthermore, physician Hannah Wulffsberg acted as medical adviser and visited the expedition in the middle of July.

TRANSPORT

On July 1st the group left Reykjavik in a hired landrover and after having visited SÓlheimajökull it moved on to Höfdabrekkujökull where a base camp was established at the foot of Rjupnafell south of the river Leira in the northern part of the extensive outwash plain Mýrdalssandur (see fig. 3). From the camp there was a magnificent sight towards the three outlet glaciers, Öldufellsjökull, Sandfellsjökull, and Höfdabrekkujökull, all of them extending from the eastern part of Mýrdalsjökull. Further on to the research area at the snout of Höfdabrekkujökull there was 7 km of which the first 6 km across the flat Mýrdalssandur were daily covered by landrover.

Contrary to this the travel to the margin of Sléttjökull was met with an unusual number of difficulties. Theoretically, there were four access roads or rather wheel tracks to this area: one northwest of Mýrdalsjökull and three east of it. However, in the early days of July travel by landrover was impossible northwest of the ice-cap because of snow and landslides blocking this elevated route. To all appearances two of the three roads east of the ice-cap were passable, and they were tried but without success. The first one, a very rough and narrow spur north of Blafjall and leading southwest along the eruption fissure Eldgja, was too steep for the heavily loaded landrover; furthermore, the spur was here and there intersected by gullies The second one, a spur from Snæbýli towards the west crossing Snæbylisheidi, was covered to the torrential river Hólmsá where further travel became impossible. In addition to this the landrover was damaged and had to be repaired.

Finally, the third spur from Snæbýli leading 25 km towards the northwest crossing Ljótarstadaheidi,Tjaldgilshåls, and the river Hólmså at the ford just north of the lake Brytalækir, was tried (see fig. 3). It was attended with some difficulties, but owing to a serious effort from all members of the group the expedition arrived safe at the promising research area at Sléttjökull. A base camp was established directly in a system of marginal moraine ridges 1.5 km southeast of Mælifell (see fig. 2). From this camp to the glacier front there was only a distance of 1-1.5 km. After having returned to the research field at Höfdabrekkujökull and stayed there for some days the expedition arrived Reykjavik on the 28th of July.

FIELD WORK

Unfortunately the programme of work was not completed. The main reasons were not only the above-mentioned troubles but also bad weather conditions with heavy rain and temporarily strong winds retarded the research work. During the 28 days' stay precipitation occurred on 13 days, and the total precipitation was measured to be about twice the monthly mean of July. In front of Sléttjökull the very heavy rain was often accompanied by strong winds which loosened the tents and knocked them over.

At the northeastern margin of Sléttjökull the following objects were investigated: 1) Detailed geomorphological mapping in the scale 1:10,000 of the glacier forefield southeast of Mælifell. 2) Observations on deglaciation processes. 3) Preliminary studies on textures and structures in lodgement till as well as the mechanisms involved in subglacial deposition.

At the Höfdabrekkujökull the investigations were mainly concentrated on the following objects: 1) Observations on the geomorphology of ground moraine and hummocky moraine. 2) Preliminary studies on processes of englacial transportation and supraglacial flowage processes and areal downwasting. For the purpose of a coming expedition to Mýrdalsjökull in 1979 aerial photographs were taken in the autumn of 1978 by Landmælingar Islands (the Icelandic Geodetic Survey).

PHYSIOGRAPHY AND GEOLOGY OF THE MÝRDALSJÖKULL DISTRICT

The Myrdalsjökull is a small almost circular plateau ice-cap in south Iceland, approximately 150 km east-southeast of Reykjavík. The ice-cap covers about 600 km^2 centred on what appears to be a mountainous massif (see fig. 3). In the north this massif borders on a southern arm of the inland plateau which is between 300 and 700 m in elevation. The inland plateau is a very open plain diversified by ridges, table mountains, and numerous crater rows. Eldgjá, which is a linear eruption fissure, runs NE-SW parallel to the ridges and crater rows. To the southeast, however, the Mýrdalsjökull-massif is bordered by extensive areas below 100-200 m elevation. To the south these low-lying areas continue as a narrow fringe along the coast. West of Mýrdalsjökull the massif continues as a kind of broad ridge capped by the glacier Eyjafjallajökull. North of this glacier the Markarfljót river valley pushes an isolated finger of lowland inland to the Mýrdalsjökull-massif. All mountain slopes facing the lowland south of Mýrdalsjökull and the Markarfljót river valley to the west are irregular in outline and incised with numerous steep-sided valleys.

The ice-cap Mýrdalsjökull terminates around the 700 m contour in the north and east and lies above the 900 m and 1100 m contours in the south and west, respectively. The ice-cap culminates in a gently rising summit at 1450 m in its southern part. From the eastern, southern, and western margin of the ice-cap there flows a radial system of lobes which form outlet and/ or piedmont types of glaciers, among others the Sólheimajökull and the Höfdabrekkujökull. The northern part of Mýrdalsjökull, Sléttjökull, slopes gently down to the high-lying inland plateau.

Referring to the geological map of Iceland sheet 6, South-Central Iceland, the geology of the area surrounding Mýrdalsjökull is relatively simple as only three formations of bedrock are represented (see fig. 4):

(1) The Late Tertiary and/or Pleistocene Old Grey Basalts which only occurs southwest of Sólheimajökull,

(2) The Pleistocene Young Grey Basalts which are found in small isolated areas, especially southwest and northeast of Mýrdalsjökull, and

(3) The Pleistocene Palagonite formation which makes up the remaining bedrock surrounding Mýrdalsjökull. The Palagonite formation is composed of a mixture of subglacial and subaerial eruptives together with glacial, glaciofluvial, fluvial and eolian deposits. These materials have been compacted into tuffs, tuff-breccias, and Palagonites.

North of Mýrdalsjökull a sheet of pumice-stone covers the Palagonite formation in topographic lows. Furthermore, glaciofluvial deposits occupy extensive areas east and southeast of Mýrdalsjökull in the shape of the outwash plain Mýrdalssandur. Glaciofluvial deposits are also common in areas directly north of Mýrdalsjökull.

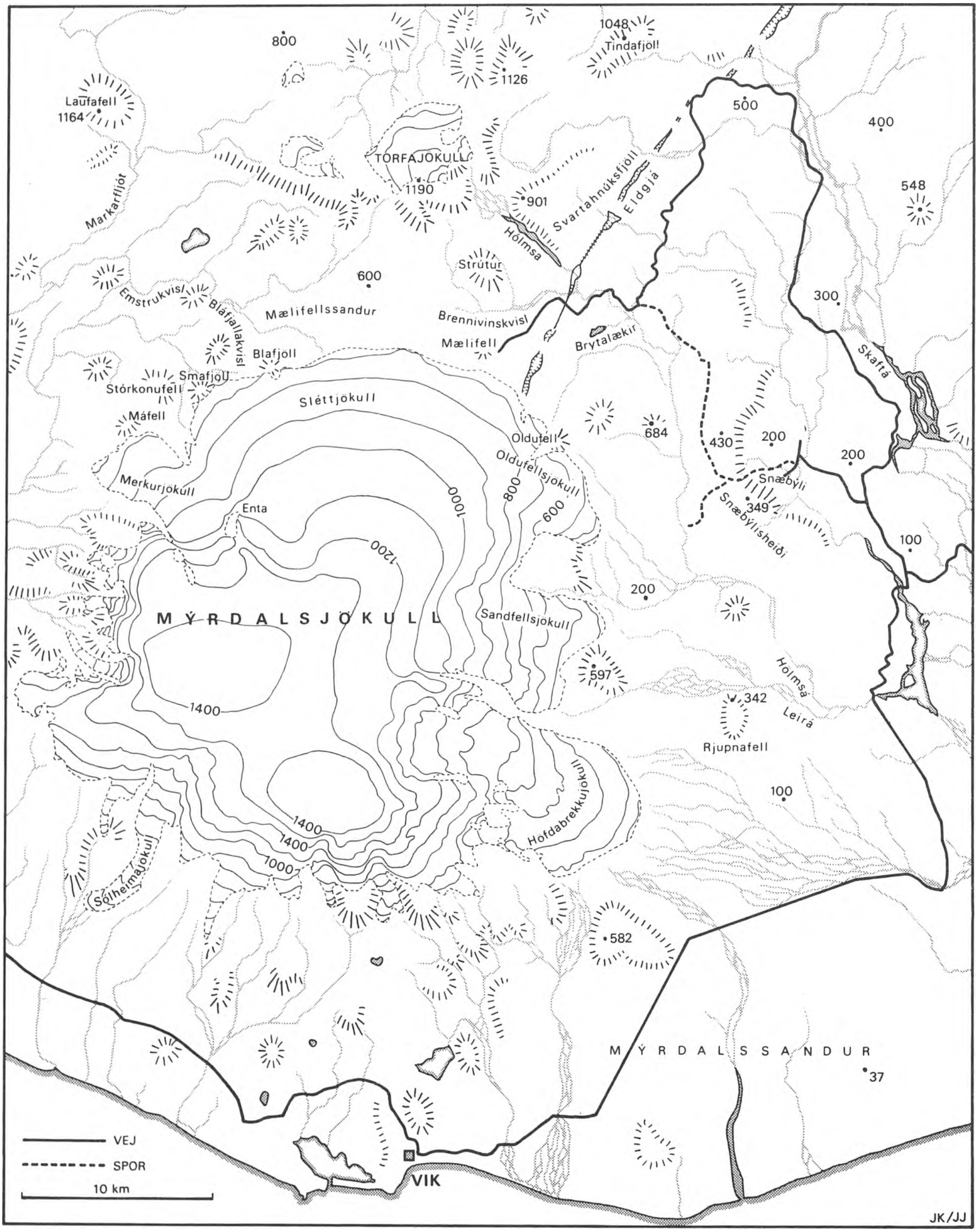


Fig. 3. Topographic map of the Mýrdalsjökull district stating the routes to the research areas. Contour interval 100 m.

Fig. 3. Topografisk kort af Mýrdalsjökull-området med angivelse af ruter til forskningsområderne. Kurveækvidistance 100 m.

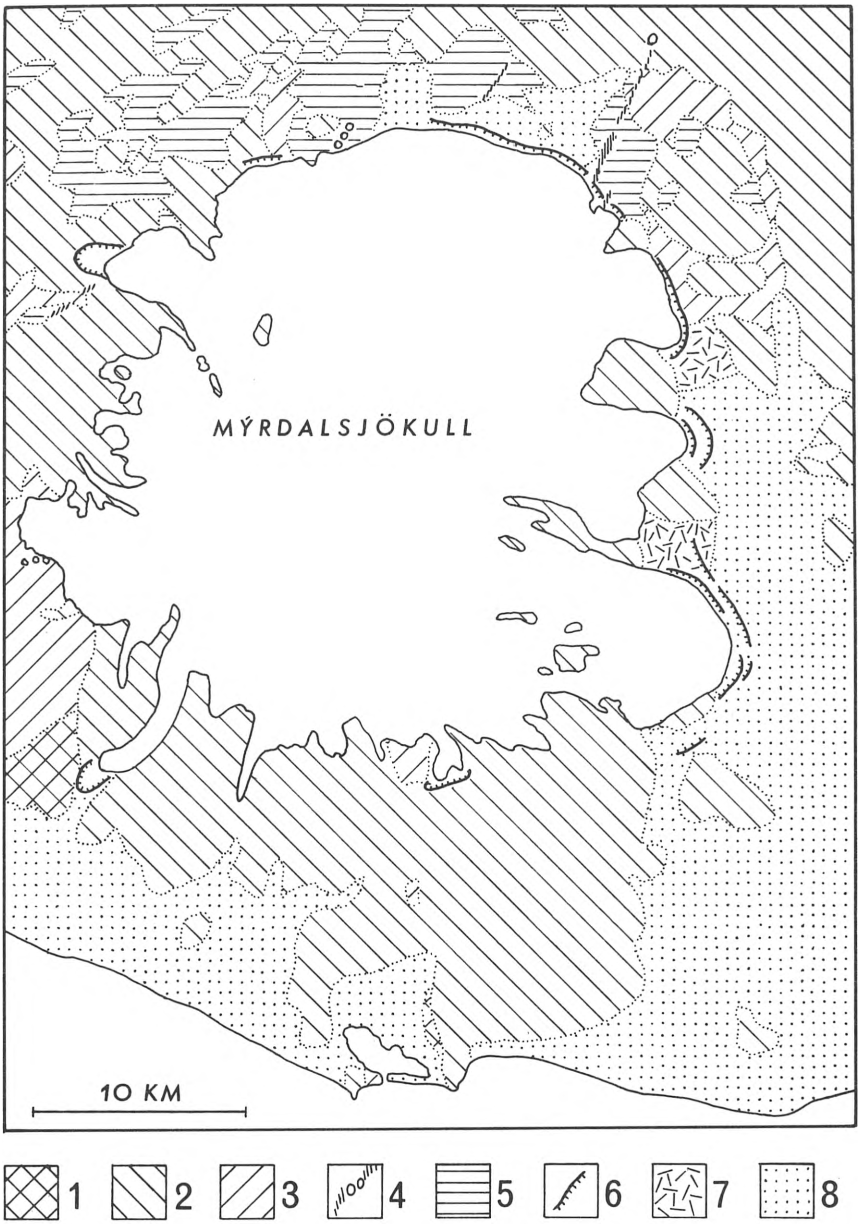


Fig. 4. Geological outline map of the Mýrdalsjökull district. (1) Old Grey Basalts. (2) Palagonite Formation. (3) Young Grey Basalts. (4) Eruptive fissures and craters. (5) Pumice-stone. (6) Terminal moraine. (7) Ground moraine. (8) Glaciofluvial deposits . A sector of the geological map of Iceland, sheet 6, South-Central Iceland (G. Kjartansson, 1962) .

Fig. 4. Geologisk oversigtskort af Mýrdalsjökull-området. (1) Ældre grå basalter. (2) Palagonitformationen, (3) Yngre grå basalter. (4) Eruptive sprækker og kratere. (5) Pimpsten. (6) Randmoræne. (7) Bundmoræne. (8) Smeltevandsaflejringer. Udsnit af det geologiske kort over Island, blad 6, South-Central Iceland (G. Kjartansson, 1962) .

LARGE-SCALE GEOMORPHOLOGY IN THE FOREFIELD OF HÖFDABREKKUJÖKULL

The glacier Höfdabrekkujökull - also called Kötlujökull - is a 15 km long outlet-glacier extending from the southeastern part of Mýrdalsjökull (see fig. 3). It drains ice from about 60 km^2 of the caldera containing the subglacial volcano Katla. Volcanic eruptions at Katla are known to trigger the most catastrophic jökulhlaups in Iceland flooding large areas of the 600 km^2 outwash plain, Mýrdalssandur, south and southeast of the glacier (Thorarinsson 1957; Björnsson 1975). During these "Katlahlaups" the peak discharge may exceed 100,000 $m^3 s^{-1}$, that is almost as much as discharged by the river Amazon, or more than twice as much as a Skeidarárhlaup at its maximum (Thorarinsson 1957). Between 1580 and 1918 there has, on an average, been 42 years between Katla's eruptions, but since 1918 no eruption has occurred. Only a small jökulhlaup took place in 1955 (Rist and Thorarinsson 1955, Thorarinsson 1957), and in June 1977 earthquakes were registered (Thorarinsson, personal communication). Höfdabrekkujökull terminates in a terrain of low relief, generally sloping gently away from the glacier margin, where the glacier spreads out to form a piedmont-lope with a total perimeter of almost 12 km (see figs. 3 and 26). Only at the northern flank and to the extreme southwest the glacier terminates in a hilly landscape belonging to the Palagonite Formation.

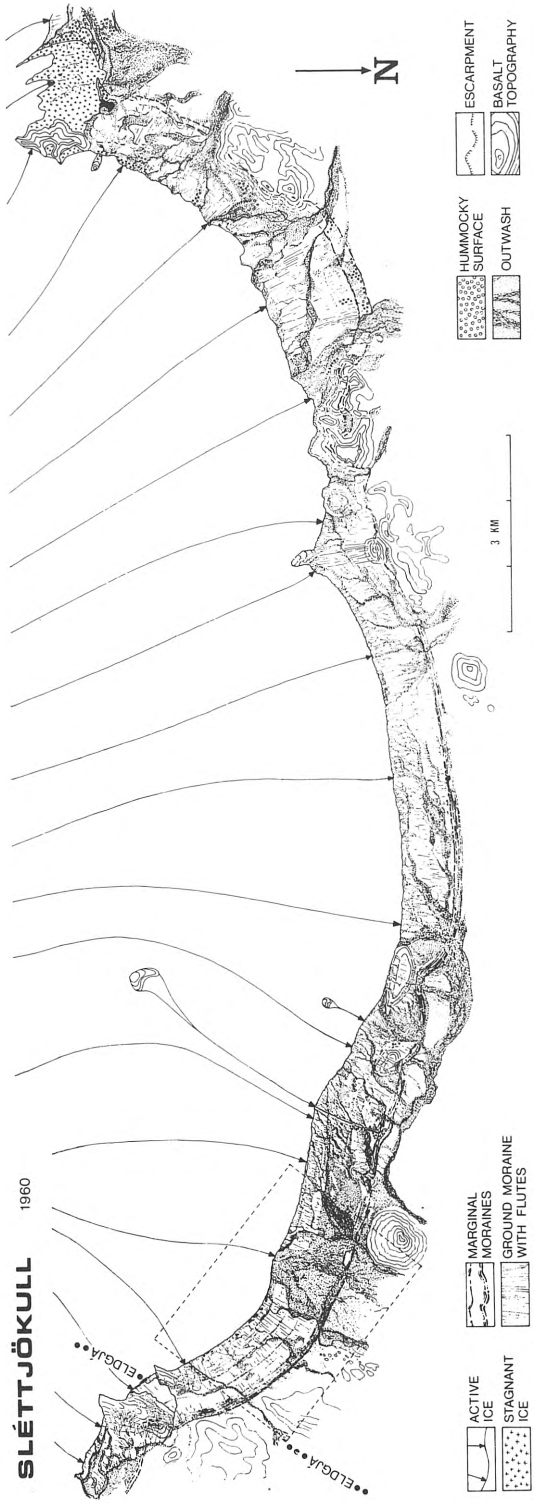
In contrast with the margin of Sléttjökull the terminal 2-4 km of the glacier snout of Höfdabrekkujökull shows a gradiation from actively flowing, relatively clean ice with many crevasses to active ice covered with volcanic ashes and debris. At several places the glacier snout terminates in a zone of stagnant ice and dead-ice blocks detached from the active ice mass and thickly covered with fine-grained debris as well as many large boulders.

The glacier forefield is chiefly dominated by meltwater deposits. Besides proximal extensions of the large outwash plain, Mýrdalssandur, several meltwater channels and outwash fans are found behind the outer system of marginal moraine ridges. Thus, meltwater deposits make up about 75 percent of this part of the glacier forefield (see fig. 26).

The drainage from Höfdabrekkujökull appears to be concentrated in four main systems ; one in the extreme south and one in the north, one emerging from the southeastern part of the glacier front, and one from the central part of the glacier margin. Except for the drainage system in the north, these main systems consist of 2-3 large streams emerging at 400-1200 m intervals. Most of the jökulhlaups from Katla in historical times have taken place in the southernmost drainage system, but indications of jökulhlaups are also found in other parts of the glacier forefield. Thus large areas of the proximal part of the Mýrdalssandur are overstrewn with boulders which are 0.5 - 3 m in dia-

Fig. 26. Glacial geomorphological outline map of the Höfdabrekkujökull forefield based on air photographs taken in 1960. The location of the air photograph shown in fig. 27 is indicated.

