GEOLOGINEN TUTKIMUSLAITOS

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N:o 170

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ITS ORIGIN AND MORPHOLOGY

BY

VEIKKO OKKO

WITH 35 FIGURES AND ONE TABLE IN TEXT.
32 FIGURES IN PLATES I—XVI

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Helsinki 1956. Valtioneuvoston kirjapaino

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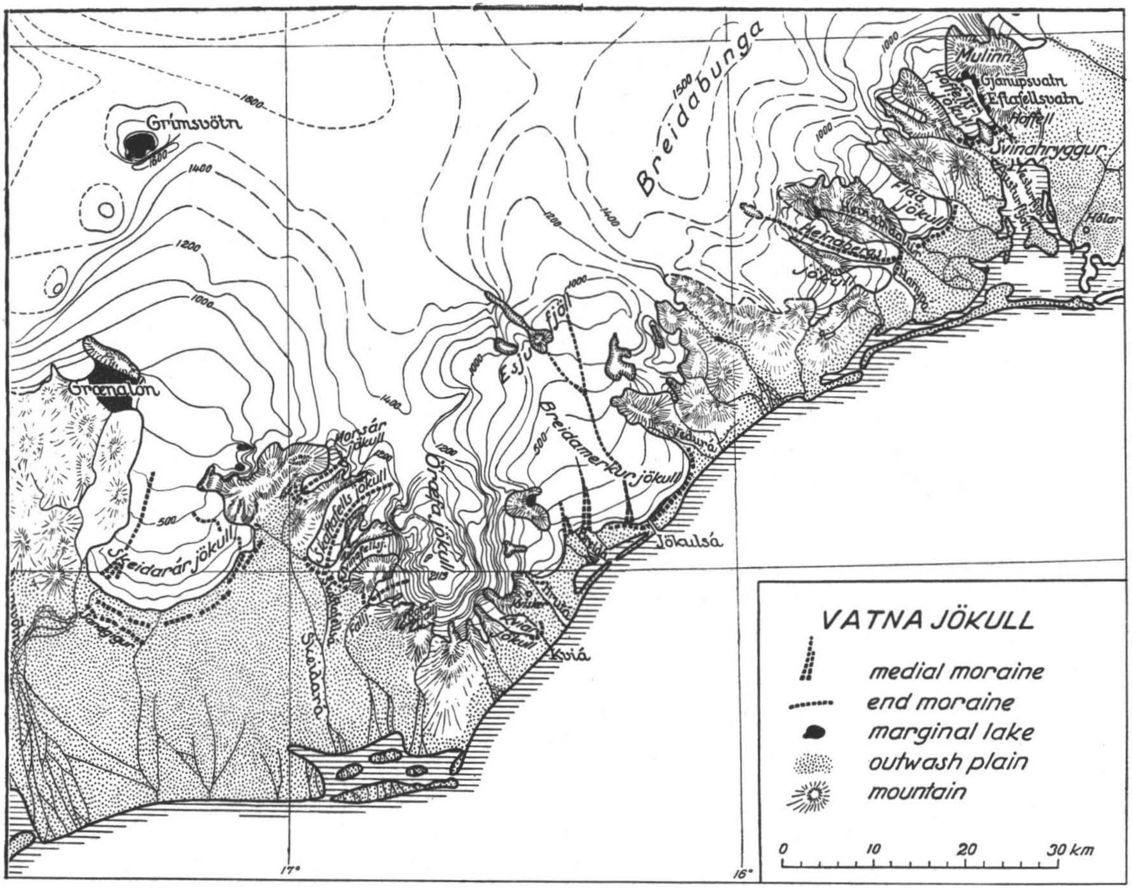

Fig. 1. The southern part of the glacier Vatnajökull. Compiled after various sources (Ahlmann 1937 c, Hjulström 1954 b, the topographical map sheets).

ACKNOWLEDGMENTS

In studying geography and geology at the University of Helsinki under the direction of my esteemed teachers Prof. Väinö Auer and Prof. Matti Sauramo, I learned to appreciate the importance of the work done by glaciers in building up the land surface and forming the landscapes of Finland. My understanding of the matter deepened upon my joining the staff of the Geological Survey of Finland, in the Department of Sedimentary Deposits, headed by Dr. Esa Hyyppä. I am profoundly grateful to my teachers for opening my eyes to see wonders created by Nature.

My knowledge of glacial morphology I was able to broaden on trips to northern Norway, Sweden and Denmark. In 1949 the Cultural Fund of Finland and the Emil Aaltonen Foundation awarded me grants to study the marginal zones of the existing glaciers of Iceland. I take this opportunity to express my appreciation. I set off on my journey in June of the same year and returned at the end of August. The main goal of my journey was the southern margin of Vatnajökull, but in addition I had an opportunity to acquaint myself also with the margin of Langjökull, terminating in the interior of the island, at Hagavatn.

I owe a debt of gratitude to my Icelandic friends, Sigurdur Thorarinsson, Tómas Tryggvason, Glúmur Björnsson and Helgi Jónasson frá Brennu, who have assisted me in many ways. Thanks are likewise due my splendid guides and hosts, notably Leifur Gudmundsson of Hoffel and Gudjón Jónsson of Flatey, whose contributions to the success of my trip are incalculable.

In the treatment and study of the material brought back with me from my trip, I have been assisted by the Misses Kyllikki Salminen, M. A., Kyllikki Parkkonen and Annikki Parkkonen, of the staff of the Geological Survey. My thanks to all three for work well done! Mrs. Lyyli Orasmaa and Mr. Erkki Halme have lent a hand in illustrating this study: the former has painstakingly done the drawings and the latter made the photographic prints. Some of the photographs are from Mr. Helgi Jónasson's extensive collection. Those who have helped me in my work I have to thank for much.

During the stages of collecting the material and writing I received valuable support from Prof. Risto Niini, who has continued to give me encouragement. To him as well as to my co-worker Miss Marjatta Syvänen, M. A., I wish to express appreciation for many fruitful discussions and much good advice.

After the completion of the manuscript, Prof. Väinö Auer read it through, making a number of pertinent observations and corrections. He has continued to follow with interest the progress of the work. I am indeed grateful to my teacher for his inspiration.

Then, it is my gratifying duty to thank my honored chief, Prof. Aarne Laitakari, director of the Geological Survey, for permitting me to complete my study at the institution and to have it included in its series of publications. I want to acknowledge my obligation to the Geographic Society of Finland, moreover, for accepting this work for inclusion in its Acta Geografica series.

Mr. Paul Sjöblom did the English translation under pressure to meet the publication deadline, for which I want to make known my appreciation.

Finally, I wish to thank the Emil Aaltonen Foundation for a second grant, with which it helped to carry this study through.

Helsinki, November 1955

Veikko Okko

INTRODUCTION

As a result of the effective glaciological research carried out in recent decades, it has become clear that the glaciers of today are geographically »living» entities, whose ice masses are continually being regenerated. From the glacier's *firn* or *accumulation area* the ice flows to the *ablation area,* bringing new ice to take the place of melting ice. If the annual accumulation and ablation are of equal magnitude, the *regimen* of the glacier remains in *balance;* but if the ablation exceeds the accumulation, the balance becomes negative. The regimen of a glacier is naturally reflected also in its other activity, such as the velocity of the glacier movement and the position of the glacier margin. Inasmuch as these factors affect the erosion, transport and deposition action of the glacier, its regimen must also be evident in the stratigraphy and forms of the glacial accumulations resulting from this action. On the other hand, it is to be expected that local conditions as well, such as the topography and quality of the glacier floor, add special features to glacial action, which emphasize the individual geomorphological behavior of each glacier.

The material transported by glaciers, considered in general, is herein termed *glacial drift.* According to the terminology of R. F. Flint, which the present author aspires to adhere to, »glacial drift embraces all rock material in transport by glacier ice, all deposits made by glacier ice, and all deposits predominantly of glacier origin made in the sea or in bodies of glacial meltwater, whether rafted in icebergs or transported in the water itself» (Flint 1947 p. 102). In addition to mineral matter, the present author includes under the term of glacial drift also the organic matter in transport by glacier ice, although its share, alongside that of mineral matter, is slight.

Thus understood glacial drift includes two parts: 1- the *load* being carried by the ice, and 2- the *deposits* formed therefrom but already freed from the ice. Load travels toward the glacier margin *superglacially, englacially* and *subglacially,* and its position in the ice varies during transport. Already during the transport stage glacial drift forms morphological accumulations on the glacier surface, e. g. surface moraines, which sometimes are called *active moraines* to distinguish them from *inactive moraines* freed from the ice. Part of the glacial drift is subject already in the moving glacier to *glacifluvial action*. This treatment takes place both on the glacier surface and, especially, under *subsurficial* conditions. It is often difficult to decide whether the subsurficial meltwaters flow along englacial or subglacial channels to the glacier margin. Upon being subject to the action of flowing water, glacial drift freed from ice is washed and sorted. It often forms its own accumulations, *glacifluvial deposits;* but sometimes glacifluvial material is contained quite abundantly in accumulations of glacial drift, or *moraines*, created by the direct action of the glacier. The prevailing material of moraines is usually, however, unsorted, unwashed and firm *till*. Inasmuch as the division of the material does not follow the morphological grouping of the formations, the present author joins Flint (1947) in regarding moraines as the morphological accumulations of glacial drift, alongside which glacifluvial deposits constitute another morphological accumulation category.

The treatment of glacial drift and the forms coming about as a result of it are at present under way in the marginal zones of the glaciers. In this respect Iceland is one of the best investigation areas. Glacial drift travels along with the ice to the glacier margin, where it becomes detached from the ice and forms various accumulations of drift, which numerous investigators have described. At the same time, the present formations of glacial drift in Iceland have been compared with those occurring in old glaciated areas. Already the classical studies of Torell (1857), Helland (1882), Keilhack (1883), Ussing (1903) and Thoroddsen (1905—06), brought the *sandurs* and *end moraines* of Iceland into scientific literature; and their counterparts were discovered in e. g. the glaciation area of Scandinavia. Later the marginal formations of Iceland were compared with e. g. the Salpausselkä ridges of Finland (Leiviskä 1928) as well as the marginal formations of North Germany (Woldstedt 1937, 1939). The glaciological features of the Icelandic glaciers did not become known, however, until the Swedish-Icelandic expedition published its investigations (Ahlmann and Thorarinsson 1937, 1938, 1939, 1940, 1943). It is against this glaciological background that the glacial drift collecting on the major glaciers of Iceland will be scrutinized in the following, including its transportation, its treatment at the glacier margin and its various accumulations. The material, structure and morphology of drift accumulations are placed in a causal relation to the general action of glaciers and from this basis a genetic grouping of the formations is arrived at. Finally the observations and conclusions made are compared with the results obtained in the study of other glaciers.

There is reason to underscore the fact, however, that the glaciers of Iceland are in a stage of rapid melting (Thorarinsson 1940) and the detailed features of their margins are constantly changing. As the observations presented in the following date back to 1949, it is probable that certain of the places described are by now different in appearance from what they were then, although no changes have taken place in the behavior of the glaciers.

THE EXISTING GLACIERS OF ICELAND

THE CONDITIONS OF GLACIERIZATION

The island of Iceland is one of Europe's most glaciated areas (Fig. 2). The island is built up of young volcanic rocks and their erosion products (Thoroddsen 1905—06, Pjeturss 1910). These rocks are generally soft, easily erodible, and they disintegrate from the effect of mechanical weathering. Consequently, exogenetic processes have left visible traces on the relief of the island. Glaciers and rivers have eroded valleys running toward the coast and along this coast there has evolved at an elevation of about 100 m a coastal plain, or *strand flat*, terminating in a precipitous cliff (Hjulström 1954 b). It continues under the sea to a depth of about 200 m,

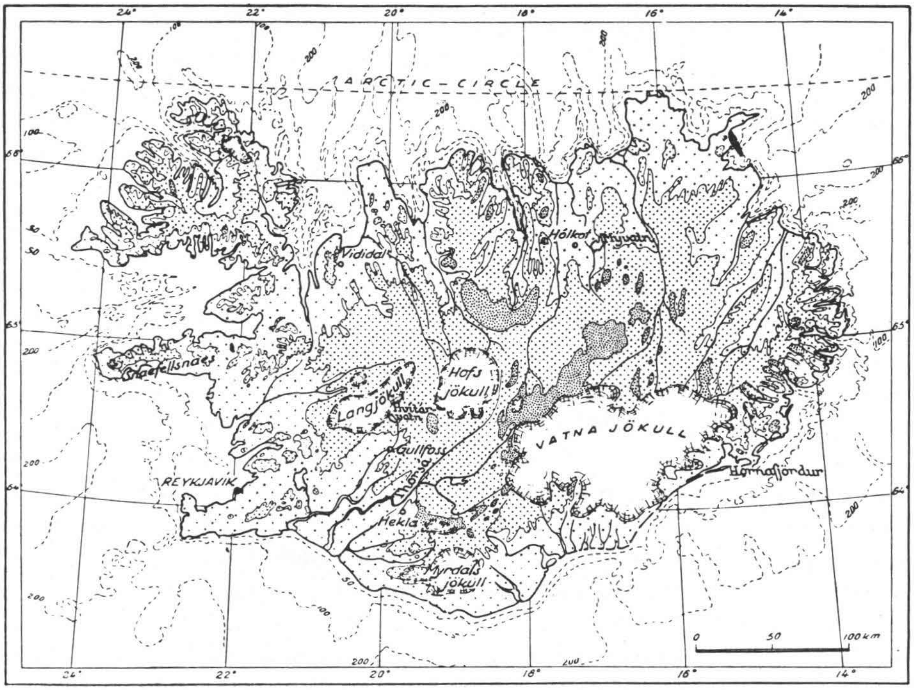

Fig. 2. The island of Iceland with its relief in rough and largest glaciers. Compiled from various sources.

as is to be noted e. g. in submarine contours. The strand flat (as the coastal plain is termed by Scandinavian geographers) is broadest along the southern and southwestern coast, whereas along the steep northeastern and northern coast it is narrow and broken.

The interior consists of a highland, varying in relief, with an elevation of 400—800 m above sea level. It is built of lava and tuff beds and their erosion products, and its surface is broken by tectonic fractures, which are clearly to be seen in the plantless highland landscape. A third elevation zone rising above the highland, consists of volcano cones and plateau horsts. Such eminences are scarce in the northern and central parts of Iceland, but in the southern part of the island they increase in number to the extent of forming a continuous mountain group beyond the strand flat, the tallest peak of which is over 2 100 m high. This mountainous barrier blocks the moist winds blowing from the Atlantic and forces them to rise. At the same time the moisture carried by them condenses and falls on the high southern part of the island in the form of snow. The interior and northern parts of Iceland, on the sheltered side, receives much less precipitation, for the north winds blowing from the Arctic Ocean seldom reach the island because the southwestern weather front usually extends over Iceland. The annual precipitation of the interior averages only 500 mm, as compared to 870 mm at Reykjavík (Thorkelsson 1946 p. 7) and 1 300 mm along the southern strand flat. On the northern side of the latter area an annual precipitation of as much as 3 000 mm has been measured on the glacier (Ahlmann 1939 a p. 50). Inasmuch as the greater part of the precipitation takes place in the winter months (Thorkelsson op. cit.), snow accounts for most of the total in the mountains and the interior. A continued accumulation of snow is possible only on the slopes of volcanoes and plateau horsts, which extend above the climatic snowline. This snowline was situated in 1936 in southern Iceland at an elevation of about 1 100 m, from which it rose to its maximum of 1 450 m in central Iceland. From there the snowline descended northward, being at about 1 000 m in North Iceland; and its lowest elevation of 700 m it reached in the northwestern part of the island (Ahlmann 1937 c p. 228). As above the snowline remain scattered and relatively small areas, which furthermore are situated far apart, the territory covered by ice is divided into several different glaciers.

THE ICE CAPS OF VATNAJÖKULL AND LANGJÖKULL

The present glaciers of Iceland cover an area of approximately 11 100 km², or 11.5 % of the total area of the island (Thorarinsson 1943 p. 18). Many of them are small valley glaciers on the northern slopes of mountains.

In addition, there are a few ice caps on the island characterized by a central dome formed on an elevated floor. Surrounded by a lobate margin, this dome either undulates gently or then rises evenly toward the center from every side (Ahlmann 1937 b p. 203). The largest ice caps are Vatnajökull, Hofsjökull and Langjökull, of which the firstmentioned is situated in the southern part of the island and the other two in the interior (Fig. 2 p. 9).

Vatnajökull comprises over 70 % of the glacierization area of Iceland and it covers 8 410 km² (Thorarinsson 1943 p. 17). Measured on the map (Fig. 2) the length of the glacier W—E is about 150 km and N—S about 100 km. The map (Fig. 1 p. 4) shows the highest part of the glacier to extend about 2 000 meters at the southernmost end of Vatnajökull, where the main ice dome connects with Öræfajökull, covering the upper slope of Iceland's highest mountain. The central ice plateau of Vatnajökull, extending across its northern end, is situated 1 300—1 800 m above sea level. Its highest points consist of two centers, of which the eastern one reaches an elevation of 1 400 and the northwestern one 1 800 meters. These centers are separated by a low, broad depression oriented N—S. At the southern end of the ice plateaus the relief becomes irregular and numerous nunataks pierce the surface. The topography of the floor divides Vatnajökull into several connected parts, each of which has its own outlets. The largest of Vatnajökull's subsidiary glaciers projecting southward are the following (Thorarinsson 1943 p. 17): Skeidarárjökull 1 722 km², Breidamerkurjökull 1 266.5 km², Heinabergsjökull 274 km², Fláajökull 244.5 km², Hoffelsjökull 312.5 km². Their outlets take the form of long ice tongues extending from the central plateau to the strand flat and their termini spread out in the form of round-curved expanded feet. The best developed are the expanded feet of the largest outlet glaciers of Skeidarárjökull and Breidamerkurjökull, the length of the margins of which are about 30 km. The profile drawn on the basis of seismic soundings (Fig. 3) gives a conception of the cross-section of Vatnajökull at the point of Breidamerkurjökull (Eythórsson 1953 p. 650). The expanded foot, according to this source, is 470 m thick at the center and its base reaches below sea level. The ice dome situated be-

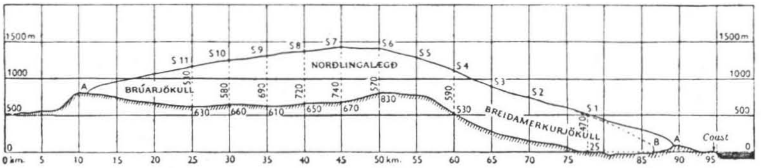

Fig. 3. A cross-section of Vatnajökull through Breidamerkurjökull, based on seismic soundings. The glacier surface is drawn after the topographical maps, while the dashed line shows the position of Breidamerkurjökull in 1951. By courtesy of J. Eythórsson (1953).

hind the outlet rests on a fairly flat base 800—900 m above sea level. The average thickness of the ice sheet there is 500—700 m, the extreme values at the measurement points being 1 014 and 360 m.

Between the five major outlets there remain numerous ice tongues resembling valley glaciers (e. g. Morsárjökull, Skaftafellsjökull and Kviárjökull), which terminate either at the edge of the strand flat or the valley hollowed out of the highland slope. Similar tongues of ice project outward also from the eastern margin of Vatnajökull, forming a »*Zungenrand*» (Spethmann 1912). Only in the north and in the west does the glacier margin rest on a relatively even floor. The ice tongues grow shorter there, taking the form of broad, curved lobes, which terminate in the highland already at 700 m above sea level. Spethmann (op. cit.) uses the term »*Lappenrand*». Simultaneously, the glacier receives a regular form: its surface is steepest in the marginal zone, from which the gradient decreases toward the center of the ice cap.

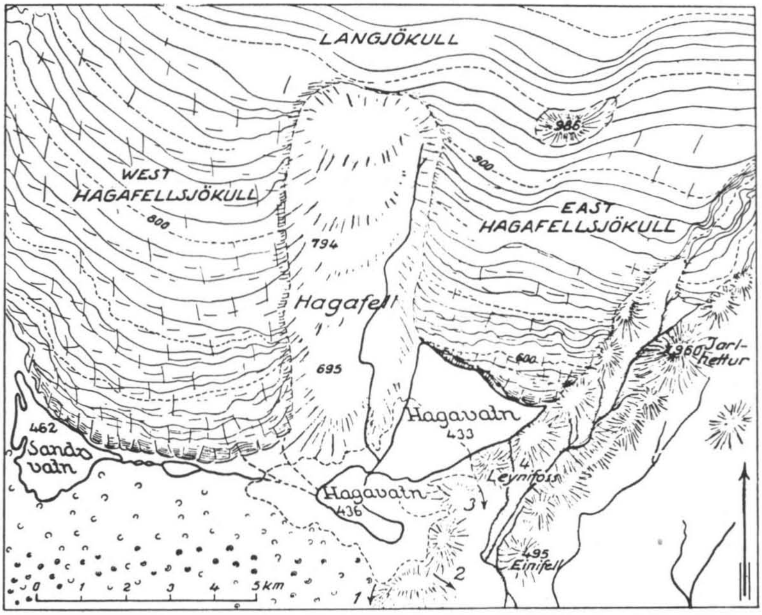

Fig. 4. Hagafellsjökull and Hagavatn at the southern end of the glacier Langjökull. The sketch is drawn according to the topographical map sheet No. 46, but modified after various sources (Wright 1935, Thorarinsson 1939 c). The dashed line around lake Hagavatn indicates the shoreline before the outburst in 1939. The outlets of the lake are indicated by arrows.

The ice mass of Langjökull (Thoroddsen 1905—1906, Bárdarson 1934) fills a valley about 75 km long and oriented NE—SW in the western half of the interior of Iceland. There are a few local glaciations in the mountains, over 1 000 m high, around this valley, of which Geitafellsjökull, attached to the SW part of Langjökull, extends about 100 m above the surface of the main ice dome, or to an elevation of 1 400 m. In the firn area of the main glacier there are two ice domes, the regular shape of which and the lack of nunataks indicate either thick ice or an even base, or both.

The ice tongues of Langjökull are generally short and broad and terminate in the highland at an elevation of 900 m above sea level. Only at a few points do they resemble broad valley glaciers. One of them extends as a twin projection into Lake Hvitárvatn, the surface of which is 419 m above sea level. At about the same level there terminates also the bi-lobal Hagafellsjökull, projecting out of the southern margin of Langjökull (Fig. 4). Its western lobe forms a round-edged arc in the highland valley, while the eastern lobe terminates in Lake Hagavatn, situated at an elevation of 433 m.

Generally speaking, the outlet glaciers of Langjökull are shorter than those of the southern margin of Vatnajökull and terminate at a higher elevation. They resemble most nearly the broad lobes at the northern margin of Vatnajökull.

THE REGIMEN OF THE GLACIERS

The regimen of Vatnajökull is known largely on the basis of the investigations carried out by the Swedish-Icelandic expedition in the eastern part of this glacier in 1936—38 (Ahlmann 1937, 1938, 1939, 1940 and Thorarinsson 1937, 1938 b, 1939 and 1943). It was proved that Vatnajökull ranks among extremely active glaciers.

Its activeness is exhibited in its heavy accumulation of snow above the climatic snowline, rapid melting below this line and swift ice flow from the central area to the margins. In the southern parts of Hoffelsjökull the climatic snowline is situated about 1 050 m above sea level. It divides the glacier in such a way that the accumulation area is 1.7 times as large as the ablation area. Though the accumulation area annually collects snow in abundance, the wastage in the ablation area exceeds even this intake. In the budget years 1936—37, 1937—38, 1938—39 the annual loss averaged 94 million m^3 of water. The glacier thus has a negative bilance. As a result, the glacier is at present shrinking. The wastage of the ice takes place chiefly as surface thinning, for the glacier margin has retreated on e. g. Hoffelsjökull relatively little in recent decades, though the glacier is known to have simultaneously become appreciably thinner. The annual ablation reaches a maximum (over 1 000 cm/annum) on the snout of the outlet terminating at an elevation below 100 m, but the wastage of ice is also promoted by calving of the glacier in the ice-dammed lakes along the sides of the outlet (Fig. 5).

The heavy accumulation causes a rapid movement of the ice from above the snowline toward the glacier margins. The effect of the glacier motion begins to be evident already in the accumulation area, where at the starting points of the outlets broad, spoon-shaped depressions are created in the surface of the ice cap. Toward the intake of the ice tongue the velocity of the motion increases and transversal crevasses open up on the surface; farther downstream these crevasses close. The glacier flow has proved to be most rapid at the neck of the outlet, which on Hoffelsjökull is situated about 500 m above sea level and about 7.5 km from the terminus.

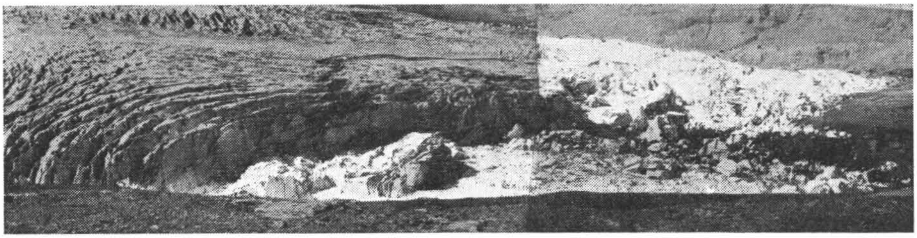

Fig. 5. Ice-dammed lake Gjánupsvatn after its drainage. The ice barrier (left) is broken and ice blocks fill the lake bottom. The black stripe in the ice (center left) is a volcanic ash layer. The ice wall is 10—15 m high.

Already at this point the surface of the outlet has become convex and since the transversal profile of its base is evidently concave, the ice body is thickest around its central line, where its surface flow is likewise most rapid. The maximum velocity of the surface of Hoffelsjökull, as measured in 1936, was 1 770 m/annum, but the velocity varies from year to year. E. g. the maximum velocity of the surface layer of the glacier measured in the summer of 1937 was 211 and in the summer of 1938 only 138 cm/day. The differences in the velocity of flow derived from fluctuations in accumulations, inasmuch as in 1938 the total was 30 % less than the year before. If the annual excess in certain years falls below average, the pressure is reduced and the glacier flow becomes slower. An above-average accumulation, again, makes the glacier flow faster and possibly causes an advance of the ice front.

Below the neck the flow of the glacier begins to slow down. This does not, however, take place evenly, but the velocity of flow depends also on the slope of the base. Downhill the ice advances so rapidly that its surface cracks or ruptures into ice cataracts. Below the drop the ice grows solid again. According to Thorarinsson's measurements the surface layer of

Hoffelsjökull moves at an average velocity of 15 m/annum 40 m from the snout. The terminus has thus become almost stagnant.

The regimen of the other parts of Vatnajökull to the south correspond to that of Hoffelsjökull. This is indicated e. g. by the fact that regardless of differences in shape and size there prevails on these subsidiary glaciers nearly the same glacial ratio between the ablation and accumulation areas. This ratio is 1 : 1.7 at Hoffelsjökull, Heinabergsjökull and Breidamerkurjökull, and 1 : 1.8 at Fláajökull; but it changes at Skeidarárjökull to 1 : 2.4 (Thorarinsson 1939 b p.196). Thorarinsson assumes that volcanogenic glacier outbursts account for the deviation (op. cit. p. 194). Inasmuch as these subsidiary glaciers are situated in climatically identical areas, their regimen and activity correspond. The subsidiary glaciers are in other words exceedingly active and their margins tend to move readily, as the results of measurements carried out in recent years show (Eythórsson 1949 b).

The regimen of Langjökull is not so well known as that of Vatnajökull. The climatic snowline there is relatively high, in the southeastern part of Langjökull being at an elevation of about 1 175 m (Ahlmann 1937 c p. 218). Judging by this, together with the shape and size of the ice tongues, the annual accumulation on Langjökull is smaller per unit area than in the southern part of Vatnajökull. As the pressure pushing the ice outward is thus correspondingly smaller, the ablation area is narrow and the ice tongues are shorter. The gradient of the glacier margin is thus great and stagnant ice occurs in front of the »living» margin only seldom. It began to form in the 1930's at the sides of the outlets terminating in Hvitárvatn (Nørvang 1937 p. 186). These outlets terminated in the lake as steep ice cliffs, and the glacier wasted away at these points by calving. The same kind of ice cliff occurs also at the terminus of the outlet extending to Hagavatn. This ice tongue earlier extended farther into the lake, covering the sills which divide the lake base. As the glacier margin retreated, one sill after another became exposed from under the ice and the outlet of the lake has shifted several times (Reynolds 1930, Wright 1935, Thorarinsson 1939 b).

In the behavior of the glaciers of Iceland there occur from time to time anomalous changes resulting from the volcanism. The best known of these are the glacier outbursts (*»jökullhlaup»* in Icelandic). They occur as sudden, heavy floods in the rivers fed by the glaciers. The cause of the floods is subglacial eruptions, which melt the ice around the craters. Meltwater forces a way under the ice and bursts forth through openings along the glacier margin, but at the height of a flood the water is discharged in a broad front from under the margin. The margin is thereupon shattered, forming ice walls scores of meters high. Glacier outbursts occur especially on Skeidarárjökull, on the ice plateau of which are volcanic craters (Nielsen 1937, Thorarinsson 1938 a). During the eight-day glacier outburst of 1934 about ten million m^3 of ice broke off the margin of Skeidarárjökull (Thorarinsson op. cit. p. 493) and at the same time 10—15 km^3 of water was discharged by the glacier (Nielsen op. cit.). This glacier outburst was of medium magnitude, according to Thorarinsson's estimate, for most of the glacier outbursts along the southern coast of Iceland wear away the ice the same way. The glacier outbursts recur at such long intervals, however, that the tunnels disappear and the glacier margins recover from the damage in the meanwhile. The effects of glacier outbursts are visible longest on the strand flat, where the masses of gravel and icebergs torn off the glacier margins are carried.

Subglacial eruptions at times also cause a local advance of the glacier margin. This happens when the ice mass cracks from the force of the eruption and the marginal part becomes detached from the glacier proper and slides into an area freed from ice. There it melts in place, because the glacier no longer nourishes it. Such an advance of a glacier margin took place in 1890 on the northern side of Vatnajökull, where the margins of Bruárjökull and Eyabackajökull advanced several kilometers. The glacier thereupon broke up into immense blocks of ice measuring as high as 200 m and at the same time a vast crevasse oriented W—E opened up (Thorarinsson 1938 a p. 495).

The frequent earthquakes occurring in Iceland have not been observed to cause changes in the behavior of the glaciers (Thorarinsson op. cit.). Evidently the thick ice constitutes such a plastic mass that the crevasses possibly opening up during a quake are quickly pressed together again. The ice does not crack at all during minor earthquakes (Nielsen 1937 p. 53). Nor have hot springs been observed to affect appreciably the activity of glaciers either, for the springs cause only a relatively slight rise in temperature at the surface of the earth. Locally, subglacial springs add to the volume of water discharged from the glaciers. As the water from the springs is often hot, it also melts the ice and thereby increases the quantity of meltwater.

Anomalous changes in the activity of glaciers are generally sudden and recur in the same places only after long intervals. Inasmuch as, moreover, they affect only a small part of the glacier at one time, the anomalous changes do not have any important effect on the regimen of the glaciers of Iceland. This rhythm depends on major climatic fluctuations.

As regards the earlier development of the glaciers of Iceland, it is known that the current negative balance has prevailed since the 1890's, when most of the glaciers had reached their maximum size during historical times and several of them perhaps during the entire postglacial period (Thorarinsson 1937 c p. 194, Ahlmann 1937 c p. 198). Before attaining this magnitude, the glacier margins had retreated even beyond their present position. This is indicated e. g. by the fact that the southern outlets of Vatnajökull yield fragments of peat and pieces and stumps of thick birch steams (Pjeturss 1907, Reck 1911, Bárdarson 1934, Ahlmannn 1937). Bárdarson (op. cit.) places them on the level of the postglacial clima optimum, when the areas at present submerged under glacier ice would have been covered with birch forests and swamps. The same outlets also yield chunks of clay and shells of marine molluscs (Thoroddsen 1905—06, Pjeturss 1907, etc.). The mollusc fauna indicates an arctic sea of considerable depth (Pjeturss op. cit.). It may have extended up to the area currently covered by the outlets during either the late glacial period or Interglacial stages, of the latter of which there were either one (Pjeturss 1910) or two, (Nielsen and Noe-Nygaard 1936). The marine limit of the late glacial period is situated in southern Iceland at an elevation of over 100 m (Pjeturss 1901, Thoroddsen 1905—06, Áskelsson 1934, Kjartansson 1939). The shore-line is so weak, however, that its exact position has proved difficult to determine. Distinct shore cliffs have been found so far only at elevations of 40—50 and four meters above sea level (Bárdarson 1910). According to Bárdarson they are the product of marine transgressions, and to the lowermost, or 4 m shore, the sea rose from a level 2 m below the present water line. Thorarinsson finds a parallel to these stages in North Iceland, and in his opinion the 4 m shore corresponds to the younger Tapes-transgression in Norway, while the 40—50 m terraces are Gotiglacial. Iceland represents, according to this investigator, an upheavel area where isostatic reactions to changes in the size of the glaciers take place more rapidly than in Fennoskandia (1951). The Hólkot end moraines, situated some 50 km from the northern coast correspond in age, according to Thorarinsson, to the Salpausselkä-Raerne Stage in Fennoskandia (op. cit. p. 79). During the period of glacierization before it, there were probably ice-free areas on the Icelandic coast (Thorarinsson 1937b p. 174), where plants were able to survive through the last Ice Age. The flora underwent a change during this time, however, for in the interglacial layers underlying the moraine there have been found e. g. *Alnus viridis* leaves, and among the pollen flora of the same layers there is an abundance of alder pollen (Áskelsson 1938, Lindal 1939). The most widely distributed of interglacial deposits consist of shelly clays, which have been met with e. g. at Reykjavík, Gullfoss and elsewhere in western Iceland (Pjeturss 1903, 1905, 1910, Bárdarson 1929 and Thorkelsson 1935). Their distribution indicates that during the Interglacial a large part of Iceland lay under the sea.

GLACIER TRANSPORT

The moving ice transports to the marginal zone various foreign material that in one way or another has become imbedded in the glacier or deposited on the surface of it. Part of this glacial drift consists of glacier erosion products while another part consists of foreign matter deposited on the surface. The latter includes wind-blown material, mechanical disintegration products, and in volcanic regions also ash layers.

The conditions prevailing in Iceland favor the forming of glacial drift. The glaciers are exceedingly active and the ice motion in them is fast. As under the glaciers there are soft and easily erodible species of rock and as the floor formed by them is furthermore in many places uneven, the quality and relief of the floor promote the erosive effect of the glaciers. Material is transported by the ice even more readily in places where it moves over loose deposits.

The conditions also favor the creation of drift on the surface of the ice. The often stormy winds blowing from the sea reach the glaciers freely, but first they must cross the land area surrounding the glaciers. In addition, the glaciers receive their share of the volcanic ash-falls; and, in the event of subglacial eruptions, coarse eruption products are likely to accumulate a top the ice in the vicinity of the eruptions. The uneven relief promotes also the formation of surface drift. From the effect of the relief the margin of the glacier in places receives a *Zungenrand* form and its projections lie tangent to the icebordering mountains. The latter, like the nunataks, are often precipitous. As in the climate of Iceland the mechanical disintegration of rocks is intensive, the surface of the rocks is covered with disintegration products, which slide down the slopes on top of the ice.

The drift participating in the glacier transport is divided by the author into wind-blown detritus, volcanic products, surface moraines, basal load, washed material and crevasse fillings. The classification has been carried out largely according to the manner in which the drift appears in the glacier, but at the same time it observes to a certain extent the grouping based on the origin of the material. The wind-blown detritus and volcanic products have come to the glacier from elsewhere and the glacier has only acted as the receiver of the material; the surface moraines contain in part disintegration products originating elsewhere, whereas the basal load has become formed out of the products of glacier erosion. The washed material includes mainly the washing products of the aforementioned and the crevasse fillings comprise the material accumulated in the glacier crevasses from the same.

In the following it will be shown how these drift materials of different origin occur in the glaciers and what happens to them during transport and what kind of accumulations they form on the ice.

WIND-BLOWN DETRITUS

Wind-blown detritus gathers on the glaciers of Iceland for the most part in the summer time, for then the winds are drier and the terrain around the glaciers is snowless. Moreover, the surface of the glaciers is damp in summer and this promotes the adhesion to the ice of eolian drift.

Eolian drift contains both minerogenic and organogenic detritus, which varies in amount, depending on the quality of the ground eroded. The content of organic matter in a sample taken from the Thorsá river valley in SW Iceland was 9.75 weight per cent, whereas the sample taken from Hoffel in SE Iceland contained 5.12 weight per cent.

Minerogene thus constitutes the main part of the eolian drift. It contains small fragments of volcanic rocks as well as mineral grains detached from the dried surfaces of fine-grained sediments. This material is blown by the wind in such abundance that e. g. the peat layers in bogs include minerogene to the extent of about fifty per cent. According to the studies of G. Jónsson (1930) the surface peat in the bogs of Iceland contains an average of 64.14 % minerogene, while the content in the peats of southern Iceland ranges between 42 and 53 per cent (Emilson 1911). During its transport by wind, the mineral material sorts itself. The prevailing fraction is fine sand, representing by a grain size between 0.5 and 0.02 mm (curves 1 and 2 in Fig. 6, also Emilson 1911, Hörner 1949), but strong winds also blow coarse sand and small pebbles, whereas light breezes blow off the ground only light organic waste matter, together with very fine sand and silt.

The organic component of eolian drift consists of the leaves of plants, pieces from twigs, stalks of grass, seeds, sedge fruits, and other debris. In addition, the organic matter includes pollen and spores from plants. The pollen rain originating from Iceland's present vegetation consists mostly of pollen from *Cyperaceae* and *Gramineae*. Arborous pollen is represented by *Betula* pollen. This may be noted e. g. in two pollen diagrams (Figs. 7 and 8). The one (Fig. 7) has been made from the soil profile at Hoffel, SE-Iceland about 30 m above sea level and the other (Fig. 8) from the swamp at Laugardalur in the vicinity of Reykjavík, SE-Iceland (about 15 m above sea level). The pollen spectra of the uppermost samples in the diagrams represent the pollen rain of the present vegetation at the same time as the diagrams give an idea of the postglacial pollen flora. They show that the flora earlier contained *Betula* pollen in considerably greater abundance than nowadays. In the lowermost part of each diagram the *Betula* again declines and in its place there comes an abundance of *Ericaceae* and *Salix* pollen. Scattered occurrences in diagrams of *Alnus, Corylus, Pinus, Quercus, Tilia,* and *Ulmus* are to be interpreted as of distant origin as it has been shown by Aario in Finnish Lapland (1940, 1943). These trees do not belong to the

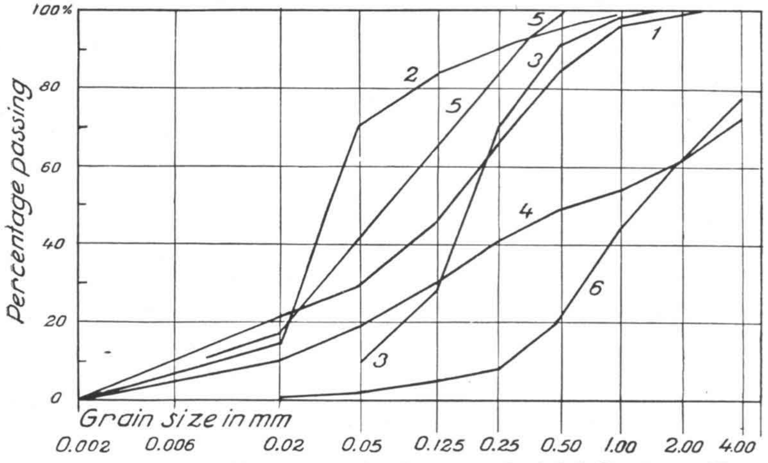

Fig. 6. Grain size distribution in the superglacial drift: Curve No. 1 eolian deposit from Hoffelsjökull, No. 2 the same from Breidamerkurjökull, No. 3 volcanic ash from Breidamerkurjökull, No. 4 basal load from a transversal moraine on Hoffelsjökull, No. 5 washed material from a delta on Hoffelsjökull, and No. 6 sorted drift from a lens in Hoffelsjökull.

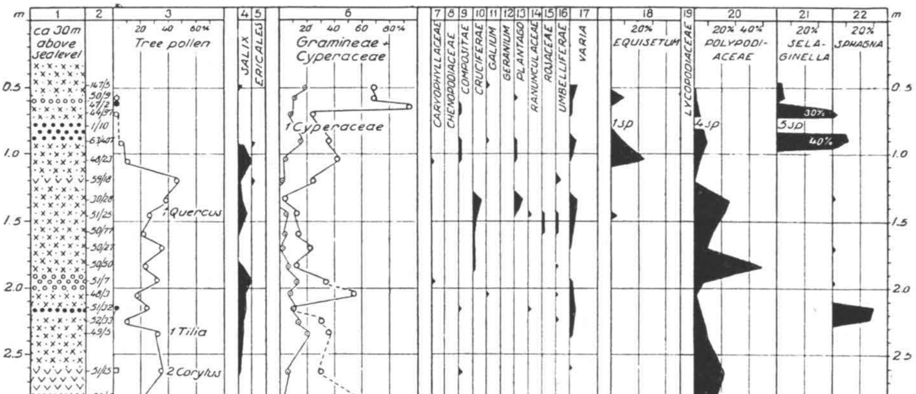

Fig. 7. Profile and analytical pollen diagram from Hoffel, SE-Iceland. The samples are taken from a section at the eastern bank of the sandur valley beneath Hoffels farm. The figures in column 2 indicate the amount of pollen and spores found in each sample. The percentages are counted from the common sum of pollen and spores. All samples are treated with HF.

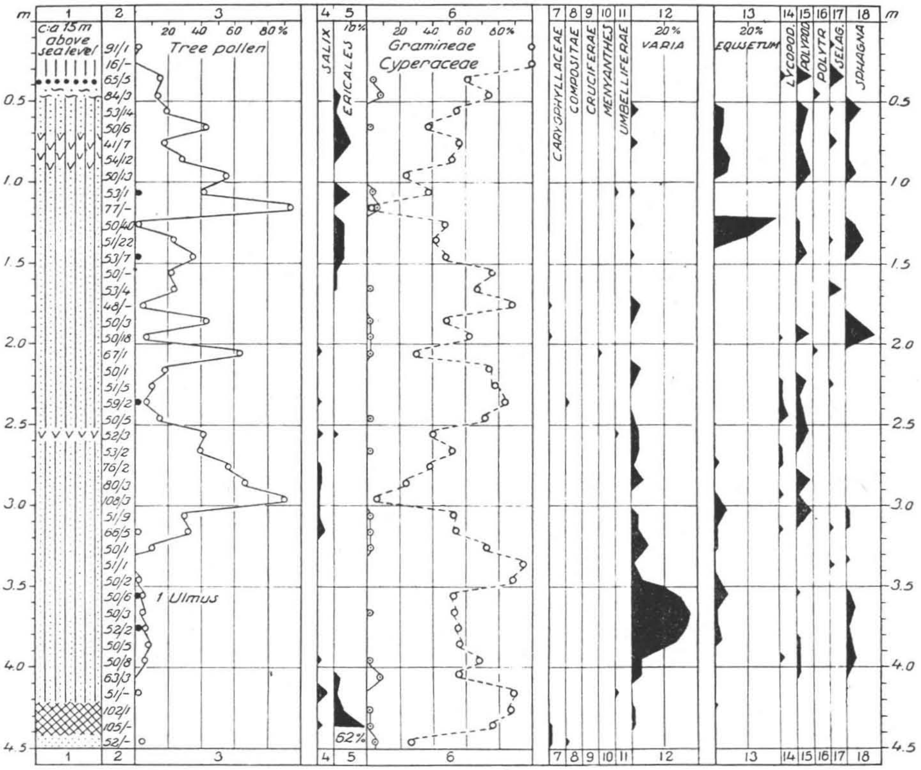

Fig. 8. Profile and analytical pollen diagram from a swamp at Laugardalur, near Reykjavík, SW-Iceland. The symbols used are the same as in Fig. 7. All samples are treated with HF.

present flora of Iceland. — Without undertaking in this connection any dating of the diagrams, we may note in their upper parts the same kind of regularity as in Thorarinsson's (1944) two pollen diagrams. The interglacial pollen flora of Iceland differs from this in that it contains an abundance of *Alnus* pollen. Áskelsson (1938) has investigated two samples from Snaefellsnes, W-Iceland, and Jessen two samples from Vididal, N-Iceland (Lindal 1939). The list of pollen and spores met with is following:

	Áskelsson		Jessen (Lindal)	
	Sample H	Sample K	Sample 1	Sample 2
Alnus	1 %	44 %	5 sp.	43 %
Betula	3 »	—	3 »	35 »
Pinus	4 »	—	—	—
Picea	1 »	—	—	—
Salix	10 »	3 »	—	22 »
Caryophyllaceae	3 »	—	—	100 %

Chenopodiaceae	4 %	—	—	—
Compositae	1 »	1 %	—	—
Cyperaceae	15 »	5 »	—	—
Ericales	18 »	—	—	5 sp.
Gramineae	32 »	46 »	—	40 »
Hippophae ?	1 »	—	—	—
Plantago	1 »	—	—	—
Varia	6 »	1 »	—	6 »
	100 %	100 %		
Dryopteris			—	2 »
Lycopodium			1 sp.	1 »
Sphagnum			—	2 »

In the eolian sediments originating during the postglacial period there are naturally the pollen and spores of the same species of plants as appear in the diagrams presented in the foregoing, but their abundance is affected not only by the vegetation prevailing in the environment but also by the season of the formation of the sediment. If the eolian sediment has accumulated during the early summer it contains in the main pollen from plants blossoming at that season. Thus, the pollen spectra of eolian sediments vary according to the time of year the winds happen to be blowing. The most important observation, however, is that eolian drift continuously gathers on the glaciers of Iceland, with the drift containing not only waste matter but also recent pollen flora. E. g. a sample taken from the dirt cone of Breidamerkurjökull contained the following pollens:

Betula	5
Salix	1
Artemisia-type	1
Caryophyllaceae	1
Cyperaceae	2
Gramineae	5
	15

In addition, 1 *Polypodiaceae* and 1 *Sphagnum* spore were met with.

Eolian drift accumulates practically everywhere on the glaciers of Iceland. It stands out from the white ice and snow by being dark and dirty. In the ablation zone it forms on the surface of the glacier a fairly uniform, if thin, film. The dirt layer is thickest in cracks and hollows in the ice. On level surfaces it fills rough spaces. In winter the surface dirt is likely to freeze onto the glacier, but the thaw of the following summer releases it anew. As new matter gathers on the surface of the glacier each year, blown by the wind and exposed by melting, the amount of surface dirt increases steadily. Simultaneously, the dirt layer moves along with the ice toward the glacier margin.

Besides the loose surface dirt there is to be observed in the ice of the ablation zone dark bands containing eolian dirt. They form with the cleaner ice alternating, almost parallel stripes, which arc in the direction of the glacier margin. Such dirt bands occur in the ablation zones of both the Vatnajökull and Langjökull glaciers. Whenever cracks cut the dirt bands and whenever the glacier margin has been ruptured and become steep, it may be noted (Fig. 9) in the vertical sections that the dirt bands continue into the ice. The bands, in other words, have formed in places where layers of ice containing dirt intersect the surface. These ice layers slope back downward, though their declivity varies. At Skaftafellsjökull the dip of the dirt bands was steepest, or 40—45°, about 200—300 m from the glacier snout; but it became more gentle both toward the end of the ice tongue and the snowline. The gentlest dips varied between 10 and 15° in both directions. A change in dip was observed also when measurements were carried out along the same dirt band. The gentlest positions were obtained in the region of the center line of the ice tongue, while the dip became steeper towards the sides of the ice tongue at the same time as the course of the band turned, following the margin, and finally ended up nearly at right angles to the course, as measured from the center line. Observations indicating the same tendency were also made at Hagafellsjökull.

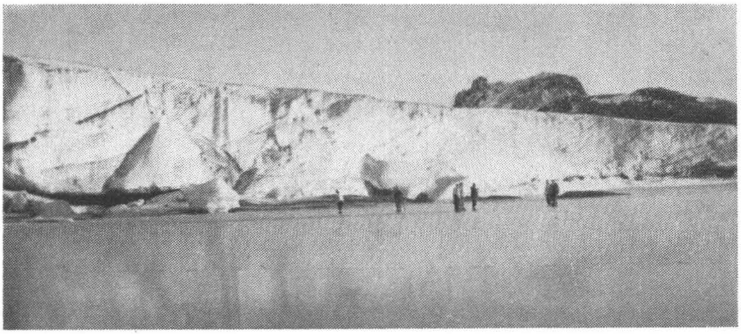

Fig. 9. The front of Hagafellsjökull forms a steep cliff in the lake of Hagavatn, which is covered by winter ice. Englacial drift appears as dark bands in the ice wall. The peak of the mountain Jarlhettur in the background. Photo Helgi Jónasson, 1951.

The strike and dip of the dirt bands on Hoffelsjökull proved to deviate from the foregoing. There, too, gently sloping dirt bands occurred in the glacier snout, oriented in the direction of the margin and inclined upstream. Their dip varied greatly, however, and the bands occurred brokenly. This was because the glacier had broken up into blocks of ice, which had evidently moved in relation to each other, causing breaks in the dirt bands. Deformation of the dirt bands was also noted at Morsárjökull, where the glacier breaks off in chunks from the top of a precipice, forming a heap of ice at its foot. As a result, the dirt bands that previously had run parallel are broken up and their dip turns every which way. Furthermore, new dirt (as well as winter snow) gathers in the openings between blocks of ice, adding to the diversity of the ice breccia.

The amount of eolian drift varies in each individual dirt band, just as on the surface of the glacier. At times the dirt occurs as such weak impregnations that it promotes melting of the ice so that the surface of the glacier becomes depressed where it contains dirt. Usually, however, there is so much dirt that the layer of it melted free of the ice retards the melting of the ice underneath. The band thereupon becomes prominent on the surface of the glacier as a sharp, dark, ridge-like formation. Such dirt ridges rose on the southern outlets of Vatnajökull a maximum of a meter above the glacier surface. The surface of the dirt ridges consists of a loose layer of drift melted out of the ice, and from it the dirt spreads over the ice surrounding the band.

Both in the Alps (Vareschi 1935, 1937, 1942) and in Alaska (Heusser 1954) pollen analyses have revealed that the substance of the dirt bands consists of eolian sediment embedded in the ice. Quite evidently, eolian matter is deposited in summer on the surface of the accumulation area and is then covered with snow, thereafter becoming buried in ice. Such layers are transported along with the ice to the ablation area, where they become exposed as bedded bands in the melting ice. The eolian sediment thus brought up anew to the surface and freed from the grip of the ice moves with it until the movement of the glacier stops. Simultaneously this surface drift »riding» on top of the ice promotes roughening of the surface by in places retarding and in other places accelerating the melting of the ice.

The same kind of movement of eolian drift occurs when dirt gathers in crevasses and depressions in the ice. The transversal crevasses occurring at the climatic snowline likewise collect dirt. When the crevasses close up, the accumulated dirt becomes embedded inside the ice and forms bands and lenses. Corresponding gathering of dirt also occurs in the crevasses of the ablation area. Only the dirt accumulating in the open radial crevasses of the glacier terminus no longer becomes embedded within the glacier.

The dirt cones (Fig. 1, Plate I) occurring on the eastern part of the glacier snout of Breidamerkur, the eastern margin of East Hagafellsjökull and Hoffelsjökull were conceivably created by the dirt collecting in cracks. Such cones are formed upon the melting of dirt lenses in the ice and are often situated apart from the dirt bands proper. When such a dirt lens comes to the surface as a consequence of melting, it prevents the ice underneath from melting, whereupon the area containing dirt becomes covered with a melted layer of dirt and there forms a sharp-pointed ice pyramid (Spethmann 1908, Wilson 1953).

VOLCANIC PRODUCTS

On the volcanic island of Iceland some 30 eruption centers are known that have been active during historical times. In addition there are countless ancient craters on the island. The number of eruptions exceeds the number of craters many times over, as the eruptions often occur in the same centers. E. g. Hekla is known to have erupted 23 times since Iceland was settled (Thorarinsson 1944). During an eruption the vicinity of the crater becomes covered with various eruption products. There is a rain of ejectments, especially during the initial stage on an eruption, when the atmosphere often becomes filled also with volcanic ash. It spreads out from the eruption center with air currents in the direction of prevailing winds, forming a fanlike pattern upon raining down, the tip of the extended fan being at the eruption center. As the winds in Iceland most generally blow from the southwest or south, most of the sectors of ash falls open to the northeast, north and east. The volcanic ash is sorted when blown by the wind in such a way that the coarsest and, in part, also the heaviest material falls closer to its source than the fine silicate dust (Thorarinsson op. cit. p. 87). The latter material has been observed to travel thousands of miles, for volcanic ash from Hekla has been blown as far as Finland (Salmi 1948). In the soil profiles of Iceland volcanic ash layers may be seen in the form of horizontal bands lying one on top of another. As volcanic activity occurs mostly in the southwestern part of the island, the western and central areas of Iceland most often receive ash falls. Moreover, the ash layers in those areas are thicker and contain coarser material than in the eastern part of the island. At Skallakot, which is situated about 20 km NW of Hekla. Thorarinsson has found 14 ash layers in the soil profile (op. cit. p. 50), whereas in the Hoffel profile (Fig. 7 p. 20) there are six ash layers and in the Laugardalur profile (Fig. 8 p. 21) there is only one.

Volcanic products accumulate also on glaciers. For the most part, they consist of sorted ashes, as coarse eruption products are deposited on the ice only in the vicinity of subglacial eruption centers. When Grimsvötn erupted in 1934, volcanic gravel was deposited, according to an estimate by Nielsen, to a thickness of 20—25 m in the vicinity of the eruption center in Skeidarárjökull. Since it was hot upon falling onto the ice and cooled down slowly, the gravel melted the ice underneath and remained snowless. Only after cooling down, the gravel was covered with snow and became embedded in the glacier (Nielsen 1937). During the same eruption volcanic ash fell also onto the eastern and central parts of Vatnajökull, but it formed on the ice a thinner and finer-grained layer, the ash of which had cooled down already during its transport through the air and was quickly buried under snow (Ahlmann and Thorarinsson 1939 a p. 39). At Hoffelsjökull Thorarinsson estimated that during the past 1 000 years only 5 cm of volcanic ash has fallen (Thorarinsson 1939 b p. 213).

Volcanic ash acts on the surface of a glacier like eolian drift. In the accumulation area it becomes buried under snow and imbedded within the ice, and in the ablation area it forms on the surface of the ice a loose, dark layer, which becomes subject to the action of rain and meltwaters. In ablation areas also layers of volcanic ash deposited in accumulation areas come into view again, when they form broad stripes on the surface of the ice, recalling dirt bands. The ash layers wind parallel to the glacier margin in dark belts, and they stand out already at a distance from the lighter surface of the ice between them. Such ash belts were photographed by Palmi Hannesson in 1938 at Skeidarárjökull (Thorarinsson 1944, p. 122). Similar dark ash belts were seen also in 1949 on the surface of both Skeidarárjökull and Breidamerkurjökull. These ash belts were transported slowly along with the ice toward the glacier margin. An ash belt forms on a glacier at a place where an ash layer buried in the ice meets the surface. Like dirt bands, these layers dip down backwards. In broken up parts of a glacier the ash layers are also deformed (Fig. 5 p. 14).

With the melting of the glacier surface the volcanic products become detached. The ash band extending up to the surface is thereupon covered with a loose ash layer, which retards the melting of the ice underneath so much that the ash belt is raised above the surrounding surface. There form crests and pyramids of ice covered by ash, remindful of the surface formations of eolian drift. From the steep slopes ash is washed into hollows on the glacier surface. At the same time the volcanic matter becomes mixed up with eolian and other surface drift. Thus e. g. the ash cone occurring on the surface of Breidamerkurjökull contained 0.24 % organic matter. The sorting and grain size of the ash are revealed in Fig. 6 p. 20.

The share of volcanic products in the drift varies in the glaciers of Iceland both in respect to time and place. They occur most abundantly in the surface drift of ablation areas when the layers formed in the accumulation areas reach the glacier margin, yielding there the material contained in them. Locally, volcanic products are mostly met with in the western part of Vatnajökull and there on the ice tongue of Skeidarárjökull. With the exception of the coarse eruption products heaped around subglacial eruption centers, the volcanic products accumulated on the glaciers of Iceland are sorted. The grain size ranges from coarse to fine sand. These deposits usually contain more coarse material than eolian drift, which they resemble in many ways.

SURFACE MORAINES

By surface moraines are herein meant accumulations of glacial drift occurring on the surface of a glacier that have a certain form and trend. Their material is for the most part unsorted. Surface moraines are classified as medial, lateral and transversal.

Looked at from the air, there can been seen on the southern outlets of Vatnajökull dark belts running downstream. These belts, at times winding and at times directed at right angles toward the ice margin, are medial moraines (Fig. 1 p. 4). According to the maps, medial moraines occur on most of the southern outlets of Vatnajökull. All the starting points of the medial moraines are situated below the elevation of 1 000 m, or below the climatic snowline. The majority of the medial moraines start from nunataks or come to the glacier surface immediately below them. Some medial moraines, however, such as those of Skeidarárjökull, Morsárjökull and certain ones of Breidamerkurjökull appear on the glacier at spots where outcropping rocks are lacking. Many medial moraines proceed in a fairly straight line from their point of departure to the glacier margin, but some (those of Skaftafellsjökull and Morsárjökull) arch out, following the outlet lengthwise, while others wind considerably (the easternmost medial moraine on Skeidarárjökull).

The situation of the medial moraine on the glacier surface determines the point of departure. If the starting point of a medial moraine is situated approximately on the center line of an ice tongue, the moraine runs along the center of the tongue to the glacier margin (the medial moraines of Morsárjökull, Breidamerkurjökull and Heinabergsjökull). If, again, the medial moraine begins at one side of the outlet glacier, it advances also along this side (e. g. the medial moraine of Skaftafellsjökull runs from the nunatak east of the center line, remaining just about equidistant between the lateral side of the glacier and its central line). The two largest medial moraines of Skeidarárjökull are situated in such a way that one runs near the western margin and the other near the eastern margin of the outlet. The former divides at its lower end into branches, spreading out fan-like apart from each other and terminating within the bounds of the glacier.

The medial moraine of Heinabergsjökull is likewise marked as terminating before reaching the glacier margin. In 1949 this medial moraine extended as far as the glacier margin (Fig. 10), but the margin at the time was 450 m farther back than is shown in the map (Eythórsson 1949 b). With these exceptions, the medial moraines carry their material up to the glacier margin. For most of the distance they are relatively narrow moraine belts and they spread out, like on open fan, only at the margin of an outlet.

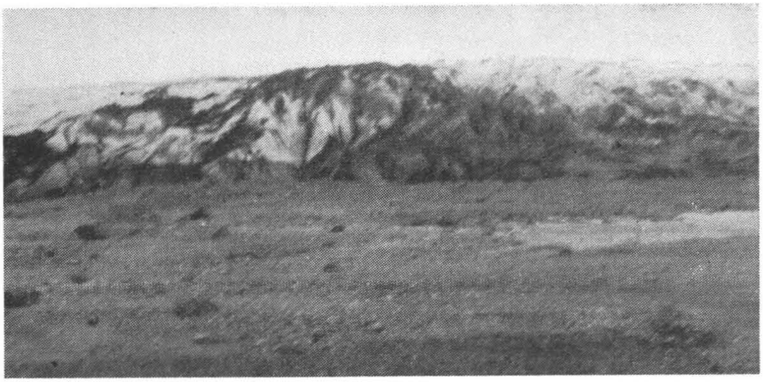

Fig. 10. Radially crevassed terminus of Heinabergsjökull bears a dark medial moraine on its surface. White clean ice comes into sight in crevasse walls. In front of the glacier an ablation moraine.

Thus the medial moraine, which is the longest in Iceland, running along the center of Breidamerkurjökull to the glacier margin, starts as two narrow branches from the nunataks of Esjufjöll. The branches join at an elevation of about 500 m, forming a moraine belt over 10 km long and 250—200 m broad. It begins to widen out about four km from the glacier margin, and a km away it is already 1.2 km broad. Toward the margin of the glacier the width of the medial moraine expands rapidly and it reaches the margin on a front approximately 2 km broad (Fig. 11).

At the same the glacier is crevassing. Radial crevasses are also thereupon created in the part covered by the medial moraine. Their walls stand out from the dark moraine-covered surface by virtue of their whiteness, for both at Breidamerkurjökull and Heinabergsjökull clear ice shows under the medial moraine. The same observation is to be made also at Hoffelsjökull, where the slight medial moraine derives from the Mulinn mountains at the eastern margin of the neck of the glacier. In the summer of 1949 numerous cracks ran across the drift-covered ice, and clear ice shone through from the walls of the crevasses. These observations indicate that the medial moraines originating below the snowline from nunataks and marginal mountains have formed on the glacier surface and been transported downstream by the ice. On the other hand, it is evident that the medial moraines originating from nunataks above the snowline as well as from all the peaks of the bedrock covered by the glacier are first embedded in the ice, where they are transported invisibly until exposed by melting. The medial moraines thereby created appear to grow straight out of the glacier.

The drift layer of medial moraines is generally so thick that it effectively retards the melting of the ice underneath. The moraine belt accordingly rises above the rest of the glacier surface and forms on the ice a long and narrow ridge. The slopes are steep, but the summit is comparatively flat. The glacial drift deposited in this moraine belt thus, as it were, rides on top of the glacier, moving at the same speed as the ice transporting it. During transportation the material is no longer subject to wear. This is evidenced e. g. by the fact that moss-covered stones have been found on the medial moraine of Vatnajökull — the vegetation, as it is explained, having developed during the transport phase (Eythórsson 1951, p. 503). The material of the medial moraine is unsorted and contains an abundance of boulders and stones. These are usually angular and sharp-edged (Fig. 2, Plate I), but glacier erosion marks, facets and striae are seldom observed on them. Petrographically they represent almost exclusively the same rock type, for the starting point of the same medial moraine ordinarily consists of a relatively small rock outcrop.

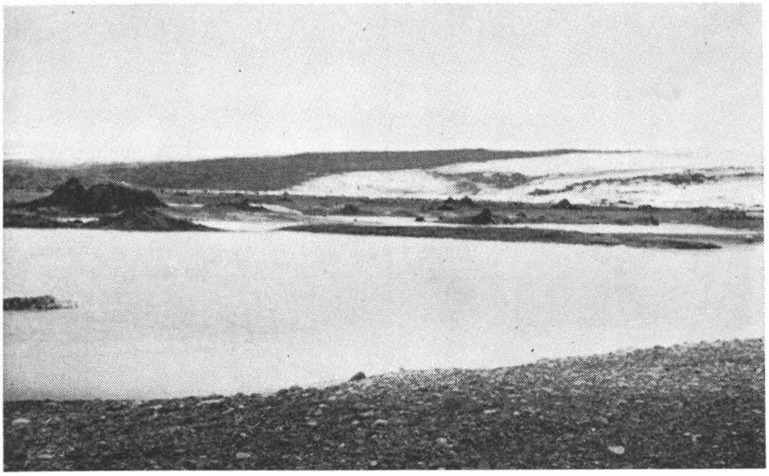

Fig. 11. The terminus of Breidamerkurjökull with its large medial moraine sinks down into the marginal lake at the source of the river Jökulsá.

The material of the medial moraine continues to represent the quality of the initial material even in the marginal zone. Especially its stones and blocks retain their original form during transport. If the point of origin of the medial moraine is situated underneath the glacier, it contains exclusively the products of glacier erosion. If, again, the point of origin of the medial moraine is a nunatak cropping out of the ice, the material of the medial moraine will include, in addition to erosion products, also mechanical disintegration products.

Lateral moraines originate at the line where the glacier margin meets the surrounding mountainsides. Frequently, they cover the side of the glacier as a narrow belt. Lateral moraines travel along with the glacier in the direction of the ice flow and often form the start of medial moraines. A lateral moraine receives a large part of its material in the form of frost wedging and disintegration products sliding down the valley slopes as well as loose deposits covering steep rock walls. This could be plainly observed e. g. at Skaftafellsjökull and Hagafellsjökull, at the joints of which there still remained in the summer of 1949 snow from the previous winter. On top of this snow stones had fallen down the rock walls, leaving tracks to mark their trail. As the snow underneath the lateral moraine thus formed was clean, it would seem that the avalanching of the material had taken place mainly during the summers. The material thus falling down nearer the accumulation area from steep mountainsides is evidently buried in wintry snow and becomes enveloped by the glacier. In the ablation zone, on the other hand, it accumulates on the surface of the ice sheet and there forms an ever-thickening mantle, which covers the side of the ice tongue (Fig. 3,

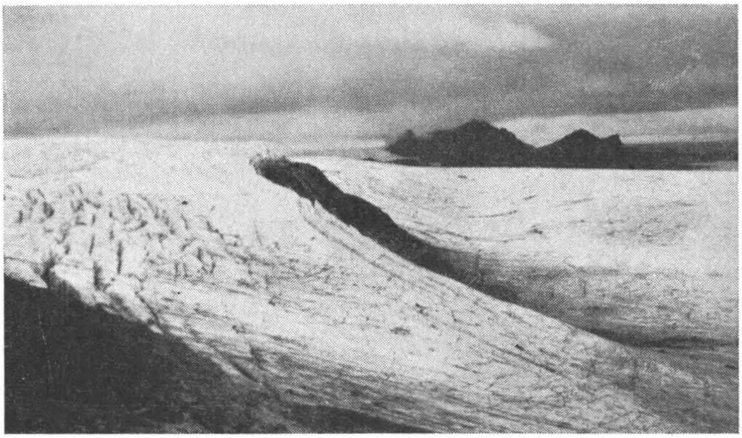

Fig. 12. A small nunatak piercing East Hagafellsjökull dispatches no medial moraine. Photo Helgi Jónasson, 1946.

Plate II). Such lateral moraines occur especially at the lower ends of outlets, where they grow to be several meters thick. E. g. on the western side of Skaftafellsjökull the lateral moraine was observed to cover the ice below as a layer more than two meters thick (Fig. 4, Plate II). As the melting of the glacier is faster beyond the lateral moraine than underneath it, there forms between the lateral moraine and the glacier on the surface of the ice a valley paralleling its edge, whence the lateral moraine becomes detached and forms on the mountain slope a bank containing ice. Before this can happen, the lateral moraine is likely to be transported by the side of the glacier and erode the joint between glacier and rock, with the result that its material becomes mixed with erosion products. The ice must thereupon extend in relative thickness to the mountain slopes. If, however, the edge of the glacier is thin and its movement slow where it adjoins a nunatak or lateral mountain, its transportation capacity is so slight that disintegration products will make up the main substance of of the lateral moraine. This conception is supported by the fact that on small nunataks newly projecting out of the ice and still lacking in disintegration products and to which the glacier extends as a thin sheet (Fig. 12) there occur no lateral moraines whatsoever and from them no medial moraines originate either.

From the foregoing it follows that the material of which lateral moraines are composed include an abundance of products of slumping and rolling. In addition, products of glacier erosion are also likely to the found. The amount of each component depends both on the erosion capacity of the ice border and on the position and steepness of the rock walls surrounding the ice. As lateral moraines often act as the sources of the material composing medial moraines, it is understandable that a substantial part of the medial moraines thereby originating consists of the products of disintegration and frost wedging. For this reason, there is an abundance of sharp, jagged rock fragments in the material, on which erosion marks often are lacking.

In the ablation zones of Icelandic glaciers there occur also surface moraines whose accumulations are situated parallel to the glacier margin. Woldstedt (1954 p. 20) calls them transversal moraines *(Quermoränen)*. At Kviárjökull such a transversal moraine has formed on top of stagnant ice in front of the »living» glacier (Todtmann 1936). The transversal moraine occurring at Dyngjujökull in the northern part of Vatnajökull has evolved in the same way (Spethmann 1909 p. 422, Woldstedt 1937). Both are extraordinarily large, for ordinarily transversal moraines occur as a number of successive bands parallel to the ice margin. Moraine bands have formed in places where glacial drift, filling forwardrising transversal crevasses, meets the ice surface. Often the drift forms a wall-like ridge along the

Fig. 13. Transversal moraine on Hoffelsjökull appears as a crest along a narrow crevasse. Its material consists of upthrust basal load.

crevasses (Fig. 13). From such ridges drift spreads over the ice surface, forming accumulations parallel to the glacier margin. Their material is unsorted and to such a degree like that of a basal load that its discussion has been deferred until now.

BASAL LOAD

Fast motion of glaciers and the softness of volcanic rocks, together with irregular relief, enhance glacial erosion and increase the amount of glacial drift and the relative abundance of erosion products in it. According to estimates by Helland (1882), based on the silt content of the rivers starting in the glacier, the area of Vatnajökull erodes annually 0.647 mm. On the same basis, Thorarinsson (1939 b) has carried out a corresponding estimate for Hoffelsjökull, concluding that the floor of the glacier erodes on an average of 5.5 mm a year, or one meter in 180 years. Compared with Jostedalsbrae (Helland 1882) and Aletsch-Gletscher (Collet 1925), the degradation of Hoffelsjökull is notably greater.

Erosion does not, however, take place evenly throughout the glacier floor, for it must be strongest in places where the motion of the basal ice is most rapid and where the floor is most irregular or is composed of less resistant material. From such places the glacier wears away material and drags it along underneath as a basal load as far as the glacier margin or until the friction overcomes the forward-thrusting force. The basal load situated between the glacier and its floor is subject to constant wear, which scratches the stones and causes the stuff to disintegrate. This material, upon being released from the ice, forms basal till (Flint 1947 p. 111).

As the formation of basal load occurs subglacially, it cannot be observed directly. Basal load comes into sight only at the glacier margin and at the basal part of crevasses, and there too it has already become detached from the ice. In other words, basal load originates in the glaciers of Iceland under subsurficial conditions, is transported in the basal part of the ice and mostly also becomes detached already under the ice. Thus the ice melts simultaneously both on the surface and at the base. This is to be observed mostly plainly at the termini of ice tongues, but the same phenomenon recurs also in places situated farther up, as in the mountains of Svinahryggur between the ice tongues of Hoffelsjökull as well as between the mountains exposed along the eastern margin of Hagafellsjökull. In both places the ice covering the melted and detached basal load was clean.

At the southern outlets of Vatnajökull basal load occurs under the snout, at least at Hoffelsjökull, Fláajökull, Heinabergsjökull and Breidamerkurjökull. At all the observation sites the load occurred as water-soaked porridge-like till, over which the glacier projects, roof-like. In some places there was a narrow empty space between this roof of ice and the till, indicating that the ice did not press down on the till. The basal part of the ice was there impregnated by the load, for both on the surface of the ice tongue and in the walls of crevasses load could be seen in the ice. It contained glaciated stones, gravel and sand. Among them were rounded cobbles with weak striations (Fig. 14). The load extended in the ice of Hoffelsjökull about 15 m higher than the glacier snout and was limited sharply against the overlying clean ice. The corresponding border on the eastern side of the ice tongue of Breidamerkurjökull was situated at an estimated height of 8—10 m. The upper surface of the ice containing the basal load had a dip of about 30° downward and back toward the glacier, which could be noted from the walls of the radial crevasses. The longitudinal axes of most of the stones stuck in the ice were oriented in the same direction, for from the walls of the radial crevasses it could be observed that the stones lay oriented forward downstream and that the longitudinal axis of most were approximately perpendicular to the margin. In the walls of the crevasses there could also be observed cavities, hollows, that were extended in the same direction (Fig. 5, Plate III). Their flattened and

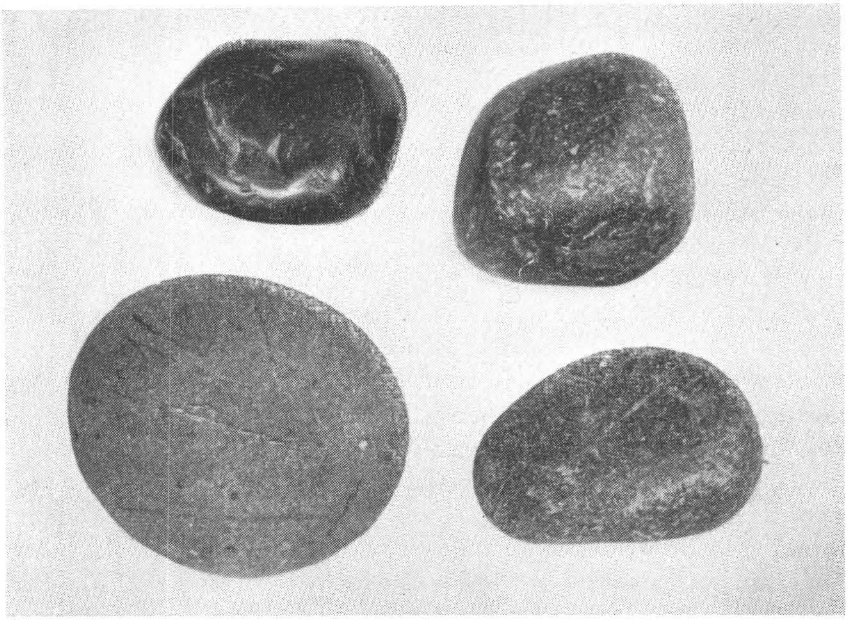

Fig. 14. Weakly striated roundstones picked off the ice on Hoffelsjökull. The size is reduced 1: 2. Photo Erkki Halme.

elongated oval shape indicated that movement continued even at the marginal zone within the ice.

In addition to regular load-impregnation, in the margins of outlets there occur bands of basal load forming transversal moraines (p. 31). They occur both in the overlying and the load-impregnated ice. In numerous places underneath a transversal moraine there is to be found a parallel crevasse sloping upstream full of melted and wet basal load. At the edge of Hoffelsjökull such crevasses were 30—50 cm broad and they were bounded on either side by relatively clean ice (Fig. 6, Plate III). The grain sizes of the load filling the crevasses are shown by the curve 4 (Fig. 6, p. 20). Compared to the grain-size curves for till to be presented subsequently (Fig. 19, p. 42), it proves to be quite identical, revealing the crevasse filling to be basal load in composition. No pollen or spores could be found in the load. The same kind of water-soaked material comes forth also out of transversal bands situated farther from the glacier margin, and sometimes it appears as if the load of a transversal moraine had been squeezed upward out of a crevasse (Fig. 7, plate IV). These crevasses are narrow and in them drift occurs here and there. To judge from the slope of the crevasses, the drift has risen at an angle of about 30° from below up to the surface of the glacier. It is probable that the crevasses bringing forth drift act as shear planes when ice sheets farther back thrust up on top of those in front (Philipp 1920). Still farther from the glacier margin the transversal moraines end. Simultaneously the walls of the radial crevasses turn to clean ice. As certain of these crevasses extended on the ice tongue of Hoffelsjökull open to a depth of about 15 m, or a few meters lower than the level at which the glacier snout was situated, they bore evidence that the rising up of the basal load occurred only at the glacier margin. At the glacier snout there is in places so much drift detached from the ice that it forms a wall-like transversal moraine on top of the snout (Fig. 8, Plate IV). Underneath it the ice melts more slowly than farther back, where there is less drift on the surface.

The rising up of the basal load to the glacier surface takes place on other ice tongues of Vatnajökull as well. During the glacier outburst caused by the eruption of Grimsvötn, the margin of Skeidarárjökull was rent into high walls of ice, in which could be seen numerous layers of englacial load, one on top of the other and inclined upstream. The uppermost of these layers were situated about 40 m above the base of the ice tongue (Nielsen 1937). Similar layers of englacial drift and ice occur also at Breidamerkurjökull, Heinabergsjökull and Fláajökull (Fig. 9, Plate V). The moraine bands thicken there too toward the glacier snout. As this snout often projects eaves-like at an upward slant, with its lower surface accordingly inclined upstream, it is possible that the visible glacier margin actually consists of a sheet of ice situated between load bands. Thus the true margin would be hidden, buried under glacial drift. We shall return to this matter subsequently (p. 85). Be it mentioned here, however, that in many places outside the visible glacier margin there occurs ice covered by glacial drift.

The rising up of the basal load to the surface of the ice in the marginal parts of a glacier cannot be caused by the configuration of the glacier floor, for from the profile presented in Fig. 3 p. 11, as well as from the common shape of the outlets, it is clear that in most cases the glacier floor is either flat or rises toward the glacier snout. At Hoffelsjökull, Breidamerkurjökull (Todtmann 1936 Tafel 18) and Skeidarárjökull (Todtman op. cit. p. 82, Thorarinsson 1939 p. 205) the base of the ice tongue is situated on a level below its snout; but at Langjökull the basal load rises up in bands to the surface of an outlet terminating in a valley sloping outward from the glacier. The basal load rises up in slanting bands also in the ice cliff (Fig. 9 p. 23) of Hagafellsjökull terminating at Hagavatn. The causes for the rising up of the loads are evidently to be found in the movement mechanism of the glaciers of Iceland.