Fig. 26. Glacialmorfologisk oversigtskort af det proglaciale område ved Höfdabrekkujökull udtegnet efter luftfotos fra 1960. Beliggenheden af fig. 27 er angivet.



sar, Stórkonufell, and Mófellshaúsar).

The Mælifellssandur averages between 500 and 600 m in elevation. The principal part in the relief constitutes a complex of glaciofluvial landforms of low relief, but here and there low ridges and isolated hills belonging to the Palagonite formation break the monotony of the plain (Mælifell 791 m and Bláfjöll 744 m). To the east between Mælifell and Ö1-dufell the plain is furthermore diversified by the Eldgjá eruption fissure striking NE-SW.

The glacier forefield is dominated by a coherent system of marginal moraine ridges which extend in a festoon-like chain 1-2 km beyond the present-day glacier front,separating the glaciogenic deposits exposed during the last 70-80 years from the extensive areas of outwash sediments (see fig. 7).

The system of marginal moraine ridges which dates back to an advance of Mýrdalsjökull at the end of the 19th and the beginning of the 2oth centuries (see below) consists of a series of sub-parallel ridges. In the eastern and central part this system consists of 3-4 rows of ridges close together, whereas to the west there is 2-3 well-defined rows of moraine ridges with intervals of 50-100 m (see fig. 5).

Following the configuration of this marginal moraine system it can be clearly seen (fig. 5) that in most cases the moraine ridges climb even rather high basalt hills almost without changing direction (Smáfjöll 800 m).

Fig. 5. Geomorphological outline map of the Sléttjökull forefield. The location of the detailed geomorphological map of the Mælifell area (pl. 1) is shown.

Fig. 5. Geomorfologisk oversigtskort af landskabet langs Sléttjökulls rand. Beliggenheden af det detaljerede kort over Mælifell-området (pl. 1) er angivet.

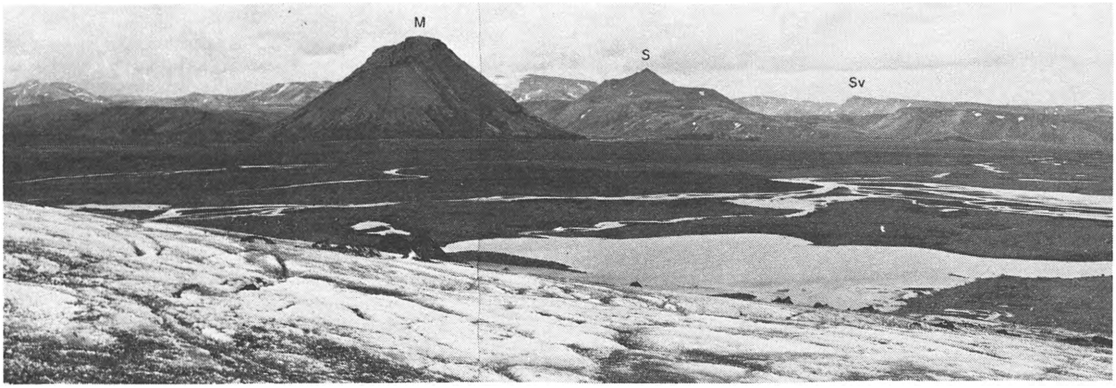


Fig. 6. View from the northeastern margin of Sléttjökull towards the north showing the proglacial area. (m) Mælifell. (S) Strútur. (Sv) Svartahnüksfjöll.

If passing at close range outside basalt hills, however, the moraine system shows a well- marked concavity such as can be seen north of the small hills 4 km west of Mælifell; this is another evidence of the effect of the submarginal relief on the glacier front configuration.

In this part of the glacier forefield inside the marginal moraine ridges the retreating glacier front has exposed areas of slightly undulating ground moraine with fluted surface. Fig. 5 shows that ground moraine makes up extensive areas in the eastern and western part of the

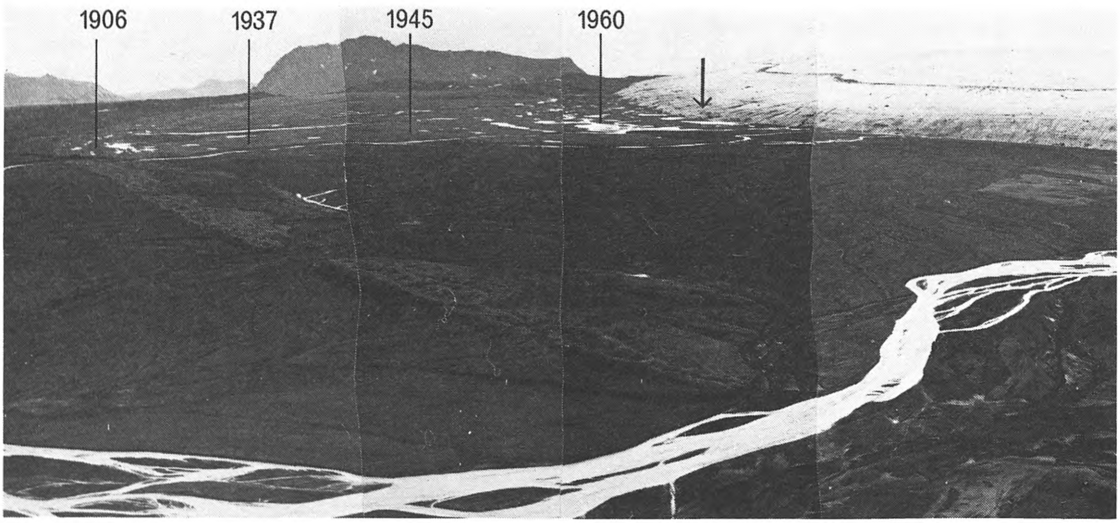


Fig. 7. View from the top of Mælifell over the glacier forefield and a part of the outwash plain beyond it. Datable stages of glacier retreat are shown. The arrow indicates the point from which the photograph shown in fig. 6 has been taken.

Fig. 7. Udsigt fra toppen af Mælifell over det proglaciale område. Kendte deglaciations-stadier er angivet. Pilen viser hvorfra fig. 6 er optaget.

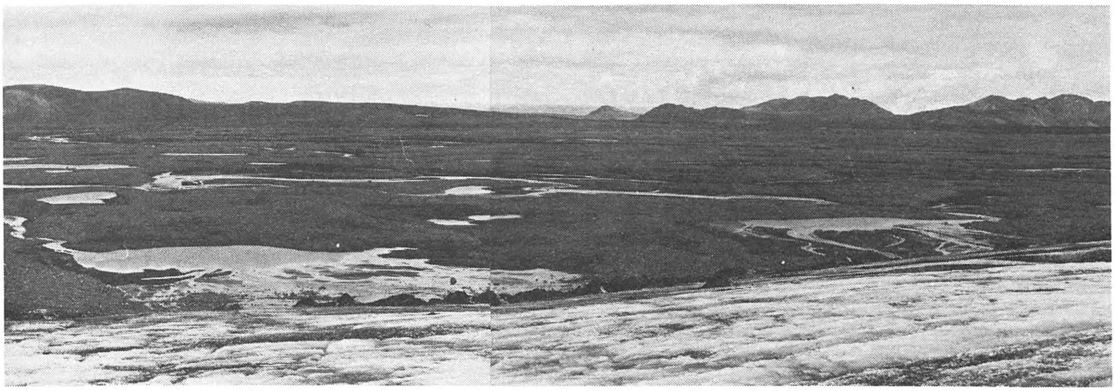


Fig. 6. Udsigt fra den nordøstlige rand af Sléttjökull mod nord over det proglaciale område. (M) Mælifell. (S) Strútur. (Sv) Svartahnúksfjöll.

glacier forefield.

From the glacier margin meltwater is drained off by a widespread network of proglacial streams. The innumerable feeder streams issuing directly from the ice front become increasingly concentrated towards the marginal moraine system where the collecting meltwater channels cut through the moraine ridges. South of Mælifell migrating braided meltwater streams have produced an outwash fan just in front of a subglacial meltwater tunnel.

It appears from fig. 3 that meltwater issuing from the eastern part of Sléttjökull is drained off northeastwards by the river Brennivínskvísl which carries the meltwater into the river Hólmsá. Meltwater runoff from the western part of the glacier, however, is drained towards northwest by two collecting rivers, Bláfjallakvísl and Innri-Emstruá, which flow into the river Markarfljót.

It thus follows that a drainage divide occurs in the central part of the proglacial area between channels cut by streams draining meltwater either to the northeast or to the northwest. Aerial photographs show that in the dry area close to this drainage divide the glaciogenic and glaciofluvial landforms are strongly influated by wind activity.

On the basis of the geomorphological outline map shown in fig. 5 especially promising research areas were selected in the eastern and western part of the glacier forefield where a full series of deposits of glacial and glaciofluvial accumulation appears. However, during the 1977-expedition only parts of the eastern research area (the Mælifell area) were studied. In the following chapter this area is described.

DETAILED GEOMORPHOLOGICAL MAPPING IN THE MÆLIFELL AREA

This chapter contains the description and preliminary discussion of the glacial geomorphology in a relatively small part of the eastern glacier forefield (3.2 x 2.5 km).

A part of the aerial photograph (1:36,000) covering the area southeast of Mælifell was enlarged to 1:10,000 and was used in the field as base map (see fig. 8). The detailed geomorphological features were then drawn on a plastic overlay.

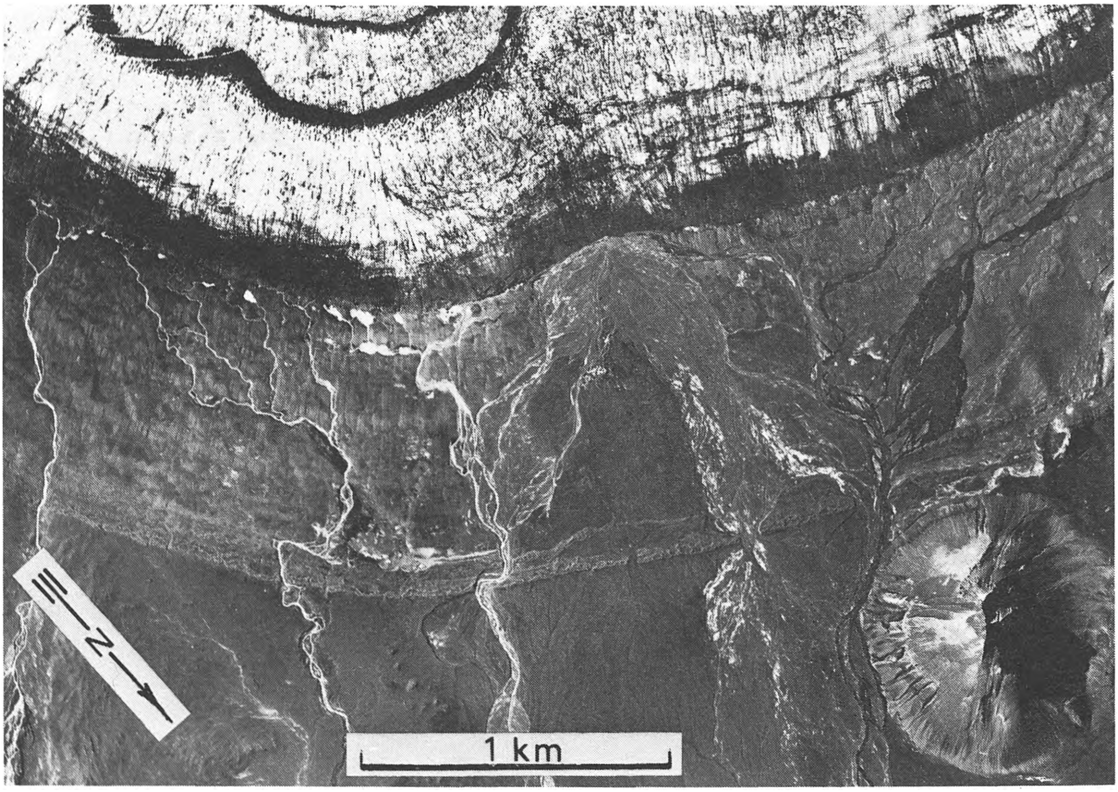


Fig. 8. Air photograph taken in 1960 of the Mælifell area showing many of the detailed geomorphological features represented on the geomorphological map (pl.I). (Landmaelingar Islands)

Fig. 8. Luftfoto fra 1960 af Mælifell-området viser mange af de detailformer, som er angivet på det geomorfologiske kort (pl.I). (Landmaelingar Islands).

Fig. 9.
Ice marginal push-moraine ridges indicating the maximum extension of Sléttjökull in historical time.

Fig. 9.
Israndsbakke foran Sléttjökull angiver gletscherens største udbredelse i historisk tid.

This map was subsequently checked and completed in the photogrammetric laboratory by using a Zeiss Jena Interpretoscope to produce the glacial geomorphological map Sléttjökull-Mælifell which makes up plate 1.

It appears that the proglacial area consists of three main units: 1) The area beyond the marginal moraine system consisting of outwash plains and meltwater channels. 2) The marginal moraine system consisting of several parallel ridges. 3) Inside the marginal moraine system the area consists of ground moraine with flutes, drumlins, small annual moraines, shallow lake basins, downwash basins, and incised meltwater channels. Furthermore, eskers, outwash fans, and areas with kettle topography are found.

THE MARGINAL MORAINE SYSTEM

In the study area the marginal moraine system is situated 8-900 m beyond the glacier margin (in 1960) separating the extensive outwash plain from the zone of ground moraine.

The marginal moraine system is 75-150 m wide forming 3-4 well-defined parallel ridges which curve slightly following the trend of the glacier front. The distal slope is clearly distinguishable from the surface of the outwash plain in front of it, whereas there is a gradational contact between the proximal slope and the ground moraine behind it (see fig. 9).

The most characteristic of the relief forms found in the moraine system are ridges with very uneven summits as high ridges are linked together by lower sections (see fig.7). Generally speaking the outer moraine ridges have sharp crests and are the biggest. Their relative height varies from 1 to 5 m, and the slope gradient is as much as 40-60 per cent. The inmost ridges are generally lower and more gentle sloped. In the southeastern part of the map the marginal moraine system is less pronounced .

The marginal moraine ridges are separated by small areas of fluted ground moraine (see p1. 1), flat-bottomed gravel beds joined to the outwash plain or elongated depressions partly filled with downwash sediments and aeolian sand. In a single case (about 600 m southeast of Mælifell) the topography is irregular with mounds and hollows presumebly produced by melting of dead ice between the moraine ridges.

Once flowing from the glacier glaciofluvial streams have broken the marginal moraine ridges at many points. Some of the gaps thus produced are only incised in the outer moraine ridges while others appear as broad channels cut through the whole moraine system. Here and there the meltwater streams fibwing from the present-day glacier front also cut through the marginal moraine system, thus maintaining fresh cross-sections in the ridges on either side of the stream.

A fresh section of the southeastern bank of one of the streams eroding through the marginal moraine system (about 1.8 km southeast of Mælifell) shows that at this point the ridges consist partly of till and partly of sorted sediments. The sorted material proved to be destinctly stratified and it shows the feature of sediments found in downwash basins in the ground moraine behind the moraine ridges or between them.

Furthermore, the section shows the many layers of sediment to be folded and dislocated. The general dip of the very irregular layers is up-glacier. In addition the section shows how the moraine ridge overlies an almost horizontal bed of glaciofluvial deposits with only few deformations.

A cross-section in one of the outer moraine ridges indicates that it is composed of relatively coarse, gravelly and sandy but unsorted till mixed with an imbricate-like arrangement of flakes of glaciofluvial gravel which inclined up-glacier, that is southwestwards. On the surface of the moraine ridge there are boulders , some of them very large. The observations confirm that the moraine ridges were produced during a glacier advance where the glacier snout pushed and folded the accumulations in the frontal terrain.

THE GROUND MORAINE AND ASSOCIATED FEATURES

Ground moraine occupies those areas between the marginal moraine system and the glacier front which have not been affected seriously by fluviogla-

Fig. 10. A part of the almost flat ground moraine beyond the margin of Sléttjökull.

Fig. 10. En del af det flade bundmorænelandskab foran Sléttjökull.

cial erosion and deposition. The surface of the ground moraine slopes gently from the glacier margin to the marginal moraine system. At the ice front the ground moraine is between 560 and 570 m in elevation and close to the marginal moraine system the general level is 550-560 m.

The surface is gently undulating or almost flat with a low relief rarely exceeding 3-4 m (see fig. 10). The surface mostly consists of gravelly till with many stones but boulders which are deeply embedded in the till also occur. Many topographic lows act as downwash basins with accumulations of sandy and silty material. Since the ground moraine extends up to the retreating ice front and continues in under the glacier margin, it has apparently been deposited subglacially and get exposed concurrently with the retreat of the glacier front (see fig. 11).

At numerous locations along the , banks of deeply cut meltwater channels and in natural, subglacial tunnels vertical sections make it possible to obtain a general picture of the glacial stratigraphy in this area. It appears that the oldest deposit is a more than 1-1.5 m thick bed of glaciofluvial gravel, which at one locality was observed to overlie a lava-flow probably belonging to the

Fig. 11. The front of Sléttjökull makes up a well-defined boundary between the active glacier and the ground moraine exposed during the glacier front retreat.

Fig. 11. Sléttjökulls rand angiver en klar skillelinie mellem den aktive gletscher og det isfri bundmorænelandskab.

Palagonite formation. No glacial striae were observed on the surface of this lava-flow. The glaciofluvial sediments are themselves overlain by two subglacially deposited tills which locally are separated by 0.1-1.0 m of fluvial and lacustrine sediments. The thickness of these tills varies somewhat, but generally the upper till does not exceed 0.5 m and appears to be more fine-grained than the lower till which may be more than 1.5 m thick. In the upper till the size fraction less than 4 Φ (63 μ) comprises between 25 and 35 % whereas in the lower till it constitutes about 20 % (see fig. 12). A similar contrast has been observed by Boulton and Dent (1974) at Breidamerkurjökull where it was shown to be the result of post-depositional crushing in the till just below the glacier sole in response to shear stresses from overriding ice (Boulton et al. 1974). However, it is too early to ascribe the contrast observed at Sléttjökull to subglacial post-depositional crushing as the difference may well be of primary origin.

In the southeastern part of the

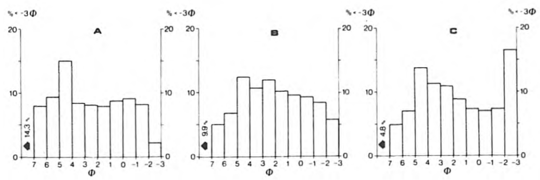


Fig. 12. Granulometric analyses from subglacially deposited till at the margin of Sléttjökull.
(A) Upper till beneath the glacier márgin.
(B) Upper till from the glacier forefield.
(C) Lower till from the glacier forefield.

Fig. 12. Kornstørrelsesanalyser af subglacialt aflejret till ved Sléttjökull.
(A) Øvre till under gletscherranden.
(B) Øvre till fra bundmorænelandskabet.
(C) Nedre till fra bundmorænelandskabet.