WASHED DRIFT

By washed drift herein is meant glacial drift not only washed by water but also transported and re-deposited on the ice by water.

All glacial drift occurring on the surface of the ice is subject to washing by water. Washing is weak in the accumulation area, where instead of raining it mostly snows and where melting takes place in the main by evaporation. Moreover, the drift accumulating on the surface of the glacier remains visible only a short time. Washing is stronger in the ablation area, which receives more rain water and where meltwater also occurs more abundantly. There is an abundance of water especially at the southern margin of Vatnajökull. To be sure, about half the abundant precipitation takes the form of snow falling during the winter, but since the snow no longer accumulates in the ablation area, the water thereby bound is released annually. Thus of the total precipitation, which e. g. in the budget year 1936—37 was 211 cm (Ahlmann 1939 a p. 52) at the closest observation point of Hólar, 15 m above sea level, the unevaporated water takes part in washing the surface of the glacier. The rain water becomes mixed up with meltwater forming on the glacier surface, especially on sunny days in summer.

In summer the surface of the ablation zone is constantly wet and water flows down the slopes. The water gathers into depressions and forms pools, from which new streams flow down to the next hollow. These little streams bring to mind the streams formed by melting snow in spring. They furrow shallow but steepbanked V-valleys into the surface of the ice. The flowing water does not, however, remain long on the surface but disappears into crevasses, forming little waterfalls. They wear and melt away the ice so as to form round-edged, streamlined, winding pipes leading downward; their course through the blue-green ice can sometimes be followed as far as ten meters, until some roundish projection in the ice blocks the line of vision. With a change in the relief of the glacier surface, the course of a stream likewise changes and the pipe it has made runs dry. Such pipes, of which some were empty, others still in operation, could be seen on the surface of ice tongues in many places. Their diameter was under one meter and nowhere was it observed that a stream filled the whole pipe with water, although the season of thaw was at its height (July—August). Part of the water flows in little surface streams all the way to the glacier margin. By far the greatest part of the water leaves the ice, however, subsurficially.

The water flowing on the glacier surface carries out a vigorous washing of drift for a long time already during its glacier transport. The longer the drift is exposed, the longer it is subject to washing. The heat-binding effect in itself of the dark drift enhances the formation of meltwater even in the part of the glacier where ablation is otherwise slight. This becomes evident upon e. g. studying the aforedescribed medial moraine of the Breidamerkurjökull on the topographical map. On each side of the medial moraine there forms already in the upper part of the ablation zone a narrow valley that collects meltwater, which at every opportunity disappears within the glacier. Into these valleys there also collects drift washed down from the medial moraine, forming sorted, fine-grained sediments on the ice. Mostly they accumulate in the valley on the sunny side, but gradually the washings, mixed up with stones rolling down the moraine, are carried by the water into crevasses and disappear from sight.

Like the medial moraine, the rest of the surface drift is washed. The washing appears to be strongest in the fine-grained material, which is put into motion even by a weak surface flow. The film of dirt formed by eolian drift is washed by heavy rains off the surface of the ice and only after the rain does new dirt begin to spread over the cleansed ice from dirt bands and other eolian material. Eolian drift does not long remain, therefore, in the place where it has accumulated or where it becomes exposed out of the ice in the ablation area; but on the surface it becomes subject to both washing and transportation. Likewise, the water also treats the ash layers and transversal moraines on the surface, but since the stuff of which they are composed is coarser than in eolian accumulations, the water detaches from them only the finer part, while the coarser material is transported only a short distance or stays in place.

The material loosened by the surface washing travels with the water into pools on the glacier surface, where it forms sediments. Thus behind the marginal ridge at Hoffelsjökull a small delta (Fig. 10, Plate V) had formed on the glacier surface out of drift sliding down from the transversal moraine. Its proximal side faced the marginal ridge, i. e. in the distal direction of the glacier, and its layers sloped toward the saddle situated behind the marginal ridge. The material of the delta was clearly stratified. Its sorting and grain size are shown by the curve 5 in Fig. 6 p. 20.

The material was in the main fine sand, but mixed up with the fine material there occurred here and there scattered stones that had rolled down the border crest. In addition to the mineral matter the sediment also contained 1.26 % organic matter, by weight. This figure included pollen and spores from the following plants: *Betula* 4, *Cyperaceae* 1, *Gramineae* 1 and *Selaginella* 1.

A water sample taken from the small pool formed on the surface of Skaftafellsjökull, measuring 6 × 4 m across and 30—40 cm in depth, contained an abundance of *Tabellaria flocculosa* and other small diatoms of shallow, fresh water (Mölder 1951, p. 132), which accordingly in this case grew in the pool on top of the ice. There had sunk to the bottom of

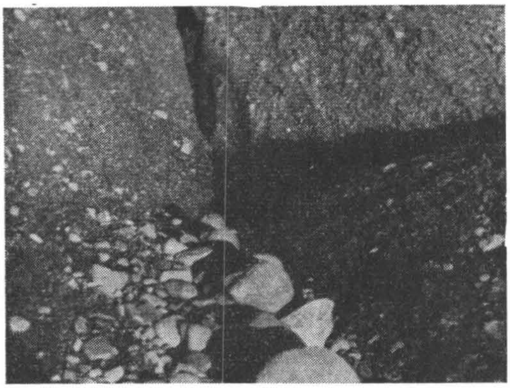

Fig. 15. A row of washed stones at the bottom of a furrow cut into the surface of Breidamerkurjökull by a superglacial river. The stones are 5—10 cm in diameter.

it sediment consisting of sand and organic matter, including e.g. brown leaves of *Betula nana* and *Salix*.

The water in streams starting in pools is always clear but it collects from the glacier surface new drift, which accumulates in the still waters farther on. Thanks to the sedimentation basins the water of the surface streams remains clear even when it runs into a crevasse or flows over the glacier margin. At times stones roll down off the ice into the valleys worn by streams; and these stones are washed and form a regular line at the bottom of the furrow (Fig. 15). As the surface relief of the glacier changes, the streams seek new channels and new sedimentation basins. The old V-valleys and pools run dry and their sediments begin to retard the melting of the underlying ice. The sediments sinking originally to the bottom of depressions are thereby eventually left at a level above the surrounding surface and in turn begin to wear away. Thereby accumulation and erosion alternate at the very surface of the ablation area, and the surface drift undergoes ever new sorting. Its accumulations begin to contain in ever-growing measure material of different origin, which stage by stage travels toward crevasses and the glacier margin.

The occurrence of washed drift on the glaciers of Iceland is not limited solely to the surface, for sorted material also appears from within the ice. On the vertical wall of Hoffelsjökull's snout it formed a lens, which appeared to continue into the ice (Fig. 16 a). The material of the lens was sorted to the extent that its basal part was composed of gravel with pebbles, which

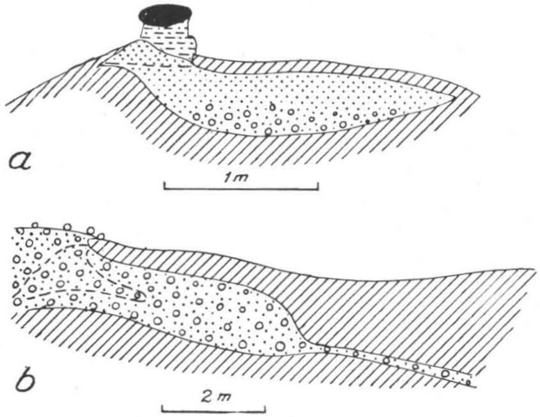

Fig. 16. Two lenses of stratified and sorted drift in the ice: a. in Hoffelsjökull, b. in Heinabergsjökull. The melted part is separated by a dashed line from the frozen material.

farther up changed to gravelly sand. Its grain sizes and sorting are indicated by the curve 6 in Fig. 6 p. 20.

The lens was covered by a thin layer of ice, which contained a weak impregnation of drift. At one point ice was lacking and there was sand instead, which in turn was covered by stratified sediment of fine sand. Overlying it like a roof rested a flat-bottomed stone.

In the marginal ice of Heinabergsjökull there occurred a sand and gravel lens about 4 m long, the end facing the glacier of which formed a narrow, downward sloping sheet (Fig. 16 b). The end facing away from the glacier was rounder and reached the surface. The core and rounded end of the lens had melted, but otherwise the sand and pebbly gravel within remained in a frozen state. No flowing water could be seen in this lens either, which signified that the material had to be sorted either during the stage of glacier transport or before its becoming embedded in the ice.

Washed drift works loose on the glaciers of Iceland for the most part through the action of subsurficial meltwaters. Extensive outwash plains, or sandurs, have been formed out of this material outside the glaciers. In some places, as at the margin of Heinabergsjökull and Breidamerkurjökull, the outwash plain has partly accumulated on the ice, for as the rivers flowing outside the visible margin of these glaciers wear away the outwash plain, a firm sheet of ice is exposed below (Fig. 11, Plate VI). This ice is apparently stagnant and melts in place, for which reason the drift layers formed on top of it can no longer be regarded as participating in the glacier movement. On the other hand, these layers are not wholly independent of the glacier action either, for they become deformed upon the ice's melting underneath them; and the accumulation built of them attains its ultimate forms and construction only after the wasting away of the ice. The accumulations covering the glacier margin thus constitute an intermediate stage between the glacial drift participating in the glacier movement and that accumulated outside the glacier.

CREVASSE FILLINGS

The crevasses of the Icelandic glaciers tend to be divided, according to the locality of their occurrence, into three groups: crevasses occurring in the upper parts of ice tongues, those occurring in the outermost parts and those in various parts of the area in between.

The crevasses in the upper part of ice tongues are long and run perpendicular to the slope of the glacier (Fig. 17). These transversal crevasses move with the ice downstream, but they do not last long, for they close up from the effect the glacier flow, the freezing of the water and snow collecting in the crevasses.

Fig. 17. Transversal crevasses crossing East Hagafellsjökull. The mountain Hagafell in the background. Photo Helgi Jónasson, 1946.

Localized crevassing occurs superglacially on ice tongues farther downstream also at points where some part of the glacier advances faster than the ice around it. On the surface of the glacier there open up at right angles to the flow crevasses which close upon moving downstream. At such places the surface of the glacier tends to break up into large blockfields of ice. As these points remain stationary on the ice tongue, the cause of the phenomenon must be the topography underlying the glacier.

Two types of crevasses occur at the terminus of an outlet. One type is oriented, as described previously (page 34), forming narrow transversal cracks. The other type consists of open radial crevasses (Fig. 18), which get narrower upstream and terminate a few score or at most a few hundred meters from the ice border.

The crevasses of every category collect water except the transversal ones filled with drift. The drift is also washed into the crevasses from the ice surface by water. Only the drift collecting the radial crevasses travels without obstruction down to the base of the

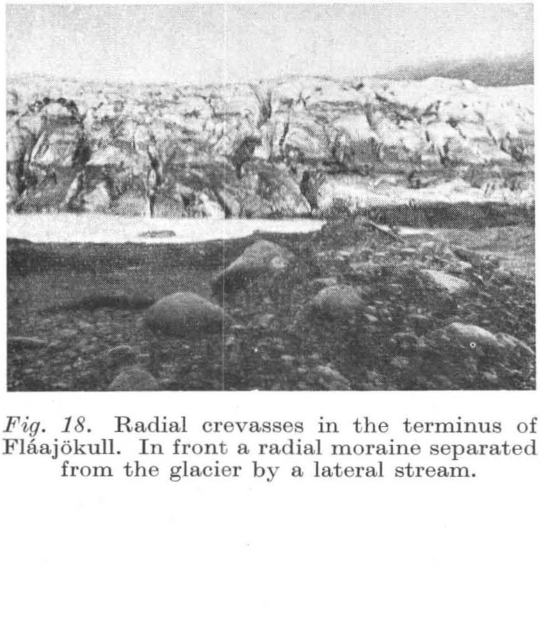

Fig. 18. Radial crevasses in the terminus of Fláajökull. In front a radial moraine separated from the glacier by a lateral stream.

glacier, for these crevasses often extend down through the entire ice sheet. At the base of such 10—15 m deep open crevasses at the snout of Hoffelsjökull there was silty, stagnant or slowly flowing water, into which stones kept falling off the ice and from the crevasse walls. The water had melted the lower parts of the crevasses into cavelike extensions, the level of the water filling the bottom of which reached approximately to the same level as the marginal lake in front of the snout. Inasmuch as the water level in at least a couple of crevasses that did not extend to the glacier margin was the same as in open ones, the crevasses may have been connected subglacially. No sample could be obtained of the sediment deposited in the water, but at those points where the base of the crevasse reached above the waterline, it had an even surface (no other kind of relief could be preserved in such wet material) and its filling consisted of a »mushy» mixture of sand, stones and in places also till. The same kind of sediment occurred likewise in the open radial crevasses of Breidamerkurjökull, at least at those points where the base of the crevasse appeared above water.

The open radial crevasses occurring at the ice margin of Fláajökull deviated from those described in the foregoing in that the free water was lacking at their base. These crevasses were more than 10 meters deep and many of them reached to the glacier margin. One of these crevasses was 1—3 meter broad at the bottom and the base of its walls consisted of ice containing basal load at a height of about 1.5 meters, measured from the bottom of the crevasse. At the base of the crevasse there was a layer of basal till at least 50 cm thick, composed of silt and fine sand (Fig. 12, Plate VI). There occurred no water-washed drift whatsoever at the bottom of the crevasse. The basal till at the bottom of the crevasse was so mushy that the stones on its surface gave way underfoot, sinking into the till. The till appeared to be squeezed into the crevasse from underneath the bordering ice walls, for these ice walls rested on top of the thawed-out and mushy till, pressing it down. The boundary between the ice and the underlying till was sharp and approximately horizontal, but was curved upward at points where boulders had become detached. The ice was thus melting from below here too and discharging its basal load. At the bottom of the crevasse the till reached 20—50 cm higher than the boundary between ice and till on either side.

Behind the terminus of the outlet the ice is already so thick (at Breidamerkurjökull as much as 470 meters), that the crevasses opening up at the surface can no longer extend through the ice (comp. Flint 1947 p. 17). This conception is supported by the fact that the crevasses do not stay open but close up on moving away from the fracturing area. The surface fractures extended to a depth of at least 10 meters, clean-walled without any accumulations of drift in view. Evidently the surface drift washed down into the crevasses by water works down even deeper, disappearing from sight. Simply by inspecting the crevasses it is impossible to decide what becomes of this drift when the crevasses close up again. If it remains in the crevasses the drift forms sorted lenses and strata within the ice. These formations travel invisibly with the ice and are exposed only after the effects of ablation. The occurrence of glacier breccia below ice falls and the exposure lenses formed out of sorted material at the glacier margin points to such a process. If, again, drift is washed by water seeking a downstream course through the plastic part of the glacier and the basal load-filled bottom layer, it changes character: from crevasse filling it first alters into washings, transported through tunnels, and then settles either inside the tunnels or outside.

MORAINE DEPOSITS

In glacial research concerned with the Pleistocene epoch moraines have commanded attention from the very start. The term designating these formations derives from a French word used by the inhabitants of the Western Alps for deposits of glacial drift in front of valley glaciers, while its meaning is given various nuances. In German, Scandinavian and Finnish literature the word *moraine* is used to designate both the formation and the material composing it. British researchers have limited moraine to signify, in particular, the morphological accumulation, while the separate term »*boulder clay*» is used for the material. American researchers observe

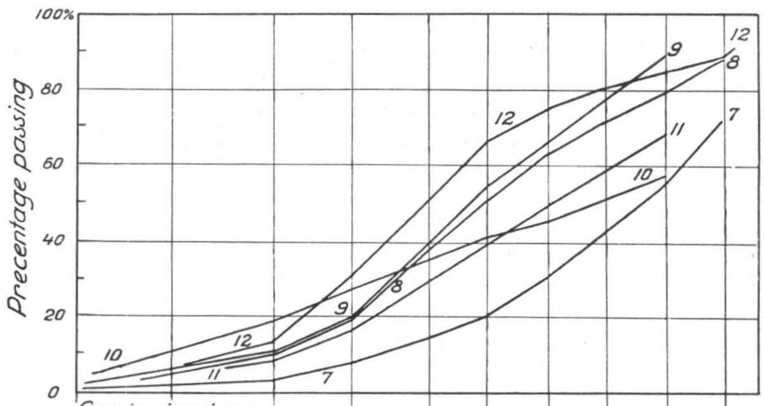

Fig. 19. Grain size distribution in the glacial drift of moraines. Curve 7 ground moraine at Breidamerkurjökull, No. 8 the same at Langjökull, No. 9 d:o at Hagavatn, No. 10 push moraine at Svinafellsjökull (Hoffelsj.), No. 11 end moraine at the river Hanypá, and No. 12 the same at Hoffelsjökull.

a similar usage, but they have substituted for the English boulder clay the Scottish word »*till*». According to Flint (1947 p. 126), »moraine is accumulation of drift an initial topographic expression of its own, built within a glaciated region chiefly by the direct action (deposition and thrust deformation) of glacier ice».

Moraines are conceived in this study, too, in accordance with Flint's terminology, largely as morphological accumulations of glacial drift forming as a result of glacier action both on the ice and beyond it. Among the former are included medial, lateral, and tranversal moraines, dealt with earlier, which take part in the glacier motion and are usually deformed when ice melts underneath them. Inactive moraines are grouped in the following as ground, radial, ablation and end moraines, each of which type has its own morphologically distinct features. Accordingly, the material composing the moraines has not determined the classification, but it will be dealt with in connection with each moraine type.

GROUND MORAINE

By ground moraine is meant in the following glacial drift directly freed from the ice, forming a regular accumulation or one conforming to the topography of its base. Such moraines cover broad areas in the highland of Iceland, but in front of ice tongues they are encountered only in small areas recently exposed from under masses of ice. In such places the ground moraine sometimes extends up to the ice border. A small accumulation of this kind occurs e. g. in front of the northeastern border of the snout of Breidamerkurjökull south of the Fellsfjall mountains. The surface of the ground moraine is almost flat but here and there occur small boulders and stones (Fig. 13, Plate VII). A large part of these are angular and striated glaciated stones, in addition to which scratched roundstones are to be found. In between the stones and boulders the surface consists of unsorted both coarse and fine sandy till, which has dried on top but become saturated with water already at a depth of 50 cm. Toward the ice margin the ground moraine became moist also on top and continued as a thick, porrige-like mass under the terminus of the glacier in such a way that the snout overlies this mass without pressing it down. The undersurface of the ice was, as could be observed from the marginal crevasses, approximately horizontal and was situated on the same level as the surface of the ground moraine in front of it. Since the ice overlying the ground moraine contained only a little glacial drift, the ground moraine had here been formed out of the basal load of the glacier. It had become detached from the ice already subglacially and remained in place undisturbed while the ice melted above it.

A grain-size analysis (Fig. 19) made from a sample taken from the ground moraine at a depth of 20 cm shows the ground moraine to consist of unsorted till. The main components are coarse and fine sand, but other grain sizes occur as well. The fairly even distribution of fractions and the presence of fine grains prove the ground moraine to be unwashed.

At the point where the sample was taken, a till fabric analysis was also carried out (Fig. 20 a). It shows the long axis of the stones to have a distinct maximum, pointing toward the nearby glacier. The orientation of the stones in the ground moraine thus shows in this case the direction of glacier flow; and because the ground moraine is in an undisturbed position, it is obvious that its orientation dates back to subglacial conditions under which the basal till still moved along with the ice.

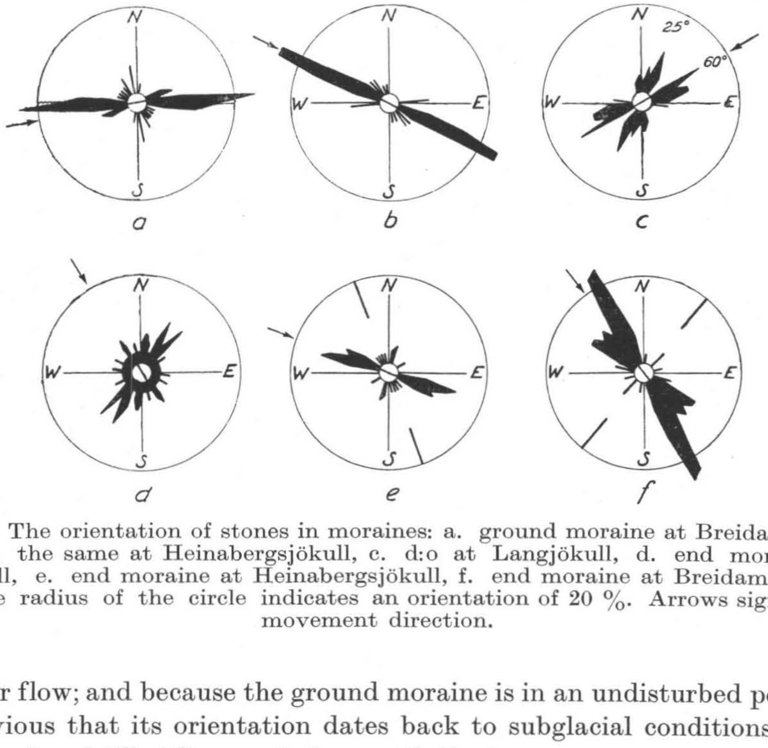

Fig. 20. The orientation of stones in moraines: a. ground moraine at Breidamerkurjökull, b. the same at Heinabergsjökull, c. d:o at Langjökull, d. end moraine at Fláajökull, e. end moraine at Heinabergsjökull, f. end moraine at Breidamerkurjökull. The radius of the circle indicates an orientation of 20 %. Arrows signify ice-movement direction.

The freeing of ground moraine from the ice may be observed also at the termini of Heinabergsjökull, Fláajökull and both tongues of Hoffelsjökull, where a ground moraine landscape is developing between the ice and frontal moraine. The basal till becomes exposed from underneath the glacier as a very wet mass detached from the ice by melting; it stays in place only in the event that it dries. On a sloping base it tends to form solifluction earth. Ground moraine dries still less readily in the trough between the frontal moraine and the glacier where meltwater often collects. The ground moraine there forms a water-soaked mass, which in addition to till contains sorted sediments and superglacial drift. If the glacier margin projects eaves-like over the drift, large fragments of ice break off, causing upon falling down the formation of ridges around it (Fig. 14, Plate VII). The imprints left by the ice fragments do not last long, for the mushy mass flows into the hollow produced by the melting of the ice and fills it, whereupon the flat surface topography characteristic of ground moraine is restored. The grain components and structure of the »till dirt» as well as the orientation of its stones naturally deviate from the features of ordinary ground moraine, even though the accumulation morphologically corresponds most closely to ground moraine.

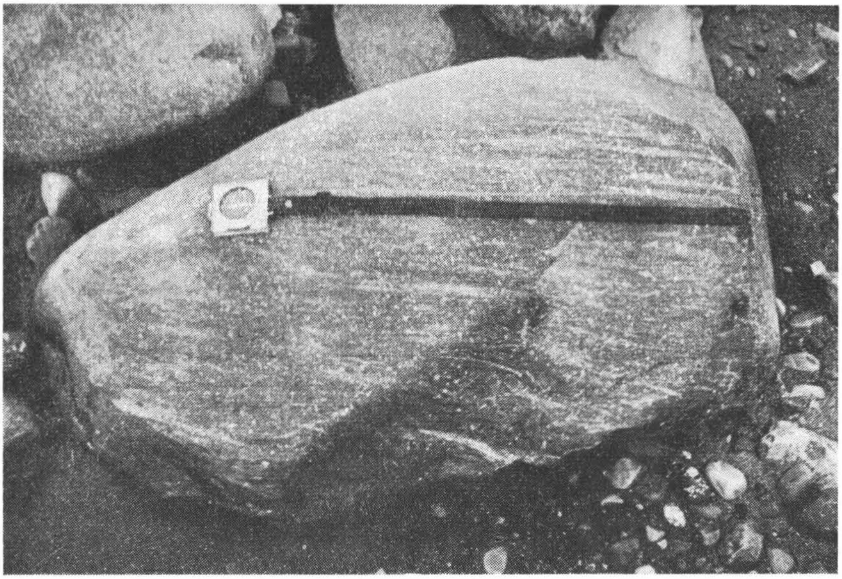

Fig. 21. Striated boulder from the ground moraine surface in front of Heinabergsjökull. Ice has moved over it from left and shaped stoss and lee sides onto the boulder just like outcropping rocks. Boulder is 70 cm in length.

The ground moraine in front of Heinabergsjökull is exposed to view at the bottom of a dried river bed. It is composed of till with an abundance of stones and boulders. They are fixed within a clayey and densely packed mass. The boulders have been polished by ice and constitute small »roches moutonnées» with stoss and lee topography and with overall striations (Fig. 21). These »roches moutonnées» have a very distinct orientation, for their stoss sides face upstream and their lee sides in the opposite direction. This can hardly be explained otherwise than that the glacier had passed over the ground moraine without destroying it and worn boulders projecting up out of the surface into »roches moutonnées». Their orientation analysis

(Fig. 20 b p. 44.) shows the longitudial axes of the blocks to be in the flow direction just about as distinctly as in the basal till in front of Breidamerkurjökull.

The structure of ground moraine becomes evident in the walls cut by the Skaftafellsá river in front of Skaftafellsjökull. The material of the ground moraine is dense and stony basal till, and in the approximately 3 meters high wall there could be seen no kind of stratification whatsoever. The ground moraine extended at least to the waterline. The thickness of the layer could not be determined.

At the margin of Fláajökull the ground moraine consists of basal till, which extends under the ice. The terminus of the glacier here clearly presses the underlying basal till, which has melted free of the ice, and squeezes it on a slant underneath the margin. The boundary between the basal till and the overlying ice is sharp and dips downward toward the glacier. At the margin one gets the impression that the terminus of the outlet rises upward and that the base of the ice sheet beyond the outlet lies below the level of the snout. From underneath the glacier a ground moraine landscape sloping toward the glacier is thus becoming exposed inside the arcuate end moraine.

In the central highland where the glacier is free from surface drift almost as far as its terminus, the ground moraine consists almost exclusively of basal till. Angular and striated glaciated stones occur both on top and inside the ground moraine. The fine stuff composing the till is clearly unwashed and unsorted. Furthermore, the stones are orientated clearly parallel to the glacier movement. Thus it does not deviate in structure from the ground moraines occurring elsewhere. Attention is arrested, however, by the fact that the ground moraine forms an unexpectedly thin layer on the surfaces recently freed from ice. Accordingly, on the eroded and polished rocks of Svinarhyggur exposed by melting out of Hoffelsjökull in recent years there occurs glacial drift only in depressions in the rocks and spaces between knobs, forming beds at most 50 cm thick; and higher surfaces there are only little stones and blocks (Fig. 24, Plate XII). Since the surface has been washed only by rain water since its exposure, the scantiness of the ground moraine must be caused by the fact that even originally the ice had not brought more than a thin layer of basal till on to the rocks. On the other hand, the ice had given them a stoss and lee topography as well as glacial striae.

The ground moraine covers the smoothed rocks outside the glacier margin at the eastern end of Hagavatn just as thinly; and the surfaces of the rocks have erosion marks as well as the products of mechanical weathering. At numerous points stones and blocks were scattered atop the rocks, lying as if atop the erosion marks they had caused. Only in sheltered places did there occur a uniform moraine, at most a meter thick. On the slope descending toward the wilderness camp of Hagavatn, this ground moraine contained an abundance of fine sand and silt and was lacking in blocks. On its surface could be seen stripes consisting of small stones, indicating solifluction.

In the valleys and dells of the central plateau the ground moraine is thicker. It forms a layer estimated to be 1—1.5 m thick in the upper part of the valley which separates the group of aforementioned mountains from the basin of Hagavatn. This valley was freed of ice only as late as very recent decades, for there was ice there in 1929 (Wright 1935 Plate I) and even as late as 1949 the margin of Langjökull extended into the northeastern part of the valley. The surface of the outlet slopes gently toward the terminus and buries itself in the ground moraine, with the result that the true position of the margin remains unknown. The ice cannot extend very far underneath the drift, however, for about 300 meters from the visible border of the glacier polished rock surfaces crop out of the ground moraine, which »climbs» up their gentle slopes. Otherwise the surface of the ground moraine is almost flat and with a gentle slope parallel to the length of the valley. Around the rocks the ground moraine is looser and drier on the surface than the parts deeper down. The grain composition shows it to be unsorted basal till (Fig. 19 p. 42). An orientation analysis carried out at the same spot (Fig. 20, p. 44) gave the longitudinal axis of the stones two maximae, the compass reading of one being 25° and of the other 60°, though the longitudinal axes of many of the stones deviate from these directions. Of the maximae one (60°) was oriented approximately parallel to the length of the valley toward the end of the outlet and evidently corresponded to the last course of the glacier flow, whereas the other (25°) pointed straight toward the glacier proper, hidden behind the mountain earlier exposed out of the ice.

The rock outcrop which the present writer examined only after performing the orientation analysis, was eroded in such a way that the stoss side, with its prominent striations indicated that the glacier had advanced over the rock from a 30° direction, thereby eroding the rock heavily. Weaker striae occurred furthermore with a 60° orientation, crossing the system of the main direction. On the basis of these cross-striations it appears certain that the ice moved over the area first from the direction of 30° and then of 60° and that the earlier stage of advance eroded the rock more than the later, which was unable to destroy the erosion marks of the earlier advance from the relatively soft rock surface.

The striae on the rock surface thus have almost the same compass directions as the orientation maximae of the till. It is accordingly evident that the advances of the glacier are reflected by the compass readings yielded by the till. The basal till thus had to be formed already during the main glacier advance and the last oscillation of the glacier had only deformed the earlier ground moraine by turning the stones in the direction of its own motion.

In order that the glacier could have advanced over the observation site from the 30° direction, it would have had to be thick enough to bury the mountain now separating the observation site from the present glacier proper, or considerably thicker than the last ice tongue to survive in the valley. Observation thus shows the strongest erosion and basal load transport to have taken place underneath relatively thick ice. The erosion marks and till orientation created at that time remain even though the ice had subsequently advanced over the same place from another direction.
Corresponding observations made in Iceland have been previously presented. Thus Kjartansson (1939) observed numerous crossing striae in southern Iceland, which are grouped into two systems of different age in such a way that the erosion forms reflecting the older, general and extensive glaciation are more distinct than the younger striations caused by later, local glacierizations.

It is natural that during the stage when the glacier erodes the rock most it also carries off the most load from its floor. The transport of basal load is thus associated genetically with the activeness of the glacier. Load in greatest abundance forms in the place where the glacier erodes its floor most. From this it follows that chronologically the greatest abundance of basal load is created during the stages of glacier advance.

The release of basal load from the ice takes place subglacially and in many cases accumulations of it remain in place undisturbed, preserving their original structure. At the ice margin it continues directly in the form of ground moraine, which mainly constitutes an accumulation of basal till formed out of basal load.

RADIAL MORAINES

In front of Breidamerkurjökull, Hoffelsjökull, Heinabergsjökull, Fláajökull and Svinafellsjökull radial moraine ridges, which often represent extensions of crevasse fillings described earlier, occur on the surface of the ground moraines. In front of Breidamerkurjökull they are evidently rapidly vanishing miniature forms, but the radial moraines in front of Heinabergsjökull, Fláajökull and Svinafellsjökull are so large and firmly built that they represent permanent accumulations.

On the ground moraine accumulated along the eastern border of the outlet of Breidamerkurjökull the radial moraines form sharp-crested ridges continuing outward from the glacier and gradually becoming lower (Fig. 15, Plate VIII). In length they are at most 10 meters and in height 0.5 meters, and at their base they measure about a meter in breadth. The main orientation of the ridges is at right angles to the glacier margin, but often the ridges run together and sometimes there are transversal ridges between them. Between the ridges there are angular ground moraine hollows. The ridges are best developed in the part along the immediate ice edge, and they become lower and the slope becomes more gradual as the distance from the margin increases.

The material of the radial moraines consists of the same kind of basal till as is contained in the surrounding ground moraine. There is the difference, however, that the material of the radial moraines is unoriented.

The glacier margin against the area of radial moraines is fractured by open longitudinal crevasses to such an extent that it breaks up into blocks of ice (p. 45). Radial moraines are in this case produced in the spaces between blocks of ice and the hollows between ridges represent the imprints of fallen ice blocks. The radial moraine levels out and disappeares from the surface of the ground moraine unless both dry rapidly. In the event that the ice contains glacial drift exposed on the surface by melting, this also forms part of the material of the radial moraines, because the surface drift slides and is washed down into the crevasses.

In the terrain in front of Heinabergsjökull the radial moraines deviate from those described in the foregoing. They form broad, flat-surfaced ridges between the old end moraine and the ice margin and continue as coherent but uneven zones for several hundred meters. A zone of this kind stands out from its surroundings not only on that it has an elevated surface but also on account of the abundance of boulders occurring in it. These boulders measure 1—2 meters in diameter, are angular and situated loosely on the surface. The material between them is gravelly and sandy till (Fig. 10, p. 28). The surface layer of till is loose to a depth of about 0.5 meters and often there is a thin layer of coarse sand under the stones. There appears to be no regularity in the lengthwise orientation of the blocks, for their longitudinal axes were turned every which way. On the other hand, the fine material indicated a weak maximum in the compass direction of 245°, which at the same time was the longitudinal orientation of the ridge. The glacier lay in this direction, too, looked at from the observation site. The ridge does not, however, extend as far as the glacier, but it is cut off by a lateral stream. On the other side of the stream there is irregular terrain, as an extension of the ridge, on the surface of which here and there large boulders occur. Such boulders were to be met with even on the surface of the ice, for just here a medial moraine appears on the surface of Heinabergsjökull. The surface of the glacier has remained elevated under the moraine and in addition it has suffered considerable fracturing. It is natural that this radial moraine has been built up out of the surface drift washed from the medial moraine.

In the terrain in front of Fláajökull radial moraines occur in abundance (Fig. 22). They start from the old terminal moraine and gradually descend the gentle slope as parallel ridges toward the glacier until here too a lateral stream breaks their descent.

Because of its winding course the bed of the stream sometimes runs along the very margin of the ice and sometimes it runs so far from it that a strip of fluvial deposits is left between stream and glacier. In places where the stream runs along the ice margin, the radial moraines extend nearest the edge of the glacier broken up by longitudinal crevasses. The fillings of these crevasses have already been discussed (p. 41). The radial moraines measure 10—200 meters in length, 0.5—1 meter in height and about 2 meters in width at the crest (Fig. 18 p. 40). The stony and block-filled material of these radial moraines differ from that of the radial moraines of Heinabergsjökull in that here the stones have been scratched by the ice, though, to be sure, some of them are rounded. Stones occur in greatest abundance on the surface, for already at a depth of 5—10 cm the material turns to dense, silty and clayey basal till, with stones here and there. It continues in this composition at least to a depth of 70 cm. A fabric analysis of the ridge carried out at a depth of 50 cm shows a weak maximum in the directions of 210° and 225°, but the distribution in all directions of the compass was so great that the material may be regarded as lacking in orientation. Inasmuch as the orientation of the ridge (as well as the apparent

Fig. 22. Radial moraines in front of Fláajökull, seen from the end moraine. The glacier terminates about 200 m west (left).

final direction of advance of the glacier) is 335°, the maximum orientation of the stones lies obliquely in relation to it.

The identical composition of the material of the crevasse fillings and the radial moraines indicates an identical origin, *i. e.* the radial moraines are in this case crevasse fillings squeezed out of basal till into radial crevasses. This conclusion is supported by the fact that the crevasses and the radial moraines run parallel and that the distance between the crevasses and between the moraines is approximately equal. As the crevasse fillings have formed on a sloping surface, they have dried and survived in the exposed area.

A fourth group of radial moraines occurs in the terrain in front of Svinafellsjökull, the western outlet of Hoffelsjökull. In part, they form islands in the lake created in front of the glacier; in part, they run along the shores of the lake in the form of wall-like ridges; and, in part, they border dry pools with flat bottoms filled with a sediment of sand and silt. The form and orientation of the ridges varies considerably, but in general they are oriented at right angles to the glacier margin, and they consist of series of short, sharp-crested mounds. In form these rows of ridges often resemble small eskers (Fig. 16, Plate VIII). The mounds are 10—15 meters long, 5—10 meters broad, and their peaked summits rise up 1—4 meters above the surrounding sediment.

The surface of the mounds consists of fairly evengrained gravel and small stones as well as an abundance of pebbles (Fig. 17, Plate IX). A close examination of the stones reveals that many of them have been scratched by ice, whether they be angular glaciated stones or roundstones. Inasmuch as the material of the ridges changes immediately below the surface so as to contain fine-grained fractions as well, it must have been freed from the ice directly. It accordingly corresponds to the drift occurring in the ice of the eastern outlet of Hoffelsjökull, which in addition to glaciated stones contains roundstones. The glacier evidently advanced over glacifluvial deposits and carried away load with it. If, on the other hand, the drift of lateral moraines had been transported by streams of meltwater only after becoming liberated from the ice, all of its stones would have had to erode and become rounded, in which case the striae possibly occurring on them previously would have disappeared.

The ridge area of Svinafellsjökull is situated on the bottom of the lake once dammed up between the glacier and the end moraines in front of it but subsequently drained. The conditions prevailing during the origin of the topography had therefore been subaquatic, although the ice could not float in the shallow water. In extending into the water and disappearing therefrom, the ice tongue had apparently been broken up by radial crevasses. The radial moraines formed in these partly water-filled crevasses. Both the water-filled and dry silt and fine sand-bottomed pits between the moraines indicate the spots where the ice wasted away last. The loose structure of the lateral moraines indicates, moreover, that their material consists of till from ablation moraines caving in down the crevasses. Upon the melting of the ice bordering the crevasses, the crevasse fillings collapsed, causing the formation of steep slopes and sharp crests. The whole accumulation might thus be regarded as belonging to the ablation moraine; but, on the other hand, the orientation of the ridges together with a morphology identical with the radial moraines of Breidamerkurjökull and Fláajökull, described in the foregoing, speaks in favor of their being classified as radial moraines.

The observations reported in the foregoing represent all the radial moraine types encountered by the author in Iceland as regards the conditions of origin of which it was possible to drawn a definite conclusion. Accordingly, radial moraines form in Iceland during the melting stage from both medial and lateral moraines as well as crevasse fillings. In the former instances, they produce a broad, irregular zone, whose material is rich in blocks and unwashed. In the latter instance, the radial moraines form in the radial crevasses of the glacier margin in two different ways: 1- surface drift avalanches into the crevasses, and 2- mushy basal till is squeezed up into them. Furthermore, blocks of ice breaking off the snout of glacier outlets and falling into the mushy ground moraine throw the till up to form ridges, which under suitable conditions remain.

Radial moraines thus form on the very glacier margin, where the material embedded in the ice is released by melting. Inasmuch as the glacier motion determines the location and orientation of both medial moraines and radial crevasses, the orientation arising during this motion becomes evident also in the direction in which radial moraines run, even though the ice might have turned stagnant at the time of their formation.

ABLATION MORAINES

In the marginal parts of the glaciers of Iceland there occurs, as pointed out previously, an erichment of glacial drift on the surface of the ice. This is caused partly by the fact that the material coming onto the glacier remains on the surface of the ice and partly that drift embedded in the ice becomes exposed. Rapid melting of the surface belongs among the characteristic features of the margins of Icelandic glaciers. This is because the ice tongues project far below the climatic snowline. Because the glacier motion slows down upon the ice mass's getting thinner, there occurs stagnant ice at the termini and flanks of outlets. The ice disappears most slowly at places where the surface drift forms such thick layers that they retard the melting of the underlying ice. Upon the ice's gradually melting beneath the drift, the accumulations of drift are deformed and produce irregular ablation moraines. According to Flint (1947 p. 131), »ablation moraine is a deposit of drift let down irregularly from the surface of the glacier onto the ground by gradual ablation of the intervening ice». If surface drift does not form, ground moraine appears from underneath the ice; hence, ablation moraine does not occur everywhere in the area of so-called dead ice.

The formation of ablation moraine is to be observed in many places in Iceland. Especially at the northern end of Vatnajökull it covers an extensive area in front of Bruárjökull (Woldstedt 1939, Todtmann 1951, 1952, Hoppe 1953). Extensive ablation moraines have formed also in the vicinity of Langjökull during recent decades (Nørvang 1937). Likewise, they have made their appearance in northwestern Iceland, where the local glaciers have melted away altogether (Keilhack 1934).

Ablation moraines form also at the southern margin of Vatnajökull at places where there is an abundance of surface drift on the ice. Their formation is further to be observed at the margins of Langjökull. As the ice melts under overlying drift only very slowly, it is not possible to ascertain in a single summer how the entire development takes place in one area, but its study requires prolonged work on the same site. Some sort of conception of the origin of ablation moraines can, however, be obtained by quickly examining the gradual transformation of the lateral moraine at the side of an ice tongue into an ablation moraine. Such a developmental sequence could be observed e. g. along the eastern margin of Hagafellsjökull and the western margin of Skaftafellsjökull.

Along the eastern margin of Hagafellsjökull, lateral moraine appears at an elevation of 800 meters above sealevel. Here it contains alternate layers of snow and drift. By degrees the snow disappears from the border zone, now composed of a uniform layer of drift. Only in places where the stream flowing in the zone between the mountain and the ice erodes openings into the lateral moraine is it possible to see that underneath the drift there is hard ice. The surface of this ice was situated higher than the surface of the outlet in front of the lateral moraine and between them occurred crevasses. The ice underneath the drift had thus evidently become detached from the glacier proper and was melting *in situ*. Near the lake of Hagavatn the snow disappeared between the ice and the surface drift. At the same time the lateral moraine became irregular on its surface, where there began to appear kettle holes with steep sides and which measured less than 10 meters in diameter and 2—4 meters in depth. The walls of these holes consisted at the top of drift and below of hard ice. Often there was water at the bottom, which melted the ice at the same time as drift slid down the sides into the hole. Gradually the holes widened and became connected together, whereupon there remained between them sharp-crested ridges of ice and overlying drift. Drift soaked in meltwater flowed slowly down the slopes to the bottoms of the holes, bringing the new, underlying ice into view. The irregular topography had thus been produced by the ice underlying the drift. The drift mantle at the same time underwent perforation. As a consequence of the exposure of the ice, its melting became accelerated, with a concomitant increase in the volume of meltwater. Gradually the regular drift surfaces disappeared totally between the kettle holes and the formation changed so as to consist altogether of interconnected broad hollows and the ice ridges in between. Somewhat farther from the glacier the ice ridges vanished from between the holes, and in place of them there developed the deepest holes of all. The relief thus became contrary to what it had been some distance away. In other words, the bottoms of the holes first formed remained elevated on account of the deposited drift in relation to the new hollows resulting from the melting of the ice last to be exposed. At the same time the topography became more even, because the difference in elevation was slighter and the slopes gentler than in the area containing ice. As Hagavatn's ablation moraine is situated on a slant base between the mountain side and the bottom of the valley, it has been subject to erosion, for its mushy moraine flows down the slope, in addition to which the little brooks streaming down the mountain also act erosively.

A corresponding developmental sequence was to be observed earlier on the shore of Hagavatn south of its present outlet, but in 1949 only an ablation moraine free of ice any longer remained. According to Helgi Jónasson, a native Icelander, there had been a relatively flat-surfaced lateral moraine in the same spot 10 years ago, which at first had become irregular, with ice becoming exposed at the lower ends of the sides of the resulting holes (Fig. 18, Plate IX). The margin of Hagafellsjökull had already retreated from the lake basin, so that the drift-covered ice had become detached from the glacier proper already earlier. After the ice had melted underneath the drift, the topography gradually levelled out.

The lateral moraine at the western margin of Skaftafellsjökull is also turning into an ablation moraine. The lateral moraine is situated at first on top of the ice between the living ice tongue and the bordering mountain, but gradually it runs off the margin of the glacier to follow the foot of the mountain in the form of a fairly flat-surfaced drift zone. Underlying the drift here too is a layer of ice which begins to melt only at the side of the visible terminus of the ice tongue. The melting is promoted by the water flowing under the lateral moraine; the water has worn channels with vertical walls in the ablation moraine in the process of formation and the underlying ice. The upper part of the walls consists of drift and the lower part of ice, but at times the water flows beneath the surface. As a result of the streaming of the water, the ice melts faster and the drift deposited in the holes and channels is sorted. And as a consequence of the simultaneous melting and washing process, an irregular ablation moraine forms in the place, the material of which is in spots unsorted surface drift directly freed from ice and in other spots washed drift.

Ablation moraine forms likewise in places where medial moraines reach the glacier margin. In fact, the medial moraine in front of Heinabergsjökull described in the foregoing (p. 49), which was classified among radial moraines, is composed at certain points of mounds and depressions lacking to such a degree in orientation that these sections might be regarded as ablation moraines, even though the formation as a whole has a distinct radial lengthwise orientation. The medial moraine terrain extending from the great end moraine of Breidamerkurjökull to the glacier is so broad, on the other hand, that it lacks any distinct longitudinal direction. This area, consisting of medial moraine, taken as a whole too, is accordingly most nearly an ablation moraine, the surface of which is irregular on account of mounds and hollows of different shapes. If the glacier were some day so disappear between the starting point of the medial moraine and the present ice margin, it would likewise form a broad radial moraine.

Ablation moraine occurs on the outlet glaciers of Iceland mainly in places where lateral and medial moraines come to the ice margin. The ice covered by such moraines melts so slowly that it becomes detached from the part of the glacier in motion and turns stagnant. Elsewhere there is usually so little surface drift that it does not produce ablation moraine topography proper. An exception, however, consists of such points where a border crest occurs on the snout (p. 35). The part of the glacier behind it melts faster than the ice underneath the border crest and in sinking lower forms a fosse, onto which surface drift slides down both slopes. Inasmuch as meltwater collects in the fosse and erodes it, the border crest is gradually detached from the glacier proper to form an end moraine under which is buried slowly melting ice, which deforms the moraine. In the event that the border crest and the fosse are situated so high or on such a sloping base that it does not collect water, either ablation or ground moraine topography is created by drift at the fosse. More commonly, however, the fosse becomes submerged upon sinking down and in its place a sediment plain forms.

Kettle topography of the ablation moraine type forms also in areas where glacifluvial material has accumulated on top of the ice. In front of the visible snout of outlet glaciers there are at many points on the surface sorted sediments. When the ice melts underneath them the smooth surface of the sediment becomes deformed so as to resemble ablation moraine. Considering that the material of the formation is not a direct product of the action of the glacier but it has been transported and deposited by flowing water, the treatment of such accumulations will be taken up in connection with glacifluvial deposits.

Kettle topography resembling ablation moraine in morphology is produced also when ice blocks broken off the glacier margin melt away. Although the glaciers of Iceland generally terminate on land, kettle topography at times occurs in the frontal terrain. This is true e. g. of Skeidarárjökull, where the kettles are formed as a consequence of glacier outbursts (comp. Leiviskä 1928 p. 188, Nielsen 1937). The blocks of ice torn loose by flood waters and transported to the sandurs are buried in part or entirely under drift carried by water and melt underneath slowly. In place of the ice blocks there then form hollows inside the accumulations; the roofs eventually cave in, leaving holes. Other kettle holes have been open from the very beginning and their sides have been steep; but both types become funnel-shaped fairly rapidly when gravel slides in. If the ice blocks had been densely distributed, the holes are situated so close together that the level stretches between them vanish and they are separated by sharp-crested gravel ridges.

The kettle topography produced by melting ice blocks is met with also at the bottom of ice-dammed lakes. The basin of Gjánupsvatn emptied in July 1949. At the same time the margin of the glacier had become broken

Fig. 23. A melting ice block in a funnel-shaped hole, which has been pressed into the bottom of the ice-dammed lake Gjánupsvatn when this ice block anchored. The ice remnant is about 50 cm in diameter.

up and the detached ice blocks had formed miniature ice-bergs. As the waterlevel fell, the icebergs caught on the bottom; and since the bottom was soft sediment or, in places, water-soaked till, it gave way beneath the weight of the blocks, forming depressions (Fig. 23). Melting blocks of ice were to be met with in such holes at the bottom of the vanished lake in great abundance. The ice blocks varied in size and the melting took place rapidly. Some of the holes were already empty. The holes created by the ice blocks measured at most 1 meter in depth and less than 5 meters in diameter. Inasmuch as the exposed lake bottom dried at the same time as the blocks melted, it appeared probable that the holes would remain at least until the waterline of the lake rose again to their level.

The kettle and knoll topography characteristic of ablation moraine thus forms in several different ways and in different accumulations. Ablation moraine proper in this topography is represented only by such formations as have originated upon stagnant parts of a glacier slowly melting from underneath overlying glacial drift. The amount of drift and its prevalence in the different part of the glacier determine in turn where the ablation moraine forms.

END MORAINES

By end moraine is meant a ridgelike accumulation formed in front of and parallel to a glacier margin as a result of either thrust or deposition action of the ice (comp. Flint 1947 p. 127). German researchers, such as Gripp (1938) and Woldstedt (1954) divide end moraines into two chief categories *(Stauchendmoränen* and *Satzendmoränen)* according to the manner of their creation. In North America end moraines are classified according to three types: push, dump and lodge moraines (Chamberlin 1894 b). Of these the push and dump moraines correspond to the main German divisions. Lodge moraines have originated out of basal load pushed by the ice margin and squeezed in front of it as a marginal ridge. In the German terminology such moraines fall under the heading of *Satzendmoränen.*

End moraines (also termed terminal moraines) are notable along the terminal margins of the southern outlets of Vatnajökull. As high and long ridges, generally visible from a considerable distance, they separate the glaciers from the coastal plain. Very well known are e. g. the great terminal moraines of Skeidarárjökull, Kviárjökull and Breidamerkurjökull, which were described already by Helland (1882), Keilhack (1883), Thoroddsen (1905—1906), Herrmann (1907) and Spethmann (1912) and which have subsequently been dealt with in numerous studies. Among the latter, noteworthy examples are the reports by Leiviskä (1928), Todtmann (1936, 1951 and 1952) and Hoppe (1953). According to these investigators, the end moraines in front of the southern outlets of Vatnajökull belong mainly to the class of *Stauchend*-moraines, though among them occurs also the structure of the *Satzend*-type. Leiviskä drew attention to the fact that under the basal till of the great end moraine along the eastern terminal margin of Breidamerkur there occurred folded peat layers (op. cit. p. 193). His explanation of the phenomenon was this: the accumulation was created by ice advancing over an earlier end moraine, folding its surface layer and then depositing a new moraine bed over the folded layers. The same kind of structure occurs also in the end moraine of Svinafellsjökull at Öræfi (Todtmann 1952, Hoppe 1953) as well as in the end moraine of Kviárjökull (Hoppe op. cit.). The occurrence of ground moraine on top of *Stauchend*-moraine need not, in Hoppe's opinion, signify a new thrust of the ice, however, but the ground moraine could have accumulated along thrust planes in the ice from uprisen basal load, which upon the melting of the ice has deposited as ground moraine on top of the push moraine (op. cit. p. 257).

Large end moraines occur also along the northern margin of Vatnajökull. The end moraine that formed in 1890 in front of Bruárjökull is, in the view of Spethmann (1909), Thorarinsson (1938 a) and Woldstedt (1939), mainly of the *Stauchend* type, but, as Woldstedt later stresses again (1954 pp. 101—102), it varies in nature greatly, even at short intervals. In one spot it consists of folded layers, in another it forms a broad zone of knolls and in a third just an irregular accumulation of boulders. It is thus hard to divide end moraines into different types on the basis of the evidence of special points, especially when there are few cross-sections and the moraines are situated so far from the ice margin that their mode of creation can no longer be observed. A couple of points, *i. e.* the termini of Hoffelsjökull and Svinafellsjökull at Öræfi, the glacier still extends into large end moraines, and at these points Hoppe has become convinced that the squeezing forth of basal till in the ice margin and transport in open crevasses play a major part in the formation of the end moraines (Hoppe 1953 p. 257). They would thereby be *Satzend*-moraines, or, according to American terminology, most nearly lodge moraines.

The margin of the eastern outlet of Hoffelsjökull extended in 1949 at several points to the end moraine, which had earlier (according to Thorarinsson about 1890) formed along the ice margin. The end moraine rises up from the surface of the sandur as a plantless rampart of stones, which hides from view the ice tongue, visible only from the summit of the moraine. The breadth of the end moraine on top is 50—70 m and its height, measured off the surface of the sandur, about 6—7 m, but on the proximal side the ground is lower and the height of the end moraine may be estimated at about 10 m, measured from the foot of the proximal slope. The rampart is almost symmetrical, but the slope varies so greatly that in places the distal side and in other places the proximal side is steeper. In those places where the slope of the proximal side is gentle, earth has obviously slid down from the end moraine ridge toward the glacier. This is quite comprehensible, as the proximal slope was generally wet, while the distal side and the top were dry. The summit of the end moraine was unexpectedly uneven and consisted of several small ridges. The ridges were linked together by lower sections in a chain, but often they ran parallel and merged. In between the small ridges lay elongated hollows, some of which contained water, though the bottoms were situated above the level of both the sandurs and the waters at the glacier margin. The surface of the small ridges, together with that of the distal side, was covered by uniform stony till, whereas there were fewer stones on the wet proximal side and the spaces in between consisted of normal till, which, however, was not pressed into as dense a mass as the ground moraine, for it could be shoveled like sand. There were two kinds of stones in the end moraine, some being angular and the others rounded (Fig. 19, Plate X). On the surface of both careful search would reveal fine scratches. In addition, the material of the proximal slope of the moraine yielded three mollusc shells, classified by Dr. Segerstråle of the Department of Zoology, Helsinki University, as belonging to the species *Saxicava artica* and *Leda permula*. Both are forms native to the Arctic Ocean. The same species have previously been found along the margin of Hoffelsjökull (Pjeturss 1907). Inasmuch as the *Leda permula* exists at present in water at least 30 m deep, its occurrences by Hoffelsjökull prove that the sea had extended up to the area nowadays covered by the glacier. Well-preserved fragments of birch roots and stems were also found in the proximal slope of the end moraine. Pieces of wood appeared in such abundance out of Hoffelsjökull that they were collected for firewood.

Underneath the surface the material of the end moraine proved to be loosely deposited till containing stones of various sizes. Three fabric analyses carried out on top of the end moraine at different points to a depth of 1 m yielded no certain orientation. It would appear that the till of the great end moraine along the terminal margin of Hoffelsjökull lacked orientation (comp. Hoppe 1953 p. 257). A sample taken at a depth of 1 m contained, in addition to mineral matter, some pollen and spores *(Betula* 4, *Pinus* 1, *Caryophyllaceae* 1, *Cyperaceae* 12, *Graminaceae* 4, *Myriophyllum alterniflorum* 1, unidentified 1 as well as *Polypodiaceae* spores 2, or a total of 24 pollens and 2 spores).

The material of the end moraine of Hoffelsjökull proved to be distinctly stratified in some places. The stratification was caused by the alternation of layers of coarse sand with others of fine sand. The borders between the layers were irregular and often the layers of coarse sand broke up and became divided into wedges, sunk into fine sand. The dip of the layers proceeded every which way. The structure of the moraine gave the impression that the sorted material had been sedimented elsewhere and been transported along with drift to the end moraine. In the main, however, the end moraine of Hoffelsjökull is unsorted, if loosely stratified till, which occurs on the surface of the moraine both on top and both sides. On the proximal side the surface consisting of it is wetter and less stony than elsewhere.

The snout of Hoffelsjökull formed in places an eaves-like projection over the base of the moraine. Blocks of ice falling off the snout had raised the mushy moraine and the overlying sediments into wall-like ridges, as related on p. 45. The confused and, in its detailed topography, varied structure thereby created was joined to the proximal part of the end moraine. Since the miniature ridges thus built up correspond in composition, structure and form to the ridges occurring on top of the end moraine, it is likely that both had evolved in the same way. The ridges and hollows in between them on the summit of the moraine would, accordingly, have originated through the falling down of ice fragments from the glacier margin, with the hollows indicating where the blocks had dropped and the ridges the accumulations of drift squeezed upward by them. Upon its happening, the ice margin would have had to extend as far as the end moraine. Nowadays the snout of the glacier is so low and is located so far from the end moraine that it works up the lower part of the proximal slope only at a few points.

West of the »calving» point the ice margin changes into a drift-covered border crest, behind which the surface of the glacier sinks down into a fosse (see p. 35). The layer of drift covering the border crest was about 50 cm thick and contained gravelly and sandy till. If there were more surface drift, it would protect the ice from melting even after the border crest had become detached from the glacier proper. At the site of the border crest there would then evolve an end moraine, which would contain ice melting in place and deforming the moraine. The thin drift covering over the present border crest would hardly suffice to bring about the creation of an end moraine. Possibly earlier, when the ice margin had been thicker and more active, it may have brought more drift on top of it, whereupon end moraines could have been built up also out of ablation moraines covering the margin.

At the margin of Hoffelsjökull there can be observed also a third way in which end moraine forms. East of the eaves-like projection mentioned in the foregoing the snout contains so little glacial drift that on the surface of the ice there are, in addition to the film of dirt, only little stones melted free of the ice here and there. The outlet terminates in a low, wedge-like snout, overhanging the basal till, which slopes downward toward the glacier. In front of the margin there occurred a symmetrical ridge about 100 m long and 1—0.5 m high. It was in contact with the ice edge at several points, but generally its crest was situated 1—3 m away from the margin. The ridge had evidently been built up out of basal till the winter before. It could well be a »push» moraine resulting from a slight advance of the glacier. In shape and size it resembled so-called annual moraines. The same kind of end moraine built of basal till occurred also along the terminal margin of Hoffelsjökull's western outlet, Svinafellsjökull. The crest of this moraine was situated at a distance of 8 m from the visible margin of the glacier. The guide, Leifur Gudmundsson, who knows Hoffelsjökull very well, reported that the margin had been situated at the point of the ridge the winter before. The grain size analysis (Fig. 19 p. 42) shows that the material consists of silt and clayey till, in addition to which the following pollens were found: 1 *Betula*, 1 *Cyperaceae* and 1 *Graminaceae*, as well as 1 *Polypodiaceae* spore.

The end moraines of Hoffelsjökull have, in the present author's view, been created out of material transported by the glacier. They therefore constitute »dump» moraine, with the reservation that the last-described minor ridge accumulations of basal till are »push» moraines.

Corresponding end moraines lie along the terminal margins of other ice tongues too. The large and irregular end moraine of Heinabergsjökull glacier is situated on the whole far from the ice margin and only at the northeastern end of the outlet does the ice extend up to the proximal slope of the moraine. The terminus of the glacier forms an arching projection at this point (Fig. 20, Plate X), overhanging the ground moraine a couple of meters below. As the material of the ground moraine consists of wet till, it is obvious that it will be deformed when the snout crashes down. The same process as at Hoffelsjökull is thus under way in respect to the proximal slope at hand. To be sure, the glacier has here diminished in size to such an extent that the margin has already been cut off from the end moraine and sunk down below the level of its summit. The end moraine must have developed here too as the result of stronger and more effective glacial action than at present.

Next to the preceding observation site the ice margin extends into the proximal side of the end moraine in such a way that the border crest rising above the fosse constitutes the proximal part of the moraine. Its ice is dark, hard and uncrevassed, and it forms at least three sharp-pointed, overlapping ice sheets slanting upward. The uppermost rises above the surface of the end moraine. The ice sheets thrusting up from underneath it terminate on a lower level and their ends are covered with drift, which also fills the cracks between the ice sheets inclined upstream and narrowing in the same direction. In the fosse between the marginal crest and the glacier the ice covers like a bridge water collected underneath the glacier. The ice has thus melted free of its base at the point of the fosse and the bridge formed by it is supported only at either end. If the bridge were to break from the effects of melting, the marginal crest would lose contact with the glacier proper and melt in place, creating kettle topography in the proximal part of the end moraine. If, again, the glacier were to become more active, it would push the snout of the outlet forward, whereupon this would plow the summit of the end moraine more vigorously than the ground on the proximal side of the moraine, because the ice is there detached from the base.

Apparently it is in the latter fashion, *i. e.* through oscillation of the thin margin of the glacier, that the end moraines along the bank of the Hanypá river, in front of the einabergsjökull, have originated. They comprise four successive ridges situated on the south side of the river a full half a kilometer from the present ice margin. The section eroded by the river shows how the end moraine ridges lie on top of the glacifluvial gravel beds. The nearly horizontal gravel strata continue without any deformation under the end moraine (Fig. 21, Plate XI). The border between the end moraine and the glacifluvial material is abrupt. The end moraine consists of relatively coarse, gravelly and sandy but plainly unsorted till (Fig. 19 p. 42). The orientation of the stones is weak, though small maxima are to be noted in the directions of 320° and 230° (Fig. 20 d, p. 44). The former corresponds to the direction of the apparent motion of the glacier, for the ice margin lies in this direction from the observation site, while the latter runs parallel to the longitudinal position of the ridge. A more distinct orientation maximum (Fig. 20 e, p. 44) occurs at the summit of the end moraine along the margin of Heinabergsjökull. The material is clayey till and the longitudinal axes of the stones in it lie parallel to the apparent direction of the glacier motion, for 40 % of the directions measured ranged between 280 and 300 degrees, the margin of the ice being about 50 m from the observation site in the 290° direction.

The end moraine of Breidamerkurjökull forms a ridge chain nearly 30 km long and 1—2 km broad. In places streams have eroded channels through the end moraine. Their gravel beds slope seaward between the hills. In the main, however, the end moraine forms a uniform crescent rising above its surroundings and separating the sandur from the irregular, lowlying and in many places water-filled ablation area. The surface of the sandur starting at the distal side of the end moraine is situated higher than the base level of the proximal side. The glacier snout is also below the level of the sandur. The glacier must have extended beyond its present margin and been thicker at the time the end moraine and proximal part of the sandur had formed. The visible margin of the glacier has by now become detached from the great end moraine at every point.

Along the eastern margin of the tongue the end moraine has broken up into hills and small ridges, which the dry beds of streams once flowing from the glacier separate from each other. According to Thoroddsen (1905—06) the erosion action took place in 1869, when the Vedurá river overflowed its banks and flooded the fields cultivated down the coastal plane. Subsequently the wind levelled out the end moraine hills, which from a distance resemble dunes (Fig. 24). The zone of knolls is about a kilometer broad and over five kilometers long. It forms a unified arc, in front of which begins an outwash plain terminating in the sea. The surface of the knolls consists of drift containing sorted, rounded stones. At least in some spots it is stratified and the layers dip upstream. They are loose and sandy, resembling the surface layer of the sandurs. A fabric analysis of such material was carried out on the summit of the easternmost end moraine hills yielded a broad but weak maximum between the directions 210°—255°. This corresponds by and large to the apparent course of the glacier during its advance, inasmuch as it is very nearly perpendicular to the orientation of the ridge (320°—325°).

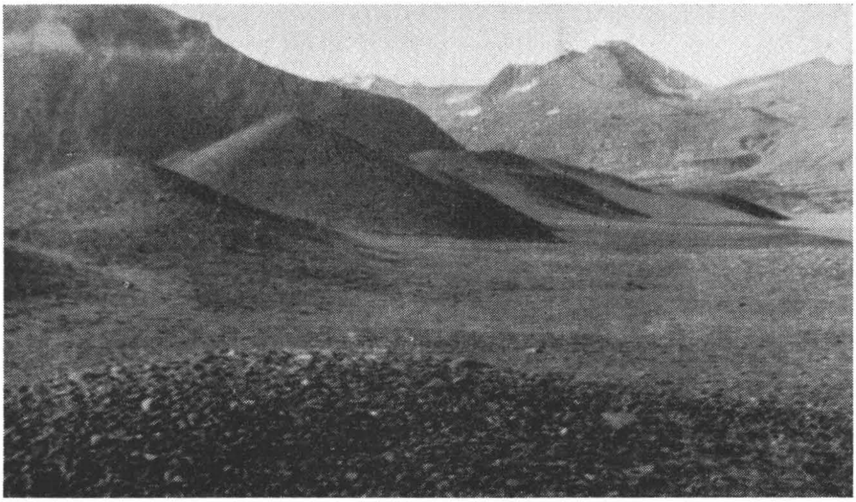

Fig. 24. The end moraine of Breidamerkurjökull appears in its eastern part as a group of separate, dune-like hills. The glacier on left.

By and large the frontal moraine of Breidamerkurjökull is a coherent, broad and lofty group of ridges, whose parallel crests alternate with the long and narrow depressions in between. The sides of the frontal moraine are fairly even and slope about equally steeply both toward the sandur and the glacier. In places the distal side, the lower slope of which forms a distinct angle with the sandur, is steeper than the proximal side, which runs directly into the ablation area. Moreover, the distal slope is drier and has more vegetation than the proximal slope, which is sheltered from the winds. The middle part of the frontal moraine consists of several ridges, the summits of which ascend to different levels. The structure of such a ridge becomes evident in the old river bed, which intersects the end moraine about six kilometers from its eastern end. Although the section has collapsed, primary strata could be observed in them. In both sections they began at the upper slope of the distal part of the moraine ridge and inclined upstream (Fig. 22, Plate XI), but their slope varied and many of the layers were weakly folded. In the northern wall could be seen the thin, folded peat layers photographed by Leiviskä (1928) and Todtmann (1936) and in the southern wall too could be distinguished corresponding pieces of grass-peat in the collapsed gravel. The intersection consisted almost altogether of sorted sediments, for only at the summit of the ridge and in the section continuing from it to the upper part of the proximal slope there occurred a layer of till 2—3 meters thick. Many of its stones were cobbles, but their surfaces were scratched and the mass between the stones was dense clayey till, revealing a press structure (Fig. 23, Plate XII). A fabric analysis of the till yielded a clear maximum in the direction 345°—360°, paralleling the motion of the glacier. Inasmuch as the direction of the frontal moraine itself was 40°—220°, the orientation of the till produced a 40°—55° angle with the moraine. Underneath the till of the frontal moraine there occurred densely packed both fine and coarse sandy sediments. Such layers were met with under, between and on top of the peat beds (Fig. 24, Plate XII). Toward the surface their material became coarser, and in the upper part of the southern wall it was covered with a loose gravel of roundstones, extending up to the surface of the ground and forming there an esker-like ridge in the direction 40°—220°. A fabric analysis (Fig. 20 f, p 44) carried out on this ridge gave a distinct maximum parallel to the direction of the glacier motion. (The glacier was situated in the direction 325° from the observation site.) Since the material was so plainly oriented, it must be considered ground moraine, though it is not as dense as on the northern side of the river bed. Apparently the glacier had advanced on top of the »push» moraine; and it had accumulated earlier, transporting basal load there, as Leiviskä (1928) and Todtmann (1936) have explained.

The frontal moraine is intersected by the Jökulsá river, starting from the glacier. The fresh section of the eastern bank of the river showed that the moraine at this point consisted of sorted material, in which the stones were rounded pebbles less than 10 cm in diameter. Between the layers of stone there occurs sand beds. Both of them slope downstream from the glacier. The layers receive this slope already on the proximal side of the ridge and continue in the same direction throughout the entire 20—30 meter broad ridge. The slopes of the ridge are steeper and intersect the stratification, possibly being erosion forms.

On the western side of Jökulsá the frontal moraine spreads out and rises higher. It reaches its greatest magnitude at the point where the medial moraine meets the terminus of the outlet. The coarse material of this medial moraine, with its large boulders, covers the frontal area up to the distal side of the end moraine.

The Hrutá river starting from the western part of Breidamerkurjökull has eroded a channel for itself, like Jökulsá, through the frontal moraine. The section from the eastern bank of the river (Fig. 25) shows the frontal moraine to be composed of 3 parts: at the bottom an even-surfaced basal till making up the base of the whole ridge, a sediment overlying it in an undisturbed position and consisting of almost horizontal strata, and uppermost a till layer covering the sediments at two sites. One of these forms the proximal slope of the ridge and joins toward its bottom the till below and the other appears as a separate occurrence at the upper part of the distal slope. On account of the strong current the author could examine the occurrence only from the opposite bank of the river. From there one gained the impression that the ice had advanced over the place twice and that between the two advances there had been a peaceful sedimentation phase. In the sediment could be seen about 0.6 meters from the bottom a light yellowish ash layer in an undisturbed position. The later advance of the glacier had worn part of the sediment away but had not deformed the remaining part. Although the ridge in cross-section and orientation is a frontal moraine, it should perhaps more correctly be regarded as an

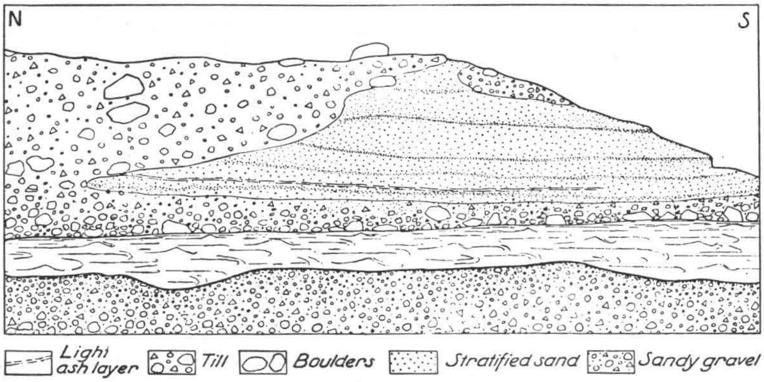

Fig. 25. A section of an end moraine at the river Hrutá in front of the western part of Breidamerkurjökull. The glacier has moved from the north (left), carrying till on stratified sand without disturbing its strata. The section is c:a 5 m high. Drawn after a picture taken by the author.

erosion form, because only its proximal slope had gained its shape (and substance) as a result of direct glacier action.

On the hills on the western side of the Hrutá river there occur several successive moraine ridges, which run parallel in winding bands 100—300 meters long. They are 2—4 meters high and 10—15 meters broad at the base. The ridges are oriented southeast by northwest and they are situated on a slope slightly rising in the WSW-direction. At numerous points the northeastern slopes of the ridges were covered with blocks, whereas the southwestern slopes were sandy. These ridges were of the so-called annual moraine type, though exceeding in size ordinary annual moraines. Since the glacier had retreated long before, the manner of their origin could not be judged solely on the basis of the moraines. The topographic conditions, however, make it certain that the stony northeastern sides are proximal and the sandy sides distal slopes. On the other hand, it remains undecided, whether the ridges represent frontal or lateral moraines. The occurrence of glacial striae in the compass direction 325°—330°, about one kilometer southward from the end moraines, at Kvísker, strengthens the case for lateral moraines. This interpretation is also supported by the fact that on the eastern side of Hoffelsjökull by Gjánupsvatn, there occurs on the mountain slope the same type of lateral moraine, which indicates the position of the glacier flank in 1890 (Thorarinsson 1937 a p. 192).

Kviárjökull, situated on the western side of Breidamerkurjökull, descends in a form of an elongated and narrow valley glacier the south-

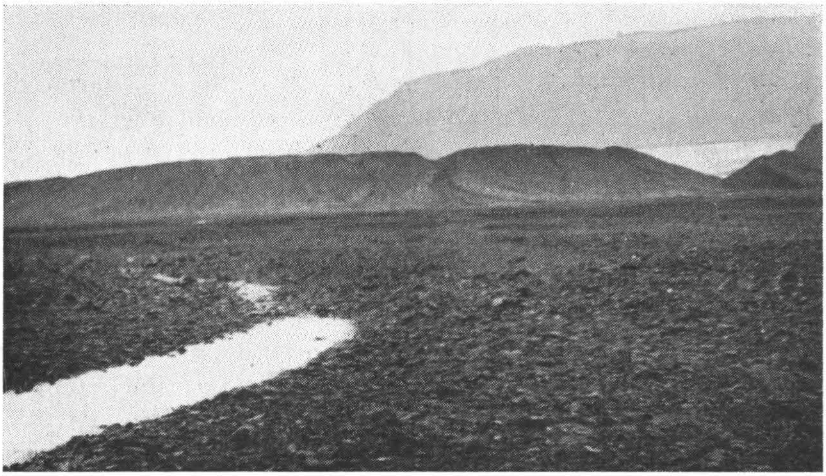

Fig. 26. The high terminal moraine of Kviárjökull seen from the east. In foreground, a ground water pool (light spot) on the sandur forms the start of a clear-water brook.

eastern slope of Öræfajökull to the coastal plain. This glacier has become known for its great end moraines (Thoroddsen 1905—06, Spethmann 1912, Todtmann 1936 and 1951, Hoppe 1953), which rise up from the low-lying coastal plain to heights of more than a hundred meters (Fig. 26). The frontal moraine is cut by a river starting from the glacier. The distal slope of the frontal moraine as well as the upper part of the sandur bordering it is sandy and covered with moss. Here and there on the distal slope are isolated blocks, some of which are very large (e. g. one measuring an estimated 7 × 7 × 7 meters) and they appear to have rolled down from the summit of the frontal moraine. The slope facing the glacier was bare and somewhat steeper than the distal slope, and traces of earth flow were to be observed in it. Also water flowing from the moraine had worn furrows into the proximal slope. This slope sinks lower without any clear boundary to become an ablation moraine, whose depressions are filled with water. Ice could be seen here and there and the ablation moraine gradually altered into broken-up ice covered with drift. The ice had turned stagnant by 1931 and the margin of the living glacier had forced up a transversal moraine on top of the dead ice (Todtmann 1936).

High frontal moraines like the end moraine of Kviárjökull occur in front of other hanging glaciers flowing down from Öræfajökull, such as Rotárfalljökull and Falljökull. The frontal moraines of the broad and gently sloping outlet glaciers are lower than the foregoing and form irregular groups of knolls. Their belt separates the sandur from the ablation moraine. Broad ridge and knoll zones occur along the margins of e. g. Svinafellsjökull and Skaftafellsjökull.

In front of Morsárjökull there are two frontal moraines crossing the valley. The outer one is of greater dimensions and more irregular than the inner one. The outer ridge has several short crescents, the convex sides of which face away from the glacier. The slopes of the furrow-like depressions between the crescents are asymmetrical in such a way that the side facing the glacier is generally steeper than the one facing away. The material of the crescents consists of fairly dense till. The longitudinal axes of the stones lie parallel to the motion of the glacier. This shows that the crescents were formed out of load directed by the motion of the glacier. They could have been thought to originate by the ice's having brought several sheets of basal load to the end moraine. These sheets overlap obliquely in layers sloping backward. The bed structure is visible also in the river bank at the northern part of the end moraine. It had, however, collapsed to such an extent that it was impossible to determine whether the whole end moraine had been composed of till or whether the till constituted only a surface layer. Layers of glacial drift rising obliquely upward are also to be seen at the low glacier margin sinking into meltwater and already drawn back from the frontal moraine (Fig. 25, Plate XIII). When the ice melts from in between the drift layers a sheet structure results also in the proximal side of the frontal moraine.

The frontal moraine of Skeidarárjökull is situated like the aforementioned between the sandur and the ablation moraine. The frontal moraine here consists of several sections separated by flat-bottomed gravel beds joined to the sandur. The short ridges of the frontal moraine running parallel to the ice margin are primarily irregular of surface (comp. Leiviskä 1928 p. 192), but in the view of the present author their shapes are also results of secondary deformation. Thus, the wind has both eroded and in places levelled out the original surface form. Glacifluvial streams have had an even greater effect on the frontal moraine. The often recurring glacier outbursts have broken the frontal moraine at many points. Likewise the present glacifluvial stream erodes it. E. g. the Kvistár, the middle one of the three streams starting from Skeidarárjökull, has changed its bed and worn away the frontal moraine on each side of the stream. In the same way the western part of the crescent has eroded into mounds called »Sandgigurs». The easternmost branch of the Nupsvötn has cut through one of these mounds. The section discloses the proximal part and middle of the ridge to be till rich in boulders. Near its upper surface there occurs in the till a fragment of a sandy layer about 20 cm thick, covered with boulders. In the distal part of the ridge the till is buried in sand, which forms the distal side of the frontal moraine. It joins the surface of the sandur as an embankment. The sandur layers continue under the sand up to the till. The border between the till and sand slopes sharply and more steeply than the distal side up to the level of the waterline of the stream. The formation has thus been built up of two different kinds of material, till and sand. They appear to have formed in such a way that the ridge of till accumulated first and only after that was the sand deposited on its distal side. Judging from the direction of slope of the layers, the sand had been deposited by water streaming from the glacier over the frontal moraine. Apparently, subsequent to the accumulation of the moraine, there had taken place such vigorous glacifluvial action that the end moraine was submerged. The water flushed the surface layer of the moraine and caused a sandy margin to accumulate along its distal side. The moraine evidently constituted at this point such a firm obstruction to the erosive action of water that the flood was unable to destroy it, though elsewhere it succeeded in breaking up the end moraine crescent, insofar as such a ridge ever occurred unbrokenly. As the end moraines of Skeidarárjökull have been subjected to greater erosion than the other tongues of Vatnajökull, it is natural that in its marginal moraine there should occur deviating forms and structure.