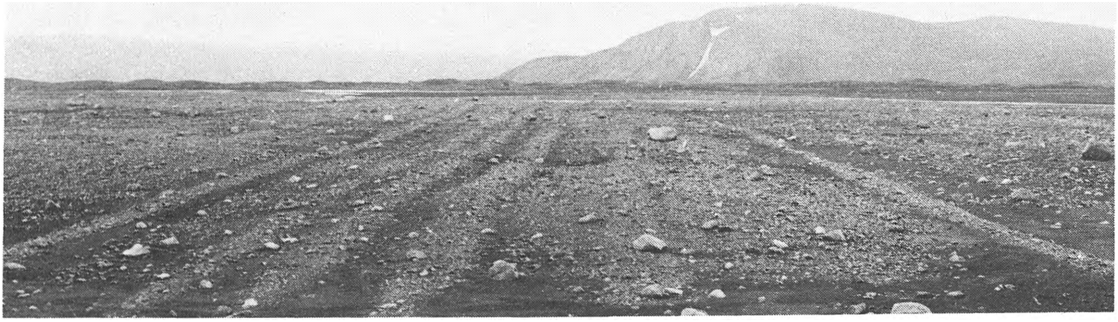


Fig. 13. Large flutes in front of Sléttjökull.

Fig. 13. Store flutes foran Sléttjökull.

area of ground moraine the cover of glacial drift is estimated to be very thin because basalt bedrock crops out in some places. It is most likely to assume a relationship between the scarcity of glacial drift and the formation of only small push-moraine ridges in this area.

In the study area flutings are the most common feature associated with the ground moraine. These streamlined features elongated in the direction of glacier flow are seen both on the surface of the ground moraine and emerging from the retreating ice front.

The largest area of fluted ground moraine is east and northeast of the outwash fan where the fluting has the form of parallel ridges or stone stripes which all run perpendicular to the glacier front (see fig. 13). Close to the glacier there is a dominance of smoother ridges of various dimensions which pass into distinct ridges under the glacier margin. Some distance away from the glacier, however, the flutings appear merely in the shape of stripes of stones, probably because heavy rain and strong winds have remodelled the small-scale topography in the glacier forefield.

At the glacier front where the fluted moraine ridges have recently been exposed, two types of ridges were distinguished: a) Large flutes corresponding to those commonly presented in the literature are low, narrow ridges but very long. The height is between 10 and 50 cm and the broadness, which is fairly constant, amounts to approximately 1 m. The length is usually 50-200 m but ridges/stripes more than 500 m long occur. Thus, the largest flutes can be followed from the present-day glacier front as far as to the marginal moraine system. Many of the large flutes are associated with boulders at their up-glacier end. Apparently they consist of unsorted gravelly and sandy till corresponding to the mechanical composition of the till which constitutes the ground moraine between the ridges. Some distance away from the ice front the fine component has been removed by rain and wind and deposited in lows between the ridges. b) Small flutes which are only 1-5 m long and consist of sorted material. In most cases there were a boulder or large stones fixed in the ground moraine at their up-glacier end (see fig. 14).

Much debate in the literature has concentrated upon the processes of formation of flutings. Generally,it is accepted that flutings are formed subglacially, but the more detailed discussion has led to controversial ideas on specific mode of formation of flutings (Dyson 1952, Hoppe and Schytt 1953, Baranowski 1970, Boul-

Fig. 14. Small flutes of sorted material recently exposed at the margin of Sléttjökull. Note the large stone at the up-glacier end of the flute.

Fig. 14. Lille flute af sorteret materiale, kort forinden smeltet fri af Sléttjökulls rand. Bemærk den store sten ved den proximale ende af fluten.

ton 1971, 1976, Paul and Evans 1974).

Dyson (1952) suggests that till might flow into subglacial tunnels which opened in the lee of boulders fixed in the substratum. This initiation of flutes is also suggested by Hoppe and Schytt (1953) who furthermore explain the considerable length of the individual ridges by assuming that the till freezes as it flows into the tunnel and then it is carried forward by the ice until it freezes to the substratum in the cold, outer zone of the glacier.

Kozarski and Szupryczyński (1973) assume that boulders cannot be regarded as a decisive factor in the formation of fluted moraine ridges because large boulders are absent at the up-glacier end of many flutes. However, Boulton (1976) puts forward that lightly embedded boulders could easily be removed from the heads of flutes, if the ice thickness is reduced and thereby the strength of the embedding till which, hitherto, retarded the boulder.

Humlum (in prep.) has developed a theory of flute formation from observations of the shape, size, and structure of flutes beyond the margin of glaciers in Greenland, Norway, and the Alps, and the present study of flutes in front of Sléttjökull supports his theory. It is shown that subglacial cavities behind lodged boulders will drain water from the substratum and, subsequently, fines may be transported into the small cavities to produce small flutes consisting of sorted material (see fig. 15). If larger cavities develop more serious internal erosion by piping may be expected in the substratum and this may ultimately lead to complete failure of the till around the initiating boulders and the cavities. Till is then squeezed into the cavities and large flutes of unsorted

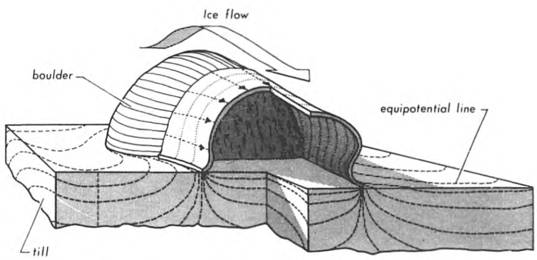


Fig. 15. The formation of a flute in the ice-bed interface. The pattern of equipotentials in till around a lodged boulder with a lee-side cavity is shown. The value of the potentials decreases towards the diagram front.

Fig. 15. Dannelsen af en glacial flute ved grænsefladen mellem aktiv gletscher og underlag. Ækvipotentialmønstret i till omkring en aflejret blok med læsidecavitet er vist. Potentialet falder i retning mod diagrammets forside.

till may be formed. Humlum concludes that glacial flutes of this type are a highly diagnostic criterion for till deposited under an active glacier with a temperate base.

The extensive areas of fluted ground moraine beyond the margin of Sléttjökull are found to be a promising research area for further investigations of flutes.

In the southeastern half of the geomorphological map there are several large-scale transverse features giving a ribbed appearance to the ground moraine surface. On the aerial photograph shown in fig. 8 they occur as light lineaments which are gently arcuate in conformity with the marginal moraine system and the glacier front. In the field they appear as very low and smoothed ridges, often with a fluted or drumlinized surface. The ridges stand 1-2 m above the general level of the ground moraine surface and their broadness is between 50 and 100 m. The distance between the ridges was measured to be 100-200 m.

A fresh section cut by a meltwater stream through one of the ridges shows the following stratigraphic relationships: In the lower part of the section an imbricate-like arrangement of till beds steeply inclined southwestwards. This dislocated series is overlain by gravelly till, apparently supraglacially deposited till, and sandy downwash sediments. The top of the section, however,consists of densely packed till with a fluted surface.

The authors consider the ridges to be formed as push moraines one by one during glacier advances prior to 1890. Subsequently these marginal push-moraine ridges were overridden by the advancing glacier at the end of the 19th century. Hereby the ridges were smoothed and capped by a bed of subglacially deposited till.

Todtmann (1960) reports similar overridden moraine features in front of Bruarjökull which is a northern extension of Vatnajökull. There the overridden moraines date back to 1810 and 1840, but within the present area of study the overridden moraines have not yet been dated.

The occurrence of overridden moraine ridges invites reflection because they show that all glacial geomorphological features observed in a landscape do not necessarily belong to the last glacier behavior. In the present case the marginal moraine ridges evidently constituted such a firm obstruction to the erosive action of the ice that the overriddening glacier was unable to destroy them completely.

Moraine ridges in the shape of small, low-relief drumlins are widely distributed in the glacier forefield close to the glacier margin where they rise 2-4 m above the general level of the ground moraine surface. The drumlins are 30-100 m long and their broadness average between 15 m and 40 m. They show a strong long-axis orientation in the ice movement direction and with the summit situated in the proximal end (see fig. 16). In the ground moraine area southeast of Mælifell most of the drumlins are superimposed on the overridden push moraines and thereby form a pattern with a predominant trend in conformity with the glacier margin. In other parts of the glacier forefield, however, such as the area west of Mælifell, a large number of small drumlins covers extensive areas. Similar drumlin forms have been observed to continue in under the glacier margin. The intimate adjustment of the basal debris-band foliation to this glacier bed topography is obvious (see fig. 17) and indicates the drumlin formation as a result of glacial erosion and accumulation processes in the ice-bed interface.

Detailed investigations of the above drumlin fields occupy an important position in the program of a coming expedition to Mýrdalsjökull.

Between the marginal moraine system and the present glacier front series of small-scale transverse moraine ridges are found on the ground moraine surface. Near the glacier these

Fig. 16. Small drumlin on the ground moraine beyond the margin of Sléttjökull. The longitudinal section clearly shows the shape of the drumlin indicating the highest most point to be situated in the up-glacier end of the small drumlin ridge.

Fig. 16. Lille drumlin i bundmorænelandskabet foran Sléttjökull. Det longitudinale erosionsprofil viser tydeligt bakkens form med toppunktet forskudt mod den proximale ende.

ridges are generally 0.3-0.5 m high and 0.7-1.5 m wide (see fig. 18). Further from the glacier the ridges are less conspicuous, and near the marginal moraine system they are only recognized as lines characterized by coarser sediments. Although several of the ridges are continuous over considerable distances most of them can only be followed for distances of 50-150 m. It is worth notifying that the moraine ridges become more frequent in certain areas of the ground moraine (see the geomorphological map, p1. 1). Close to the marginal moraine system the spacing between the ridges is 10-20 m, whereas it is between 20 m and 100 m in the area halfway to the 1960 glacier front. Near the 1960 glacier front the spacing again decreases to 10-30 m, and at the present glacier margin there is only 2-10 m between the youngest moraine ridges.

Flutings are seen to climb over the moraine ridges without interruption, and the moraines are therefore considered to be the result of glacier-induced folding of subglacially deposited till along the glacier margin. That is, each moraine ridge is

Fig. 17. A small drumlin ermerging from the retreating ice front at the margin of Sléttjökull. Note that the ice foliation in the basal ice curves up the drumlin.

Fig. 17. En lille drumlin under frismeltning fra Sléttjökull. Bemærk at foliationen i isen kurver op over drumlinen.

Fig. 18.
Several transverse moraine ridges (annual moraines) near the ice front at the margin of Sléttjökull. Note that flutings climb the ridges without interruptions (at the spade).

Fig. 18.
Transversale morænerygge (årsmoræner) nær Sléttjökulls rand. Bemærk hvordan flutes løber hen over ryggene uden afbrydelse (ved spaden).

regarded as one coherent anticlinal parallel to the glacier front and not as the result of pushing material together at the margin. Also, they have nothing to do with the squeese-mechanism proposed by Price (1970) for moraines at the glacier Fjallsjökull, Iceland.

The largest number of moraine ridges recorded along lines between the present glacier front and the marginal moraine system was 53, a number roughly corresponding to the number of years (70-80) with deglaciation of this area. The moraine ridges are therefore designated as annual moraines. A support for this hypothesis is provided by the large spacing between individual moraines halfway between the present glacier front and the marginal moraine system. This zone was deglaciated around 1930-40 (see below) during a period characterized by anomalous rapid downwasting of Icelandic glaciers (Thorarinsson 1943). Contrary to this, the decreasing spacing between moraine ridges towards the present glacier margin may be interpreted as the result of the cooling after 1940 (Waltraud and Brinkmann 1976).

As the glacier margin in July 1977 was only 1-3 m from the youngest moraine ridge at that time, and two younger moraine ridges have been formed between July 1977 and July 1979, it is furthermore suggested that these small moraines are usually formed by small-scale glacier advances during the winter.

THE OUTWASH FANS AND ASSOCIATED FEATURES

Beyond the marginal moraine system the principal landform is an outwash plain between 540 and 560 m in elevation .(see p1. 1). In the northeastern part of the map low ridges and knobs of tuff and basalt-breccias crop out and break the monotony of the plain. Further to the northeast the outwash plain is bounded by the Eldgjá eruption fissure. To the northwest the plain is domi-

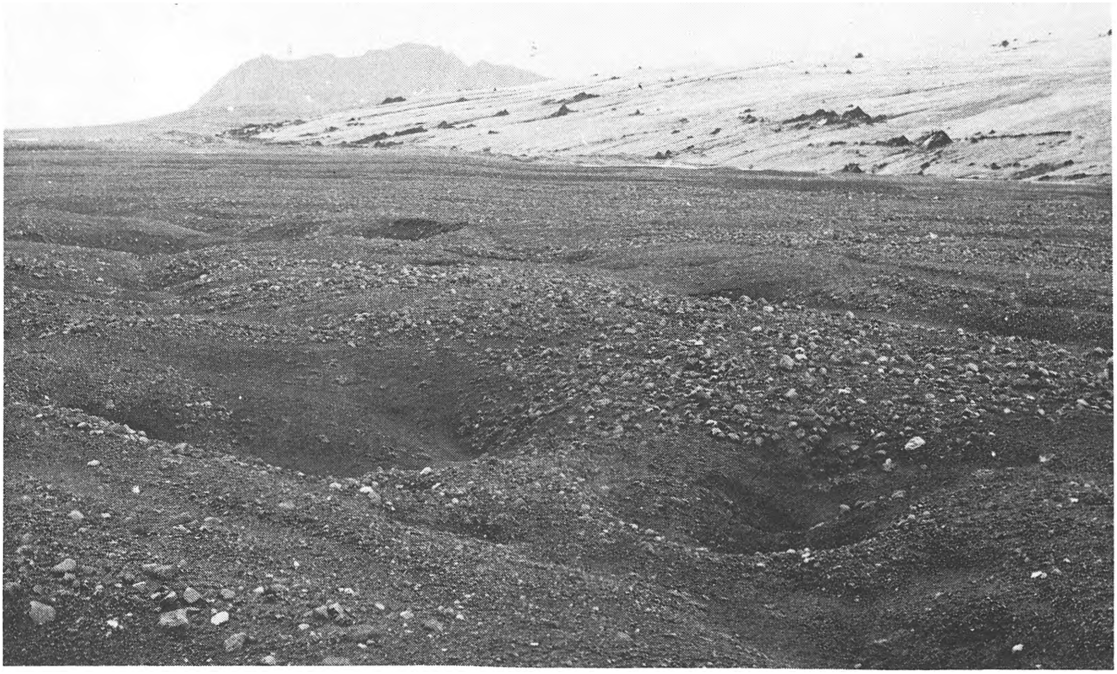


Fig. 19. Kettles in the surface of the glaciofluvial complex between the marginal moraine system and the glacier front southeast of Mælifell.

Fig. 19. Dødishuller i smeltevandsaflejringerne inden for randmorænen sydøst for Mælifell.

nated by the cone-shaped mountain, Mælifell, which rises 240 m above the outwash plain.

The highest-lying areas of the outwash plain constitute a series of fan-shaped features each of them situated close to the marginal moraine system. On the geomorphological map (see p1. 1) it is seen that these fans are connected with gaps in the marginal moraine ridges indicating that the fans are produced by meltwater issuing from the ice margin at the time of maximum extent of the glacier. The slope of some of these outwash fans was levelled and found to be between 1 in 35 and 1 in 100.

Further downstream the fan-shaped features join and overlap each other producing the extensive outwash plain with gradients between 1 in 50 and 1 i 200. The many abandoned channel systems on the plain surface represent the changing pattern of the drainage system during the development of the plain.

During the recent phase of glacier retreat the outwash plain has been dissected into sharp-cut terraces which can be traced up to the marginal moraines. Close to Mælifell the meltwater has eroded material from the proximal area of the outwash fans and developed new outwash surfaces by redistribution of this material. In the central part of the plain, however, the recent principal drainage routeways are confined to distinct channel systems with many individual channels with floor-level about 2-5 m below that of the adjacent outwash plain.

In the area between the marginal moraine system and the present-day glacier front migrating braided streams have produced fan-shaped wedges of fluvioglacial deposits concurrently with the glacier retreat. The relatively high-laying apexes of these fans have divided the main stream issuing from the subglacial tunnel into two lateral streams.

Parts of this glaciofluvial complex display a distinctly kettle topography (see p1. 1). This applies especially to the outwash fan built up around and after 1945 (the apex of that fan is found about 500 m behind the marginal moraine system), but also to the proximal part of the older fan. In some cases individual kettle holes connect to form more or less coherent valleys, 10-25 m wide and 2-5 m deep, running approximately normal to the glacier margin; more often, however, kettle holes are distributed in no regular spatial arrangement (see fig. 19). The largest of the kettle holes are some 30 m in diameter and 3-7 m deep, while the smaller ones are 1-10 m in diameter and only 1-3 m deep. Comparison of the 1945 and 1960 aerial photographs reveals that the number of kettle holes nearest to the 1945-glacier margin has increased during the 15 years, thereby indicating the presence of buried ice on the 1945 photo. Observations along an ice-marginal meltwater stream during fieldwork in 1977 have shown that at least the southeastern part of the most recent meltwater fan is underlain by glacier ice. This ice which is more than 0.5 m thick is overlain by 0.2-1 m of stratified sand and gravel forming the present outwash surface.

Three eskers are found in the Maelifell area, all in connection with the large fan-shaped complex of glaciofluvial sediments inside the marginal moraine system.

The oldest and outermost of the eskers is a feeding esker linked to a small outwash fan situated between two lines of marginal moraine ridges about 800 m southeast of Mælifell (see p1. 1). This esker is sharp-crested, 2-7 m high and about 300 m in length. The esker is discontinuous and makes up a winding system of five individual segments, each 10 to 70 m in length. The distal end of the esker is connected to the apex of the small outwash fan, and it is therefore most probable that the esker is comtemporary with this small fan. Later, the esker has been surrounded and probably partly buried by younger glaciofluvial sediments.

Halfway between the present glacier margin and the marginal moraine system another esker is found (see p1. 1). It is connected to the apex of a somewhat larger meltwater fan southwest of the outermost one. It differs from the above esker by having a flat top. Furthermore, it is 5-10 m wlde, over a considerable part of its total length of about 125 m, and its height above the surroundings ranges from 1 to approximately 5 m. The esker is surrounded by glaciofluvial sediments of sand and gravel with a distinctly hummocky surface with many kettle holes. Between them the surface reaches the same altitude as the flat-topped esker. On the 1945 pho-

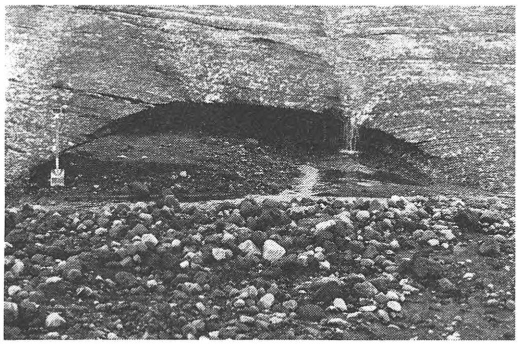


Fig. 20. A small subglacial esker melting out of the glacier front at the margin of Sléttjökull. Note that the meltwater tunnel intersects the foliation in the basal ice.

Fig. 20. Lille subglacial ås under frismeltning fra Sléttjökull. Bemærk at smeltevandstunnelen skærer isens foliation.