According to the view of the present author, the great end moraines in the frontal terrain of Vatnajökull's outlets originate during a more active stage in the life of the glacier than the present. The ice tongues extended farther at that time and were thicker than now. The snouts of the outlets have then folded the accumulations in the frontal terrain by pushing, and finally the glacier had advanced up to the »push» moraines thereby created, bringing basal till onto their surface. Furthermore, the observations made at Morsárjökull indicate that at least in places basal till had risen within the ice obliquely already at the time when the glacier extended as far as the end moraine.

In some spots the glacier terminus still extends up to the proximal part of the end moraine. The end of the snout usually melted free from its base forms an overhanging projection roughly in the shape of the pointed end of a ski, from which fragments of ice fall into the mushy till (p. 45). From the imprints made by the falling chunks and the till squeezed to the side there form hollows and miniature ridges in the proximal part of the end moraine. Besides these, only recessional moraines accumulating apparently in winter and the *Absatz*-moraines constructed through the detachment of border crests are in process of formation during the present stage. The creation of end moraines under current circumstances is rare, however, for the ice margin thins down so rapidly that it loses its power of motion and turns stagnant. Between the stagnant part and the living ice beyond, end moraines still form even at present by the edge of the live ice, thrusting over the dead ice and lifting basal till over it to produce a transversal moraine. When the ice melts from under the transversal moraine, it becomes deformed into a knolly and hollow-studded end moraine.

In general, the topography of the end moraines of Iceland is irregular, for even the large arcuate end moraines have formed out of short ridge mounds and the hollows produced by dead ice in between them. Moreover, streams have cut channels through the end moraines. From the stream sections it can be observed that the material of the end moraines is partly till and partly sediments from the frontal terrain. In addition, the end moraines contain superglacial drift mixed in with the till. Together they form inclined beds in the end moraine. A gently sloping distal side formed of stratified layers is a rarity in the end moraines of Iceland; and such a structure appears to have resulted only from exceptionally powerful glacifluvial action. Usually, the distal slope of an end moraine is clearly distinguishable from the sandur surface bordering on it, for the inclination of the latter is slighter.

ON THE GLACIER FLOW

The occurrence of glacial drift in the ice depends not only on the origin of the drift but also the movement of the glacier. On the basis of the drift, conclusions may thus be drawn regarding the mechanism whereby the drift is transported from its place of origin to the site of its occurrence. The migrating drift on top and inside the ice reflects the current behavior of the glacier, while on the basis of drift accumulations previously freed from the ice it is possible to reconstruct the behavior of the glacier at the time they were being formed.

Among moraines met with on the surface of glaciers, most interest is excited by medial moraines, which stand out distinctly from their surroundings (see p. 27). The longest of the medial moraines in Iceland, the great one on Breidamerkurjökull, indicates that the ice collects at the intake of the ice tongue in the center of the valley. The ice mass accumulating here continues its flow toward the terminus pretty uniformly. Only at the margin does the motion of the glacier begin to diverge, as evidenced by the spreading out of the medial moraine. The medial moraines starting from the nunataks situated farther down do not move toward the center during transit but run parallel to the winding course of the ice stream and remain the whole time at the same distance from the center line of the glacier. Inasmuch as medial moraines preserve the same shape for a long time, the movement of the ice tongue transporting the moraine must take place along the same courses, apparently determined by the topography. On the other hand, the fact arrests attention that medial moraines do not develop from nearly every nunatak. According to the present author's conception, the ice bordering on such nunataks is so thin that it no longer erodes their sides but melts free at bottom and becomes thinner from the effect of the heat stored up in the nunataks more rapidly than the ice farther away. As it wastes away both at the base and on the surface, the edge of the ice around a nunatak loses its erosive power.

The flanks of ice tongues likewise border in many places on warm mountain slopes. The edge of the glacier thins down in such cases, too, more rapidly than in the middle. In suitable spots between mountain and glacier there form ice-dammed lakes. The ice does not, however, fill their basins; but its main flow parallels the length of the outlet. Glaciers thus behave differently from flowing water, where pressure is distributed evenly in all directions (Flint 1947 p. 16). The transformation of lateral moraines into ablation moraines already in places where the middle part of the tongue is in motion as well as the process of detachment from the »living» ice offer evidence of the friction's growing so great along the flanks of the outlet that the main body of the glacier no longer is able to drag along the passive marginal ice. Between them there open up, as a result of the tension, crevasses, which separate the stagnant ice from the moving glacier.

The volcanic ash layers and dirt bands occur on the glacier in corresponding fashion: they form thin parallel bands that ascend forward between sheets of ice. The layers have not spread out nor scattered during glacier transport. This indicates that at least the rigid crust of the glacier moves as a sheet and its component parts advance at the same velocity. It also explains the fact that the material of the dirt bands does not undergo wear during transport but that e. g. the pollens contained in it remain intact and recognizable. Likewise the stones caught in the ice preserve their original form. The dirt bands and accumulations of ash travel to the ice margin in such a way that their flanks lag behind the center and turn parallel to the sides of the tongue.

The transversal moraines occurring in the terminal part of an outlet resemble in appearance dirt bands and ash layers, proving that the movement of the glacier is here inclined upward. The material of transversal moraines is, in many cases at least, thawed-out, mushy till, which is squeezed out onto the surface through transversal crevasses. Such a crevasse evidently acts as a shear plane (Philipp 1920, Seligman 1943). Till also may rise under hydrodynamic pressure (Nicols and Miller 1951 p. 278). Transversal moraines appear most distinctly along the border between moving and stagnant ice, but more commonly the snout of an outlet is divided into numerous successive sheets of ice separated from each other by drift bands. The movement of the glacier ends then by advancing along an upward inclination at a rate diminishing sheet by sheet toward the terminus. The friction in the basal part of the glacier must accordingly be greater than in the corresponding part of the surface layer, inasmuch as the ice at the bottom does not advance in the snout at the same rate as the ice layers overlying it. Since also the stones occurring in the sheets of ice and the hollows left in the ice walls upon their falling out are so situated that their longitudinal axes lie forward at an upward gradient, movement in this direction has taken place within the sheets too. The observations of the present author do not suffice to make it clear whether this motion is intergranular or whether it takes place also within the ice crystals (comp. Rigsby 1951, Sharp 1954), but they suffice to prove, in any event, that movement has not confined to the shear planes but occured within the ice as well. Motion directed along an upward gradient occurs in the snouts of outlets terminating as valley glaciers on a rock floor sloping downstream. The same kind of glacier movement may be noted also on the snout of Breidamerkurjökull, which, according to seismic soundings is situated on nearly an even floor. As Breidamerkurjökull forms an expanded foot at the coastal plain, an upwards-inclined movement of the ice occurs likewise at the margin of a Piedmont-type glacier. Upwards-inclined sheet movement has been described from the margin of Skeidarárjökull too (Todtmann 1936), where the snout has been observed to lie higher than the glacier bed behind it (Thorarinsson 1939 b p. 205). Thrust planes are met with, furthermore, in the terminal zones of Hoffelsjökull and Heinabergsjökull, where the border of the tongue rises uphill to the proximal slope of the end moraine. The obstructed flow thus occurs in the termini of the southern outlets of Vatnajökull regardless of the slope of the floor.

This type of movement is not characteristic of the southern margin of Vatnajökull alone, but it is encountered elsewhere in Iceland, too. As shown in Fig. 9 p. 23, the drift bands incline upwards on the ice cliff of Langjökull terminating in deep water of Hagavatn (Wright 1935). Transversal moraine bands occur also on the snout of the outlet terminating in the valley on the eastern side of Hagavatn, which snout lies on either a flat bed or one sloping gently downstream. Transversal moraines are to be observed even more distinctly on the surface of the broad lobes terminating in the highland of the northern margin of Vatnajökull (Spethmann 1909, Woldstedt 1937, 1939, Hoppe 1953). According to Hoppe's observations (op. cit.), accumulations like this occur especially on Bruárjökull, which resembles in shape the margin of an ice sheet terminating on flat ground.

Marginal ice thus moves along upthrust planes of the outlets, expanded feet and broad ice lobes of Iceland. Inasmuch as the slope of the floor does not seem to affect the manner of motion of the ice margin, it is evident that this motion results from the general behavior of the present glaciers of Iceland. In consequence of it, basal load rises within the ice in the shape of bands until it forms on the surface moraine bands running parallel with the margin. On Hoffelsjökull, Svinafellsjökull, Breidamerkurjökull and the ice tongue of Langjökull on the eastern side of Hagavatn the transversal moraines terminate at an elevation of less than 10 m from the terminus. On the ice cliff terminating in the waters of Hagavatn, they rise higher from the ice floor — an estimated 30 m. Likewise, at the margin of great Skeidarárjökull the moraine beds extended up to the surface in the 40 m-high ice cliff. On Bruárjökull the ground moraine at times travels to a height of several dozen meters (Hoppe op. cit. p. 248). As the transversal moraines usually come to an end at a distance of 100—200 m from the ice margin and as the strata carrying basal load dip backward, motion of sheets of ice reaching all the way to the bottom takes place only in the outermost part of the glacier. This is observable from the fact too that the crevasses of Hoffelsjökull extended below the level of the snout and that no drift was to be seen in their walls. The rising up of moraine onto the surface of the glacier causes in turn a retardation in the melting of the ice covered by it and the formation of border crests paralleling the margin. Under certain conditions, such as when a tongue has extended far below the climatic snowline and melts rapidly on its surface, a fosse develops behind the ice underlying the border crest; this eventually causes the border zone to become detached from the glacier proper. Thus the mechanism governing the motion of the glacier margin promotes the formation of stagnant marginal ice as well as creating irregular ablation and end moraine topography.

The accumulations of glacial drift that occur outside the ice margin, having lost contact with the glacier, afford an opportunity to investigate whether the aforedescribed movement mechanism of the glacier margin is characteristic only of the present stage of melting or whether the same kind of activity can be demonstrated to have taken place also earlier, when the glaciers of Iceland were larger than at present.

The thinning of the southern outlets of Vatnajökull has taken place so rapidly in recent decades that even the observations of Leiviskä (1928), Spethmann (1912) and Thoroddsen (1905—06) bring out differences in the ice margin as compared with the present. The ice tongues extended in their day to the great end moraines and the snouts were steeper and thicker than nowadays. The surface of the ice margin was in numerous places covered with surface moraine to such an extent that it was sometimes difficult to determine where the true margin of the glacier was situated. The moraine had, as Thoroddsen (op. cit.) mentions, risen to the surface of the glacier in layers inclined up toward the margin. Leiviskä (op. cit.), again, emphasizes the importance of englacial load as the carrier of the material of both eskers and end moraines, pointing to the observations made by him in Iceland. From the foregoing and other accounts dating back to the same period, it may be judged that obstructed flow had taken place also during the time when the tongues were larger than they are now. Simultaneously, there formed in front of the tongues large end moraines, the topography of which reveals that dead ice was buried underneath. Their formation in front of glaciers terminating on land can hardly be understood otherwise than by conceiving the ice margin as having operated in the way herein depicted. The structure of the end moraine of Morsárjökull, in particular, supports the conception of the ice moving obliquely upward. If this motion for some reason becomes stronger, the terminus of the ice tongue glides easily, like a ski, over the accumulations in the frontal terrain. Those accumulations standing in the way of the advancing snout are thereupon chiefly subjected to erosion. Push moraines are the result. It is from such material that the cores of the great end moraines are produced in front of both the southern tongues and the broad ice lobes terminating in the interior to the north (Spethmann 1912, Thorarinsson 1938 p. 495, Woldstedt 1954 p. 31). A marginal moraine of this kind came into existence along the northern edge of Vatnajökull e. g. in 1890, when the margin of Bruárjökull suddenly advanced. The advancing margin of the glacier thus creates an obstruction in its path and surmounts it.

Such behavior of the glacier margin is evidenced at numerous points. The end moraines appear on top of undisturbed layers at the Hanypá (p. 62) and Hrutá rivers (p. 65). The erosion of the floor by the ice margin has been extremely slight also in front of Heinabergsjökull, where the ice has advanced over the ground moraine and eroded its uppermost stones in the direction of the movement (p. 45). In the frontal terrain of Langjökull on the eastern side of Hagavatn the glacier has advanced across the same spot twice, without the later advance having erased the traces of the earlier erosion (p. 47). Even in the moraine the orientation of the stones caused by the earlier advance remains.

The observations presented in the foregoing regarding the transportation of glacial drift on the surface on the ice and within it show that the drift travels at the same velocity as the ice mass carrying it. The drift exposed from the bottom of the glacier reflects other conditions. It forms load in the basal part of the ice, increasing in quantity toward the bottom. This load is oriented in the ice of Hoffelsjökull and Breidamerkurjökull in such a way that the longitudinal axes of the stones are parallel to the ice movement. To judge from this, internal movement takes place also about the base of a glacier, during which its parts shift in relation to each other. There is only a slight amount of basal load in the bottom layer of marginal ice, for the main part of it melts free of the glacier earlier, forming ground moraine. This is pressed tight underneath the ice and preserves the orientation given it during the glacier motion even after the ice margin has advanced over it once more. The transportation of basal load thus takes place underneath the thick ice mass behind the margin. Without knowledge of the petrology of the glacier floor, it is impossible to judge how far the basal load has traveled during its transport, how rapidly it has eroded and where it has started to become detached from the ice carrying it. It is apparent that the accumulation of basal load depends both on the friction prevailing on the bottom and the formation and location of meltwaters. Inasmuch as both factors vary underneath the ice at different points, basal load accumulates irregularly during transport. The main erosion and transport of a glacier thus occur subsurficially and cannot be observed except by applying very special methods. Conclusions concerning this movement mechanism have been reached on the basis of the erosion forms of the rock bed as well as glaciological observations, and they have led to numerous theories of ice flow (see e. g. Sharp 1954).

From the erosion forms of the rock bed, the basal part of a glacier has been thought to move like a plastic mass (e. g. Demorest 1937, 1938, 1939, 1942). The theory has been supported by the evidence of so many investigations that it may be regarded as having been demonstrated to correspond to the facts. Moreover, observations have been made in Iceland (Hoppe 1953), which show the movement of a glacier to follow the microrelief of the floor. The present author clearly noted the same phenomenon in the rocks of Svinahryggur recently exposed from Hoffelsjökull (Fig. 26, Plate XIII). They form several less than 1 m-high »roches moutonnées», on the surfaces of which glacial striae are clearly visible. Even 0.5 m-high knobs of smooth outcrops divide the striations into two systems, turning around each side of the rocks. On the lee side they come together to form parallel striae again. The motion of the base of the glacier thus seems to have molded the detailed topography of the base and become adapted to its forms. Such motion calls for plastic ice. Since the very finest striae in the rocks have been produced under plastic ice and since they have remained fresh and unmarred, the rock no longer eroded after the glacier had lost its plasticity. According to Flint's conception (1947 p. 17), the rigid crust of a glacier extends to depths of 100 to 200 feet, below which added pressure causes the ice to flow together and close up all openings. Under certain conditions open tunnels have been encountered in ice even deeper (comp. Battle 1951 p. 563), which presupposes an even thicker rigid upper zone of ice.

Another proof of the plasticity of the ice eroding a rock bed is afforded by the gouges in the outcrop in front of Morsárjökull. They have eroded nearly vertically in the rock wall situated parallel to the movement of the glacier at the foot of the southeastern slope of the valley. The smooth surfaces of the gouges together with the thin and sharp striations in them show that ice impregnated with drift had pressed against the rock and eroded the gouges into their present form. The basal zone of the glacier has, in other words, striven powerfully in the narrow valley to expand sideward. There are no other signs of erosion at this point; but somewhat nearer the glacier, within the large end moraine, younger striae are also to be noted in the same vertical wall. They form a fan-shaped system of striae opening in the direction of the ice flow at a slant upward. Since in the end moraine there occur overlapping till sheets inclined in the same direction (p. 67), and since in the ice within it there can be seen drift bands that have risen at a slant upward (p. 67), these slanted striations must be regarded as evidence of obstructed flow occurring in the glacier margin. They are, accordingly, younger than the gouges worn by the aforesaid plastic ice. Erosion marks of two different ages occur also along the eastern side of Hagavatn, in front of Langjökull (p. 47).

The erosion marks on the rock bed accordingly demonstrate that the bottom zone of a glacier moves plastically and carries enough basal load to erode its base. The ice under such conditions must be subjected to strong pressure. Forms revealing such strong pressure, plastic ice and heavy erosion have either survived as the sole marks of glacial erosion in the rock bed or are clearly visible underneath erosion marks of later origin. This proves that a thinner mass of ice has operated at the later date, causing weaker erosion than the earlier thick ice; in fact, often the erosive action of the thin ice has not reached down as far as the rock floor at all.

The erosion marks on rock surfaces lead, together with a study of glacial drift, to the following conclusions:

1. Ice motion begins from the accumulation area either in such as way that the ice mass collects into the intake centers created by the topography and from there it presses out in the form of tongues or in such as way that the ice moves in a broad front outward from the firn area.

2. The movement of the upper zone is at first evidently directed at a slant downward, but in the ablation area it turns obliquely upward.

3. The surface ice of outlet glaciers advances toward the snout as a firm and rigid crust in such a way that its parts move along parallel winding flow lines. The movement is more rapid in the middle part of the tongue than at the edges or along the borders of nunataks.

4. If the glacier is sufficiently thick, its lowermost part flows like plastic material and erodes its base most. The motion in such cases takes place within the ice mass.

5. At points of obstruction the motion is retarded, while downhill in the direction of the flow it speeds up, whereupon the surface of the glacier is fractured.

6. The movement of the glacier in the marginal zone at an upward grade extends down to the base, where sheets of ice and the thrust planes between them lift basal load to the surface.

7. At the glacier margin the motion ceases in such a way that the sheets of ice separated by thrust planes slide over each other and this upward-inclined motion decreases from sheet to sheet toward the terminus.

8. At the frontal margin of the glacier and along the flanks of ice tongues there forms drift-covered stagnant ice, which participates in the movement of the glacier only in rare instances.

These conclusions are supported by measurements carried out at Hoffelsjökull (Thorarinsson 1939 b) and referred to on p. 14. Comparing his observations on ice flow with various theories, Thorarinsson concludes that in different parts of the same glacier appear different kinds of motion. At Skeidarárjökull he has seen the »Scherflächen» of Philipp (1920), at Kviárjökull »shear overlapping» (Todtmann 1936), and the meandering movement observed at Skeidarárjökull and Hoffelsjökull indicates plastic flow in certain parts at least, while in the more rapidly flowing parts of these glaciers there likewise occurs »block movement» or »Schollenartige Bewegung» (Finsterwalder 1929, 1931 and 1937).

The several theories presented in regard to glacier movement differ among themselves when dealing with the movement of ice on a horizontal and even floor. The basic conception behind the various theories may be illustrated, after Perutz (1953), by means of a rubber tube imagined to be forced vertically through the ice and subjected to deformation by the motion of the glacier. According to the main theories, the tube would behave in the ice in the manner shown in the illustration (Fig. 27).

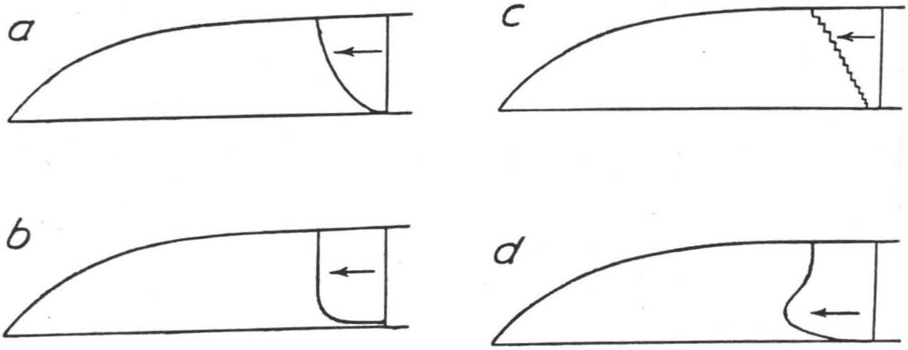

Fig. 27. Distribution of velocity along a vertical line through a glacier according to the main theories of ice flow (across on even floor): a. viscosity theory, b. plasticity theory, c. thrust plane theory, and d. extrusion flow theory. According to Perutz (1953).

According to the *viscosity theory* (Somigliana 1927), the tube representing the movement would be deformed into a parabola, wherein the part at the bed would remain stationary and the uppermost part advance most.

According to the *plasticity theory* (Hein 1885, Hess 1904), the lower part of the tube would be considerably bent while the upper part would remain vertical, inasmuch as ice must attain sufficient thickness before it can become plastic. The action of the glacier would thereupon be concentrated near the bed.

According to the *thrust plane theory* (Chamberlin 1894—95, Philipp 1920), the rubber tube behaves after the fashion of a broken line, the lower end of which moves least and the upper part most. The movement would take place along the shear planes within the ice in such a way that the uppermost layers slide forward more than the ones beneath them.

According to the *extrusion flow theory*, the tube is deformed in such a way that fairly far down there appears a bulge representing strong, fast flow within the glacier, while the movement in the surface zone and, especially, at bottom lags (Demorest 1937, 1939, 1942, Streiff-Becker 1938).

None of the theories herein presented can be considered as explaining the flow mechanism of a glacier, however, until it is backed up by precise measurements. This state of affairs has spurred researchers to elucidate the laws whereby glacial ice flows and to demonstrate in practice their validity. In recent years the theory of plasticity, in particular, has gained new supporters, for both the theoretical calculations (Glen 1952, Nye 1952, Körner 1954) and measurements carried out on glaciers (Perutz 1950, Haefli 1951, McCall 1952, Sharp 1953 a and b) consistently weight the scales down in favor of this theory. On the other hand, the plasticity theory has been criticized especially on account of the fact that the ice does not appear to turn plastic as a function of pressure, as presupposed in calculations, but the phenomenon is affected also by other factors, such as the formation of meltwater, the air content of the ice as well as the friction at the bottom (Sharp 1954).

The theoretical calculations together with observations made up to now thus lead to the conclusion that the surface crust of ice advancing over a flat floor is transported to a depth of about 100 m by the underlying plastic layer at approximately the same velocity but that lower down the motion slows down gradually toward the base, where the internal velocity of the glacier approaches zero. Such an explanation is in conflict, however, with the fact of erosion along the bed of the glacier, which remains unexplained. The floor of a glacier is seldom an evenly inclined plane. Usually the ice advances across a base made up of small basins alternating with steps. Accordingly, one might expect the topography of the floor to affect velocity in such a way that when the ice descends over a step it moves faster and becomes thinner whereas in the basins the ice thickens and simultaneously loses speed (Perutz 1953). According to Nye's calculations, the differences in the thickness of the ice cause the velocity distribution to be distorted from a straight line to an ellipse (op. cit.). This, in turn leads to stress and the production of shear planes intersecting the surface at a 45° angle. The sheets of ice sliding along these thrust planes erode the floor of the glacier, pick up the debris and carry the load up toward the surface. This would explain the erosive action along the glacier bed. It has been demonstrated through observation (Lewis 1949, Clark and Lewis 1951, McCall 1952) that the motion of a glacier takes place by rotation around an imaginary horizontal axis. Since these observations have been made in the ice cirques of Norway and the valley glaciers of Switzerland, generalizations cannot probably be made to the extent of also explaining the flow mechanism prevailing in the continental ice sheets. Only the future can show what importance the glacier rotation might have in explaining the floor erosion of ice sheets.

If the conclusions presented in the foregoing (p. 76) regarding the movement of glaciers in Iceland are compared with these theories, it must be affirmed that they do not suffice to decide according to what theory the glacial ice of Iceland moves. The erosion forms of the rock bed and the structure of the ground moraine show that the part of the glacier toward the base flows under pressure after the manner of a plastic mass, whereas the surface zone is rigid and brittle and rides on top of the flowing lower strata of ice. If the glacier thins, as happens both on the surface and at the base by melting, the rigid surface layer turns stagnant and moves only when pushed from behind.

In regard to the flow mechanism of the glacier margin, the different theories approach common ground. On the basis of the majority of them the motion of the glacier in the marginal zone is inclined upward, whether the margin in question be that of a valley glacier or continental ice sheet. This motion has been termed by the author obstructed flow, in conformity with most other researchers; and, as has been shown in the foregoing, the phenomenon is met with quite generally in the marginal zones of the glaciers of Iceland today. Examination of the accumulations of glacial drift and earlier observations made in Iceland prove that obstructed flow had taken place also in the past, when the glaciers of the island were more extensive than now and their margins extended to the great frontal moraines. As such a flow mechanism in an ice margin is independent of both the shape of the margin and the topography of its bed, it is evident that obstructed flow belongs to the mechanism of movement characteristic of the glacier types of Iceland. As a consequence of it, basal load rises in the marginal zone of a glacier to the surface of the ice, forming englacial load and increasing the amount of surface drift. Obstructed flow also causes the ice margin to erode its bed only slightly during an advance of the glacier. The erosion zone proper is situated farther back, underneath the thicker ice mass.

GLACIER DRAINAGE

The glacifluvial deposits produced as a result of action by water flowing from glaciers are an essential part of the glacial drift of Iceland. As the origin and appearance of these deposits depend directly on the action of water, it is necessary to consider the drainage of Icelandic glaciers before dealing with the glacifluvial deposits.

The abundance of water run off the glaciers is determined by both the annual precipitation and the amount of unevaporated meltwater. Together they bring it about that from the southeastern and southern parts of Vatnajökull there flows into the sea such a volume of water that it has been compared to the amount emptying out of the Amazon river (Ahlmann 1936).

During glacier outbursts the runoff is multiplied many times over normal, causing short-term changes in glacier drainage. In the interior evaporation and less rainfall cause a decrease in the runoff to such an extent that the drainage of the glaciers in the interior differs from that along the southern margin of Vatnajökull. Common to both, however, is the lack of surface waters on the ice, for they disappear down into the crevasses and glacier mills, and do not appear before reaching the glacier margin. Only in exceptional cases does one meet with surface rivers, which flow over the ice in the ablation zone.

Ordinarily the water discharged from a glacier emerges only at the margin, where it collects in marginal lakes and pools of various sizes. From these the water then continues on its course, streaming powerful seaward. Thus the glacier drainage frequently takes place in three stages: the outflow from the ice mass, the formation of marginal lakes and the flow in braided rivers to the sea. Each stage affects glacifluvial drift in its own way. Accordingly, each of the stages is dealt with separately in the following.

OUTFLOW

The water discharged from a glacier may be classified in two categories, namely, surface water and subsurface water. The former includes the unevaporated water accumulating through rain and melting of the ice surface; it flows over the surface or along open crevasses to the ice margin. The subsurface water comprises that flowing both englacially and subglacially. Since it is often difficult to decide in what part of the glacier subsurficial water has flowed, no effort has been made in the following to break down the classification; the exact situation of the water within the glacier will be discussed in another connection.

A. Water discharged from the surface of a glacier. In spite of rapid melting and heavy precipitation, but little water collects into streams on the ice surface. Evidently the ice surface is too much broken up to favor the formation of surface rivers. In the upper part of the ablation area, where water begins to occur in abundance and where there are fewer crevasses, rivulets form on the surface of the ice; but they empty their waters eventually into crevasses. Only in rare cases does a surface river flow as far as the ice margin. Such surface streams and rivers flow through channels with a natural slope, which determine the rate of flow. The channels cut into the ice, and if drift collects on the bottom, the stream begins to meander. Such streams are not long-lived enough to develop any regular longitudinal profile, for they run dry when the temperature falls; and in winter the surface of the ice is waterless. The channel-systems of the previous summer disappear with the freeze-up and the following summer the water must wear down new channels. Thus in the summer of 1948 a surface river of unusual size flowed across the eastern part of Hagafellsjökull (see Hoppe 1950 p. 49), but by the following summer, when the present author visited the area, it had vanished. The river starting from the glacier in 1949 received most of its water from two snow-covered crevasses. Over the snowless and uncrevassed ice surface next to them there flowed only small streams with clear water. Similar streams occurred that summer almost everywhere on the southern ice tongues of Vatnajökull. Slight surface flow takes place on the glacier in the summertime also in the northern marginal zone of Vatnajökull (Spethmann 1909) and it appears to be general in the ablation areas of the Icelandic glaciers. The volume of water carried by surface streams is so small, however, that it has no appreciable importance in the drainage of the glaciers.

The crevasses on the ice surface naturally serve as collectors of surface water; but the water does not remain in them but vanishes from sight so fast that the crevasses are waterless to as great a depth as it is possible to see down into. The radial crevasses at the ice margin represent an exception in that there is usually water at their bottom. It has not, however, accumulated directly from surface flow but collects within the crevasses subsurficially. If the bottom of a crevasse is so high that the crevasse does not extend to the general water level, no water gathers in it.

B. Water discharged subsurficially. Most of the water of the Icelandic glaciers is discharged from subsurficial water systems, where it collects in different ways. Some apparently represents the water disappearing down into the crevasses and glacier pipes or tubes. Another part of it derives from the ice bordering nunataks and mountain slopes, where in addition to meltwater there collects rainwater flowing down the mountains; while a third part forms in the lower zone of the glacier. The masses of water released by subglacial eruptions likewise flow subsurficially to the ice margin. Thus Nielsen (1937) emphasizes that the water generated by the eruption of Grimsvötn flowed the entire 55-km distance from the eruption site to the margin of Skeidarárjökull subglacially.

Ordinarily the subsurface waters flow out of the mouths of tunnels along the margin from which water has previously been discharged with great force (Thoroddsen 1905—1906, Spethmann 1912, Todtmann 1936, Ahlmann 1939, Thorarinsson 1939). The mouths of the tunnels are situated for long stretches of time at the same points along the ice margin, but sometimes they become clogged, whereupon a new opening appears next to the old, blocked one. According to the observations of the present author, the mouths of the glacier tunnels situated along one or the other flank of an ice tongue near a point where the edge of the tongue began to curve free from the slope of the bordering mountain (Hoffelsjökull, Skeidarárjökull, etc.), or then at the center of the curved margin of the tongue (Breidamerkurjökull, Kviárjökull). The latter had formed at points where long medial moraines reach the glacier margin. E. g. the strongly flowing rivers, Jökulsá and Breidá, on the Breidamerkursandur originate at the site of the medial moraines. From all evidences, medial moraine promotes the generation of meltwater (comp. p. 37). The streams flowing out of the flanks of ice tongues derive, at least in certain places (Skaftafellsjökull's western margin and the eastern margin of Hagafellsjökull), from the water collecting under the lateral moraine at the point of contact between the glacier and the bordering mountain; in addition to meltwater it includes rain water streaming down the mountainsides. Underneath the glacier margin the water flows laterally along the edge of the valley, for in places the babble of water can be heard and in other places the brook comes into sight in the openings. The water soon vanishes into tunnels, out of the mouths of which it is discharged. A dry tunnel was to be seen in the summer of 1949 in the stagnant ice at the southeastern margin of Morsárjökull. Both ends of the tunnel were open and it had obviously formed part of an earlier waterway but had fallen into disuse when the water had found a new channel for itself. The tunnel had formed in clean, unbroken ice, and only its lowermost part extended down into the bottom layer of ice containing basal load. At the bottom of the tunnel there was no loose glacifluvial drift. The meltwater flowing along the flank of the glacier had thus, at least in the case of this particular tunnel, run englacially without penetrating down to the floor.

The stream flowing down into the lake of Hagavatn along the eastern flank of Langjökull ran out of a tunnel that had been worn through moraine-covered ice bordering on a mountainslope, which ice became clean in depth. The tunnel extended for a distance of only about 150 m, however, for the stream changed farther up into a smoothly flowing river. Its point of origin was the mouth of a new glacier tunnel, from which the water was discharged in a swift and even flow. The water did not fill either tunnel wholly, but considerable air space was left beneath their arched ceilings. It was not possible to ascertain on the spot what the base of the tunnel was like; but next to the lower tunnel could be seen another, empty one, situated a bit higher, which had previously been in use. The walls, ceiling and floor of this tunnel consisted of clean ice. The diameter of the tunnel was approximately 50 cm. It was open at its lower end and its floor rose gently upstream.

The lakes dammed up along the southern outlets of Vatnajökull add, upon discharging subsurficially, to the volume of water in the rivers originating in the glacier. The discharge flow does not follow the joint between glacier and bordering mountain, but e. g. the ice-dammed lakes along the eastern flank of Hoffelsjökull discharge their water via the Austurfljót river, which starts from the southwestern margin of the same glacier (Thorarinsson 1939 b). The water thus flows slantwise underneath the ice. In the past the Austurfljót ran out of the glacier tunnel in mighty cascades (Thorarinsson 1939 b p. 204). Pressure of equal power used to prevail also at the mouths of most of the glacier tunnels, as e. g. at the discharge point of the Jökulsá, flowing out of Breidamerkurjökull (Ahlmann 1936), and during glacier outbursts it has increased above normal. During glacier outbursts caused by volcanic eruptions, the ordinary water ways cannot accomodate the whole volume of water discharged from the ice, so new tunnel openings appear. For instance, during the Grimsvötn eruption, meltwater was discharged out of thirteen tunnels opening up in the glacier margin (Nielsen 1937). According to Ahlmann (1936), Nielsen (1937) and Thorarinsson (1939 b), the flow of water in the glaciers takes places subglacially. Inasmuch as the margins of at least Hoffelsjökull, Heinabergsjökull, Breidamerkurjökull and Skeidarárjökull are higher than the floor the water must flow uphill in order to emerge from under the ice. It must, in other words, flow under hydrostatic pressure. Observations of powerful spraying at the mouths of glacier tunnels seem to verify the thesis of a subglacial flow of water. Other evidence to support it can also be produced, such as e. g. the fact that meltwater erodes the glacier floor of Hoffelsjökull and Breidamerkurjökull (Thoroddsen 1905—06, Pjeturss 1907, Ahlmann 1937 b). Keld Milthers, who, as a member of Niels Nielsen's expedition, was the first to examine the mouths of glacier tunnels opened up by the glacier outburst at Skeidarárjökull and who entered a tunnel, related that the tunnel was, in truth, at the bed of the glacier and, consequently, had been opened up in the ice by subglacial flow of water (oral report).

All students of the glaciers of Iceland do not, however, agree with the thesis that meltwater flows within the ice along the bed under hydrostatic pressure. Leiviskä (1928) emphasizes that the pressure of the water discharged from glacier tunnels is insufficient to transport large amounts of gravel except during glacier outbursts. The same conclusion was reached by Todtmann in making observations in the summers of 1931 and 1934 of the conditions prevailing along the southern margin of Vatnajökull (1936). In studying the mouths of glacier tunnels she noted that the meltwater flowed from them in channels with a natural slope. Only in the event that the glacier breaks up or sinks down to block the stream does the water dam up and issue forth in powerful eddies. When the obstruction has been worn away, the slope of the stream is restored and the mouth of the tunnel begins to function regularly again. As the surface of the sandur and the ice margin bordering on it are situated above the level of the glacier bed, the meltwaters running out of tunnels down a natural gradient must, according to Todtmann's conception, flow englacially rather than subglacially. Todtmann further argues that the ice flow is retarded first in the basal part of the ice, over which the surface ice advances along shear planes. These planes guide the meltwater deriving from the glacier surface and aspiring downward to the margin instead of its penetrating through the rigid basal zone of the stagnated ice (op. cit. pp. 84—85).

The question of the manner of flow of subsurficial water is thus for the time being an open one. Speaking in favor of Todtmann's conception are the shear planes, the results of seismic sounding (see p. 11) — which show the expanded ice of Breidamerkurjökull to be so thick that the existence of subglacial tunnels at its base becomes doubtful — and the absence of pressure at the point of origin of the Jökulsá, though the glacier bed is still below the ice margin. It is also hard to imagine the meltwater of the medial moraine penetrating a mass of ice 500 m thick, flowing along the glacier floor and being discharged uphill without inducing hydrostatic pressure. The diminishing of pressure is no local or accidental phenomenon, for the mouths of the tunnels studied by the present author had changed in nature. The Austurfljót, which starts from Hoffelsjökull, formed a lake at the site of its emergence, which extended into crevasses in the ice margin and received water from the glacier so evenly that no precise point of discharge could be detected. The water flowed calmly forth also at the eastern margin of Breidamerkurjökull, from under Fláajökull and Heinabergsjökull. In front of the margin lakes dammed up by end moraines had formed at numerous points; the lakes continued under the ice, with the snout forming a roof over the water. Under the ice was 5—30 cm air space and the flow could be deteched only by watching the movement of objects floating on the surface of the water. The Swedish investigators Hjulström (1953, 1954 a and b) and Hoppe (1953) noted the same phenomenon in the summers of 1951 and 1952. The lakes forming in front of the southern tongues of Vatnajökull had remained and gathered the water running from the glacier. Hydrostatic pressure has thus, in the view of the present author, generally diminished in the subsurface streams of Iceland. As an illustrative example, be it mentioned that Jón Jonsson, who, as a member of Hjulström's expedition, studied Hoffelssandur, reported having found the young of sea salmon in Gjánupsvatn. The salmon had to swim 5—6 km upstream to reach the lake. Hjulström (1954 b p. 34) regards the formation of marginal lakes a consequence of the current climatic change.

The discharge of the waters of the Vesturfljót river, which originates in the ice of Svinafellsjökull, gives a good picture of how water at present issues forth from a glacier. Part of the water purled as little brooks over the glacier surface and part flowed into view as a somewhat larger but gentle stream from the mouth of a tunnel at the southeastern corner of the ice tongue. This was situated under the ice edge in such a way that the arched lower surface of the glacier formed the ceiling of the tunnel. The bottom of the tunnel consisted of soft and clayey moraine, which the flow eroded. About 15 m from the ice margin the volume of water in the stream increased many times over, for it was fed additional water from five Artesian springs welling up through its bottom (Fig. 27, Plate XIV). These springs were situated in water-saturated till outside the visible border of the glacier. As the moraine was unable to obstruct the passage of water, there must have been a denser layer underneath through which the water under pressure forced itself into the river. A separating stratum consisted of ice buried in the moraine, the existence of which could be ascertained by prodding it with a rod. The true margin of the glacier thus extended beyond the visible border. This meant, at the same time, that the mouth of the tunnel at the border of the glacier constituted, in fact, the point of discharge of englacially flowing water.

In front of Heinabergsjökull the water came as a river flowing from Heinabergsdalur, on the northern side of the ice tongue. Judging from the dry beds, the river had earlier flowed past the terminus of the ice tongue seaward (comp. Thorarinsson 1939 c p. 219). In the summer of 1949 the river curved toward the terminus and flowed in the direction of the glacier margin, in places being bounded by the glacier margin and in other places vanishing under the ice. Finally, the flow grew weaker and the water formed marginal lakes between the ice and the end moraine. The volume of water in the stream increased gradually, for it appeared to collect the meltwater flowing from the glacier. The flow was so smooth that it could hardly be distinguished. No hydrostatic pressure occurred here either, therefore, but, on the contrary, the stream even flowed back under the ice.

The waters of the eastern margin of Breidamerkurjökull issued out of the mouth of a glacier tunnel. The surface of the glacier had sunk into a hollow at the spot. The water flowed gently out of an opening about 20 m wide, which had an even ceiling of ice 10—20 cm above the water level. The water was so turbid and the opening so hard to approach that it was not possible to test the depth of the stream or examine the bottom of it. The river received additional water from 5 or 6 little brooks flowing on the surface of the glacier and eroding furrows in the margin of the ice tongue. The volume of water brought by the brooks was insignificant compared with that discharged subglacially (perhaps 1/100). In front of the ice margin the river flowed through a steep-walled channel 2—3 m deep running across the gravel plain; it received additional water from Artesian springs welling up through the bottom of the river; this increased the volume of water by an estimated half. The stream became swifter over a distance of about 100 m and produced small rapids, the sills of which were formed by a hard and unbroken stretch of ice (Fig. 11, Plate VI). This stratum of ice, which the river was eroding, continued on each side of the stream bed underneath the gravel plain. Here, too, outside the visible terminus of the glacier, there was ice buried under glacial drift, ice that formed the true but invisible margin of the glacier somewhere on the proximal side of the end moraine. Thus, the aforedescribed opening must, in the present author's view, be situated here too between two sheets of ice and represent the point of discharge of the englacially flowing stream. The fountains occurring at the bottom of the stream, from which water spouted 20—30 cm above the surface, evidently received their pressure water from under a sheet of ice, as in front of Svinafellsjökull. The river running parallel to the ice margin soon disappeared from sight, for its flow became subsurficial — within its own outwash (and the ice underlying it). From here it emptied into the lake formed on the proximal side of the end moraine.

A lake collecting meltwater had formed in front of Breidamerkurjökull also at the source of the Jökulsá (Fig. 11 p. 29), where it had previously emerged from the mouth of the tunnel. Now the tunnel had vanished and the water seemed to flow into the lake along the ice margin from both directions. The margin of the glacier descended at a gentle incline into the lake and small rafts of ice broken off it floated on the water. A great abundance of meltwater collected at the ice margin now, too, but its flow did not become swift until it reached the neck of the Jökulsá river. The Jökulsá was crossed in 1949 with a small boat by rowing over the lake, whereas previously the river and the mouth of the glacier tunnel were circumvented across the ice (Leiviskä 1928).

The Skaftafellsá river starting from the W-margin of Skaftafellsjökull flowed along the edge of the ice tongue as a subsurficial lateral stream. It came into sight as a small brook from between the clean-surfaced tongue and the dead ice buried under the moraine alongside. The brook received additional water from another brook with clear water running off the glacier surface as well as from numerous short tributaries originating in the ablation zone. The latter flowed through 7—8 m-deep »canyons», whose vertical walls consisted of firm ice underlying surface moraine 1—2 m thick. The brook valleys joining together from different directions combined to form two river branches, separated by moraine-covered islands of ice; and these two branches represented the source of the Skaftafellsá river (Fig. 28). Pressure water was not met with in this locality either, for the river started from meltwaters flowing together from different directions. On

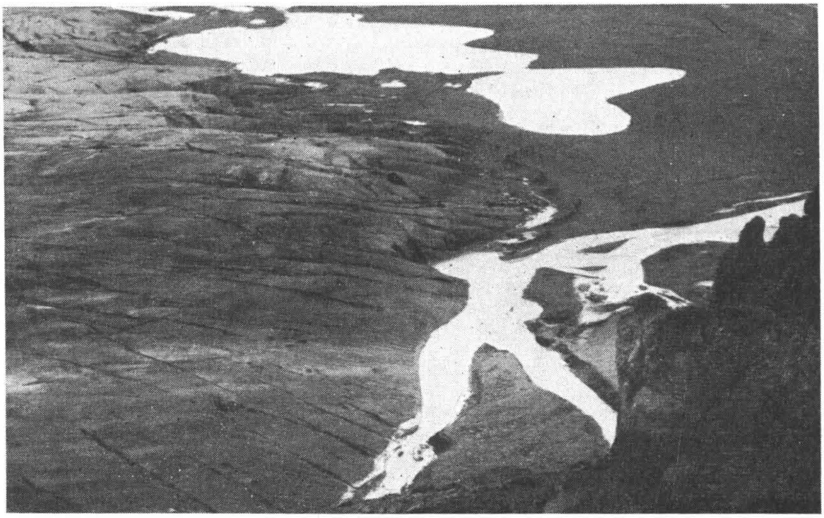

Fig. 28. The terminus of Skaftafellsjökull (left) seen from the bordering mountain. A lateral moraine and the source of the river Skaftafellsá separate the mountain from the glacier. Small push moraines appear in front of the glacier between the river and a marginal lake (in the background). Black stripes on the glacier surface are ice-cored drift ridges.

the spot one could not determine whether they flowed through ice-bottomed channels or whether they had cut channels through the ice.

Pressure water was met with in two places along the margin of Langjökull. At the eastern margin of Hagafellsjökull terminating in Hagavatn, near the mouth of the glacier tunnel mentioned previously, on p. 82, there occurred on top of the clean-surfaced ice, which sank at a gentle incline into the lake, two fountains. The water spouting from them was clean and rose above the surface of the glacier. The other Artesian wells occurred at the margin of eastern Hagafellsjökull. At a distance of about 20 m from the visible margin of the glacier there had appeared on the ice two fountains, from which the water spouted to a height of about 30 cm. At both points so little Artesian water was discharged that it had to derive from slight, local pressure. There was no outflow point for subsurficial meltwater streams at either site. These two observation sites were the only ones where pressure water was obserwed to rise up from the clean surface of the glacier.

The observations described in the foregoing show that a large volume of water is discharged from the glaciers of Iceland, especially during the summers. It flows in the ice subsurficially, for only a slight amount of water reaches the ice margin on the surface of the glaciers. Under normal conditions subsurface water runs to a large extent through englacial tunnels.

Outside the visible ice margin pressure water is encountered in places where the true margin of the glaciers extends beyond the visible terminus. This water flows evidently subglacially.

The volume of subsurface water multiplies during glacier outbursts many times over, and the water is discharged under high pressure from the mouths of glacier tunnels. According to the conceptions of Nielsen (1937) and Thorarinsson (1939 b), the water at such times forms subglacial basal streams, which extend from the point of discharge to the ice margin.

MARGINAL LAKES

Water drained in various ways from a glacier usually collects outside the ice margin, forming lakes and ponds, from which new streams flow onward. Part of these accumulations of water are ice-dammed lakes and part have formed behind the end moraines or proximal sides of the sandurs.

Ice-dammed lakes occur along the flanks of southern outlet glaciers, but they are met with also along the margins of other Icelandic glaciers. They have usually formed in the »armpits» between ice margins and bordering mountains, in which both rain and meltwater accumulate. The amount of water in such a lake is likely at times to be quite considerable. Iceland's largest ice-dammed lake, Grænalón, along the flank of Skeidarárjökull is 18 km^2 in area and contains an estimated 1 500 million m^3 of water. And Hagavatn, bordering on the margin of Langjökull, was 11 km^2 and contained 150 to 200 million m^3 of water before the formation of its present discharge (Thorarinsson 1939 b pp. 240 and 237). The volume of water in ice-dammed lakes varies tremendously, however, for many of the lakes have subsurficial outlets. According to calculations by Thorarinsson (op. cit. p. 227), the sill of lake Graenalón was overlain at the turn of the century by an ice mass 300 m thick. At the same time there was ice 225 m thick at the sill of lake Vatnsdalur, dammed by Heinabergsjökull, but by 1938 the glacier had wasted down to a thickness of 170 m at the same location (idem. p. 222).

When the ice-dammed lakes are at their maximum, they are so deep that ice barrier begins to float and calve, with the walls of the margin becoming quite steep. Upon a lake's suddenly emptying out, its bottom is exposed and the streams running down the mountains flow across it toward the glacier, until they vanish under the ice or begin to refill the basin. Such a stream flowed in the summer of 1949 across the dry bottom of the Efstafallsvatn at the eastern margin of Hoffelsjökull. The flow halted only upon reaching the glacier margin, where water began to accumulate.

The lake of Hagavatn, (Fig. 4 p. 12) discharges its water through a col situated outside the glacier, the sill of which regulates the water level. Such a col serves as the outlet until the water finds a new, lower sill under the ice, whereupon the outlet shifts to this point. At the same time the waterline sinks down to the level determined by the height of the new sill. The present outlet of Hagavatn developed in 1939, when the water in the lake melted or eroded the glacier so much that it was able to flow out over a sill 9.5 m lower than before underneath the ice. The outflow lasted 3 days, during which the ice margin wore away 400 m, exposing the point of discharge (Thorarinsson 1939 c). Since the outburst the surface of the lake has remained at the level fixed by the new sill. Only the erosion of the outflow sill and the changing of the seasons have caused alterations in it. In the summer the water level rises, for water accumulates at that season faster than the outlet is capable of discharging. In the winter the waterline descends, since less meltwater is produced and precipitation is mostly in the form of snow.

If the margin of the glacier terminating in the lake of Hagavatn is studied during the season of high water, it will be noted how the ice tongue descends gently into the lake (Fig. 18, Plate IX). Only in the middle part of the lake does the glacier form an ice cliff (Fig. 9 p. 23), extending 5—6 m above the waterline. The lake is evidently so deep at this point that the glacier begins to float there and its margin to calve. No calving bay has, however, resulted, for the ice margin remains straight. In 1934, *i. e.* before the last outburst of Hagavatn, an expedition from Cambridge University drew up a depth chart of the lake (Wright 1935), which shows that in front of the ice margin at that time there had been water to a depth of 140 feet (42 m). Since then the level of the lake has sunk nearly 10 m lower and the ice margin has retreated. As the lake, according to its sounding profile, deepens toward the glacier, the probability is that there is at present water to a depth of 30—40 m. This depth suffices therefore to lift the terminus of the ice tongue free from the base, provided that the steepness of the glacier margin really results from this cause. In studying Hvitarvatn, situated near Hagavatn and likewise bordering on Langjökull, and the glacier margin terminating in that lake, Nørvang (1937 p. 188) came to the conclusion that warm surface water hollows out the glacier and causes calving of the upper part of the margin. This conception is supported by observations made at the glacier margin during low water. The sides of the ice tongue, which slope gently down into the lake during high water extend down below the surface also during low water. The position of the high water is indicated on the ice by an erosion indentation below which the gradient of the ice surface is appreciably gentler than higher up, in the supra-aquatic zone(Fig. 29). In the ice cliff along the central part

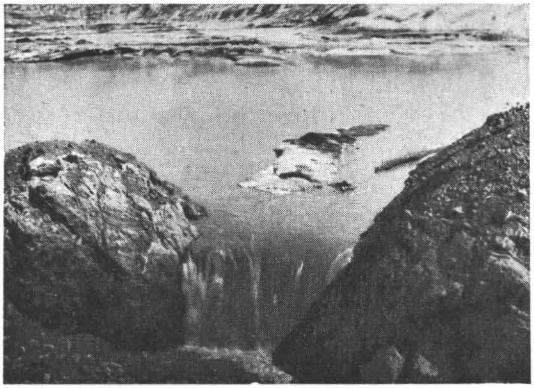

Fig. 29. A marginal lake, situated at the western side of Hoffelsjökull, is draining through a rock col (foreground). Before the outbrust the lake water melted a terrace into the ice (background) so that a thin sheet of ice has been left at the bottom of the lake. This ice becomes visible, forming islands behind the sill.

of Hagavatn there is to be seen during low water at numerous points along the summery waterline a deep trough, which surging of the surface has worn into the side of the glacier. The trough is roofed over by a long eaves-like projection of ice, which has broken off in places and left ice blocks floating in the water (Fig. 30). The glacier margin terminating in water thus wastes away during high water (in the summertime) along the waterline and the level immediately below it, whereupon the supra-aquatic part of the ice becomes steep.

In deeper water the melting is slower and the ice there forms a thin, gently sloping sheet, which extends appreciably farther out than the margin at the waterline. Possibly this thin and therefore stagnant and probably sediment-covered sheet of ice is an obstruction to movement by the glacier and causes it to thrust upwards (see Fig. 9 p. 23).

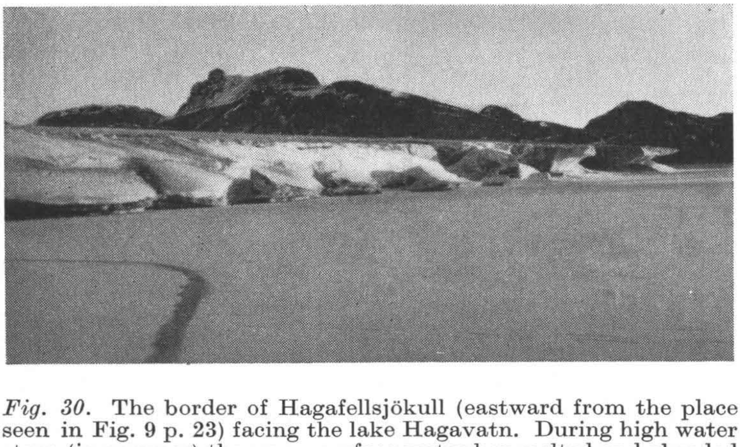

Fig. 30. The border of Hagafellsjökull (eastward from the place seen in Fig. 9 p. 23) facing the lake Hagavatn. During high water stage (in summer) the warm surface water has melted and abraded a deep trough into the ice. Overhanging ice is partly broken into floating blocks. Photo Helgi Jónasson, 1951.

The border lakes dammed up by frontal moraines and the proximal sides of sandurs — termed *»lón»* by Icelanders — are situatedat a lower level than ice-dammed lakes and they do not hold as great an amount of water at any one time. In 1952 the lón of Hoffelsjökull was 23 m and that of Falljökull 45 m deep (Hjulström 1953 p. 189). The marginal lakes, however, form sedimentation basins, from which new streams carry the meltwater out to sea. The majority of these accumulations of water are missing from the topographic map of Iceland, for at the beginning of the present century, when the map was drawn up, the glacier outlets generally extended as far as the end moraines and their water ran off into streams that flowed without interruption out to sea. It is mainly in recent decades that behind the end moraines has there been exposed a low-lying trough, which continues on underneath the ice. Water fills the most depressed parts of this zone up to the level determined by the height of the sill of the river starting at the lón. This level is naturally situated at different heights in different basins. It also varies in the same basin at different times, inasmuch as the river rapidly erodes its sill and as the water opens up for itself new outlets at lower levels than before. The waterlevel sinks down by degrees, therefore, from the time the lake forms, but simultaneously the lake spreads out toward the glacier. Following the melting margin of the glacier, it moves steadily on and fills the area being exposed.

The water of these lakes likewise submerges the lower border of the glacier or penetrates into crevasses and underneath the ice, thereby promoting the melting process. The ice at the waterline melts fastest, and there it simultaneously forms a sedimentation limit, for beneath it the ice surface begins to be covered by drift, which retards the melting. Earlier the sedimentation limit was, of course, situated higher than at the subsequent, lower stages of the lón. The basal ice buried under sediments disappears slowly by melting, often only after the area has already been drained of water and become dry land. Also the outwash deposits accumulated on the ice turn into marginal lakes. First steeply sloping hollows (Fig. 31) appear on the gravel bed. There is water at the bottom of them and gravel covered ice can be seen in their sides. Gradually these hollows expand, for the stagnant water in them warms up and wastes away the ice, thereby undermining the gravel bed. The earlier gravel plain thereupon is transformed into a group of lakes dotted with drift-covered isles of ice (Fig. 32). Gradually these melt and the lakes merge to form one large body of water. The ablation moraines sink lower in the same fashion, with the ice wasting away inside and water frequently filling up the depressions. The relation of the ground to the level of the water and to the height of the point of discharge of the lón determines whether the ablation moraine in process of formation rises above the water surface or is submerged.

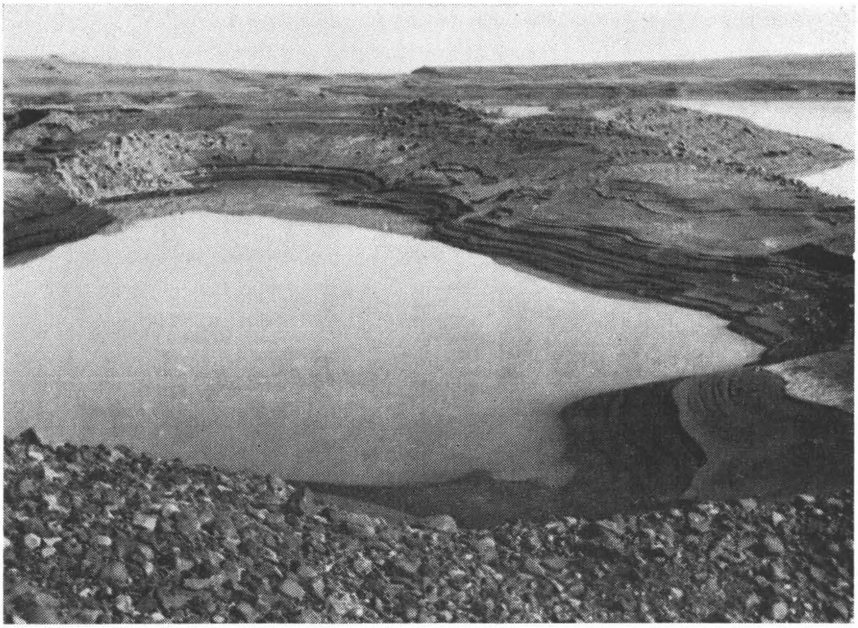

Fig. 31. A kettle hole in outwash deposits on Breidamerkursandur. Demarcation lines along the slopes indicate higher water levels. The diameter of the hole is about 20 m and its visible walls are 2.5 m high.

Fig. 32. A marginal lake at Breidamerkurjökull (near the hole presented in Fig. 31). The dark islands in it are drift-covered dead ice remnants. Dead ice underlies outwash gravel around the lake and becomes visible in the lowermost parts of the steep banks.

The waters in the radial crevasses of a glacier margin are connected with the marginal lakes, for the surfaces of both are situated on the same level (comp. p. 41). The water stagnating in the crevasses warms up and begins to melt the lower parts of the crevasse walls. Under such conditions a crevasse widens out like a cavern at the base. As the melting continues, the water undermines the ice and eventually joins the crevasses to each other, forming corridors and caves at the base of glacier. Thereby the lake expands underneath the ice and effectively promotes further melting.

A marginal lake is, in the view of the present author, an accumulation of water subject to continuous changes. The height of its waterline is determined by the height of the sill at the point of discharge, and its dimensions depend on the size of the low-lying area behind the sill. The quality of the glacier margin, on its part, determines to what extent water accumulates within and underneath the ice as well as in the crevasses and to what extent it is dammed up in the area from which the glacier ice has retreated. From the standpoint of glacier drainage the chief significance of the accumulations of water probably lies in the fact that they represent reception centers in which the flow of water from a glacier halts for a time before continuing its course towards the sea.

During glacier outbursts the marginal lakes lose their importance for under such circumstances so much water is discharged from the ice that the flow continues uninterruptedly across the lake basins, wearing down the sills damming the lóns.

BRAIDED RIVERS

The obstruction damming a lón, whether it be a frontal moraine or the proximal side of a sandur, is usually highest in front of the center line of an ice tongue and grades down toward either flank. As a result, waters accumulating behind an obstruction flow laterally between it and the ice margin until the lowest point in the obstruction is reached. The water is discharged over this point and continues on its seaward course. The starting points of the majority of the streams originating in the southern outlets of Vatnajökull are situated along the side of the ice tongues. The Jökulsá river, in front of Breidamerkurjökull, is an exception, for it intersects the end moraine in the center. In the view of the present author, this river has been active since the end moraine was formed, thereby preventing the moraine from obstructing its flow. The western branch of the Kviá river, starting from Kviárjökull, flows likewise through a deep channel in the frontal moraine. Several of the streams deriving from Skeidarárjökull also cut through moraines along similar channels. The normal volume of water in these streams is so slight that it could hardly suffice to wear out the present channels, but they must have been created during glacier outbursts. Such frequently recurring heavy floods in the frontal terrain of Skeidarárjökull pass over the marginal moraine at many points and wear down their sills so deep in the moraine that the existing rivers can discharge over them. In front of this glacier, therefore, as large lóns as those e. g. in front of Breidamerkurjökull have not been able to form.

The stream starting from a marginal lake discharges either over a rocky sill, thereby forming an erosive waterfall, or along a channel cut by it through glacial drift, whereupon the current is not so strong — in the latter case the river forms a swift stream rather than true rapids.

The water flowing over a rock sill erodes soft rocks of Iceland so rapidly that a canyon is produced relatively fast. Ultimately the river forms rapids at the bottom of such a steep-walled canyon. If the lake produced along the margin of a glacier empties out so fast that the sill has not enough time to flatten, a »dead waterfall» is left in the rock. Such relics are met with e. g. along the western side of Hagavatn, indicating the points where the lake had discharged its waters in the past (Fig. 4 p. 12).

Along the southern margin of Vatnajökull rock sills are rare, for the streams there flow out of the lóns into the sea through channels worn out of glacial drift. At only a few places near the glacier margin are there rock sills. In the summer of 1949 lake that had formed by the western flank of Hoffelsjökull emptied over such a sill into another, situated lower down (Fig. 29 p. 90). The flow had evidently started quite a short time before, when the sill had become exposed out of the ice, for it was only slightly eroded, although the lake had sunk down several meters, bringing into view the glacier foot extending out into the water.

A stream flowing over a sill formed of glacial drift usually cuts a vertical-walled channel for itself, the base of which is several meters below the surrounding ground level. The water is discharged through such a steeply sloping channel in a rapid flow, eroding the sill. The erosive (and transport) action of a river actually begins at this narrow point, for the water in a lón is for practical purposes stagnant. Usually the water accumulating in a lón area is discharged in a single stream, the water volume of which includes the entire run-off of one outlet glacier. On the basis of measurements carried out already by Ussing (1903) and subsequently by Thorarinsson (1939 b) and Hjulström (1953), the volume of water in rivers varies greatly. There is least water in the rivers in the winter and most in the summer. The largest rivers, Jökulsá and Skeidará (the chief river emanating from Skeidarárjökull), carry 300—400 m^3 of water a second in July (Thorarinsson op. cit. p. 211), but an even greater volume of water is estimated by Thorarinsson to have been drained out of Hoffelsjökull in the period July

29—30, 1937, namely 400—500 m³/sec. This figure surpasses the maximum run-off measured by Hjulström's expedition in 1951 — 240 m³/sec —, which was caused by a subglacial outburst of Gjánupsvatn into the Austurfljót. The level of the lake sank 25 m on this occasion (Hjulström op. cit. pp. 171 and 173).

The run-off of rivers also varies greatly during the different times of the day. There is most water in the evening and least in the period just before dawn (Thorarinsson 1939 c p. 209). These variations are, however, slight, compared to those at the different seasons of the year.

The variations in the volume of water reflect, at the same time, changes in rate of flow, which for its part affects the transport capacity of the river. When the capacity diminishes, the river unloads the mineral matter carried by it, deposits sediments on the bottom and begins to meander. Its course becomes winding and streams branch out. As the current quickens, it transports the sediments and continually changes its course. Both the main stream and its countless branches wind serpentlike toward the sea down the sloping plain. Hjulström has emphasized the lateral erosion action of glacial streams as creators of the strand flat (1954 b). Gradually the gradient of the river diminishes, the erosive power of the flow decreases and sedimentation becomes the chief operation. The branch streams broaden out and flow together to form shallow lagoons, separated from the ocean by a long offshore bar. At only a few points along the length of the bar is it broken, and through the openings the water emanating from the glaciers flows out to sea.

In the submerged coastal plain beyond the river mounths, there are depressions resembling submarine valleys radiating outward from the shore. They expand and deepen out to sea (Fig. 2 p. 9). The valleys are clearly visible at depth contours of 150 and 200 m, whereas the depth curves of 100 and 50 m do not yet reveal their existence, but run parallel to the shoreline. Thorarinsson (1937 b p. 166) considers these valleys the submarine extensions of fjords filled with glacifluvial deposits, expressing at the same time the thought that they could have been eroded by glaciers during times past when the sea level was 100 or 200 m lower than at present. The depth curves drawn at intervals of 50 meters do not make it possible to judge whether the valleys are the result of glacier erosion or river erosion; however, the depressions are too extensive to represent tectonic valleys. They greatly resemble the submerged extensions of fjords along the steep eastern, northern and western shores of Iceland, but they differ from them in the respect that the depressions in the fjords are visible even in the 50 m depth curve. The difference is caused, as the present author understands it, by the fact that the valleys along the southern coast have been filled in the shallow coastal zone with sediment deposited by the currently existing rivers. Taking into consideration the present volume of water in the rivers and the rate of flow of the water emptying into the sea through the shore rampart, it appears probable that under prevailing conditions the flow weakens already in the coastal zone to the extent that sedimentation begins. The erosion of the submerged valleys must, accordingly, have taken place earlier, when the basal level of erosive action was situated considerably lower than at present. The extension of the valleys to a depth of at least 200 m does not, however, necessarily mean that the level of the ocean was so low at the time the valleys originated, for the volcanism of Iceland could have brought about vertical changes also in the situation of the coastal plain.

GLACIFLUVIAL DEPOSITS

The water drained out of glacier washes and sorts glacial drift released from the ice at as early a stage as the flow of meltwater over the glacier surface (see p. 36) as well as in subsurface streams and rivers outside the ice mass. During such treatment the glacial drift changes and begins to differ in both composition and structure from the till directly freed from the ice. Whereas lack of sorting characterizes the latter material, washed drift is sorted. Certain grain sizes have decreased in amount, while the remaining components have correspondingly been enriched. The structure of the strata formed of sorted material varies vertically in such a way that layers of different composition alternate. The sorted material, in other words, is also stratified. The designation *stratified drift* is, to be sure, often used to represent the sorted components of glacial drift. Stratified drift is produced by other agencies besides fluvial action (comp. Flint 1947 p. 103); hence stratified drift is broader than glacifluvial matter as a term, including e. g. eolian sediments. Inasmuch as the action of the water discharged by glacier decisively affects the differentation of Icelandic glacial drift, the accumulations resulting as an outcome of this action are herein termed *glacifluvial deposits*. The term thereby also includes the sediments of ice-dammed lakes and lóns. Only when it has been desired to emphasize the structure of the material has the designation *washed drift* been used; and »stratified drift» has been employed only as a stratigraphic term to indicate that the deposit comprises different strata.

As demonstrated in the previous chapter, the flow of water discharged from glaciers takes place nowadays in different stages, each of which affects in its own way the treatment of glacial drift. Consequently, in dealing with glacifluvial deposits, this study is observing a corresponding division, and deliberately deviating from the general grouping of these deposits. First, we shall take up for examination the accumulations forming in water drained off glaciers. Then we shall turn our attention to the sediments in the marginal lakes. And finally we shall consider the deposits of the rivers starting from these lakes.

DEPOSITS AT THE ICE MARGIN

Glacifluvial accumulations form already both on the surface of the ice and also evidently subsurficially. Sorted drift accumulates on the surface of the glacier as a result of washing and the action of surface streams. Subsurface deposits, on the other hand, do not come into sight except at the edge of the glacier.

Surface washing was described previously, on p. 36. The amount of water taking part in the surface washing process at any one time is so slight that its flow does not transport other than the finest grains. As a consequence of the irregular melting of the glacier surface and the washing of the finegrained material, the stones and even boulders fall into labile positions and roll down into depressions, where they become mixed up with the sorted drift. The sediment forming on the ice often therefore contains scattered stones. Furthermore, the structure of the sediment becomes disturbed upon the ice's melting underneath.

Surface drift rolls and slides also into the channels of surface streams. Near the ice margin, where there is more surface drift than higher up on the glacier, there forms here and there at the bottom of channels a unfied row of stones, from which the water washes the finer material away. If the current is strong, the water also transport the sand away from the stream bed and leaves only the stones in place. If, again, the current is gentler, the spaces between the stones fill with sand. A line of stones of this kind at the bottom of a V-valley was met with in the summer of 1949 at Breidamerkurjökull (Fig. 15 p. 38). Its stones were rounded only at the edges. The stones were 2—10 cm in diameter. The flow was so slow and the volume of water so slight that the stones remained stationary, and the water eroded them only through the agency of the sand running downstream. The line of stones extended up to the margin of the glacier, where the stream was discharged down a waterfall 1.5 m high onto ground moraine situated in front of the ice mass. On the surface of the moraine there could be seen, as an extension of the channel of the stream, a miniature esker (Fig. 24, Plate XIV), the breadth of which was about 50 cm and height 10—15 cm. Its material was composed of washed stones and sorted sand. The little esker could be followed for about 15 m, after which it sank lower and merged with the moraine. The stones of the ridge were unoriented, which evidently resulted from the fact that they had fallen off the ice margin on top of the moraine. At the bottom of the waterfall the material still underwent washing and the stones only then attained the position in which they were left on the little esker.

The miniature eskers were rare, however, for ordinarily in the channels of streams flowing over the glacier surface there was so little drift that no accumulations whatsoever formed in front of the ice margin. For example, the streams flowing off the margin of Hoffelsjökull as little waterfalls washed only the surface of the ground moraine. As this surface sloped toward the glacier, the water continued its flow under the projection formed by the ice margin and passed out of sight. From under the waterfall there formed a row of stones on the surface of the moraine leading under the projection. It will be deformed, however, as soon as the projecting ice collapses. Since the volume of water in the surface streams was extremely small in the summer of 1949 and their transport capacity was limited, the accumulations were more in the nature of curiosities than glacifluvial deposits, properly speaking. They indicate, however, that under certain conditions glacifluvial deposits may form, as an outcome of the action of surface streams, both on top of the ice and in the frontal terrain of a glacier.

Subsurface waters constitute the chief part of the flow in the drainage of Icelandic glaciers (p. 81). The water ran out of the glacier tunnels so gently and lacking in hydrostatic pressure that its capacity to transport material was exceedingly small. The water was, to be sure, turbid and contained an abundance of fine sand and silt, but the flow could not be observed to carry along stones from underneath the ice even along the bottom. If subsurface water did transport glacial drift, stones, gravel and sand, this action terminated before the water was discharged from the ice margin. It is possible that glacifluvial material was deposited in crevasses and tunnels (comp. Todtmann 1951, Hoppe 1953 p. 263, Ives and King 1955 p. 480), through which the water runs. The filling up of tunnels with glacifluvial material is not, however, a general phenomenon in the glaciers of Iceland, as indicated by the fact that the glacier tunnels of Morsárjökull and Hagafellsjökull were empty of glacifluvial material in the summer of 1949 (p. 82).

Nor did stones and gravel appear in the water forming springs beyond the visible margin of the glacier. At the »eye» of such a fountain, however, the flow was so strong that it lifted, e. g. in front of Breidamerkurjökull, stones measuring 2—5 cm in diameter above the level of the stream and kept under 10 cm stones constantly moving to and fro. These stones originated, however, in the deposit through which the water was discharged, for no glacifluvial material could be detected carried by the water into the fountain. The water of the fountains spouting out of the ice was still clearer.

The observations described in the foregoing lead the present author to the conclusion that under normal conditions, such as prevailed in the summer of 1949, the water draining from the glaciers of Iceland transports only fine-grained drift.

DEPOSITS IN MARGINAL LAKES

Marginal lakes and other accumulations of water at ice margins receive most of the glacier drainage. As the rate of flow diminishes or ceases altogether in the basins, deposition of the material transported takes place. Sediments lie submerged until the water level sinks and the bottoms first come into sight after the lakes have been drained off.

Ice-dammed lakes at the eastern side of Hoffelsjökull had become emptied just before the author visited the place (July 14, 1949) and their bottoms were still bare. The author could study the bottoms of the lakes of Efstafellsvatn and Gjánupsvatn. At the bottom of the former there flowed a river emanating from the mountains toward the edge of the glacier along a steep-walled channel, which had been worn down into the bottom sediments. These deposits contained alternating beds of stones, gravel and sand, cutting each other at different angles (Fig. 29, Plate XV). At one point the whole strata was bent, saddle-like, and at other points distinct cross-bedding could be seen in the sandlayers. All the beds contained some scattered stones, a few of which were rounded and the others subangular. The most flattened of the stones had an orientation parallel to the slope of the strata. From the inclination of the layers and the cross-bedding, it could be seen that the ice-lake deposits had been carried to the basin by the river from the mountains. It is probable that the irregularities in stratification are due to the proximity and instability of the ice margin. For the same reason the lake bottom is uneven, containing gently sloping knolls of gravel and sand with depressions in between. In the present author's opinion, they originated during outbursts of the lake, which cause the ice margin to collaps and scatter an abundance of floating blocks of ice. The topmost part of the deposit contained coarser fractions, in general, than the lowermost parts. At the bottom of the section there were sandy deposits (Fig. 33, Curve 13, p. 100).

The bottom deposits cover the foot of the hill, too; but when the slope turns steeper, the sediment mantle disappears, until a narrow gravel bench marks the water level of the lake. Seen from a distance, the benches form rather plain horizontal lines, but closer up they become scarcely distinguishable (Fig. 30, Plate XV). Likewise insignificant, though perceptible from a longer distance, benches occur along the shore lines of other ice-dammed lakes as well. Upon comparing these with the ancient shores of Finland and Sweden, they are weaker and were the land surface not so bare, it would be quite difficult to observe them at all.

The bottom of lake Gjánupsvatn resembled the former in that the surface was there, too, uneven, though sections were lacking. In some places a thin layer of sorted sand and gravel was to be found on the surface, which generally consisted of till, with small angular rock fragments. Kettles described on p. 56 had been imprinted on the soft bottom. Many of them still had melting ice blocks, but in addition to these fresh ones, ice-free kettles of older origin, with gentle slopes, dotted the bottom.

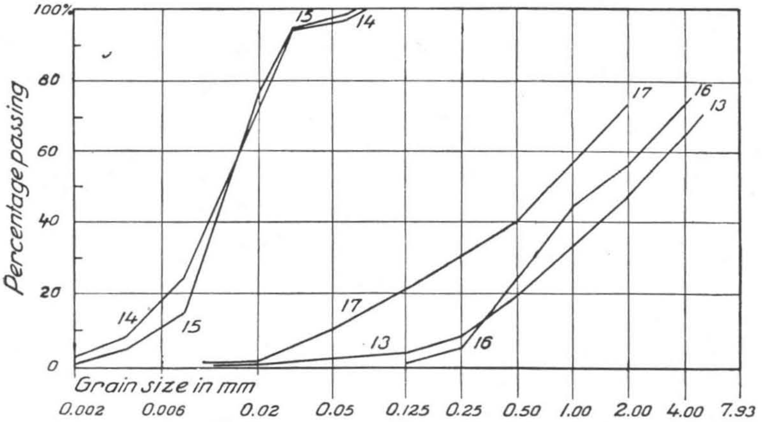

Fig. 33. Grain size distribution in glacifluvial and glacilacustrine deposits. Curve No. 13 ice lake deposits in Efstafellsvatn, No. 14 varved ice lake sediment, east of Hagavatn, Langjökull, No. 15 ice lake deposit from the same locality, No. 16 glacifluvial deposit from an erosion esker, Morsárjökull, and No. 17 drift from the sandur plain in front of Hoffelsjökull.

The third bottom of an ice-dammed lake was laid bare in the valley on the east side of lake Hagavatn at Langjökull. The ice barrier damming the lake had melted some thirty years before, causing the lake to drain off. Shore benches were still visible, showing that the ancient waterline had been situated about 45 m above the valley floor. Along this valley there flowed a river fed with meltwater from the glacier. In some places it had worn its channel into the lake bottom, while in other places it had spread its own deposits on the lake sediments. A flat-topped gravel knoll on the western side of the river displayed the following stratigraphy: the top was composed of stratified gravel and sand to a depth of fifty centimeters. It was followed by cross-bedded coarse sand (60 cm), which became finer downward and contained thin laminae of silt. Underlying this there followed a layer of varved sediment 30 cm thick. The varves were regular and varied between one and two centimeters in thickness. Each varve had a lighter (coarser) and a darker (finer) part consisting mainly of silt (Fig. 33, p. 100). As the present author understands it, they were true annual varves, resembling the diatact varves found in Finland (Sauramo 1923). The deposition of such sediment in a marginal lake can be conceived of by assuming that the lake was covered with ice in winter (as Hagavatn is nowadays).

As the meltwater activity diminished at the same time, the silt suspended in water could deposit and form the fine-grained winter parts of the varves. In this respect the sediment differs from the ice-lake clays of Denmark, which have much thicker and more irregular varves, as described by Hansen (1940). The same difference was observed also by the author in the summer of 1951, when he had an opportunity to see some Danish ice-lake clays under the guidance of Dr. Sigurd Hansen.

Beneath the varved clay there was a layer of silt 25 cm thick, the bottom part of which was stratified. This stratification was caused by thin laminae of silt and fine sand. A sharp boundary separated this sediment from the underlying gravel bed. Judging by the stratigraphy, the ice-lake has had a short passive stage, during which varved sediment could deposit. Similar »very beautiful warved clay» appeared at the bottom of Hagavatn after its drainage in 1939 (Thorarinsson 1939 p. 238). From the marginal lake of Langvatn (west of Hagavatn) Wright has described and photographed »the typical varve or banded clays deposited in glacial lakes, presumably due to the different rates of sedimentation in summer and winter» (1935 p. 225). In addition to these, varved clay has been found in southern Iceland, where short profiles have been measured and compared to the Swedish time scale by Ebba Hult De Geer (1928) and J. Áskelsson (1930).

From the afore-mentioned varved sediment and from the silt layer beneath it pollen and diatom analyses have been made. Here is the result of pollen analysis:

	Varved sediment		Silt	
	sp.	%	sp.	%
Betula	7	17.5	14	30.4
Pinus	1	2.5	1	2.2
Salix	11	27.5	—	—
Ericales	—	—	1	2.2
Cyperaceae	10	25.0	12	26.1
Gramineae	6	15.0	10	21.7
Caryophyllaceae	—	—	2	4.4
Varia	5	12.5	6	13.0
	40	100.0	46	100.0

In addition, 5 *Lycopodiaceae* and 4 *Polypodiaceae* spores were met with in the silt sample.