Fig. 21.
A meltwater volcano on the surface of an outwash fan at the margin of Sléttjökull. In the foreground the ice front is visible.

Fig. 21.
En smeltevandsvulkan på smeltevandssletten umiddelbart foran Sléttjökulls rand.

tographs this area appears as the proximal part of a meltwater fan with only few signs of kettles. It is, therefore, suggested that in 1945 much of the proximal part of this meltwater fan must have been underlain by ice. The gradual melting of the buried ice on both sides of the present esker has led to the development of the kettle topography and exposed the esker. Thus, the flat esker top probably formed parts of the surface of the meltwater fan observed on the 1945 photographs. This interpretation is identical with that proposed by Howarth (1971) for an esker observed at Breidamerkurjökull, Iceland.

The third esker was observed melting out of the glacier front at the point of emergence of a small subglacial meltwater tunnel near the apex of the most recent fan in the glaciofluvial complex (see fig. 20). The length of this esker is not known, and it is currently being destroyed during the glacier retreat by a meltwater stream parallel to the glacier front. Inside the tunnel the esker is flat-topped, 2-3 m wide and only 0.5-0.7 m high, and is made up by stratified sand and gravel.

Close to the present-day glacier margin the authors have also observed five small volcano-like features of glaciofluvial material. They ranged in diameter from 5 to 15 m and were more or less circular with a well-formed central crater (see fig. 21). They are formed by meltwater welling up through the proximal part of the outwash fan. Sediment in the rising columns of water is. deposited both in the many small channels leading from the fountain and on the edge of the fountain thus producing a cone-shaped meltwater volcano. During periods of heavy rain the meltwater volcanoes undergo catastrophic changes indicating efficient connection between the glacier surface and the subglacial drainage system. The rising flow increases the diameter of the central vent and flows away from the fountain source in one or two incised channels. It was observed that within a few days the sediment cone could be completely destroyed by this mechanism.

HISTORY OF GLACIER FLUCTUATIONS IN THE MÆL I FELL AREA

THE GLACIER ADVANCE

The crescent complex of well-defined marginal moraine ridges near Mælifell was probably formed during a glacier advance at the end of the 19th and the beginning of the 20th centuries. This is based on information provided by K. Sapper (1909).

In the summer of 1906 Sapper travelled on horseback round the north of Mýrdalsjökull where he had opportunity to pass at close range to the ice margin in the Mælifell area. Unfortunately certain circumstances prevented him and his Icelandic guide from staying more than one day in the Mælifell area, but from his brief stay Sapper gives valuable information on the position of the ice margin at that time (see p1. 1). Sapper states (p. 301) that 'ein schmaler doppelter Moränensaum von 50-60 m Breite zieth am Ende der Eldgjá am Gletscherrand hin. Der äussere Moränenwall ist hier etwa 15 m breit und 3 m hoch, der innere gegen 20 m breit und etwa 1½ m hoch; zwischen beiden befindet sich stellenweise ein ganz schmaler niedriger Zwischenwall eingeschaltet'. Furthermore, Sapper mentions (p. 302) that 'in der Nähe des Maelifell ist die Moränentwicklung etwas stärker; die Breite beträgt hier etwa 120-140 m. Die mässig hohe Moräne ist aber hier nicht in deutlich geschiedene Wälle getrennt, sondern ziemlich unregelmässig entwickelt. Sie zieht in der Nähe der Quelle des Brenninsviskvisl über einen kleinen Hügel weg' (see fig. 5).

On the basis of the above information it seems most likely that the outer push moraine ridges have been produced during a maximum extent of Sléttjökull prior to 1906. However, the diversity in age between the outer moraine ridges and the moraines at the ice front in 1906 is expected to be insignificant because no differences neither in vegetation nor in the modifications by weathering and mass movement are visible. Most probably the outer moraine ridges therefore date back to 1890 when many Icelandic glaciers were of great extent (Thorarinsson 1943; Todtmann 1960; Jaksch 1975). Beyond the 1890 moraine ridges no evidences of older marginal moraines were observed by the authors. Neither the many small knobs of lava in the vicinity of the Eldgjá eruption channel show traces of glacial abration although tephrachronological studies reveal that this lava is of prehistoric age (Thorarinsson 1955). In the ground moraine behind the marginal moraine system, however, overridden push moraine ridges indicate stages of small glacier advances prior to 1890. Thus, it is most likely that the 1890 moraine ridges represent the maximum extent of Sléttjökull in this area in historical time.

Sólheimajökull, a southern outlet glacier from Mýrdalsjökull (see fig. 1), may also have had its greatest advance in historical time about 1890 (Jaksch 1975) and thereby exceeded the advance related to earlier periods in the Little Ice Age (defined as covering approximately the period AD 1600-1900).

However, a main problem lies in explaining why the maximum extent of glaciers in historical time is about 1890 in the southwestern part of Iceland while glaciers in the southeastern part reached their maximum earlier in the Little Ice Age (Todtmann 1960; Bogacki 1973). A possible explanation is the ocean current anomalies such as reported by Lamb (1979). Lamb puts forward that during periods of the Little Ice Age, polar water (the East Iceland Current) dominated the eastern part of the Atlantic Ocean as far south as the Faero Islands where the average water temperatures presumably were 4° to 5° below the average of the last 100 years. Along the south coast of Iceland this polar water took the form of a tongue which narrowed westwards and was met by warm saline Atlantic water reaching southwest Iceland from the south. These ocean current anomalies which gave rise to a negative temperature gradient from west towards the east along the south coast of Iceland must have affected the glacier regime in this part of Iceland.

Returning to the map (pl. 1) it is believed that the development of the great outwash plain beyond the marginal moraine system has been very complex and must mainly be related to advances and retreats of Sléttjökull because glaciofluvial gravel beds are found underlaying the till beds which make up the ground moraine behind the marginal moraine system.

During the maximum extent of Slettjökull about 1890, meltwater streams running from the ice front cut small channels through the moraine ridges and built further up deposits on the surface of the outwash plain. In certain places, especially in the central part of the mapped outwash plain, the fossil channel systems clearly show the changing drainage system at that time (see p1. 1).

By 1906, the drainage systems were modified. Most of the small channels cut through the outer moarine ridges were left by the meltwater streams while other channels were maintained. Some of the channels must have drained meltwater directly from the glacier surface or from englacial tunnels because no traces of glaciofluvial activity are seen

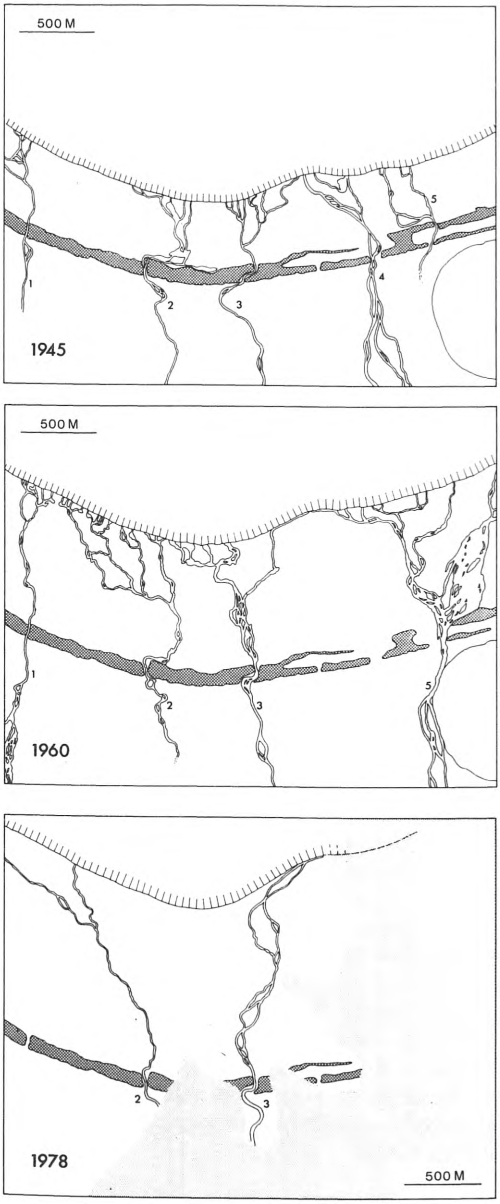


Fig. 22. Stages of glacier retreat in the Mælifell area with some of the more prominent meltwater channels. The cross-hatched areas indicate the marginal moraine system, and the dotted area shows the cloud cover on the 1978 air photograph.

Fig. 22. Afsmeltningsstadier i Mælifell-området med angivelse af større smeltevandsløb. Randmorænen er angivet med krydsskravering, mens områderne med grå raster er skyer på 1978-billederne.

in the present ground moraine behind these gaps in the moraine ridges.

After 1906 the glacier has retreated continously leaving areas of slightly undulating ground moraine and a complex of outwash fans behind the marginal moraine system. In the following the stages of glacier retreat and the development of the drainage systems produced during the retreat of the glacier front over the last 72 years will be discussed (see fig. 22). The positions of the ice margin during this period are based on aerial photographs taken in 1945, 1960, and 1978. Furthermore, the approximate position of the ice margin in 1937 was obtained by extrapolation of the evidence of the 1937 ice-front location west of Mælifell as provided by oblique photographs.

THE RETREAT BETWEEN 1906 AND 1945

Between 1906 and 1945 the glacier retreated 400-500 m (see fig. 22). Meltwater channels gradually incised the exposed ground moraine, and the drainage systems beyond the marginal moraine ridges were subsequently modified by a few drainage routes through the marginal moraine ridges. Inside the moraine system a drainage system developed according to the nature of the surface exposed as the ice retreated. Since the ground moraine surface slopes gently away from the glacier, the channels carried meltwater directly away from the ice front following the slope of the fluted ground moraine.

Sometime between 1906 and 1945 there was a lake just behind the marginal moraine system in a topographic low between two meltwater channels Nos. 2 and 3. On the 1945 aerial photography this lake could still be seen. The evolution of the lake is unknown, but an abandoned channel following the proximal side of the inmost moraine ridges (see p1. 1) indicates that the lake has supplied meltwater not only to the channel situated east of the lake, but also to the channel west of it (No. 3).

Of particular interest is the gradual modification of the drainage route-way No. 4. After 1906 the gap cut through the moraine ridges by meltwater issuing from a subglacial tunnel was abandoned. However, an outwash fan began to form behind the marginal moraine system because meltwater still issued from almost the same point at the retreating ice edge. As the ice continued to retreat, the anastomosing stream system on the highest-lying parts of this outwash fan was also abandoned. The meltwater from the subglacial tunnel began to diverge and flowed into the two channel systems indicated by Nos. 3 and 4. Beyond the marginal moraine system the easternmost of these channels is shown to have a relatively simple course incised into the outwash plain whereas the western one is depicted as typical braiding streams which have built up an extensive outwash fan (see p1. 1).

THE RETREAT BETWEEN 1945 AND 1960

Between 1945 and 1960 the glacier retreated 250-450 m (see fig. 22). The routeways Nos. 1, 2, and 3 were sufficiently well established to be maintained during this period, but on the whole the drainage systems gradually became more complicated. Thus each channel system consisted of several feeder streams issuing directly from the ice edge, and furthermore, the gradual exposing of overridden moraine ridges permitted the development of stream channels and series of small lakes parallel to the ice front. This is clearly demonstrated by the proximal part of the drainage systems Nos. 2 and 3 .

Since 1945 the meltwater from the subglacial tunnel has established two marginal streams parallel to the ice front, and the outwash fan in front of the ice gate has furthermore been extended in a south-westerly direction concurrently with the glacier retreat. This resulted in the abandonment of the drainage system No. 4 in favour of a more western routeway.

Sometime between 1945 and 1960 a new system developed, draining to the northeast part of the ice front west of the area of study (see fig. 5). This routeway was an important stream which seriously affected the ground moraine by glaciofluvial erosion and deposition during which only areas of the highest-lying parts of ground moraine were preserved. The drainage was united with channel No. 5 and flowed as a large collecting stream through the marginal moraine system near Mælifell.

THE RETREAT BETWEEN 1960 AND 1977/78

Between 1960 and 1978 the glacier retreated 300-400 m (see fig. 22). Unfortunately the aerial photography has not allowed an accurate representation of the 1978 drainage system because of cloudiness. Fieldwork in 1977 confirms that the channel No. 1 was abandoned while only the channels Nos. 2, 3, and 5 continue to carry meltwater. Thus the marginal streams parallel to the ice front carrying meltwater from the subglacial tunnel are still maintained and the outwash fan inside the marginal moraine system are apparently still extending in southwesterly direction concurrently with the retreat of the ice front.

The sequence of events described above clearly illustrates that from an advanced position about 1890 the margin of Sléttjökull has retreated without leaving stagnant ice or dead ice except in connection with the formation of the glaciofluvial complex of fan-shaped wedges. Neither has the recession been interrupted by significant advances at any time since 1906 as inside the outer push moraine ridges no marginal moraine ridges are found except a number of small annual moraines which presumably are formed during winter time.

Furthermore, it is seen that behind the marginal moraine system the glaciofluvial complex became the focus of the meltwater drainage system in this part of the Sléttjökull forefield. It is also found that the bulk of meltwater drained by that system most likely issued from a subglacial tunnel within which the esker system rising above the outwash fan was formed.

However, attention should be paid to the orientation of this esker system and the displacement of the ice cave during the retreat of the glacier front. Generally speaking, subglacial tunnels and eskers exhibit a tendency to conform in trend with

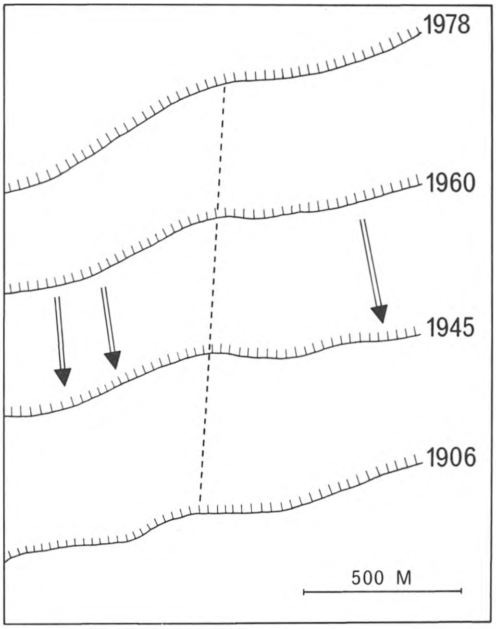


Fig. 23. Scheme of the ice-cave displacement (the dashed line) during the time period 1906-1978 and the path of some of the datable lines delimiting the retreating ice front southeast of Mælifell. The arrows indicate the ice movement direction.

Fig. 23. Gletscherportens forlægning (punkteret streg) i perioden 1906-1978. Nogle daterede afsmeltningsstadier er angivet. Pilene viser isbevægelsesretningen.

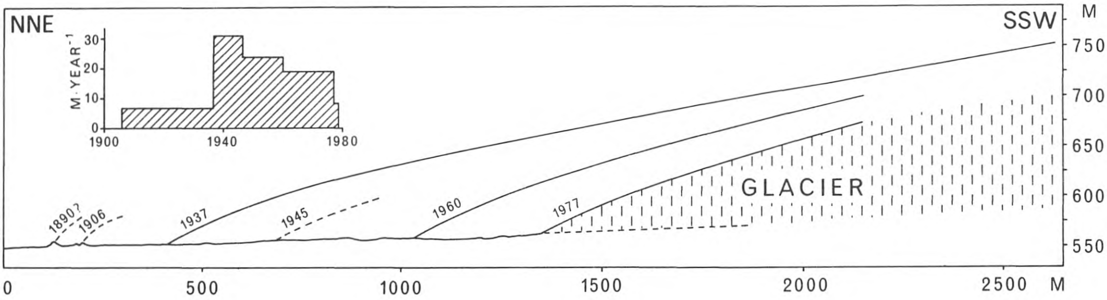


Fig. 24. Cross-section through the glacier forefield southeast of Mælifell showing the Sléttjökull recession. The incet indicates the average annual rates of retreat.

Fig. 24. Længdeprofil af det proglaciale område sydøst for Mælifell viser stadier i Sléttjökulls tilbagesmeltning. Den lille figur viser den gennemsnitlige årlige tilbagesmeltning.

the movement of the ice; it is interesting to note, however, that this is not so in the present case. Here the line of ice-cave displacement diverges consistently about 10° from the ice movement direction (see fig. 23) . That is, the orientation of the subglacial tunnel system does almost accord with that of the neighbouring Eldgjá eruption channel and the adjacent crater rows.

There is therefore reason to believe that the topography of the glacier-bed interface to some extent is in conformity with the tectonic basalt topography, thus affecting the subglacial drainage.

ANNUAL RATES OF RETREAT

In 1977 a 2.5 km long traverse was made across the glacier margin and the ground moraine in the clacier forefield. Based on field studies and air photo interpretations the average frontal retreat along this profile is shown to be 6.8 m year $^{-1}$ between 1906 and 1937 rising to 33.8 m year -1 in the period 1937-1945. During the following period 1945-1960 it fell to 23.3 m year and between 1960 and 1977 it was 18.8. m (see fig. 24) . The latest observations (on the expedition to Iceland in the summer 1979) demonstrate an unusually low rate of retreat of only 8.8. m year -1 for the period 1977-1979.

In southwest Iceland rates of retreat over land surfaces during the last century commonly range between 40 and 100 m per year (Price 1973) .

Undoubtedly the relatively high annual rate of frontal retreat for the period 1937-1945 and the steady decrease in rate for the following periods is due to changes in climate, because the observed variations at Sléttjökull fit into the regional trend for Icelandic glaciers. That is, in the Mælifell area any glacier fluctuations that may arise from vulcanic activity beneath the Mýrdalsjökull in the present century seem to be masked by the trend of glacier retreat ascribed to climatic changes.

In order to measure accurately any future displacement of the ice front along the profile shown in fig. 24 two cairns were built 50 m and 160 m from the ice front, respectively. Furthermore, a cairn was placed at the break in slope between the ice surface and the ground moraine.

Frontal retreat, however,not only represents the horizontal displacement of the ice edge, but will also be accompanied by a thinning of the glacier. In order to calculate the annual rates of down-wastage on the ice surface it is necessary to obtain information on the glacier surface slope.

Sapper gives some information on the ice surface slope towards the ice front in 1906 (Sapper 1909). He states (p. 300) that "die Neigung des wie ein weisser Riessenschiels auf der weithin fast ebenen Fläche des Maelifellsandr ruhenden Gletschers wurde mit dem Klinometer des Kompasses zu 13-15° gemessen. Weiter westlich war die Neigung wesentlich steiler".

It has furthermore been possible to measure the 1890 and 1906 glacier surface slopes in the frontal zone by photogrammetric methods. Close to Mælifell the marginal moraine system climbs a low hill as described by Sapper (1909:302). Photogrammetric measurements of spot heights on the crest line of the moraine ridges were made by Niels Gylling Mortensen and Henrik Højmark Thomsen on aerial photography taken in 1960 and by using a Wild B 8 Aviograph. The spot heigths recorded indicate the approximate 1890 and 1906 glacier surface slope as shown in fig. 24.