The samples contained the following diatoms:

	Varved sediment	Silt
Achnanthes sp.	—	2
Cymatopleura solea	—	1
Cymbella sp.	1	—
Epithemia intermedia	1	—
» *zebra var. saxonica*	1	—
Eunotia praerupta	3	1
» *sp.*	1	1
Fragilaria sp.	6	4
Gomphonema acuminatum	—	1
Melosira ambigua	—	3
» *italica*	—	1
Navicula sp.	—	2
Pinnularia borealis	3	4
Rhopalodia gibba	1	—
Synedra sp. fragm.	2	—

The diatoms in both samples represent scarce shallow and fresh water flora. It contains mainly the same diatoms that exist at present at Vatnajökull and Langjökull (Mölder 1951).

The marginal lakes, or lóns as they are called in Iceland, have evolved between the ice border and end moraines. In these lakes the main part of the material carried by meltwaters from the glacier is unloaded. The bottom of the lake is, however, so soft, long after the drainage of the lake, that it is difficult to study its deposits. In front of Skaftafellsjökull a lake bottom was laid bare, forming an undulating area between the visible ice border and the end moraine zone. This area differed from the ablation moraine in the respect that the topmost layer in the soil profile consisted of stratified sand. Stratification was caused by the altering of sand and silt layers. The sediment resembled the Danish ice-lake clays (Hansen 1940). Some separate stones were imbedded in the sediment and in some places unsorted material could be observed. Probably this had slid down into the lake from inclined ice surfaces, as such sliding processes were seen in action. The frontal part of Skaftafellsjökull was buried in sediments up to the earlier water level and the gradient of the ice surface was so slight that no sliding of drift happened there. Disturbances appeared only farther away from the visible ice margin in the zone where the buried ice had begun to melt. Here steep-walled holes occurred in the sediment plane, resembling those in ablation moraines (p. 54). Compact, dark dead ice was found in the lower part of the walls, but now it was covered with stratified drift. From the steep walls drift slid and slumped down into the holes, thereby bringing new ice into sight. At the same time water collected in the holes; and it melted the bordering ice so that the holes were widened until they joined together. The lake bottom, which was primarily rather flat, thus turned uneven and its base level was lowered. The final result of this development must be a formation whose topography is irregular and material composed of ice-lake deposits. After drying, these sediments offer the wind erosion a very suitable surface.

Similar lón sediments were visible along the shores of the marginal lakes in front of Hoffelsjökull, Breidamerkurjökull, Kviárjökull, Morsárjökull and Skeidarárjökull. The lowest parts of the lake basins were still submerged and deposition took place there. Because the ice-lake deposits cover also the emerged land, the water levels must have reached higher before the present stage. The draining off of the marginal lake in front of Svinafellsjökull had laid bare long and narrow land tongues and islands covered with lake deposits. The whole landscape thus resembled dead ice topography. The development at Morsárjökull, as seen in 1949, must bring about a similar landscape, when the marginal lake flooding over the thinned ice margin has been lowered (Fig. 25, Plate XIII).

The appearance of marginal lakes is a result of rapid shrinkage of the glacier, which happened during recent decades. When the ice margin extended to the frontal moraines, the topographical conditions prevented water from collecting at the margins; and the water ran without any obstruction to the sea. The significance of the marginal lakes in Iceland has been stressed in recent years by Hjulström (1953, 1954 a and b). It is evident that the marginal lakes have a great effect on the melting process of the ice terminus and on the deposition of glacifluvial deposits. Only dissolved material continues its way through the marginal lake without any sedimentation.

DEPOSITS IN BRAIDED RIVERS

Rivers emerging from the southern outlets of Vatnajökull have filled with their sediments valleys extending from the interior to the sea. These sediment fillings have been known as sandurs (the Icelandic name in the singular is *sandur*, the plural form being *sandar*). Many scientists have made observations on them as they have crossed the vast sandur areas along the southern margin of Vatnajökull. The best known sandur, the Hoffelssandur (Thorarinsson 1939 b, Hjulström 1953, 1954 a and b), has been built up by the Austurfljót and Vesturfljót, which drain Hoffelsjökull. According to both investigators, the gravel plain is a result of the erosion, transport and deposition activity of these rivers.

As early as 1881 Helland gathered water samples from Icelandic rivers and investigated their silt content. Like other glacifluvial streams, they were heavily loaded or braided. A water sample taken from Nupsvötn contained 570 mg silt per litre, and that from another river emerging from Skeidarárjökull contained 1 509 mg/litre. A water sample from the Jökulsá at Breidamerkurjökull had a silt content of 1 876 mg per litre (Helland 1882). Thorarinsson estimated that the Austurfljót carried in the summer months of 1939 on the average 1 070 mg silt per litre. The high average of ignition loss (3.2 %) was, according to Thorarinsson, caused by organogenic matter (1939 b p. 212).

After the forming of the marginal lakes, the transport of material has evidently diminished. The rivers beginning from these lakes cut their channels in end moraines and gravel beds eroding them. In the upper course of the river profile the gradient is so great that erosion prevails, while in the lower course deposition takes place. The transport capacity varies, greatly in time and in different parts of the stream, causing an alternation in deposition and erosion even in the same place. For that reason the rivers are continuously changing their channels, meandering and winding like pendels along their beds.

The surface of the outwash plain is filled with dry stream beds and delta islands between them. The top-planes of these islands dip downstream. So do the stream channels, too, and they are so inclined that it is easy to determine the direction of flow. Old, low-walled channels cross diagonally even the top-planes of the delta islands, which usually are triangular in shape. The sharp angle is directed upstream while the base faces downstream. The flanks slope rather steeply toward the bordering flat stream beds, which commonly lie at different levels on both sides. The erosion remnants have not always the shape of a triangle. Sometimes the stream erodes the plain from one side only, thus cutting a steep bank into it. Such banks separate two gravel plains, e. g. in front of Falljökull; and a similar bank has formed alongside the river Jökulsá at Breidamerkursandur.

The stream can also wear the plane from two sides so heavily that the plane becomes narrower and narrower, until the erosion remnant has the form of an esker. Its slopes are at first very steep, but later they take an angle of repose. The original plane now forms a very narrow flat top between two steep-sloping sides, and it has a gentle inclination downstream. In many places there are still weak channels on the flat top intersecting it at sharp angles. If the erosion continues so long that it wears away the plain totally, the erosional remnant gets the shape of a sharp crest or esker ridge. Owing to the course of eroding rivers the same »erosion esker» is likely to contain sharp crests and flat-topped narrow ridges joining together.

Erosion eskers of this kind occurred in 1949 in front of Morsárjökull and Langjökull. Their length was not more than 150, their height varied from 5 to 10 m and the basal width from 20 to 80 m. The base levels or bottoms of the slopes were at different heights and very often a channel formed by the eroding river separated the erosion esker from the lower-lying younger outwash plane. The erosion eskers were commonly directed outward from the glacier. An exception was made by a ridge in front of Morsárjökull. It started from the southeastern border of the valley and crossed the valley train diagonally downstream until the present river destroyed it. Judging from the erosion channels, this river had earlier emerged from the southeastern edge of the glacier and streamed laterally between the frontal moraine and the glacier margin. During this stage of development the river had worn the earlier delta plane and formed the erosion esker. At a later stage a marginal lake developed at the glacier border and the river now begins from the northwestern end of it. The water level is some meters lower than the top of the esker ridge, showing that the basal level of sedimentation has considerably lowered. This is quite a common feature in the proximal parts of Icelandic sandurs. In the author's opinion this part of the outwash plains was deposited under conditions when streams were stronger and carried more material than they do at present.

It was mentioned earlier (p. 103) that the rivers carry from the marginal lakes suspended and dissolved matter only. The stream very soon grows so strong, however, that it begins to erode the bed already from the sill, cutting its channel into the drift. Especially wet moraines, as they are after being released from the glacier (Fig. 31, Plate XVI), and river deposits are very suitable objects for stream erosion. The stream spreads the material and carries the finest fractions away, leaving the coarsest particles *in situ* or carrying them short distances only. As the strength of the current varies greatly, the newborne deposits become stratified and very often a certain lens-structure appears in them. On the other hand, the deposits are weakly sorted and their grading resembles that of till (Fig. 33, curve 17, p. 100).

In places where the current has been violent, as e. g. in the present discharge of Hagavatn during its formation in 1939, the stream bed is filled with blocks. These have a very regular orientation: their long axes are turned either in the direction of flow or then lie perpendicular to it. The flat topsides always turn upwards to the direction of flow. This kind of orientation is not restricted to the surface; then very often it becomes visible also in cuttings (Fig. 34 p. 106). The coarse block fields are concentrated in the proximal parts of the outwash plains, i. e. in front of end moraines. Behind them block fields were seen on the old deposits of glacier outbursts.

Fig. 34. Structure in a sandur in front of Heinabergsjökull. The stream has flowed (from right to left) to the direction indicated by the upturned ends of most of the stones.

In front of the eastern margin of Breidamerkurjökull a block field was met with in the proximal side of the end moraine arc. Its flat top was some 3—4 m higher than the water surface in the present lateral river. In this block field some peat chunks were lying among the boulders (Fig. 32, Plate XVI). They consisted of *Carex-Bryales* peat with the following pollen content:

	sp.	%
Betula	23	33.3
Pinus	1	1.4
Cyperaceae	35	50.7
Myriophyllum alterniflorum	1	1.4
Salix	1	1.4
Varia	8	11.6
	69	99.8 %
(*Polypodiaceae*	1)	

Farther away the size of the carried material gets smaller, after which gravel and sand begin to prevail in the surface material. The stones at the bottom of stream beds have settled so that their longitudinal axes are perpendicular to the stream. This comes out in the orientation analyses

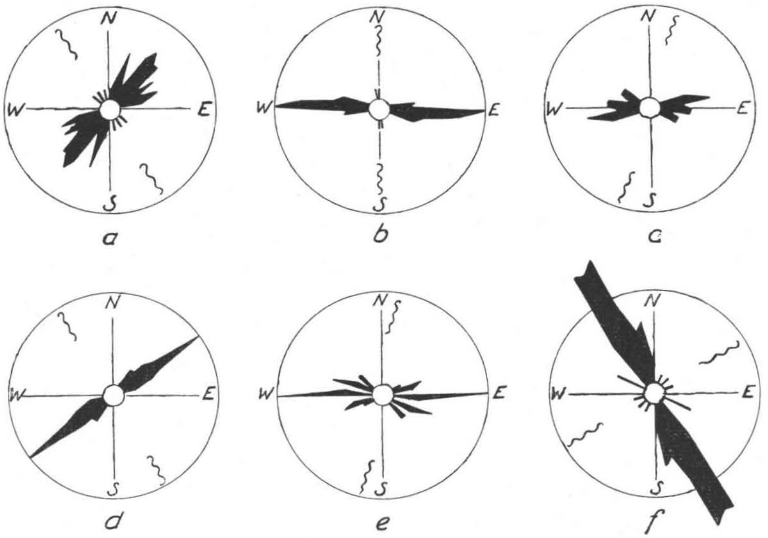

Fig. 35. The orientation of the sandur material: a. and b. on the surface of Hoffelssandur, c. in front of Heinabergsjökull, d. in a dry stream bed on Breidamerkursandur, e. in the same at Ignolshöfdi, S. of Öræfajökull, and f. in coarse outwash material at the lower end of the present gorge of Hagavatn. The direction of flow is indicated by a winding line in each diagram and it is determined from the trend of stream beds. The radius of the circle signifies an orientation of 20 %.

(Fig. 35) compared with the direction of flow marked in diagrams on the basis of the trend of the stream bed. Very often these dry beds cut the direction of the present rivers at sharp angles. In lateral stream beds the stone orientation had in some cases the same trend as the probable ice movement, though the former has, of course, nothing to do with the latter.

The sandur stones are in general rounded and they lack striations. Locally, however, there are plenty of angular stones and blocks on the sandur. They occur in such places where the material, deposited during the glacier outbursts forms, such elevated planes that the normal flow of the river has not been able to destroy them. The size of carried material indicates powerful stream action, while the shapes point to short transport also of short duration.

The angular material is mixed with the rounded stones also in places where the river erodes moraines in front of the glacier and spreads their till, washing it in the same. The coarse fractions are then carried such short distances that they preserve their shapes.

The third occurrence of subangular or angular material constitutes the fans of mountain rivers, which in many places adjoin outwash plains. These rivers carry, especially in spring, angular rock fragments from mountain slopes, and they have not time enough to become worn round before depositing.

As a whole the Icelandic sandurs are, in the author's opinion, supra-aquatic deltas or outwash plains with a downstream inclination, and their surfaces are crossed by countless stream beds. In cross profile the surface of a sandur is uneven and its central cone rises higher than the margins (Hjulström 1953 s. 179). This is plainly to be seen especially in the proximal part of the outwash plain, where the present rivers emanating from marginal lakes flow along the sides, eroding the lateral parts of the plain. The central cone joining the end moraine lies always higher than the present erosion level. The long profile shows the greatest gradient in the proximal part (op. cit. p. 178). Towards the distal part it diminishes so that the long profile is hyperbolic. According to Hjulström's measurements, the gradient of Hoffelssandur is in its proximal part 10 m per kilometer, while in its distal part the mean value is 0.5 m per kilometer (op. cit. p. 178).

The fact that the sandur plains reach over the present water level and contain in their proximal parts a very coarse material indicates that these parts have been formed as a result of a more powerful stream action than at present. During this former stage of development the glacier front remained in the end moraines. Since the glacier margin retreated from that position, the marginal lakes have diminished the glacifluvial action and hindered the outwash plains from expanding to the present ice margin. At the same time the share of carried material has diminished to such a degree that the present rivers mainly rework old deposits and transport their drift towards the sea. The finest particles are also now carried directly into the sea. Clay is lacking in the supra-aquatic part of the delta and its deposition takes place first under the sea level. This subaquatic part of the delta is separated from the supra-aquatic part by a sand bar which dams lagoons at the river mouth. They are connected through narrow sounds with the sea. The water in lagoons is seemingly stagnant but levelings show that their surfaces have a gentle seaward slope. Hjulström's map (1954 b) shows that the water level has a height of 10 m at the uppermost end of the lagoon, while the lowermost end lies almost at sea level. The water masses behind the bar are thus slowly moving towards the sea.

The sandur consequently consists of three parts: supra-aquatic outwash plain, offshore bar, and subaquatic delta. The proximal part of the sandur adjoins the end moraine belt, but some water-eroded channels connect the sandur to smaller outwash plains deposited at the ice margin and, in some instances, even on the ice.

ON THE DEFORMATION OF DRIFT DEPOSITS

Accumulations of glacial drift seldom preserve their original forms and structure. Commonly, perhaps always, the exogenetic processes rework the material outside the glacier to such a degree that the accumulations acquire new features. In other words, the accumulations of glacial drift are deformed after their deposition. In this process many agencies take part, among which the work of ice, water, and climatic conditions is decisive. Reference has already been made in many connections to these agencies; but to get an idea of their share in the deformation of glacial drift deposits, a review of these agencies is presented. It is, however, important to keep in mind that many agencies usually partake in the deformation process at the same time, though in varying degree.

The action of the ice is directly related to the behavior of the glacier. It appears in two ways: the deformation of glacial drift accumulations by the advance of the glacier, and the deformation of drift by the melting of the stagnant ice.

The margins of the Icelandic glaciers are in generally unstable and sensitive. The snouts of the outlets are pushed forward many times over the frontal terrain. In some places the ice margin advances over the drift accumulations, wearing their uppermost parts. As already shown, erosion does not reach very deep down into the drift, but the snout over-rides the deposits slightly. For that reason glacifluvial deposits are found under till cover in undisturbed conditions (p. 62). For the same reason the ground moraine has its primary structure and only the shape of the uppermost boulders indicate a later advance (p. 45). A glacier that has readvanced on push moraine loads it with a till layer without destroying its form (p. 64). The slight erosion of the glacier evidently depends on obstructed flow, which causes overthrusts in the frontal part of the glacier. The basal erosion grows stronger when the advancing ice is thicker. This erosion zone is not, however, under the edge of the glacier but somewhere more distant from the margin. If the oscillation does not reach so far that the deposits accumulated in the frontal area come into the erosion zone, these deposits retain their forms and their structure beneath the advancing ice front.

Glacial deposits accumulated on the ice undergo a much stronger deformation. Also the englacial accumulations deform as the ice melts under them. In many cases the ice cores are preserved so long in the superimposed drift that the deposits acquire their topography first after being released from the glacier. The originally smooth forms can thus change to irregular knob and kettle areas. This topography can evolve in both unsorted and sorted glacial drift, assuming that there has been buried ice in the drift. The present conditions at the Icelandic ice borders favor this development. Transversal moraines and clean ice sheets between them have caused a knob and kettle topography with a transversal orientation. Many end moraines (at Hoffelsjökull, Breidamerkurjökull, Skaftafellsjökull, Morsárjökull) have been deformed in this way. Kettle topography is produced also at the bottoms of ice dammed lakes, regardless of the kind of drift (p. 56).

The action of water in the deformation of glacial drift deposits begins already on the glacier, as the surface drift is washed by rain and meltwaters. The finest fractions are carried away, causing thereby an enrichment of coarser grain sizes in the remaining material. The variations in the quantity of water and in the velocity of flow are reflected in the deposition and erosion as well as in the stratigraphy of the drift. This process is repeated in the rivers emerging from the glacier as well in those which begin in the marginal lakes. Consequently, the deposits in both cases have a similar structure.

The deposits of both rivers correspond also morphologically as they form outwash plains. Because of the marginal lakes the transport of material diminishes and the erosion increases in importance. Especially in the proximal parts of the sandurs, where the gradient is considerable and the rivers flow along a few main channels, the river beds have been cut deep into old deposits, thereby eroding the surface of the outwash plain. Simultaneously, rivers erode their beds laterally as well (Hjulström 1953), forming steep banks. Between the river beds there form various erosion remnants, which at certain stages of development resemble eskers (p. 104); but the erosion is likely to continue so long that the original delta plane disappears and only the younger planes at a lower level remain. The surface of the outwash plain is thus deforming and lowering step by step as long as the action of the rivers continues. For that reason the surface does not always indicate the highest position of the water level, but it is a result of continuous river erosion. For the same reason the adjacent delta planes situated at a different height only signify various stages of development. The order of their age is in general such that the higher ones are older than the lower; but sudden floods, glacier outbursts, etc., can cause exceptions.

The river erosion is also directed towards the nonsorted drift at the glacier margin. This drift is so wet and soft that the river erodes it very rapidly. The ground moraine, after being released from the ice, loses its own topography and structure outside the glacier, changing to sorted material under the influence of river action. The end moraines are deformed in the same manner, too. The rivers cut their beds through the ridges during the floods, but during the normal flowage these beds stay dry. Only when the beds have been cut so deep into the moraine that the normal runoff can use them, the rivers flow directly from the glacier margin to the sandur, preventing the occurrence of a marginal lake.

The erosive action of the streams consequently works on the glacial drift quite effectively outside the glacier. It works up till into glacifluvial deposits, cuts end moraines, and wears down planes at different heights to the sandur surface. The deformation process continues as long as the rivers exist. At the present stage of development the proximal parts of outwash plains are lowering and their deposits are gradually carried into the sea.

The part played by climatic agencies in the deformation of drift is manysided and varies in different areas. Moisture, air temperature, and wind relations contribute to this process.

In moist areas, as e. g. in the southern part of Iceland, the drift being released from the glacier remains water-soaked for long periods. Along the slopes it flows slowly down. Flow earth occurs especially on the sheltered proximal sides of end moraines, which are little by little becoming smooth. The heavy precipitation also keeps the ground water level high near the glacier margin. As the drift, especially in glacifluvial deposits, is permeable, the marginal lakes drain subsurficially through end moraines and form pools on the sandur. Clean-water streams issue from these springs and they add to the drainage in braided rivers. Water fills the hollows in the dead ice, too, and in these kettles the fine-grained sediments settle down. As the walls of the kettles simultaneously slump until they achieve an angle of repose, coarser material is mixed with the fine-grained sediments. The originally steep-walled kettle holes become funnel-shaped.

Owing to the effective evaporation on the wind-sides, the soil surface very soon becomes dry. The distal sides of end moraines are much drier than the proximal sides. The drying up of the surface adds to the possibilities of wind erosion. The winds pick up mineral grains from the dry surfaces, thus forming gravelly and stony deflation planes, which cover the dried glacial drift deposits. The fine-grained material borne by the wind polishes the surfaces of blocks and stones, wearing off the glacial striations and causing instead corrasion surfaces. Most of the fine-grained material is picked up by the wind from the dried bottom sediments of marginal lakes and other accumulations of water. The »smoking» of sandurs is mainly caused by these deposits.

The southern outlets of Vatnajökull stretch so far down toward the sea coast that the winter frost does not deform the glacial drift deposits in the frontal area. Hjulström has found periglacial morphology on the Hoffelssandur only in a few places (1953 p. 180).

In the interior of the island the precipitation and the temperature are lower than along the southern coast. The ground water level lies in general deeper and the land surface is dry. The drift deposits freeze in winter and in spring their surfaces are water-soaked. Periglacial solifluction phenomena are common (Thorarinsson 1951). On the surface of ground moraine there occur frost polygons, stone rings, and other features commonly met with in arctic regions. Some marks of periglacial solifluction were seen in front of Langjökull at Hagavatn (p. 47). Because the winds are here dryer than in the coastal area and they blow over bare, open landscape, the wind erosion has a strong effect on the land surface. The fine-grained material disappears from the moraine surface and simultaneously frost wedging breaks blocks into pieces (Hawkes 1924). The slow deformation of glacial drift is thus under way in the central highland. Evidence of these processes is to be seen in the structure and material of old moraines, which are reworked, restratified and washed (Thoroddsen 1905—06).

COMPARISON WITH OTHER GLACIATED AREAS

Among the glaciers of the world today the largest ones in Iceland are in many respects in an intermediate position. In situation they are among the southernmost of the Arctic glaciers, and in size they rank among the large ones, if not among the very largest. In Klebelsberg's listing (1948 p. 209) Vatnajökull ranks fifth and Langjökull twelfth. Ahead of Vatnajökull come only the ice sheets of Antarctica and Greenland as well as the glaciers of West Spitzbergen and North East Land. After it come next the glaciers of Severnaya Semlya and southern Alaska (Malaspina). Also in form the glaciers of Iceland are in an intermediate position. They are glacier caps whose ice mass is so thin that the main body of the glacier reflects on its surface the irregularities at the base. Klebelsberg (1949 p. 582) applies to them the term *Plateaugletscher*. The outlets starting from the ice cap proper, which along the southern margin of Vatnajökull stretch out near the level of the ocean, resemble in many respects valley glaciers. The termini of the largest outlets, again, spread out upon reaching the coastal plain into expanded feet of the Piedmont-glacier type.

Climatically the glaciers of Iceland differ from the Arctic glaciers in that they belong to the temperate glaciers (Ahlmann 1933), whereas most others are either sub-polar or high polar. The temperature of the ice affects its physical properties, for the plasticity of the ice increases towards the pressure melting point. Consequently, temperate glaciers are faster moving. Since, in addition, the glaciers of Iceland receive more abundant snow than Arctic glaciers in general, they are active, although they melt rapidly (Ahlmann 1953). As a result of the heavy precipitation and, at the same time, warm climate, the ice wastes away, largely by turning to water. Rain and meltwater occur on the glaciers of Iceland in greater abundance than on other Arctic glaciers. In addition, local circumstances, mainly subglacial eruptions, cause exceptionally strong glacifluvial activity in certain parts of the Icelandic ice caps. Since the glaciers move fast, they crack up and the meltwaters run off the ice surface into the crevasses, being discharged eventually from underneath the margin.

It is natural that under the conditions described in the foregoing the formation, transport and accumulation of glacial drift should be different from what they are on glaciers of other types. Already Hobbs (1911) stressed the difference between mountain glaciers and inland ice sheets in describing the existing glaciers. »The determining factors in the case of mountain glaciers seem to be an upturning of the ice layers in this region and surface ablation or melting. In the case of inland-ice the important factor is the deposition upon the surface of snow borne by the wind from the interior of the mass» (op. cit. p. 289). Arctic ice caps are, according to Hobbs, in an intermediate position between these two principal types.

Glacier research of recent decades has moderated Hobbs' sharp boundary between inland-ice and mountain glaciers. Numerous examples have been presented from the Arctic towards proving that the margins of ice caps and ice sheets behave just about in the same way as those of Hobbs' mountain glaciers. This is perhaps because the present amelioration in the climate has begun to affect the glaciers and be reflected in the behavior of their marginal zones. According to Ahlmann (1953) the size of glaciers affects their reaction to climatic change in that the change is felt sooner on small glaciers. The valley glaciers of the Alps and Scandinavia began to melt already towards the end of last century, so that the descriptions of these glaciers from that period reveal the behavior patterns of a retreating ice margin. The Ameghino glacier in South Patagonia began to shrink in 1870—1880 (Nicols and Miller 1951). The culmination point of the Icelandic glaciers occurred in the 1890's, and the vast ice mass of Antarctica has not yet, according to data collected by the Maudheim expedition, reacted to climatic change (Liestøl 1953).

Vatnajökull is not, however, the largest glacier that has begun to react to climatic change, for also the glaciers of Spitzbergen (Ahlmann 1933, 1935, Glen 1939) and Greenland (Bauer 1955) are currently shrinking. In studying the present shrinkage of glaciers, Thorarinsson has gone through, *inter alia,* many reports of Greenland and concludes that »recession and thinning have for some decades characterized the large majority of the Greenland outlet glaciers and the margin of the inland ice» (1940 p. 147). From Thorarinsson's study it becomes quite clear that the shrinkage of glaciers is a universal phenomenon, which, with the possible exception of Antarctica, is evidenced by the present behavior of all the glaciers on earth.

Size is not the only basis for comparing the behavior of glaciers and studying the results. A different and perhaps better basis for comparisons is a grouping of glaciers into different types. Many kinds of classifications have been made; some have been pretty general, while others have been developed to a high degree (e. g. Hobbs 1911, Priestley and Wright 1922, Ahlmann 1933, Drygalski-Machatschek 1938, v. Klebelsberg 1948). Most of them are based on the morphological characteristics of glaciers and especially the placing of some among intermediate types has perforce been subjective. In order to reach firmer ground in the morphological grouping of glaciers, Ahlmann has revised his morphological type classification (1940) by carrying out analyses to determine how the area of different-type glaciers is distributed percentably at different height intervals. The results of the analyses have been presented as area distribution curves (op. cit. p. 198). When the curves thus obtained are compared, it becomes clear that ice caps and ice sheets have the same kind of curves as Hoffelsjökull and the other subsidiary glaciers of Vatnajökull. In other words, they belong to the same glacier type as Vatnajökull as a whole as well as other ice caps and Greenland. The curve shows their area as expanding toward the broad plateau of the summit. The curve of Ahlmann's transection glaciers, including e. g. the Lilliehöök and Löwenskiöld glacier in Spitzbergen, the Yakutat glacier in Alaska as well as other »*Eisstromnetze*», starts higher, rises convexly to its maximum already at the 6—8 interval and falls thereafter steeply below the level of its starting point. The curves for valley glaciers are similar, with the culmination points being situated at different intervals. The curve of the great Aletsch glacier resembles the ice cap curve most, whereas the Piedmont-glacier curve differs from it most radically, as it culminates at the lowest interval. The ice mass of Piedmont glaciers is thus situated quite differently from ice sheets and ice caps. Its expanded part is so large that it acts independently and melts at the same time rapidly. Since the main part of the ice mass of a Piedmont glacier is situated in the ablation zone, a rise in temperature does not alter the relation between the accumulation and ablation areas of such a glacier as significantly as in the case of ice sheets and ice caps — unless the melting reaches a stage where the Piedmont glacier loses contact with the ice streams feeding it. A change in temperature affects the behavior of a glacier the more forcefully the greater the relative area of the higher parts of the glacier (Ahlmann op. cit. p. 203). Accordingly, the recent amelioration in climate must be reflected most plainly in the activity of ice sheets and ice caps, for their balance has been disturbed most.

Rapid melting ought, therefore, to characterize the marginal zones of all glaciers today whose accumulation areas have recently shrunk, i. e. ice sheets, ice caps and transection glaciers. It is, of course, not evident identically in all glaciers, inasmuch as both climatic and topographic circumstances affect the behavior of each ice mass. This becomes plain upon studying the literature on the glaciers of our times.

The dead volcano Beerenberg, on the island of Jan Mayen N-NE from Iceland, provides the base for an ice cap some 70 km^2 in area but nevertheless thin (Odell 1939, Jennings 1939, 1948). From the climatic snowline, which in 1938 was situated 914 m above sea level on the southern slope and 636 m on the northern slope (Jennings 1948 p. 180), several thin but broad outlets extent seaward. Some of them extend as far as the sea, but others terminate on land. In front of the latter are two arcuate end moraines, from which the glacier has already retreated. When Odell visited the island in 1933, he noted dumps in the farther end moraine, and in 1938 Jennings found an ice core in the inner end moraine at numerous points. Ice was found also buried under lateral moraines, and in front of a number of ice tongues there occurred detached parts of stagnant ice. Furthermore, the termini of the tongues were in many places covered with drift (e. g. the eastern Weyprecht glacier). From Jennings' description it is evident that the glacier is rapidly shrinking, that dead ice occurs along its borders and that the marginal parts of the tongues terminating on land are beginning to be covered with moraine. The glacial drift undergoes the same kind of treatment, therefore, as in Iceland.

The glaciers of Spitzbergen belong to the subpolar type. They receive most rain in West Spitzbergen, where the climatic snowline is situated 200—800 m above sea level, since moist winds blow over the islands from the Atlantic. In the northeastern part of the island there is less precipitation and the climatic snowline is there situated 350—550 m above sea level (v. Klebelsberg 1949 pp. 570—571). Inasmuch as the climatic conditions become more rigorous toward the northeast, the glaciers of North East Land are more uniform and larger than those of West Spitzbergen (Ahlmann 1933).

In West Spitzbergen there have evolved transection glaciers and small ice caps, and the highest and also coldest, northeastern part of the island is covered by a uniform ice dome. From their firn areas there jut out seaward outlet glaciers, which in places calve into the sea and in other places terminate on land. The ice flow in the outlets is rapid and causes changes also in the position of the margin. The borders of such ice tongues have become known by virtue of numerous studies (e. g. De Geer 1910, Lamplugh 1911, Hoel 1916, Tyrrell 1927 and Gripp 1929.) According to Gripp's observations the movement of the ice takes place in the marginal zones of the tongues along parallel shear planes. These planes lift glacial drift upward, for the base of the ice mass turns uphill as soon as the margin encounters the slightest obstruction. The advancing margin itself helps form obstructions by building up in front of it push moraine out of deposits in the frontal terrain. In addition, basal load is squeezed upward along crevasses in the glacier. Obstructed flow thus plays a notable part in the flow mechanism of the outlet glaciers of West Spitzbergen. In consequence of it there evolves *kuppige Grundmoränenlandschaft* (termed ablation moraine in the foregoing) in extensive zones. Since the action of meltwater is slighter than in Iceland, topography like this generally survives. The meltwaters largely flow through englacial tunnels and out of their sorted material sandurs are produced beyond the glacier margin. Their occurrence in West Spitzbergen, where volcanogenic glacier outbursts do not figure, provides evidence that sandurs evolve as a result of normal glacier drainage.

Gripp's precise observations make it manifest that the glacial drift deposits of West Spitzbergen correspond in a high degree to those appearing along the southern margin of Vatnajökull. This similarity has attracted the attention e. g. of Todtmann (1932) and Hoppe (1951). The differences are mainly such that there is a greater abundance of eolian sediments on the glaciers of Iceland, the washing of drift is stronger there and basal load is released from the ice there sooner than in West Spitzbergen.

The glaciers of North East Land are uniform ice caps, separated by iceless zones. The caps lack nunataks and their surfaces form domes reaching up to the 700 m level. Their margins either terminate on·land or calve into the ocean. On land they form thin sheets of ice covered with glacial drift, many of which have become detached from the glacier proper and melt in place (Glen 1937). The disappearance of the glaciers is promoted by the undermining effect of meltwater. Thus Groft relates having found, in the winter of 1935, a crevasse in an ice cap in North East Land down into which a man could descend 70 feet. »At the bottom was an elaborate and strikingly beautiful series of caverns, with a considerable lake of water. Here was the bottom melt in full operation — a state of affairs which was very different from that on the surface» (1937 p. 249). Fracturing of the thin marginal parts of the glaciers is so common that Glen (1939) foresees the ice caps of North East Land breaking up into numerous separate glaciers in the future. According to Ahlmann they are inactive, »starving» glaciers, whose accumulation, ablation and flow are all slight. In this respect they differ from the active, maritime glaciers of Iceland. In times past the glaciers of North East Land used to be more active and built up end moraines (v. Klebelsberg 1949 p. 570).

The conditions prevailing at the southern margin of the Barnes ice cap, which the expedition of the Arctic Institute of North America investigated in the summer of 1950, afford an illuminating picture of the way glacial drift rises up in the ice margin. Shaped like an irregular ellipse oriented NW-SE, the Barnes ice cap covers an area of about 5 900 km^2 in the eastern central part of Baffin Island. Its cupola-like center rises to an elevation 1 120 m above sea level, while its margins lie at the 450 m level. According to meteorological and glaciological observations (Orvig 1951, Baird 1952) the Barnes ice cap is subpolar or high polar and receives very little precipitation. After investigating the southern margin of the glacier, Goldthwait (1951) decided that the margin had at certain points remained stationary perhaps for centuries but had receded in our own times at other points. The slope of a retreating ice margin was slighter than that of a stationary one. So much basal till rose up to the surface of the ice margin in the latter case along the numerous thrust planes that the ice was buried under surface drift. This occurred to a height of 100—200 feet, measured from the margin. In spots where the drift layer was three feet thick, it retarded the melting of the ice and formed ice-cored moraine, separated from the main body of the glacier by the more rapidly melting trough. According to gravimetric measurements (Goldthwait op. cit. Fig. 3) the toe of the glacier rests on a base rising outward along a gentle slope and the thickness of the ice at the point where dirt begins to appear on the surface is about 150 feet or 50 m. Goldthwait's investigations reveal that obstructed flow takes place also at the edges of cold ice caps. Since the surface of such glaciers undergoes less washing than that of the glaciers of Iceland, the drift cover of the border crest grows thicker and the whole process is more plainly evident than in Iceland. It is interesting to note that according to Goldthwait's conception the rise upward of drift on a slant plane occurs also when the margin of the glacier terminates as a steep cliff in water (Profile B, Fig. 3), i. e. precisely as at Hagavatn in Iceland. Ward too (1952) had made similar observations regarding both transversal moraines and the margin of glaciers terminating in a lake (Fig. 4 and photo Fig. 13). He has further noted that ice buried under drift outside the visible ice margin is likely to remain unmelted for long periods of time, because of the cold climate (p. 21). The drainage of the Barnes ice cap differs from that of the Icelandic glaciers, for on the basis of Ward's observations the meltwater forming in the summer flows across the surface of an unbroken glacier up to the margin rather than subsurficially. This is because, Ward propounds, the temperature of the ice is usually below the pressure melting point, causing water penetrating into the ice to freeze (p. 11). Likewise, crevasses opening in the ice also become sealed. On the surface of the ice behind the border crest shallow lakes form and in places in front of the glacier dammed-up marginal lakes.

Greenland's great ice sheet (Hobbs 1911, v. Klebelsberg 1949, Woldstedt 1954) naturally affords many points of comparison, for at its various margins there occur, as a consequence of both topographic and climatic conditions, various kinds of activity. The vast outlets calving into the sea rank among the most rapidly moving glaciers on earth, whereas the ice margin of northern Greenland, which in places terminates on a high, flat plateau and elsewhere forms a transection glacier type of margin in the mountains, represents a high polar, inactive glacier. As a whole, the continental ice sheet of Greenland, according to the latest calculations (Bauer 1955), is 1.726×10^6 km^2 in area and 2 135 m in average height, with the elevation of the climatic snowline averaging 1 390 m above sea level. The snowline divides the glacier in such a way that the accumulation area comprises 83.5 % and the ablation area 16.5 % of the total. According to Bauer's calculations, the budget of the glacier is negative, for the accumulation (446 km^3) does not make up for the loss caused by ablation (315 km^3) and calving (215 km^3). The annual loss amounts on the average to 100 km^3 of water.

Even though the ice sheet of Greenland as a whole is wasting away, its great accumulation area does not yet reflect it. Its even field is without crevasses, moraines or nunataks (e. g. Nansen 1892, Koch und Wegener 1911, 1930). The effect of the margin is felt farthest toward the center at the points where rapidly moving ice streams extend to the sea. In the western part of Greenland the crevassing caused by them occurs as far as 145 km from the ice margin (Quervain 1920). Possibly the terracing to be observed in the marginal parts of the ice sheet (Woldstedt 1954 p. 38) is caused by the fact that the relief of the base has begun to affect the form of the glacier. One special consequence of this irregularity developing is the formation of large lakes on the surface of the ice. Only in the marginal zone does glacial drift begin to appear on the glacier. It forms lateral and medial moraines, which are flushed by water in transit, eventually evolving into block fields on the ice (Chamberlin 1897, p. 239). On the glacier margin the amount of drift increases, for basal drift rises up shear planes and crevasses to the surface. Its occurrence has been described by many investigators (e. g. Chamberlin 1894a, 1895, 1896 and 1897, v. Drygalski 1895, Koch and Wegener 1911, 1930). According to Chamberlin's observations (1895, pp. 572, 675) load rises up along shear planes inclined forward, especially at points where the motion of the glacier takes place uphill. An obstruction is likely to be formed by push moraine accumulated by the glacier itself (p. 675). Also more slowly moving sheets of ice form an obstruction to those farther behind, forcing them to thrust forward obliquely (p. 677). Movement up shear planes takes place by jerks. According to the observations of Koch (1911 p. 438) there has evolved as a result of such movement the broad ablation area of Germanialand in NE-Greenland, where numerous clay towers and pyramids had risen on the ice surface.