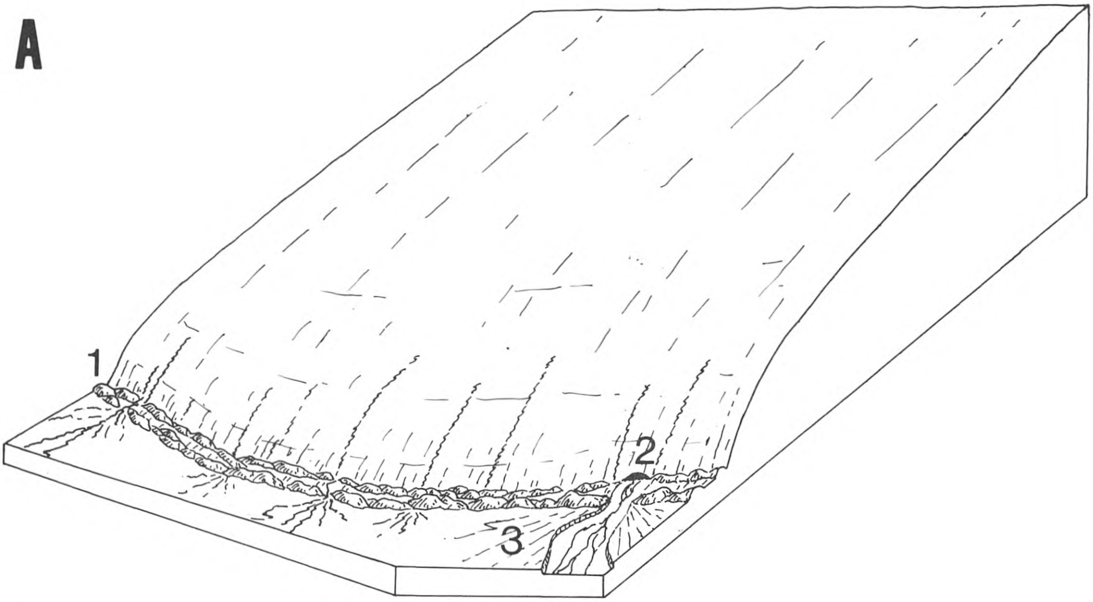
The profile of the ice surface in 1937 is according to the contour lines (contour interval 20 m) on the Danish General Staff map of 1937, scale 1:100,000 (sheet 68 Skaftártunga). The 1960 glacier surface slope was obtained from the 1960 photography. A stereographic model was established by using control points derived from a net of field measurements, and contours were then plotted at a scale of 1:10.000 (contour interval 10 m, see p1. 1). The 1977 glacier slope was obtained from detailed field measurements (see fig. 24) .

From these few records it is only possible to suggest the average rate of down-wastage on the lowermost 1 km of the ice surface for the period after 1937. The annual rate for the period 1937-1960 is 3.3 m, and for the period 1960-1977 it is 3.0 m. Furthermore, fig. 24 demonstrates a close similarity in surface slopes between the retreating glacier snout in 1937, 1960, and 1977 as the slope consistently ranged between 10° and 12°. This observation should be of interest when attempting to reconstruct near-marginal surface profiles of Pleistocene ice sheets retreating across areas of low relief.

THE MÆLIFELL AREA: A MODEL OF DEGLACIATION BY FRONTAL RETREAT

Although investigations carried out in present-day glaciated areas reveal that deglaciation takes place in many ways it is possible to distinguish between two fundamentally different modes of deglaciation: are al and frontal deglaciation (Klimaszewski 1960; Jewtuchowicz 1973;

A



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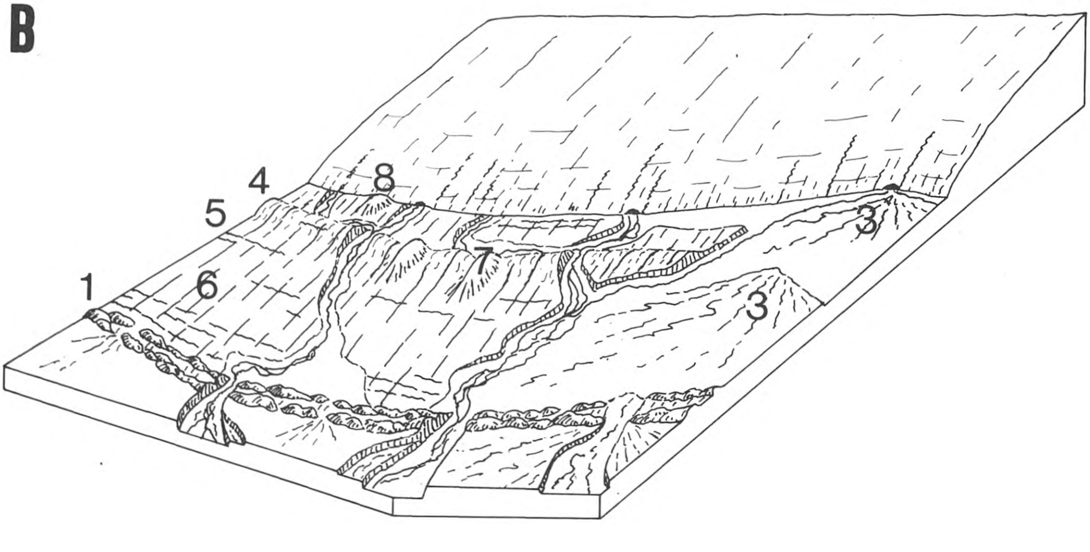


Price 1973; Krüger 1974; Krall 1977). During areal deglaciation the glacier falls into dead-ice fields or dead-ice ridges, whereas frontal retreat is characterized by recession of a glacier front which makes up a well-defined boundary between actively flowing ice and an ice-free glacier forefield.

In the Danish literature, however, Marcussen has recently (1977) confused the ideas about these two modes of deglaciation. Thus, relating glacier retreat to a displacement of a line separating the active part of the glacier from a fringe of stagnant ice, Marcussen speaks (p. 6) of frontal wasting if the movement of this line is interrupted within short distances. It is obvious that this conception of frontal deglaciation is not in agreement with the generally accepted idea of frontal retreat. If anything, it corresponds to the type of areal deglaciation where the glacier gradually falls into a number of dead-ice ridges parallel to the glacier front. This mode of deglaciation, described among others by Goldtwhait (1951) and Boulton (1972) from modern arctic glaciers, leads to the formation of "controlled" moraine forms (Gravenor and Kupsch 1959; Boulton 1968).

In accordance with the terminology given by Klimaszewski (1960), the mode of deglaciation along the margin of Sléttjökull - exemplified by the above history of glacier retreat in the Mælifell area - is by frontal retreat; i.e. the glacier front makes up a well-defined boundary between the active glacier and the ice-free forefield. This has clearly been demonstrated by photographs taken in 1906 (Sapper 1909), 1937, 1945 (see fig. 22), 1960 (see figs. 8 and 22), 1977 (see fig. 11), and 1978 (see fig. 22).

The observations from the Mælifell area are summarized in fig. 25 which shows an idealized model of deglaciation by frontal retreat across a low angle normal slope. The proglacial area is dominated by moraine forms mainly produced by subglacial deposition and slightly modified by fluvioglacial erosion and deposition as a result of deglaciation.

In the Mælifell area the existance of a gently undulating or nearly flat glacier bed surface without irregularities, undoubtedly facoured the frontal retreat. The same holds true for the almost debris-free glacier surface which is preventing a differentiated ablation and disintegration of the glacier margin. However, the relationship between ablation and re - placement of ice by forward movement also controls the mode of deglaciation. In the Mælifell area the stable ice surface slope during the glacier retreat indicates a gradual displacement of the equilibrium line favouring deglaciation by frontal retreat.

Fig. 25. Diagrammatical model of deglaciation by frontal retreat based on observations from the Mælifell area. (A) Formation of marginal push-moraine ridges during glacier advance. (B) Exposing of moraine forms mainly produced by subglacial till deposition and slightly modified by fluvioglacial erosion and deposition as a result of deglaciation. (1) Ice marginal push-moraine. (2) Ice cave. (3) Outwash fan. (4) Old ice marginal moraine which has been overridden by the glacier. (5) Annual moraines. (6) Fluted ground moraine. (7) Drumlin. (8) Drumlin emerging from the retreating ice front.

Fig. 25. Diagrammatisk model for frontal deglaciation baseret på observationer i Mælifell-området. (A) Dannelse af pushmoræner under et gletscherfremstød. (B) Frismeltning af bundmoræne, der stedvis modificeres af smeltevandsaktivitet. (1) Israndsbakker. (2) Gletscherport. (3) Smeltevandskegle. (4) Ældre randmoræne, som har været overskredet af.gletscheren. (5) Årsmoræner. (6) Bundmoræne med flutes. (7) Drumlin. (8) Drumlin under frismeltning.

LARGE-SCALE GEOMORPHOLOGY IN THE FOREFIELD OF SLÉTTJÖKULL

By way of introduction the glacier forefield along the northern margin of Sléttjökull was carefully studied by examining stereoscopically pairs of aerial photographs (1:36,000) taken in 1960. The photographs were examined in a Zeiss Jena Interpretoscope in the photogrammetric laboratory at the Geographical Institute, and a geomorphological map was then produced by drawing the geomorphological main features on a plastic overlay. This map was subsequently reduced photographically to produce figure 5.

THE GLACIER FRONT

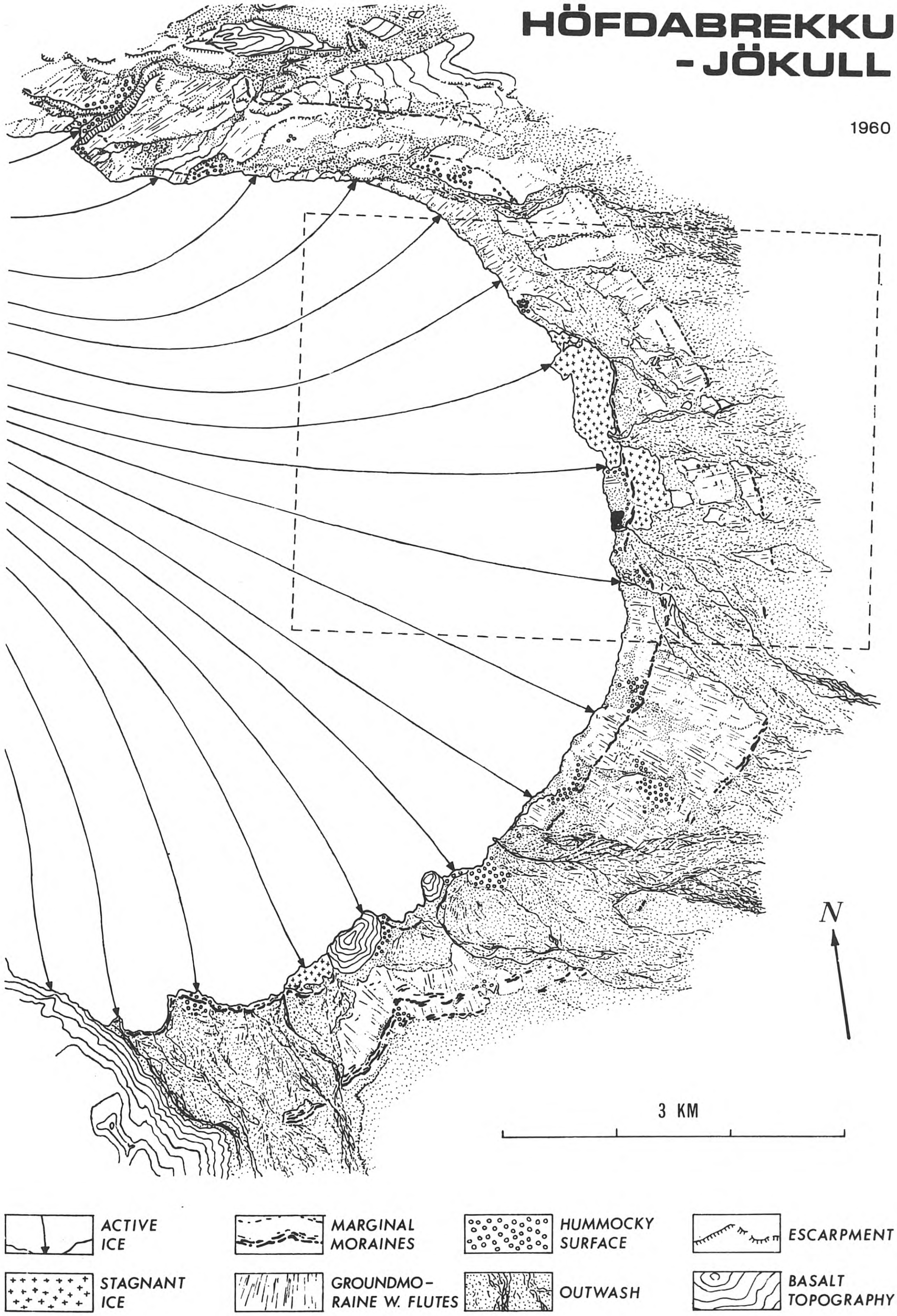
The Sléttjökull which terminates in a nearly 21 km long glacier front descends to the inland plateau at an elevation of 600-650 m above sea level. To the east this part of Mýrdalsjökull is bounded by the table mountain Öldufell (810 m) and the outlet glacier Öldufellsjökull, and to the west by the nunatak Enta (1265 m) and the glacier Merkurjökull. A large medial moraine originating from the above nunatak makes up a conspicuous boundary between Merkurjökull and Sléttjökull.

On the glacier surface few bands of volcanic ashes crop out as black, undulating lines resembling contour lines on a map; a telling characterization given by Kozarski and Szupryczyński (1973) for corresponding bands of ashes on the snout of Sidujökull, Iceland. The volcanic ashes may i.a. be assigned to eruptions from the subglacial volcano Katla situated near the Höfdabrekkujökull. After each volcanic eruption ashes may cover extensive areas and even the glacier. In the accumulation area a repeated deposition of volcanic ashes and snow produces a stratigraphy of dirty layers interbedded with clean ice. In the ablation zone, however, the dirty layers crop out as the black undulating bands.

A festoon-like configuration of the margin of Sléttjökull divides the protruding glacier front into three lobes each of which is 6-7 km across and only 1-1.5 km long. Spethmann (1912) used the term "Lappenrand" for this ice-front configuration. In the field and on the air photographs it can be clearly seen that between the curved lobes a summit line of subglacial hills and nunataks are exposed concurrently with the glacier retreat Thus it appears that the "Lappenrand" is conditioned by the subglacial topography. Medial moraines prolonging rock spurs from the nunataks in a down-glacier direction only emphasize the impression of a festoon-like configuration.

THE GLACIER FOREFIELD

The area north of Sléttjökull is known as Mælifellssandur. This area mainly consists of glaciofluvial and eolian deposits, and measured on the map the length of the Mælifellssandur E-W is about 18 km and N-S about 4 km. To the north the Mælifellssandur is bounded by a diffenrentiated mountain-area reaching heights of 800-1250 m above sea level (Strútúr 968 m, Svartahnúksfjöll 901 m, and Kaldaklofsfjöll 1278 m) and capped by. a small plateau glacier, Torfajökull (see fig. 6). To the east and west the Mælifellssandur is bounded by tuff ridges, crater rows and table mountains directed NE-SW (Nordur- and Sudur-Kerlingahnúkúr, Hvanngilshaú-


HÖFDABREKKU
-JÖKULL
1960
N
3 KM
ACTIVE ICE
STAGNANT ICE
MARGINAL MORAINES
GROUNDMO-RAINE W. FLUTES
HUMMOCKY SURFACE
OUTWASH
ESCARPMENT
BASALT TOPOGRAPHY

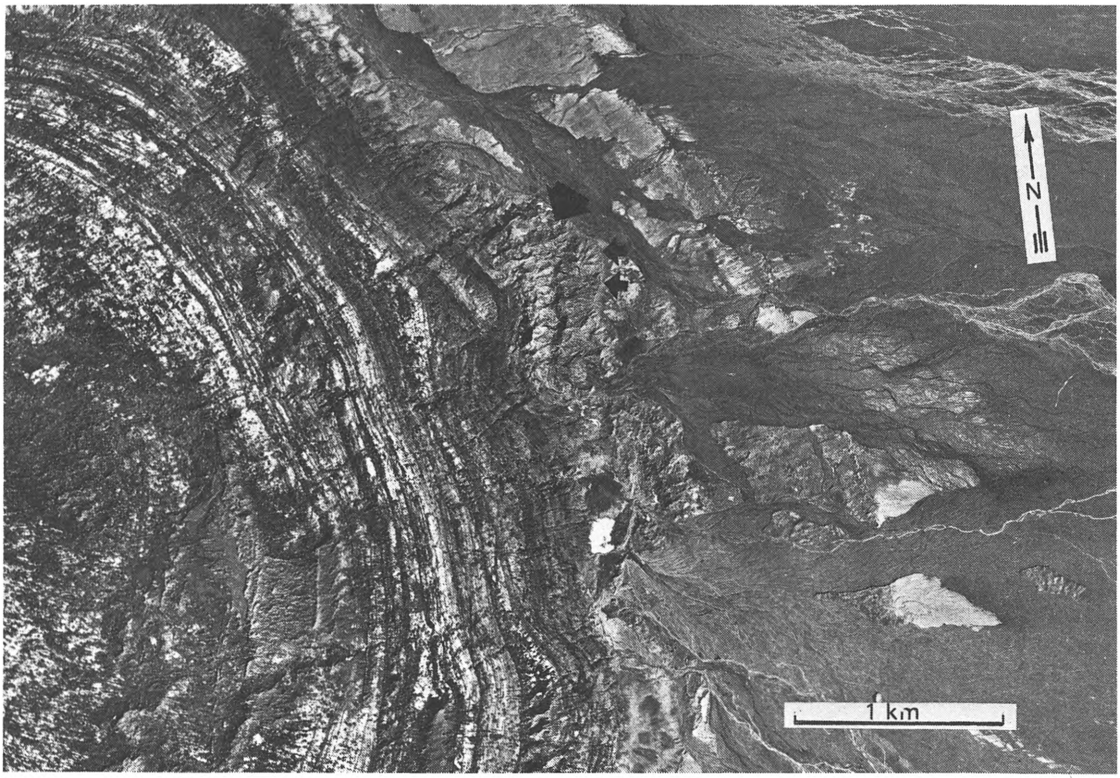


Fig. 27. Air photograph taken in 1960 showing the northeastern sector of Höfdabrekkujökull and its forefield (see fig. 26). The big arrow indicates the area of stagnant ice, and the small ones some tongues of moving flow till extending from the stagnant ice surface down the fore-slope of the inmost system of marginal moraine ridges (compare with fig. 41). On the glacier surface many downwash basins and dirt cones are visible.

Fig. 27. Luftfoto fra 1960 af Höfdabrekkujökulls nordøstlige del og det foranliggende landskab (se fig. 26). Den kraftige pil angiver området med stagneret is, mens de små pile viser flow-till lober under bevægelse fra den stagnerede is ud over det inderste system af randmoræner (sammenlign med fig. 41). Adskillige nedskylsbassiner og dirtcones ses på isoverfladen.

meter.

Two main systems of marginal moraine ridges are found ;in the forefield of Höfdabrekkujökull (see fig. 26). The outermost moraine system is situated 700-1400 m beyond the 1960-glacier margin. The longest distance between the glacier margin and the outer moraine ridges is found in front of the central part of the glacier. The individual ridges mainly take the form of small 2-3 m high push moraines. Only in the southern sector of the moraine system the ridges are higher, usually rising 5-10 m above the surrounding terrain (judging from aerial photographs as this part of the glacier forefield was not visited in 1977).

The inmost system of marginal moraine ridges is found only 0-300 m beyond the 1960 glacier margin, and especially in the northeastern sector these ridges even make up an outer limitation of areas of stagnant glacier ice (see figs. 26 and 27). However, since 1960 these areas of stagnant ice have gradually been trans-

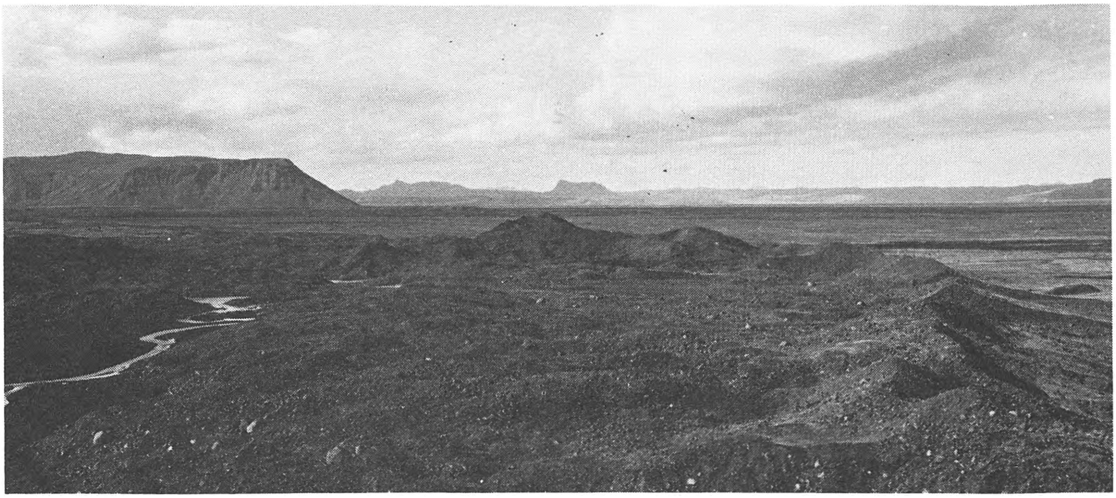


Fig. 28. View over the northeastern glacier forefield in front of Höfdabrekkujökull (see fig. 26) showing the hummocky landscape bounded by the inmost system of marginal moraine ridges. To the right of the marginal moraine the outwash fans are seen.

Fig. 28. Udsigt over den nordøstlige del af Höfdabrekkujökulls proglaciale område (se fig. 26). Dødisområdet ses inden for randmorænen; udenfor ses smeltevandskegler.

Fig. 29. Boulder-paved dry channel cut through one of the inmost marginal moraine ridges in the northeastern sector of the Höfdabrekkujökull forefield. In the background the debris-covered glacier margin is seen.

Fig. 29. Tørlagt løb gennem den inderste randmoræne i det nordøstlige område ved Höfdabrekkujökull. I baggrunden ses den smudsdækkede gletscherrand.

Fig. 30. Ground moraine in front of HöfdabrekkujÖ-kull.

Fig. 30. Bundmoræne foran Höfda-brekkujökull.

formed into a hummocky surface with an irregular topography of kettle holes and mounds of buried dead-ice blocks (see fig. 28).

Glaciofluvial streams once flowing from the glacier have broken the marginal moraine ridges at several points (see fig. 29).

Indications of a third, but not so well-defined system of marginal moraine ridges are found in the southern and northeastern sector of the glacier forefield where ridges occur 100-200 m behind the outermost moraine system.

As the glacier margin on the aerial photographs from 1960 is seen to be in close contact with the inmost moraine system in numerous locations a tentative age of 1950-55 is therefore proposed for this system of moraine ridges. The age of the outermost system is not known, but judging from preliminary lichenometric observations and from the vegetation in general, these ridges appear to represent a glacier advance somewhere in the second half of the 19th century, probably around 1890 which corresponds to the historical maximum at both Sólheimajökull 25 km to the west (Jaksch 1970) 1975) and at the margin of Sléttjökull.

Areas of fluted ground moraine are found at several places in the glacier forefield (see fig. 26) appearing as heavily dissected remnants of former coherent ground moraines. As a rule, these areas are rather flat, except in the northern sector, where the surface relief is controlled by the underlying basalt.

In contrast to the ground moraine beyond the margin of Sléttjökull, that of Höfdabrekkujökull is overstrewn with numerous boulders, many of them 0.3-1 m in diameter, obviously representing supraglacial load which has been superimposed upon the ground moraine during retreat of the glacier front (see fig. 30).

During the retreat from the inmost moraine system Höfdabrekkujökull has been characterized by the intermittent detachment of fairly large areas of stagnant ice from the glacier margin. Several examples of this are seen on the geomorphological map (see fig. 26), especially in the northeastern sector, but also along the southern part of the glacier front. These masses of stagnant ice are covered by a mantle of supra-glacial debris which, due to a differentiated ablation, produces areas with a hummocky surface. The probable causes for the detachment of stagnant ice are discussed below.

In contrast to Sléttjökull, where the glacier surface slopes gently towards the continuously retreating glacier front (see fig. 11) the present margin of Höfdabrekkujökull is exceptionally steep; perhaps an indication of a beginning readvance of this glacier (see fig. 31). Another

Fig. 31. The steep and very irregular ice front of Höfdabrekkujökull.

Fig. 31. Höfdabrekkujökulls stejle og uregelmæssige gletscherfront.

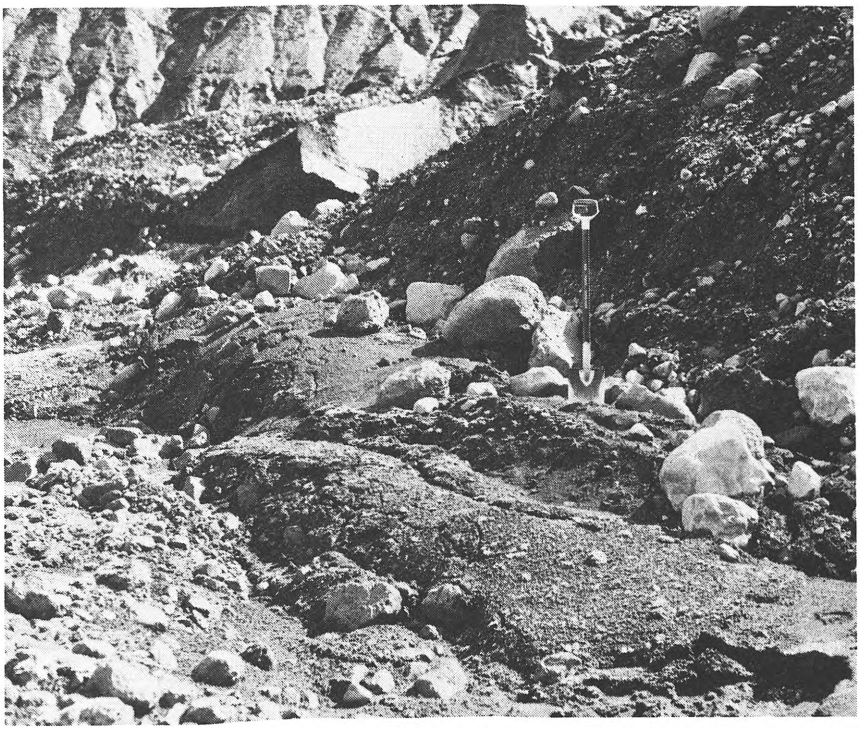


Fig. 32.
A detail of fig . 31. (the arrow) showing the formation of push moraine during glacier advance.

Fig. 32.
Detalje fra fig. 31 viser en lille pushmoræne under dannelse.

hint of a readvance is the development of a new push moraine along the glacier front in the summer of 1977 (see fig. 32). Therefore, it should be pointed out, that a close synchronization between the outlet-glacier Höfdabrekkujökull and other parts of Mýrdalsjökull is contrary to expectation because of differences in length, surface profile, coupling at the glacier-bed interface etc. (Nye 1960; 1963; 1965;). Thus the very long, but narrow outlet-glacier Sólheimajökull has been advancing during the last several years.

PROCESSES OF GLACIAL TRANSPORTATION AND SEDIMENTATION

Generally, debris transported by glaciers may be derived from three principal sources; from the air (windblown material, volcanic dust, etc.), from nunataks and valley sides, and from the glacier bed itself. Depending on the source and the point of entering glacial transport, debris may be transported supraglacilly, englacially, or subglacially.

The two parts of Mýrdalsjökull under investigation differ in a pronounced way concerning the domineering type of glacial transport. Höfdabrekkujökull, situated near the volcano Katla, is transporting huge amounts of volcanic or air-deposited material both englacially and supraglacially (see fig. 27) while transport in the glacier sole appears to be of minor importance, relatively. In the Mælifell area, on the other hand, most sediment is carried in a 0.01-0.1 m thick glacier sole. This difference in type of glacial transport is of major importance, influencing among other things the mode of deglaciation and thereby the sedimentological and geomorphological end-products.

SUBGLACIAL SEDIMENTATION IN THE MÆLIFELL AREA

Opinions differ considerably as to the mechanisms of subglacial deposition. Holmes (1941) proposed that subglacial till was deposited by "plastering on" where till accumulates gradually beneath an active glacier sole. Boulton (1975) has later formalized this model for frictional sedimentation and for the first time made it possible to obtain quantitative predictions suitable for field tests. On the other hand, Harrison (1957) suggested that subglacial tills may be deposited by slow melting out from stagnant glacier ice. Thus, Harrison concludes that the bulk of structures (e.g. till fabrics) in subglacial tills have been inherited from the original englacial structures. Lawrushin (1971), working on visible structures in tills, proposed a slightly modified model, according to which many subglacial tills are deposited by slow melting of the debris-loaded glacier sole which may be dynamically detached from the still active, but clean glacier ice above.

Much of the future work at the margin of Sléttjökull is planned to contribute to this general discussion on subglacial sedimentation. However, the preliminary investigations have already clearly demonstrated that the domineering type of subglacial deposition in this area follows the frictional model set up by Holmes and formalized by Boulton.

In the Mælifell area the authors have observed that most debris is transported in a 0.01-0.1 m thick zone above the glacier base. The glacier-bed interface appears as a well-defined plane, and no stagnant ice was found in the till below the glacier sole. Sediment in basal transport consists of abraded basalt fragments (1-30 cm in diameter) and finer material in bands and clouds of dirty ice.

Several boulders on the ground moraine surface, being currently exposed during the most recent glacier retreat and each laying at the distal end of a furrow (see fig. 33) indicate that particles in traction are lodged from the glacier sole when the force between particle and glacier bed exceeds the maximum force which

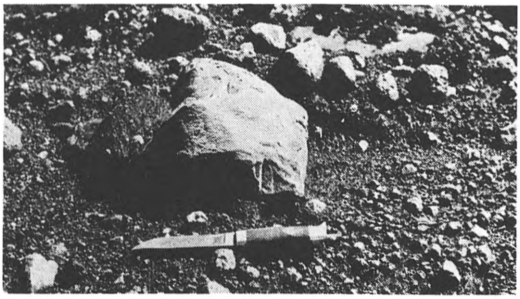


Fig. 33. A lodged clast just released from beneath the retreating glacier at the margin of Sléttjökull. Notice the till bank in front of the clast and the groove behind it. Glacier movement is from right to left.

Fig. 33. Aflejret blok, netop frismeltet fra Sléttjökulls rand. Bemærk den sammenskubbede vold distalt for blokken samt furen bag blokken. Gletscherbevægelse fra højre mod venstre.

Fig. 34. Residual of stones melting free from the glacier sole during the glacier retreat in the Mælifell area.

Fig. 34. Sten-residual under frismeltning fra Sléttjökulls gletschersål.

can be mobilised between particle and the surrounding glacier ice (Boulton 1975). According to this hypothesis small particles in subglacial traction will tend to lodge readily due to the efficiency of pressure melting and regelation and large particles will lodge readily due to increased plastic deformation of the surrounding ice. An intermediate particle size for which both mechanisms are relatively ineffective ("controlling" particles), will suffer little retardation due to traction, and will tend to stay in basal transport and thereby escape lodgement.

A support for this transportation/sedimentation model is provided by a conspicuous residual of particles 1-15 cm in diameter which were observed melting free from the glacier sole during retreat of the glacier terminus (see fig. 34). This population of particles is thought to be those which the glacier under the present subglacial conditions is able to keep from lodging against the glacier bed. The observed size-range should then be considered as specific for this locality only, as the size of "controlling" particles will depend on the sliding velocity of the glacier sole, the subglacial effective pressure, the particle form and orientation, as well as the relative depth which particles in traction penetrate into the glacier bed before lodgement. However, "controlling" particles will tend to be smaller as the subglacial effective pressure increases.

A large clast lodged against the glacier bed may act as a trap for other particles still in basal transport, causing these to lodge against its up-glacier side. By this process clusters of boulders in the lodgement till may be produced (Boulton 1975). If the glacier flow direction remains constant during development of the cluster, a row of lodged clasts parallel to the flow direction can develop which was observed at several occasions on the surface of the ground moraine in front of the glacier (see fig. 35). When lodged against the glacier bed boulders act as stationary obstacles and may be heavily abraded and striated by particles still in traction until the boulders are completely buried by material lodged from the glacier sole. Thereby a smoothing of the upper part

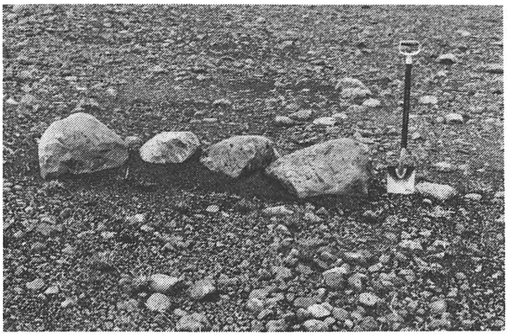


Fig. 35. A row of boulders embedded in the ground moraine surface beyond the margin of Sléttjökull. Glacier movement is from left to right. Note the up-glacier imprication of the boulders.

Fig. 35. Blokrække i bundmorænens overflade foran Sléttjökull. Isbevægelse fra venstre mod højre. Bemærk blokkenes op-gletscher imbrication.

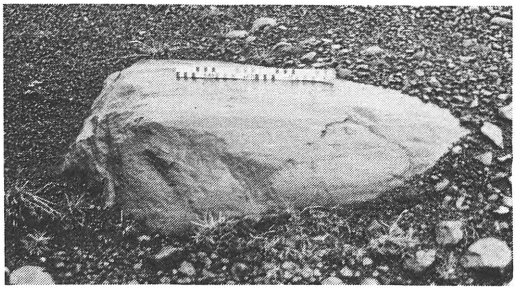


Fig. 36. A boulder with stoss-and-lee sides embedded in the ground moraine surface in front of Sléttjökull. Glacier flow from right to left.

Fig. 36. Blok med stød- og læside faststående i bundmorænen foran Sléttjökull. Isbevægelse fra højre mod venstre.

of lodged boulders may develop. If the relation sliding velocity/subglacial effective pressure increases beyond a critical value, the glacier sole will furthermore loose contact with the distal side of a lodged boulder causing a lee-side cavity to develop. As low pressures in this cavity mean that the shear strength of the distal boulder part will be at minimum (Boulton 1974), this is liable to intensive fracturing by particles in traction across the boulder. Thus large boulders projecting above the lodgement till surface may gradually develop the form of small "roches moutonnées" (Boulton 1978; Krüger 1979) each having a gentle abraded stoss side and a somewhat steeper and more roughly quarried lee side (see fig. 36).

In the ground moraine recently exposed by the glacier retreat the authors found that a large part of boulders embedded in the till surface were polished and scratched and thereby constituted small "roches moutonnées". Analyses indicate that such boulders had a very distinct stoss-and-lee side orientation as their stoss sides mainly faced upstream and their lee sides downstream (Krüger 1979). Similar boulder forms have been observed by Okko (1955) in front of Heinabergsjökull, Iceland, and he also suggests that their present form is due to subglacial erosion after lodgement of the boulders.

BASAL AND ENGLACIAL TRANSPORT AT HÖFDABREKKUJÖKULL

The many crevasses and deeply cut gullies in the glacier surface near the steep terminus of Höfdabrekkujökull provide good possibilities for studying the spatial arrangement of debris in transport. The lowermost 15-25 cm of glacier ice are debris-rich with a debris content of 10-50 percent by volume. The material varies from fine silt to coarse sand and gravel, but some larger clasts of basalt, 2-20 cm in diameter, were also observed. Furthermore numerous gas bubbles give the basal ice a milky appearance. The spatial arrangement of debris in the basal ice is somewhat irregular, but with highest concentration of debris towards the glacier-bed interface, where debris particles are transported in traction.

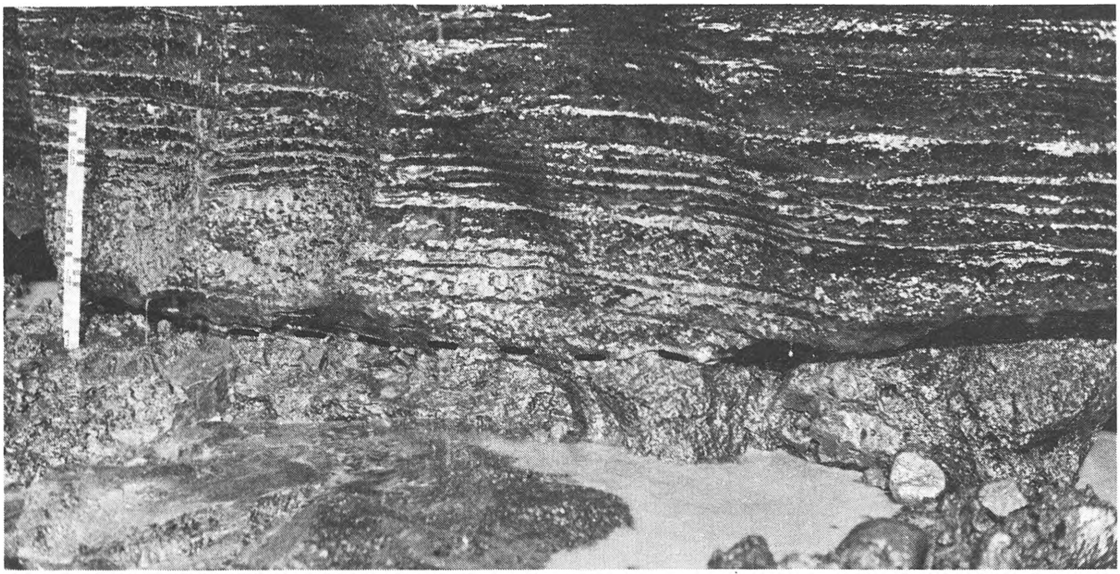


Fig. 37. The glacier-bed interface beneath the margin of Höfdabrekkujökull. Above the dashed line debris-rich glacier ice is seen; below the line deposited till is visible.

Fig. 37. Grænsefladen mellem gletscher og underlag under Höfdabrekkujökulls randzone. Over den stiplede linie ses den smudsholdige gletschersål, medens underlaget, der ses under den stiplede linie, udgøres af aflejret till.

Locally, debris is transported with only interstitiel ice between, but still the glacier-bed interface will appear as a well-defined plane with no stagnant ice in the lodgement till below (see fig. 37).

Upward the basal ice gradually gives way to generally cleaner ice with a distinct foliation composed of alternating bands of large and small ice crystals, 5-10 mm and 2-3 mm in diameter, respectively. Generally, bands of large crystals are 1-5 cm in thickness while small-crystal bands only amount to 2-5 mm. Near the glacier terminus where most of the observations were made, this foliation dips 5-15° in up-glacier direction. Occasionally the foliation was observed to be folded or displaced along thrust planes.

Debris in the sand and silt fractions is mostly concentrated along crystal boundaries in the small-crystal bands while only a minor amount is transported inside the ice crystals. Usually, these debris bands are very thin, but some may have a more massive appearance, occasionally reaching a thickness of 10-15 cm. However, bands up to 1.5 m thick were observed in ice cliffs cut in till covered stagnant glacier ice in front of the glacier.

Bands of large ice crystals occurring between debris bands are nearly clean and only contain a few larger particles such as stones and boulders.

In contrast to much of the debris in the basal dirty ice, probably originating from the glacier bed, most of the debris in the foliated zone appears to be derived from material which has fallen onto the glacier surface in the accumulation area from suspension in the air. Some of this air-deposited material may have fallen on the glacier surface in connection with volcanic eruptions, but due to the very high number of thin debris bands, deposition from the air during dust storms appears to be a more likely explanation for most of the debris bands in Höfdabrekkajökull.

Fig. 38.
The terminal part of Höfdabrekkujökull with the extremely dirty glacier surface.

Fig. 38.
Den randnære overflade af Höfdabrekkujökull, dækket af smuds.

Thus, much of the silty material is probably derived from the large meltwater plains beyond the margin of Mýrdalsjökull.

SUPRAGLACIAL SEDIMENTATION ON THE SNOUT OF HÖFDABREKKUJÖKULL

In the ablation zone the upward component of glacier movement transports the englacial load of debris and volcanic ashes towards the glacier surface where it is seen cropping out in series of dirty bands.

Because the glacier snout is in a state of longitudinal compression, supraglacial material is also derived from debris-loaded ice just above steeply dipping shear-planes. In accordance with this, the many striated and slightly rounded clasts occurring on the glacier surface in the terminal 200-500 m of the glacier most likely originate from transport in basal ice (see fig. 38).

The surface expression of the outcropping dirty bands is ridges or rather parallel rows of sharp-pointed mounds, 0.l-5 m high. The increasing surface accumulation of material gradually slows down the ablation of the underlying ice, and hereby the more rapid lowering of the surrounding ice surface produces ice-cored mounds. In the literature such mounds are termed dirt cones (Lewis 1940, ablation cones (Kozarski and Szupryczyński 1973), or debris cones (Stenborg 1968).

Among the various forms of dirt cones observed on the snout of Höfdabrekkujökull two morphological main types were distinguished. The first one which originates from the outcropping of gently dipping debris bands

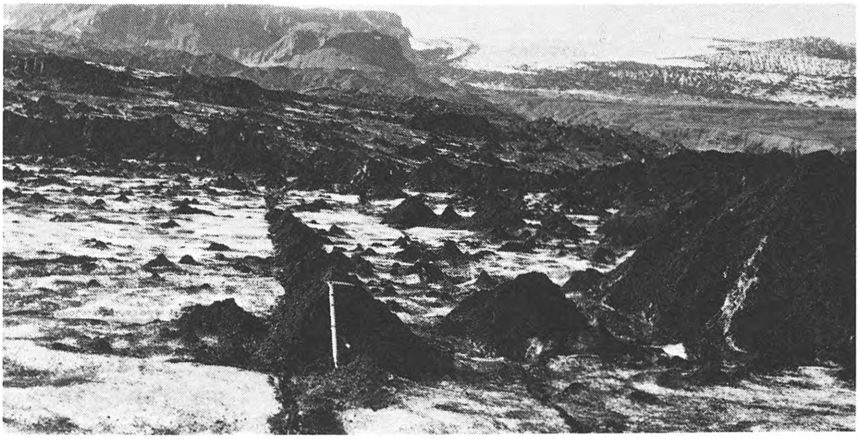


Fig. 39.
Dirt cones on the snout of Höfdabrekkujökull.

Fig. 39.
Dirt cones på overfladen af Höfdabrekkujökull.

Fig. 40.
Tongue of melt-water-soaked ashes flowing down the glacier surface near the terminus of Höfdabrekkujökull.

Fig. 40.
Lobe af vandmættet aske på overfladen af Höfdabrekkujökull.

on the glacier surface shows a down-glacier asymmetry, while the emerging of steeply dipping bands or shear-planes mostly produces symmetrical forms (see fig. 39).

Some of the dirt cones, however, appeared to originate from another mechanism namely those found in connection with supraglacial stream channels extending down-glacier at right angle to the glacier margin. These dirt cones are covered by sorted material washed from debris on the glacier surface and then re-deposited as small point bars in the stream channels. The protection of the underlying ice against melting and the rapid lowering of the surrounding ice surface produce dirt cones corresponding to the ancient bars.

This last-named type of dirt cones, which was found in many stages of evolusion on the snout of Höfdabrekkujökull, has been described by Drewry (1972) from the Bersærkerbræ in north-east Greenland and by Kozarski and Szupryczyński (1973) from Sidujökull in Iceland. More recently Jensen and Kraag (1977) have studied this type of dirt cones on the snout of the

Fig. 41. Flow-till tongues extending, from the fore-slope of the inmost system of marginal moraine ridges onto the outwash fans in front of Höfdabrekkujökull. (see also fig. 27).

Fig. 41. Flyde-till lober ved foden af det inderste randmorænesystem ved Höfdabrekkujökull (se fig. 27). Loberne overlejrer smeltevandsaflejringer.

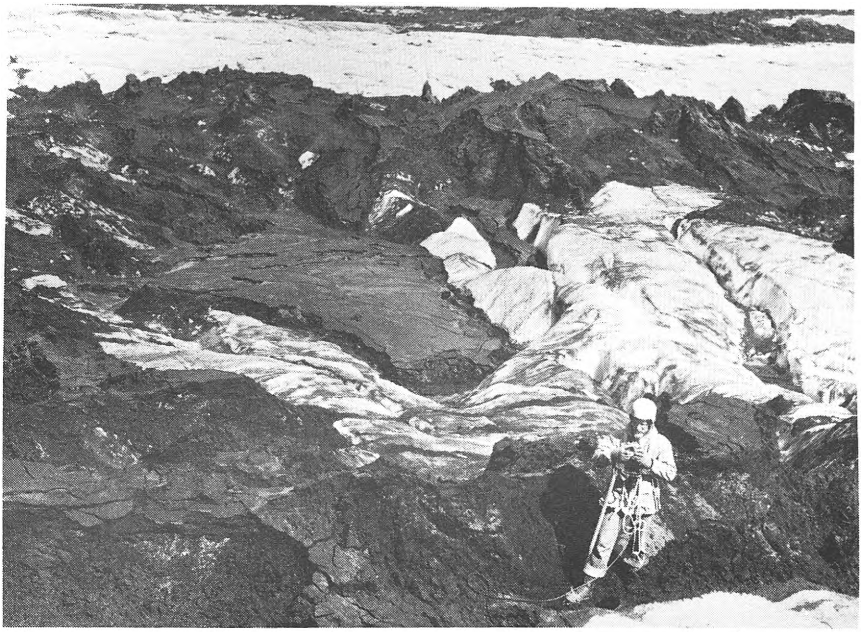


Fig. 42.
A supraglacial downwash basin situated on the snout of Höfdabrekkujökull.

Fig. 42.
Supraglacialt nedskylsbassin på Höfdabrekkujökull.

glacier Lyngmarksbræen on the island Disko, West Greenland.

The release of minerogenic material on the sloping glacier surface results in the formation of flow till. The authors have observed how subsidence and sliding of unstable material from steep slopes and pointed tops of dirt cones produces sheets of meltwater-soaked till which flow readily down the glacier surface in the shape of till tongues (see fig. 40). On the air photographs taken in 1960 (see fig. 27) corresponding tongues of moving flow till can be traced from the stagnant ice surface down the fore-slope of the inmost system of marginal moraine ridges and onto the bed of outwash fans which border the moraine ridges. During the field work in 1977 the same localities presented inactive tongue-shaped features, 20-40 m long extending from small gaps in the moraine ridges and terminated on the outwash fans (see fig. 41).

Other observations on the snout of Höfdabrekkujökull show how sheets of supraglacial material were removed by fluvial erosion and re-deposited in hollows on the glacier surface as fans and sheets of laminated sand and silt (see fig. 42). Large supraglacial downwash basins probably of similar origin are also seen on the 1960 aerial photography (see fig. 27). In contrast with the sharp-pointed cones, conditioned by outcropping bands and shears, the relatively rapid lowering

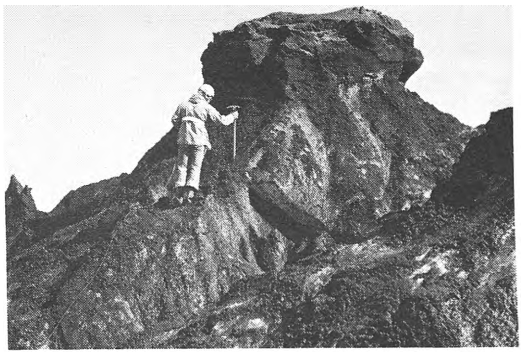


Fig. 43. Small-scale inversion of the glacier surface relief. Laminated downwash sediments resting on an ice-core.

Fig. 43. Inversion af gletscherens overfladerelief i lille skala. Lamineret sediment hviler på en kerne af gletscheris.

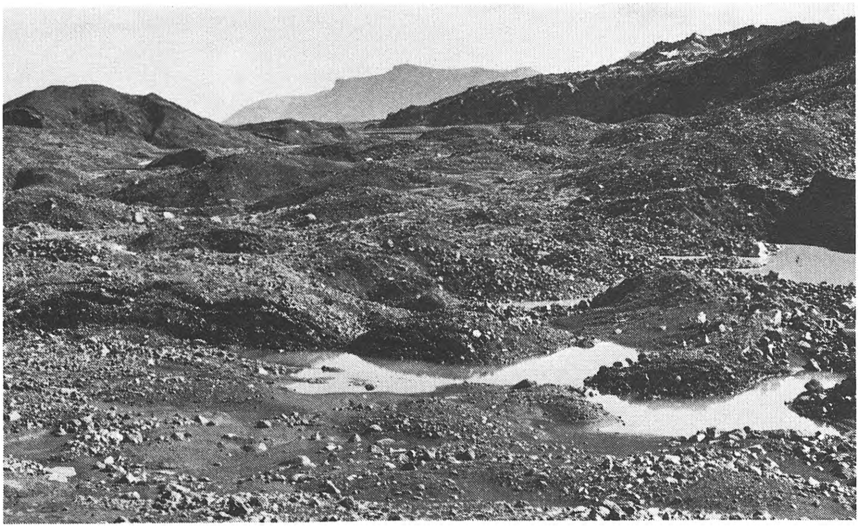


Fig. 44. Large scale inversion of the relief in the dead-ice field fringing the northeastern part of Höfdabrekkujökull.

Fig. 44. Inversion af gletscherens overfladerelief i stor skala, i dødisområdet foran nordøstranden af Höfdabrekkujökull.

of the ice surface adjacent to the downwash basins gives rise to the formation of the table-topped or plateau-like hills corresponding to the ancient throughs (see fig. 43). The release of material on the glacier surface, the movement of sheets of water-soaked till, and the fluvial removal and re-deposition of debris and ashes are the principal sedimentation processes which were observed on the surface of the actively flowing ice.

In the area of dead-ice an inversion of the initial relief of the glacier surface took place on a larger scale. Variations in thickness of flow till and waterlaid deposits have given rise to differential ablation and disintegration of the underlying ice, producing a very irregular topography where the local relief often exceeds 10 m. The hummocky topography makes up a complex of small hills, ridges and kettle holes in a chaotic pattern. At numerous points sliding of material from steep slopes has exposed an ice core, and along the border of water-logged kettle holes subsidence of material indicates the slow decay of dead-ice blocks deeply buried under deposits (see fig. 44).

Similar features of hummocky, ice-cored moraines are described by Boulton (1968) as "uncontrolled" moraine forms and by Jewtuchowicz (1973) as dead-ice fields.

Based on studies in Vestspitsbergen, Boulton (1968; 1971) gives a very detailed description of the mechanism of flow of supraglacial till in dead-ice fields. Boulton distinguishes between three basic flow processes: 1) mobile, liquid flow, 2) semi-plastic flow, and 3) downslope creep, depending on the water content of the till and the stability of the slopes.

In the dead-ice field in the northeastern sector of the Höfdabrekkujökull forefield the first type of flow was observed to be very common and affecting those tills which had a very high content of water. However, this type of flow is also the most conspicuous because the till undergoes very mobile flows whereas the other two types of flow, such as distinguished by Boulton, have much lower velocities and therefore need several days or weeks to be recorded.

Another common mechanism acting in the dead-ice fields at Höfdabrekkujökull, especielly in areas of considerable relief, was the size-sorting caused by surficial creep, sliding, or falls of boulders. The authors have observed how the blocky components as a rule travelled faster than their surroundings and therefore produce irregular agglomerations of boulders in topographic lows (see fig. 28).

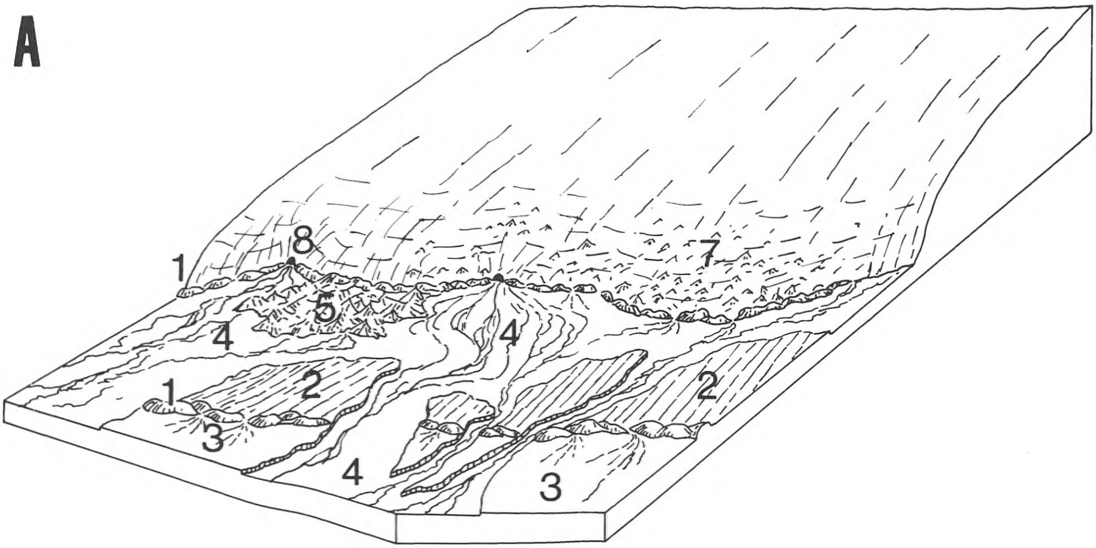
Therefore, an alternation of till flows and boulder accumulations in hollows concurrently with the inversion of the dead-ice field relief may produce flow-till sequences with a random or controlled distribution of boulder agglomerations. Future work is planned to study this phenomena.

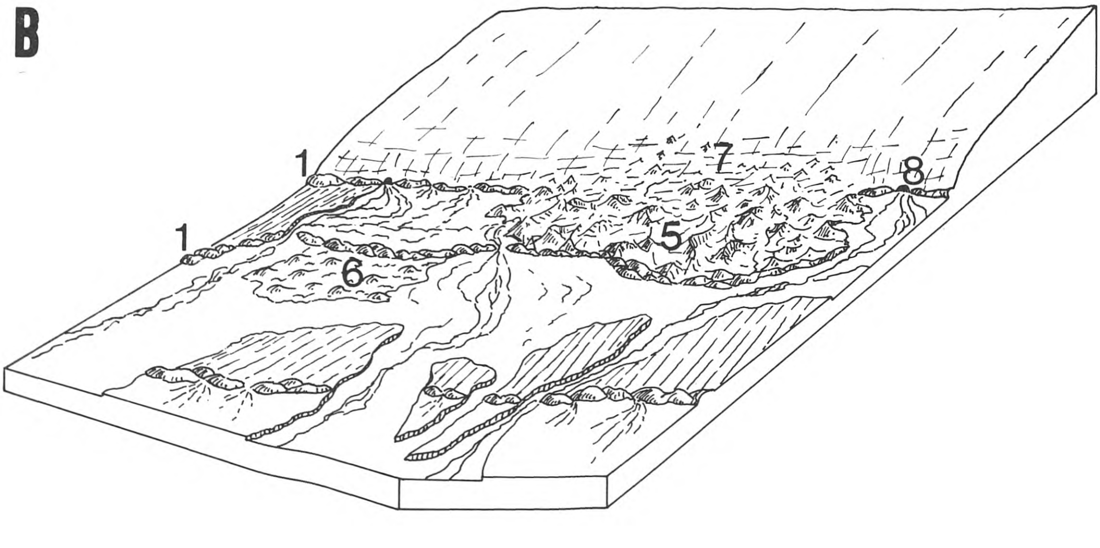
The thickness of the widespread deposits which cover the irregular dead-ice surface, varies greatly due to the topographic position. On the top of mounds and ridges where the deposits flow off the ice core they are rarely more than 0.1-0.5 m thick, but in hollows they often make up thicknesses of several meters.

The dead-ice field is fringed by areas of hummocks or gently undulating plains much like ground moraine. These areas, sparsely covered by vegetation, are the end-product of ice disintegration by irregular ablation. In contrast with areas of ground moraine, however, the landscapes of supraglacial origin show irregular agglomerations of boulders produced by gravitational sorting during the active flow-till stage as described above (see fig. 28).

HÖFDABREKKUJÖKULL: A MODEL OF DEGLACIATION BY AREAL DOWN-WASTAGE

The outermost marginal moraine system in front of Höfdabrekkujökull (see fig. 26) was probably formed during a glacier advance at the end of the 19th century. The occurrence of fluted moraine behind this moraine system indicates that from an advanced position the glacier has clearly retreated by frontal retreat just like the Sléttjökull. However, in contrast with the Sléttjökull the snout of Höfdabrekkujökull has probably been cov-





ered by scattered stones and boulders because the numerous angular and sharp-edged boulders found on the ground moraine surface are interpreted as supraglacial load superimposed upon the ground moraine during retreat of the glacier front.

Since the formation of the inmost marginal moraine system, the Höfdabrekkujökull has at several places retreated by areal down-wastage. Undoubtedly a considerable addition of supraglacial material, partly as sheets of flow till partly as large down-wash basins (see fig. 27) has given rise to this change in mode of deglaciation during the last decades.

Generally, deglaciation by areal down-wastage leads to a gradual transition from actively flowing ice with a gently sloping glacier surface to debris-covered stagnant ice and dead-ice fields, and further to an ice-free hummocky glacier forefield. However, at the present margin of Höfdabrekkujökull the development of this scheme has been interrupted as the very steep glacier front and the recent development of a push moraine seems to indicate a beginning readvance of the glacier.

The observations from the north-eastern sector of the Höfdabrekkujökull forefield are summarized in fig. 45 which shows an idealized model of deglaciation by areal down-wastage. It is seen that the glacier forefield behind the inmost marginal moraine ridges is dominated by ice-desintegration forms.

Fig. 45. Diagrammatical model of deglaciation by areal down-wasting based on observations from the north-eastern part of Höfdabrekkujökull. (A) Formation of marginal push-moraine ridges during a glacier advance caused by glacier surge. (B) Formation of ice-disintegration features during areal down-wasting of stagnant and dead ice. (1) Terminal moraine ridges. (2) Fluted ground moraine. (3) Older outwash plain. (4) Younger outwash plain. (5) Debris-covered dead-ice field. (6) Hummocky moraine. (7) Dirt cones on glacier surface. (8) Ice cave.

Fig. 45. Diagrammatisk model for areal deglaciation baseret på observationer langs Höfdabrekkujökulls nordøstlige rand. (A) Dannelse af pushmoræner i forbindelse med gletscher-surge. (B) Dannelse af is-disintegrationsformer i forbindelse med areal nedsmeltning af stagnerende og død is. (1) Randmorænerygge. (2) Fluted bundmoræne. (3) Ældre smeltevandsslette. (4) Yngre smeltevandsslette. (5) Smudsdækket dødis. (6) Dødislandskab. (7) Smudskegler på gletscheroverfladen. (8) Gletscherport.

FINAL REMARKS

The expedition to Mýrdalsjökull in the summer of 1977 has shown that in the case of the Danish glacial landscape the selected research areas in Iceland are extremely useful in comparative studies. Therefore, during the summer of 1979 the field work was continued supported financially by the Danish Natural Science Research Council.

At the margin of Sléttjökull the investigations were mainly concentrated as follows:

(1) Detailed geomorphological mapping in the scale 1:10,000 was carried out along the glacier margin in continuation of the geomorphological mapping in 1977.

(2) Within a selected area (150 x 280 m) of the ground moraine the surface topography was mapped (contour interval 0,25 m) as well as the location of annual moraines, fluted moraine ridges, and boulders more than 30 cm in length. The stratigraphy of the selected area was studied in excavations. Furthermore, a number of till macro-fabric analyses was performed and orientated samples for micro-fabric analyses were collected.

(3) In the drumlinized ground moraine a selected drumlin complex was studied in detail concerning surface topography, stratigraphy, sedimentary structures, and short-distance variations of clast fabric. In natural sections in drumlins glaciodynamic fold structures and overthrusts were investigated.

(4) At several locations the glacier sole was described concerning the debris concentration and the character of the debris. In the till bed a large number of ploughing blocks and boulders with stoss-and-lee side forms were observed and their orientation measured. Furthermore, the shape, orientation, and size of clasts left on the ground moraine surface during the glacier front retreat were studied.

At the margin of Merkurjökull geomorphological mapping of large scale landforms of fluvioglacial origin was carried out and the changing systems of glacier drainage in context with the history of deglaciation investigated. Furthermore, the sedimentary structures in inactive outwash fans and in an actively disintegrating kettle sandur were described.

In the northeastern part of Höfdabrekkujökull the following investigations were made :

(1) A 600 m long traverse was made across a hummocky glacier forefield and a zone of disintegrating glacier ice; along this profile the thickness of flow till was studied.

(2) The detailed stratigraphy of thick flow-till beds overlying debris-rich stagnant glacier ice was investigated in the many natural sections. Isolated lobate till flows were dissected and the pattern of clast orientation was studied.

(3) Within a selected area (60 x 70 m) of the hummocky dead-ice landscape the surface topography was mapped (contour interval 0.5 m). The size-sorting caused by surficial creep, sliding, or falls of boulders was described, and a number of macro-clast fabric analyses performed.

(4) In crevasses and stream channels cut in the glacier margin, the inglacial stratigraphy (the banding and the concentration and texture of debris) as well as the inglacial macro-clast fabric was studied.

(5) An active meltwater fan was mapped topographically in two situations showing the changing pattern of small

streams which results in the cone formation.

Based on air photographs taken in the late summer of 1979 by the Iceland Survey Department contour maps (contour interval 2.5 m) of the northern margin and forefield of Mýrdalsjökull are being prepared photogrammetrically at the Geographical Institute in Copenhagen for further morphological and stratigraphical investigations.

It is intended to continue the field work in the selected research areas in Iceland in the summer of 1982.

REFERENCES

Bahnson, H., Petersen, K.S., Konradi, P., and Knudsen, K.L. 1974: Stratigraphy of Quaternary deposits in the Skærumhede II boring: lithology, molluscs and foraminifera. Dan. geol. Unders., Årbog 1973, 27-62.

Baranowski, S. 1970: The origin of fluted moraine at the front of contemporary glaciers. Geogr. Ann., 52 A., 68-75.

Berthelsen, A. 1973: Weichselian ice advances and drift successions in Denmark. Bull. geol. Inst. Univ. Uppsala, N.S. 5, 21-29.

Björnsson, H. 1975: Subglacial Water Reservoirs, Jökulhlaups and Volcanic Eruptions. Jökull, 25, 1-14.

Bogacki, M. 1973: Geomorphological and geological analysis of the proglacial area of Skeidararjökull. Central western and eastern section. Geogr. Polonica, 26, 57-88.

Boulton, G.S. 1968: Flow tills and related deposits on some Vestspitsbergen glaciers. Journ. Glaciol., 7, 391-412.

Boulton, G.S. 1971: Till genesis and fabric in Svalbard, Spitsbergen. In "Till, a symposium", ed. R.P. Goldthwait, Ohio State University, 41-72.

Boulton, G.S. 1972: Modern arctic glaciers as depositional models for former ice sheets. Journ. Geol. Soc. London., 128, 361-393.

Boulton, G.S. 1974: Processes and Patterns of Glacial Erosion. In "Glacial Geomorphology", ed. D.R. Coates, State University of New York, 41-87.

Boulton, G.S. 1975: Processes and patterns of subglacial sedimentation: a theoretical approach. In "Ice Ages: Ancient and Modern", ed. A. E Wright and F. Moseley, Geol. Journ. Spec. Iss. No. 6, Seel House Press, Liverpool, 7-42.

Boulton, G.S. 1976: The origin of glacially fluted surfaces - observations and theory. Journ. Glaciol., 17, 287-309.

Boulton, G.S. 1978: Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. Sedimentology, 25:6, 773-799.

Boulton, G.S. and Dent, D.L. 1974: The nature and rates of post-depositional changes in recently deposited till from South-East Iceland. Geogr. Ann., 56 A, 3-4, 121-134.

Boulton, G.S., Dent, D.L., and Morris, E.M. 1974: Subglacial shearing and Chrushing, and the role of water pressures in tills from South-East Iceland. Geogr. Ann., 56 A, 3-4. 135-145.

Drewry, J.D. 1972: A quantitative assessment of dirt cone dynamics. Journ. Glaciol., 11, 431-445.

Dyson, J.L. 1952: Ice-ridged moraines and relation to glaciers. Amer. Journ. Sci., 250, 204-211.

Goldthwait, R.P. 1951: Development of end moraines in east central Baffin Island. Journ. Geol., 59, 567-577.

Gravenor, C.P., and Kupsch, W.O. 1959: Ice disintegration features in Western Canada. Journ. Geol., 12, 48-64.

Harrison, W. 1957: A clay-till fabric : its character and origin. Journ. Geol., 11: 61, 15-29.

Holmes, C.D. 1941: Till fabric. Bull. Geol. Soc. Amer., 52, 1299-1354.

Hoppe, G., and Schytt, V. 1953: Some observations on fluted moraine surfaces. Geogr. Ann., 35, 105-115.

Howarth, P.J. 1971: Investigations of two eskers at eastern Breidamerkurjökull, Iceland. Arctic and Alpine Research 3: 4, 305-318.

Humlum, O. 1978: A large till wedge in Denmark: implications for the subglacial thermal regime. Bull. Geol. Soc. Denm., 27, 63-71.

Humlum, O. 1979: "Fluted moraine" på Omø - isbevægelsesretning og aflejringsmåde. Dansk geol. Foren., Årsskrift for 1978, 15-22.

Humlum, O. (in prep.): The role of subglacial water in the formation of glacial flutes.

Humlum, 0., Krüger, J., and Sjörring, S. 1978: Danmark i sidste istid: En diskussion. Naturens Verden 1978, 9, 272-286.

Jaksch, K. 1970: Beobachtungen in den Gletschervorfeldern des Sólheimajökull im Sommer 1970. Jökull, 20, 45-49.

Jaksch, K. 1975: Das Gletschervorfeld des Sölheimajökull. Jökull, 25, 34-38.

Jensen, J.B., and Kraag, B.L. 1977: Lyngmarksbræens morfologi. In "Arktisk Geomorfologi, Godhavn 1976", ed. O. Humlum, Geogr. Inst. Univ. Copenhagen, 131-149.

Jewtuchowicz, S. 1973: The present-day marginal zone of Skeidarárjökull. Geogr. Polonica, 26, 115-137.

Kjartansson, G. 1962: Geological map of Iceland, sheet 6, South-Central Iceland.

Klimaszewski, M. 1960: Studia geomorfologiczne w zachodniej cześci Spitsbergennmiedzy Kongs-Fjorden a Eidenn-Bukta, Zerz. Nauk. Ud., 32, Prace Geogr. Ser. Nowa, 1.

Kozarski, S., and Szupryczyński, J. 1973: Glacial forms and deposits in the Sidujökull deglaciation area. Geogr. Polonica, 26, 255-311.

Krall, D.B. 1977: Late Wisconsinan ice recession in east-central New York. Geol. Soc. Amer. Bull., 88, 1697-1710.

Krüger, J. 1969: Landskabsformer i sydlige Sjælland. Studier over glaciallandskabets morfologi, opbygning og dannelse. Geogr. Tidsskrift, 68, 105-212.

Krüger, J. 1970: Till fabric in relation to direction of ice movement. Geogr. Tidsskrift, 69, 133-170.

Krüger, J. 1974: Glacialmorfologi. Geo-noter, særh. 2, Geogr. Inst. Univ. Copenhagen, 185 p.

Krüger, J. 1979: Structures and textures in till indicating subglacial deposition. Boreas, 8, 321-338.

Lamb, H.H. 1979: Climatic variations and changes in the wind and ocean circulation: The Little Ice Age in the Northeast Atlantic. Quaternary Research, 11, 1-20.

Larsen, G., Jørgensen, F.H., and Prisholm, S. 1977: The stratigraphy, structure and origin of glacial deposits in the Randers area, eastern Jutland. Damn. geol. Unders., II række, 111, 36 p.

Lawrushin, J.A. 1971: Dynamische Fazies und Subfazies der Grundmoräne. Zeitschrift d. angew. Geologie, 17: 8, 337-343.

Lewis, W.V. 1940: Dirt cones on the northern margins of Vatnajökull. Journ. Geomorph., 3.

Marcussen, I. 1973: Studies on flow till in Denmark. Boreas, 2, 213-231.

Marcussen, I. 1975: Distinguishing between lodgement till and flow till in Weichselian deposits. Boreas, 4, 113-123.

Marcussen, I. 1977: Deglaciation landscapes formed during the wasting of the late Middle Weichselian ice sheet in Denmark. Danm. geol. Unders., II række, 110, 72 p.

Nye, J.F. 1960: The response of glaciers and ice-sheets to seasonal and climatic changes. Proc. Roy. Soc. London, Ser. A, 256, 559-584.

Nye, J.F. 1963: The response of a glacier to changes in the rate of nourishment and wastage. Proc. Roy. Soc. London, Ser. A., 275, 87-112.

Nye, J.F. 1965: The frequency response of glaciers. Journ. Glaciol., 5, 567-587.

Okko, V. 1955: Glacial drift in Iceland, its origin and Morphology. Bull. comm. geol. Finl., 170, 1-133.

Paul, M.A., and Evans, H. 1974: Observations on the internal structure and origin of some flutes in glaciofluvial sediments, Blomstrandbreen, north-west Spitsbergen. Journ. Glaciol., 13, 393-400.

Price, R.F. 1973: Glacial and Fluvioglacial Landforms. Oliver & Boyd, London, 242 p.

Price, R.J. 1970: Moraines at Fjallsjökull, Iceland. Arctic and Alpine Research, 2:1, 27-42.

Rasmussen, L.Aa. 1975: Kineto-stratigraphic glacial drift units on Hindsholm, Denmark. Boreas, 4, 209-217.

Rist, S. 1967: The thickness of the ice cover of Mýrdalsjökull, Southern Iceland. Jökull, 17, 237-242.

Rist, S., and Thorarinsson, S. 1955: Rannsókn á Kötlu og Kötluhlaupi 1955. Jökull, 5, 32-40.

Sapper, K. 1909: Bemerkungen über einige südisländische Gletscher. Ztschr. Gletscherkunde, 3, 297-305.

Sjørring, S. 1973: Some problems in the drift stratigraphy of the northeastern part of Sjaelland. Bull. geol. Inst. Univ. Uppsala, N.S. 5, 31-35.

Sjørring, S. 1977: The glacial stratigraphy of the island of Als, southern Denmark. Zeitschr. Geomorphologie, N.F. Supp. Bd. 27, 1-11.

Smed, P. 1962: Studier over den fynske øgruppes glaciale landskabsformer. Meddel, dansk geol. Foren., 15, 1-74.

Spethmann, H. 1912: Forschungen am Vatnajökull auf Island und Studien über seine Bedeutung für die Vergletscherung Norddeutschlands. Zt. Ges. Erdk. Berlin.

Stenborg, T. 1968: Glacial drainage connected with ice structures. Geogr. Ann., 50, 25-53.

Thorarinsson, S. 1943: Vatnajökull. Scientific Results of the Swedish-Icelandic Investigations 1936-37-38. Geogr. Ann., 25:1-2, 1-54.

Thorarinsson, S. 1955: Myndír úr jardfrædi Islands III Eldgjá. Nattúurufrædingnum, 25, 148-153.

Thorarinsson, S. 1957: The Jökulhlaup from the Katla Area in 1955 compared with other Jökulhlaups in Iceland. Jökull, 7, 21-25.

Todtmann, E. 1960: Gletscherforschungen auf Island (Vatnajökull). Univ. Hamburg, Abh. Auslandsk., Reihe C., 65, 19.

Waltraud, A., and Brinkmann, R. 1976: Surface Temperature Trend for the Northern Hemisphere - Updated. Quaternary Research, 6, 355-358.

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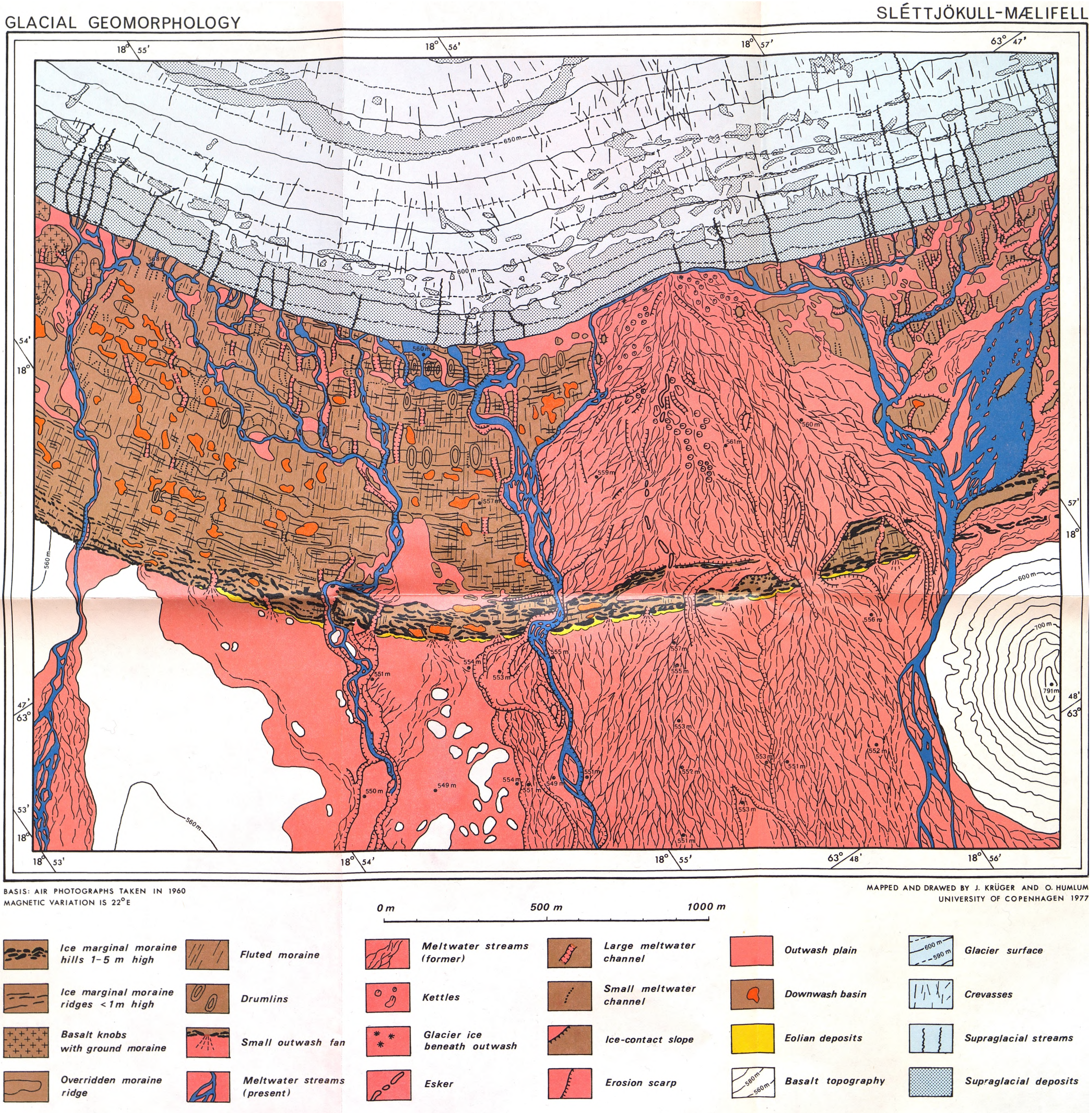
J. Krüger & O. Humlum

ERRATA

The 2 pages 12 and 36
has been interchanged.


GLACIAL GEOMORPHOLOGY
SLÉTTJÖKULL-MÆLIFELL
18° 55'
18° 56'
18° 57'
63° 47'
54'
18°
57'
18°
47'
63°
48'
63°
53'
18°
18° 53'
18° 54'
18° 55'
63° 48'
18° 56'
650 m
600 m
560 m
600 m
700 m
791 m
BASIS: AIR PHOTOGRAPHS TAKEN IN 1960
MAGNETIC VARIATION IS 22° E
0 m
500 m
1000 m
MAPPED AND DRAWED BY J. KRÜGER AND O. HUMLUM
UNIVERSITY OF COPENHAGEN 1977
Ice marginal moraine hills 1–5 m high
Ice marginal moraine ridges <1 m high
Basalt knobs with ground moraine
Overridden moraine ridge
Fluted moraine
Drumlins
Small outwash fan
Meltwater streams (present)
Meltwater streams (former)
Kettles
Glacier ice beneath outwash
Esker
Large meltwater channel
Small meltwater channel
Ice-contact slope
Erosion scarp
Outwash plain
Downwash basin
Eolian deposits
Basalt topography
Glacier surface
Crevasses
Supraglacial streams
Supraglacial deposits

Pl. 1.