Also Battle (1951) emphasizes the importance of thrust planes to ice movement in the Fröya glacier of NE-Greenland. This glacier, Ahlmann (1941) points out, is one of the best representatives of the high polar or inactive glacier type, for its regimen is characterized by very slight accumulation and equally slight ablation, combined with a low temperature. Similar glacierization conditions prevail also at the W-margin of the Greenland ice sheet at Eqe, where the glacier terminates on a relatively even high plateau. As Boyé and Cailleux recently (1954) noted, the ice margin there is surrounded by a broad ablation zone, in which both radial and transversal crevasses occur. One transversal crevasse was situated 200 m upstream from the outer border of the ablation belt and constituted the true border of the ice sheet, separating as it did the ablation moraine-covered part of the glacier from the glacier proper. Into the channel formed by this crevasse, drift avalanched from the surface of the melting ice mass. At the bottom of the crevasse could be seen morainic boulders. When Boyé and Cailleux measured the ice crystals, they were unable to ascertain from what depth the crystals had come »because of the overthrusting and folding of the ice». This interesting description reveals that the margin of the Greenland ice sheet at Eque had become buried under surface drift raised by obstructed flow and cut off from the glacier.

The development at Eqe had thus led to precisely the result represented by Rich (1943). He had reached the conclusion, in dealing with the matter theoretically, that the conditions prevailing at the ice sheets favor the burial of the ice under glacial drift. The thin and drift-covered outer edge of a glacier forms an obstruction to advancing ice, forcing it to slide upwards at a slant, which leads to rising up of drift along thrust planes toward the surface. As the ice margin thins from melting, drift is brought into view and it produces a border crest, separate from the main body of the glacier by a trough. Rich's drawing (op. cit. Fig. 2) resembles so greatly those presented by Goldthwait (1951 Fig. 2) and Ward (1952 Fig. 7) that all three might illustrate the same ice margin at different stages. The turning upward of the ice margin, which Hobbs considered characteristic of mountain glaciers, thus proved to be also characteristic of ice caps and the ice sheet of Greenland. Previously the same phenomenon had been encountered in the Piedmont glaciers of Alaska (Russell 1895, Tarr 1909, Tarr and Martin 1914, Washburn 1935), where the ice margin is covered by drift in a broad zone. Adding to this the fact that in cirque glaciers (Clark and Lewis 1951) the movement of the ice takes place up slant shear planes, it may be affirmed that obstructed flow occurs in the present margins of different glacier types. According to the observations of Ward (1952, p. 12), the drift raised by this motion is released from the ice in two ways: in response to ablation and in the case of active ice gliding over less active or dead ice. Both processes occur when drift is released from an active shear plane, but only the former upon the melting of a stagnant shear plane. To what extent upraised drift remains on the surface depends largely on the strength of the surface washing. In Arctic glaciers, where surface washing is less abundant than in more temperate conditions, surface drift has greater possibilities of forming such thick layers that melting of the underlying ice is effectively prevented (Sharp 1951). On vigorously washed glaciers, including those of Iceland, border crests do not develop as fully as in more rigorous climatic conditions. The structure of the margin nevertheless distinctly shows the same process to prevail.

From the southern hemisphere Nicols and Miller (1951) have depicted the same kind of treatment of glacial drift at the Ameghino glacier as has herein been presented in connection with the glaciers of Iceland. The Ameghino is an outlet approximately 15 km long and 2 km wide of the transection glacier situated on the western side of Lago Argentino in the Andes (50°25′—51°25′ southern latitude). On the surface of the glacier there is to be observed e. g. thrust planes generally inclined toward the center, transversal crevasses and places where the glacier has advanced on top of stagnant blocks of ice. In front of the glacier there has formed a lake dammed by frontal moraine; and the terminus of the glacier is submerged in the lake. Moreover, there is an abundance of roundstone till in the glacial drift; and this is regarded by the researchers as one proof that the glacier has advanced over the outwash plain formed at the margin and from it taken material to be deposited in the till. Thus in the case of the Ameghino glacier formations analogous to those in Iceland are met with.

The glaciers along the southern coast of Alaska, already referred to, have become known as representatives of a certain Piedmont type. Their multi-branched accumulation areas collect ice into extensive low-land glaciers, which have evolved below the snowline (Sharp 1951). The largest in size is the Malaspina glacier, whose ice bulk comprises an area of 3 840 km^2 (v. Klebelsberg 1949 p. 494). On the basis of seismic soundings the thickness of the ice in the middle part of the glacier is 1 130—2 075 feet (376—690 m) and its relatively even floor is situated below sea level, rising gently toward both the mountains and the sea (Sharp 1952). In the middle part of the glacier the ice crosses a gently sloping sill in moving seaward. Behind this sill Sharp sank a tube 1 000 feet (330 m) long in order to determine the flow mechanism of the ice. The results up to now (Sharp 1953 a and b) indicate that »the surface ice appears to be carried along by the flowing ice beneath in a manner contrary to the mechanism of extrusion flow» (Sharp 1953 a p. 184). And in another report Sharp (1953 b) writes: »The initial results are certainly not consistent with the mechanism of extrusion flow as expounded by Demorest». At the glacier margin the movement of the ice turns upward and so much drift is brought to the surface up the shear planes that the entire border zone is buried under it. The drift accumulated at the margin receives addition material from medial moraines, which spread out on nearing the edge tens of kilometers (Tarr 1909, Tarr and Martin 1914). As the Malaspina glacier is located in a region of heavy precipitation and as, furthermore, it lies wholly in the ablation area, its drainage is abundant. The water is discharged under pressure from the edge of the glacier, and it carries with it much glacial drift, from which an extensive outwash plain has been built between the glacier and the sea. In flowing across this plain the streams branch out frequently and continually change course. They behave, in other words, in the same way as the glacier-fed rivers of Iceland, with the exception that they go through only a single phase, whereas in Iceland the water drained from glaciers undergoes at a number of places three phases. The action of meltwater from the Malaspina glacier thus is about the same as during the formation of the Icelandic sandurs. The flow of water, which according to the observations of Russell (1893) and Tarr (1909), occurs both englacially and subglacially, is augmented from ice-dammed lakes located on the northern side of Malaspina between the glacier and the bordering mountains. Here too we see close similarities between the glaciers of Iceland and southern Alaska.

The drainage of the great ice sheet of Greenland naturally varies at different parts of the glacier. Meltwater is abundantly discharged from the ice tongues terminating in the fjords of the southern part of Greenland, and from the glacifluvial material carried by it outwash plains are built up at the heads of the fjords. The meltwater also washes the moraine released from the ice and re-sorts it to the extent that original moraine deposits are in many places a rarity. At the margins terminating in the interior much less meltwater is met with. It vanishes from the surface of the ice into crevasses and issues forth from the glacier tunnels at the edge. According to Nansen's observations (1892) a heavy flow of water continues out of the tunnels even after the air temperature has been below the freezing point for several months. The glacier thus seems to be melting subglacially even in the wintertime. Woldstedt (1954 p. 40) considers the reason to be either heat stored up in the land or friction caused by the movement of the ice. A similar phenomenon is encountered on North East Land, as related on p. 116. Battle (1951) tells of running across a tunnel in the Skille valley glacier in northeast Greenland at the bottom of which flowed a stream. When the tunnel was explored to a length of 500 m, it was ascertained that the water came into the tunnel from a crevasse overhead, which had opened up in the ice under a medial moraine. The meltwater forming on the medial moraine on top of the glacier thus first collected in the crevasse and then flowed subglacially through the tunnel to the edge of the glacier (comp. p. 37). At the point where the crevasse was situated there was 76 m of ice above the tunnel. Similar empty tunnels had previously been met with in the glacier of Malaspina (Russel 1893) and at Skeidarárjökull after a glacier outburst (Nielsen 1937). After the water has ceased to flow, the tunnels, however, soon close up.

In regard to abundance and activity of meltwater, the glaciers of Iceland compare most nearly with the glaciers of southern Alaska and the southern part of the Greenland ice sheet, where the meltwater flows subsurficially and is discharged from the mouths of glacier tunnels. The drainage of the

Icelandic glaciers differs most from that of subpolar and high polar ice caps, which by and large takes place superglacially. The ice margins terminating in shallow water of marginal lakes, such as those described from Hagavatn (p. 90), the edge of Hoffelsjökull (p. 90) and Hvitárvatn (Nørvang 1937) in Iceland, form the same kind of submerged outlets also in Alaska (Russell 1893, Hobbs 1911 p. 180) and Norway (de Boer 1949).

A common feature of the glaciers considered in the foregoing is that they have formed on land and their margins terminate either on land or in shallow marginal lakes. In addition, they are all currently melting away. In spite of these characteristics in common, however, distinct differences appear both in their behavior and the treatment undergone by drift. They become most clearly manifest when high polar ice caps are compared with temperate glaciers. The former are inactive and slow of movement, and wastage takes place more by evaporation than melting. The latter are active and rapid of flow and melt simultaneously both on the surface and at the base. In the case of both types glacial drift rises up to the surface as a result of obstructed flow, but these accumulations are better preserved in the marginal zones of high polar glaciers, forming on melting pitted end and ablation moraine. On the surface temperate glaciers the drift wanders more easily. It is flushed down into depressions, crevasses and in front of the glacier edge. Since, furthermore, glacifluvial activity is stronger in temperate glaciers, the glacial drift is altered into glacifluvial matter, which is deposited in front of the glacier margin to produce extensive outwash plains. Such deltas sometimes evolve also on top of the thinned-down margin of a glacier.

SUMMARY

1. The glacierization of Iceland is a result of the combined effect of two components: topography and climate. The largest glaciers on the island are ice caps, whose firn areas are surrounded by ablation zones. In the interior broad, short lobes occur on the glacier margin; but along the southern coast long outlet glaciers extend nearly down to sea level. The behavior of the glacier margin depends on the pressure prevailing at any given time on the main body of the glacier. In recent decades the glaciers have been melting fast. This can be noted in the ablation area in the thinning of the ice and in a cessation of the glacier flow. Obstructed flow is the most obvious kind of movement in the present margins of the Icelandic ice caps.

2. The moving ice carries drift in abundance to the marginal zone. This load is divided into wind-blown detritus, volcanic products, surface moraines, basal load, washed material, and crevasse fillings. During

transportation the position of the drift varies. The drift deposited on the surface of the accumulation area is rapidly buried under snow and comes into view only in the ablation area. Here it produces medial and lateral moraines as well as upturned ash layers and dirt bands. The medial and lateral moraines contain much disintegration material avalanched onto the ice surface, but some medial moraines originate from the ice-covered peaks of the glacier floor and contain only erosion products. The superglacial drift retards the melting of the underlying ice and adds to the irregularity of the glacier surface. At the same time the various components become mixed up. Thus e. g. the glacial drift receives pollen and spores from the recent eolian detritus.

Obstructed flow also forces basal load up along thrust planes to the ice surface in the marginal zone. The uplifting process takes place in various ice border types. Load rises up in the ice at least 30—50 m. On coming into sight, it is wet, filling the transversal crevasses between upthrust sheets of ice. The crevasses dip about 30°—40° towards the glacier. Thick accumulations of load remain elevated and form transversal moraines, as the ice surface thins down faster between them. At last, the border crests and other superglacial accumulations are detached, along with their ice cores, from the active glacier. If the surface washing is vigorous, border crests of long duration cannot form, for the material is flushed from the heaps into hollows and crevasses.

The hollows are liable thereupon to collect so much drift that they in turn melt more slowly and end up as mounds.

At the same time as the glacier thins down on its surface, melting takes place also at bottom, for basal load cuts loose from the ice already subglacially, forming basal till. In general the till detached from the glacier remains undisturbed in place, preserving the fabric given it during transport, but at some points, however, the ice squeezes up till into the crevasses and in front of the margin.

3. The moraines released from the ice have been divided into ground, radial, ablation and end moraines. Ground moraine covers wide areas in the gently undulating highland of the interior, where it constitutes an accumulation evening out irregularities of the bed, though still reflecting them. The occurrences of ground moraine along the southern margin of Vatnajökull are small in area. Since the nunataks and bordering mountains exposed out of the ice are usually bare, it is conceivable that the basal load does not rise high enough in the ice to form thick accumulations on the mountains. The best conditions for the creation of ground moraine exist when the ice melts in a stagnant state and does not contain much surface drift. If, furthermore, the melting takes place by evaporation, the ground moraine preserves also its own relief. At a glacier margin that oscillates

and forms meltwater in abundance, the accumulations of basal till are deformed.

Radial moraines form out of basal till in the marginal crevasses. The till is squeezed up from underneath the ice. A necessary condition for the pressing up of till is that it must have become detached from the ice already at a subglacial stage. Small radial moraines originate also when blocks of ice fall off the glacier margin into mushy drift, pressing it into the spaces between them. Radial moraines occur in limited areas only.

Ablation moraines evolve on the margins of the glaciers of Iceland nowadays quite generally. They are met with along the sides of outlets, in front of medial moraines and everywhere that obstructed flow lifts sufficient basal load up to the surface of the glacier. In the trough between the glacier margin and arcuate frontal moraine there almost invariably occurs ablation moraine. The formation of ablation moraine takes place everywhere that the ice melts underneath glacial drift. The ice first wastes away in place where there is little surface drift. Into depressions thus formed, melted rapidly by water, there slides such an abundance of drift from the surface that the original holes collect a thicker accumulation than remains on the last lingering ice. As the drift at the same time becomes sorted and re-treated, it loses its original structure. It contains deformed sediments mixed up with till.

Ablation moraine forms abundantly when the glacier melts rapidly and thins down and when the ice contains sufficient glacial drift. As a consequence of thinning, the marginal parts of the glacier turn stagnant and detache themselves from the active glacier. Stagnation of ice may also occur in places where the ice is free of drift. That is why the occurrence or absence of ablation moraine cannot be used as proof in explaining whether the glacier had been active or turned stagnant in its last phase. The forming of ablation moraine is generally concentrated along the glacier margin. If the marginal zone retreats continuously, the areas of ablation moraine are likely to spread considerably, without, however, signifying that any large parts of the glacier had simultaneously turned stagnant.

End moraines have developed most prominently in front of the southern outlets of Vatnajökull, but they are to be met with elsewhere as well. Their distal sides border on great sandurs and their proximal sides either on marginal lakes or ablation areas. In only a few places does the glacier still extend to their proximal slopes. The great end moraines have formed during the earlier stage of development, when the ice margin was thicker and extended farther than now. It formed push moraines out of the frontal deposits, thus creating for itself conditions whereunder the ice border had to advance uphill. The consequence of this was an increase of obstructed flow. The push moraines thereupon became covered by both dump moraine and basal load. The rise of basal load occurred to a much greater extent than now at the time when the ice margin was in active motion at the site of the end moraines. As this activity has nowadays changed to passive melting, end moraines form only in exceptional cases. They are modest in size and accumulate at a glacier margin when it advances or remains stationary. As a consequence of the different ways in which end moraines form, their material and structure vary considerably. In them basal till, folded sediments from the frontal area, and surface drift occur as alternating and also intermixed strata. The knob and kettle topography of the great arcuate end moraines verifies that in the end moraines there had been buried ice in abundance.

4. The wasting away of the ice is promoted by abundant rainfall, especially along the southern seaboard of Iceland. As, moreover, much meltwater forms, great quantities of water are discharged by the glaciers each year. The flow of water takes place almost wholly subsurficially. At least part of the water streams through tunnels with a natural slope. During glacier outbursts the flow takes place subglacially under hydrostatic pressure, but at other times the pressure is slight. The water collects into marginal lakes, which in places extend up to the crevasses and in other places continue under the ice or inundate the thin ice margin. The water of marginal lakes melts the ice most along the waterline, with the result that at the bottom there remains ice buried under sediments. From the lakes the water flows into swift rivers which branch out vigorously and constantly change their course. The activity of the meltwater thus commonly has three stages.

5. The glacial drift which comes into contact with the streaming water changes in character, being termed glacifluvial material. Part of this treatment takes place on the surface of the ice, part subsurficially and part outside the glacier.

The deposits forming on the ice are sometimes stratified, sometimes accumulations of fine and coarse sand with scattered stones and more weakly sorted parts. Crevasses, in particular, and the fosse behind the border crest serve to collect these sediments. During the final stage of melting these sediments usually became mixed with other surface drift and occur as lenses in ablation and end moraines. Deposition of glacifluvial material likewise takes place on thin submerged sheets of ice. These deposits deform into pitted terrain when the ice melts from underneath.

Glacial drift treated by subsurficial streams constitutes the main part of the glacifluvial deposits. During glacier outbursts the water issues from the tunnels with such force that it carries all the drift outside the glacier. In such circumstances the material forms an esker in front of the mouth of a tunnel. Ordinarily the glacifluvial drift spreads out into outwash plains. The coarsest part accumulates nearest the glacier, while the finest is carried farthest. Stones and boulders in such a deposit are orientated so that their longitudinal axes lie perpendicular to the flow. Flat-topped boulders are turned so that their upper surfaces lie at a rising angle downstream. As the central cones of the outwash plains generally lie on a higher level than the present glacier tunnels, the glacifluvial activity was stronger during the formation of the sandurs and more glacifluvial drift was discharged by the glaciers than at present.

The water drained from the glaciers nowadays flows out gently and without pressure. It carries only fine-grained material, which deposits in the marginal lakes. The coarser glacifluvial material accumulates subsurficially, forming *inter alia* tunnel eskers. Evidently, the deposition of glacifluvial drift takes place also in marginal lakes extending under the ice, which represent the first sedimentation basin for the material of subsurface streams. The sediments resemble the washing on the glacier surface. Sometimes they are stratified and often they are mixed with drift sliding down off the ice. If the sedimentation takes place off the ice onto a free base, the sediments level it out; but if they accumulate on top of ice at the lake bottom, their layers are later deformed.

The strongest treatment currently given glacial drift takes place outside the glacier border. The braided rivers emerging from the marginal lakes have so strong a current on account of the steep gradient that they rapidly erode the drift within their sphere. The moraines formed previously are worn off and their material changes under the treatment of the streams. The earlier delta planes likewise erode, with new beds and delta isles in between being created. The erosion is strongest in the proximal parts of the sandurs, from which the marginal lakes prevent the acquisition of additional load. The delta plains subject to two-sided erosion are transformed into esker-line erosion remnants. Their primary stratigraphy represents typical sandur structure. The sides of an erosion esker are at first vertical, but in time they begin to slope less steeply as the material dries and collapses. If such erosion eskers are preserved, they form an esker type of their own.

6. The accumulation of glacial drift described in the foregoing belong to two genetic stages. The one corresponds to the present behavior of the glaciers and the other represents prior conditions. In addition, the drift also contains fragmentarily material reflecting still earlier stages of glacierization. The conception of the course of development in southern Iceland is presented in the accompanying table (p. 127).

7. The treatment undergone by glacial drift on the glaciers of Iceland corresponds to that on other temperate glaciers. It is characterized by active behavior of the ice, heavy melting simultaneously on the surface and at the base of the glacier, abundance of meltwater and its subsurface

Formations	Glaciers	Meltwater	Sea	Climate	Date
Ablation moraine, ground moraine, sediments of marginal lakes, erosion and tunnel eskers. Radial and end moraines rare	Melting. Margin often stagnated Balance negative	Abundant, but occurring in three stages on account of marginal lakes' forming. Volume of water in icedammed lakes diminishes	At 0-level	Warm and rainy	Present stage
Great end moraines evolve. Troughs hollowed out under ice margin	Active. Margin extends to end moraine. Balance ±0	Abundant, subject to pressure. Discharged in one stage. Much water in ice-dammed lakes. Few marginal lakes	At 0-level	Rigorous	Latter half of 19th century
Betula peat on Breidamerkurjökull. *Betula* stems on Hoffelsjökull. *Betula* peat at Hoffel and Laugardalur	Much smaller than at present	?	Perhaps +4 m (Bárdarson 1910, Thorarinsson 1951). Does not extend to Hoffel nor Laugardalur.	Warm and humid	Postglacial climatic optimum
Ericaceae-Salix pollen at Hoffel and Laugardalur	Larger than at present. Margin perhaps at great end moraines	?	Near the swamp of Laugardalur (+15 m). Does not extend to Hoffel (+30 m?)	Colder than now perhaps dry	Preboreal
			In northern Iceland +40—50 m (Thorarinsson 1951) High water stage?		Gotiglacial
Moraine at Hoffel and Laugardalur. Striations on coastal plain	Larger than at present. Margin extends at least to present shoreline	?	Low	Cold	Last general glacierization in South Iceland
Sterile mollusc clay on Hoffelsjökull, Breidamerkurjökull, Skeidarárjökull and Öræfajökull. The sterile clay of Kvisker and the mollusc clays of Gullfoss and Ellidá originate? Shore terrace evolves	At minimum size	Strong glacifluvial activity in Icelandic interior. »Palagonite formation» produced?	As far as coastal terrace (+100 m). Cold and transgressive	Warm	Interglacial or interstadial stage
Moraine and striations, e. g. under interglacial strata. Submarine valleys evolve?	At maximum size	Glacifluvial activity on submerged coastal plain	Low, at level of submerged coastal plain (—200 m?)	Cold	Ice Age

flow. Previously produced end moraines, from which the ice margin has receded, constitute natural obstructions to the flow of meltwaters and cause it to undergo three separate phases. Local conditions also bring about an augmentation of the quantity of drift. As a consequence of its abundance, ablation moraines are generally met with. All in all, the glacial drift of Iceland affords a coherent picture of the kind of formations nowadays evolving in the marginal zones of rapidly melting and simultaneously active, temperate ice caps.

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FIGURES No:s 1—32
IN
PLATES I—XVI

PLATE I

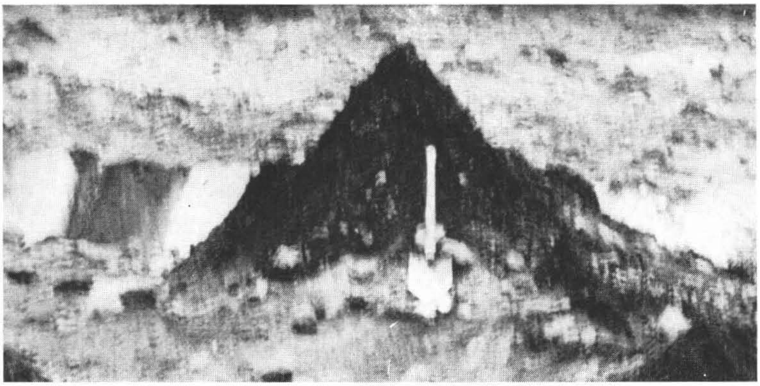

Fig. 1. Ice-cored dirt cone on Hoffelsjökull. The length of the spade is 75 cm.

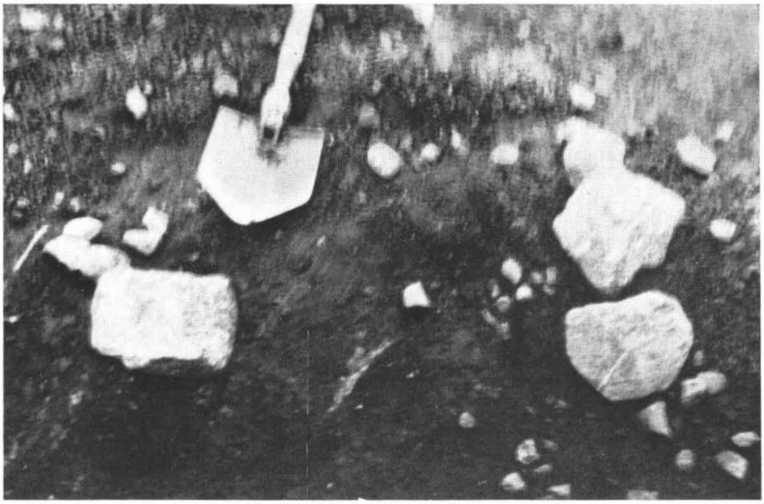

Fig. 2. Glacial drift in a medial moraine on Hoffelsjökull. The rock fragments are angular and lack striations.

PLATE II

Fig. 3. Lateral moraine along the western side of Skaftafellsjökull (left) is accumulated on the ice. It consists mainly of material from the rock slope (right). Beneath the moraine an ice core.

Fig. 4. The lateral moraine seen in the former picture grows thicker downstream. Near the terminus of the glacier it forms a mantle two meters thick on the stagnant ice.

PLATE III

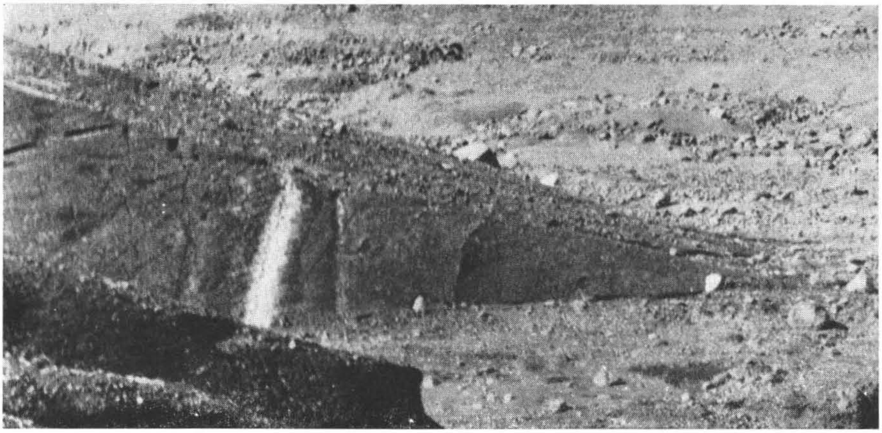

Fig. 5. The snout of Breidamerkurjökull (left) forms a thin wedge upon the ground moraine. Dark stretched ovals in the icewall (top left) are hollows in the ice and they are lengthened parallel to the ice movement.

Fig. 6. A transversal crevasse 30 cm in width in the snout of Hoffelsjökull is full of water-soaked till. The tip of the spade rests on the underlying ice while the overlying ice sheet begins behind the lower part of the spade handle. The length of the spade is 75 cm.

PLATE IV

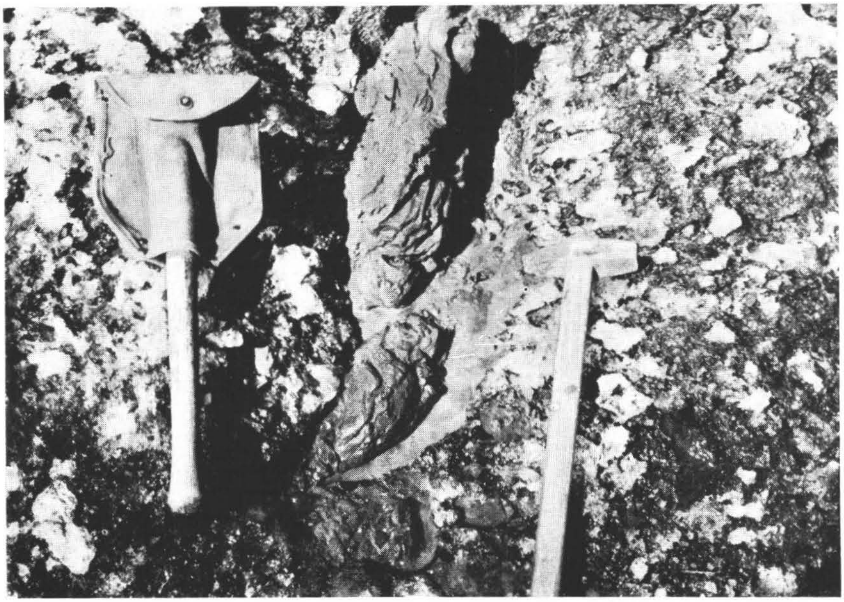

Fig. 7. Upthrust, water-soaked basal load on Hoffelsjökull (between the hammer and the spade).

Fig. 8. Drift-covered icewall on the terminus of Hoffelsjökull (left). The dark mountain in the background is Svinahryggur.

PLATE V

Fig. 9. Transversal or thrust-plane moraine on Fláajökull about 100 m from the terminus (left). Drift appears as a 10 cm thick layer between two sheets of ice and the layer inclines upstream. Owing to the different rates of melting a drift-covered slant plane occurs atop the glacier. The stone in front is about 10 cm in diameter.

Fig. 10. A small delta on the surface of Hoffelsjökull sloping towards the glacier. The proximal end adjoins the drift-covered icewall seen in Plate IV, Fig. 8.

PLATE VI

Fig. 11. Laterally flowing stream in front of Breidamerkurjökull cuts its channel through outwash gravel and dark dead ice beneath the drift. The buried ice forms sills in the river bed and continues under the outwash plain.

Fig. 12. The bottom of a radial crevasse at Fláajökull. Between and beneath the icewalls there appears water-soaked basal till.

PLATE VII

Fig. 13. Ground moraine in front of Breidamerkurjökull is composed of basal till.

Fig. 14. The projecting eaves of Hoffelsjökull has broken off and dropped into the wet drift pressing it up to crests. These connect with the proximal side of the end moraine (right).

PLATE VIII

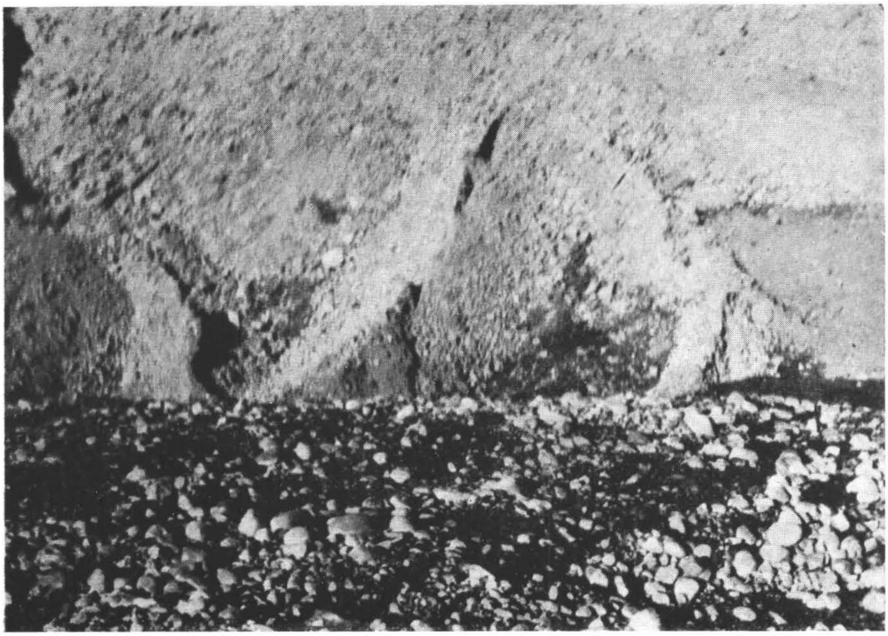

Fig. 15. Small radial moraines seen from the drift-covered terminus of Breidamerkurjökull (foreground). They are imprints of ice blocks that have broken off the glacier snout.

Fig. 16. A radial moraine in the frontal terrain of Svinafellsjökull (west of Hoffelsjökull) resembles an esker ridge along the shore of the marginal lake.

PLATE IX

Fig. 17. The material of the radial moraine seen in Plate VIII, Fig. *16* consists of angular glaciated stones and weakly striated roundstones. The length of the knife is 22 cm.

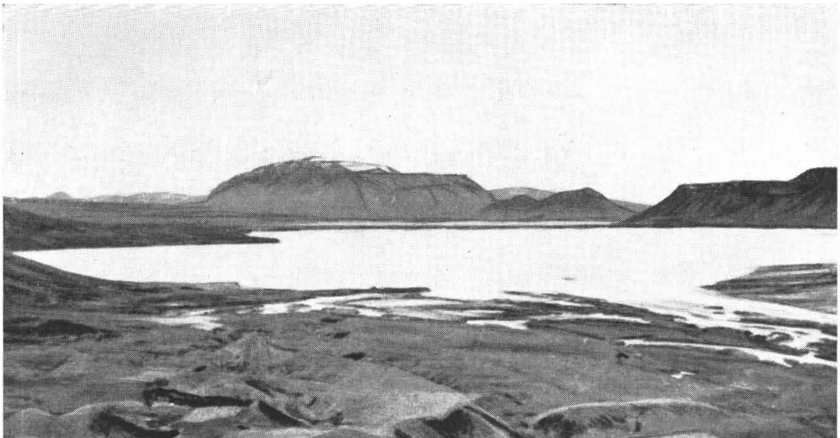

Fig. 18. Forming of ablation moraine on the eastern shore of lake Hagavatn. Black, drift-covered stripes indicate dead ice, which causes sharp forms. The margin of East Hagafellsjökull (right) continues as a thin sheet under the lake level. Photo Helgi Jónasson in 1946.

PLATE X

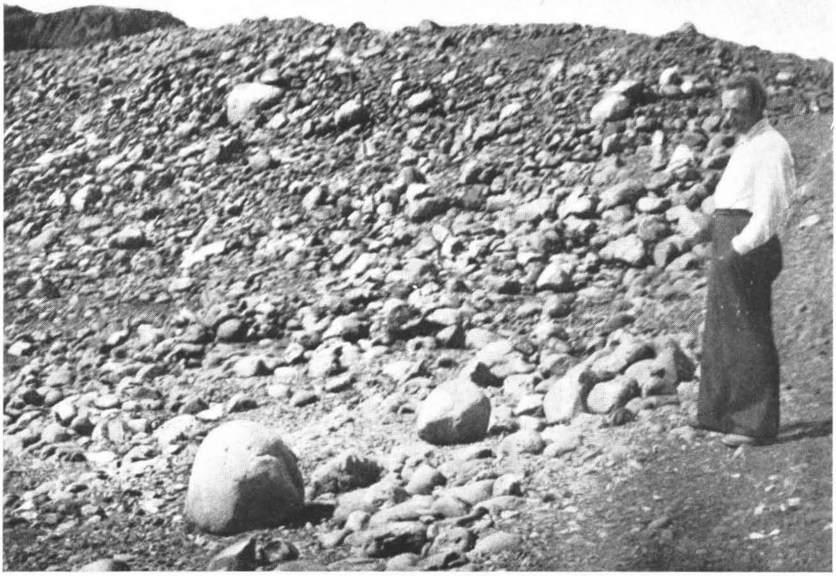

Fig. 19. Surface material on the frontal moraine of Hoffelsjökull consists mainly of roundstones, some of which are weakly striated. After the forming of the moraine (which happened about 1890, according to Thorarinsson) winds have carried the finest particles away from the dried surface.

Fig. 20. The terminus of Heinabergsjökull projects vault-like over the marginal pool and basal till. The latter is sliding into the water, and thus becoming transformed into washed drift.

PLATE XI

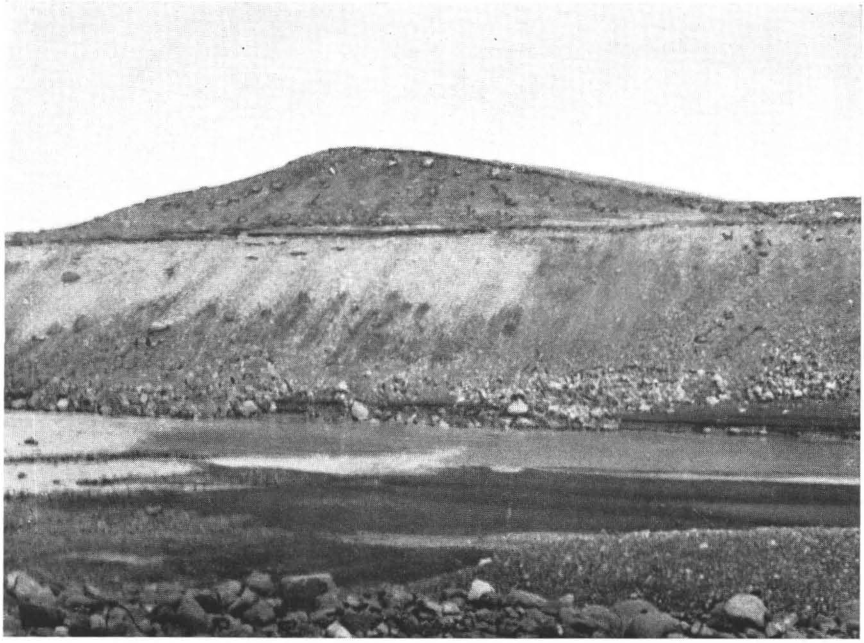

Fig. 21. The bank of the river Hanypá at Heinabergsjökull has been cut through an end moraine and underlying outwash plain. The end moraine ridge is formed on undisturbed sandur deposits.

Fig. 22. The vast end moraine belt of Breidamerkurjökull is cut by a dry river bed. In the northern wall there occurs folded layers, which incline to the proximal side (left). The dark bands are thin peat layers.

PLATE XII

Fig. 23. A bed of compact till covers the top and the proximal side of the end moraine seen in Plate XI, Fig. 22.

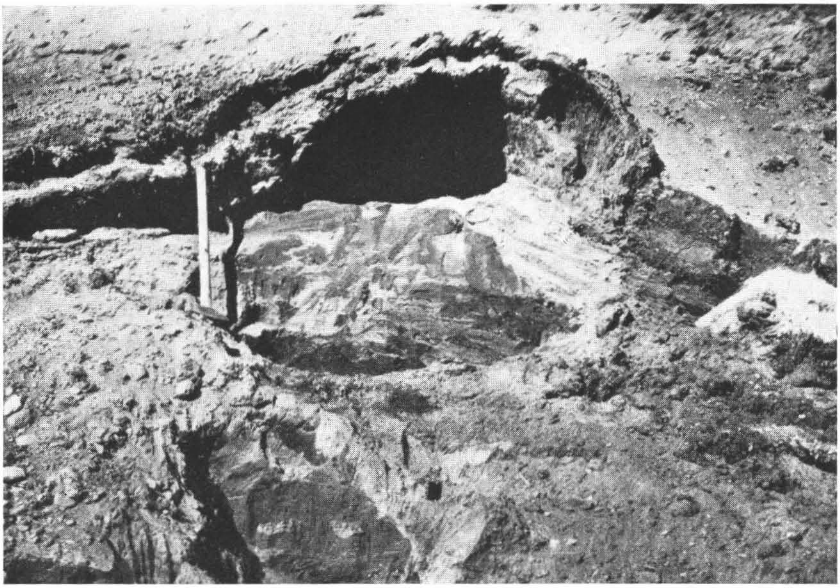

Fig. 24. One of the folded peat layers seen in Plate XI, Fig. 22, and stratified sandy deposit beneath it.

PLATE XIII

Fig. 25. The Morsárjökull terminates in a marginal lake as a thin subaquatic sheet. The tops of projecting ice islands form planes inclined upstream and their ice is full of thin drift bands dipping in the same direction. The picture is taken from the end moraine.

Fig. 26. Rock surfaces on Svinahryggur mountain have a stoss and lee topography with fresh glacial striations in the main ice movement direction. The mantle of basal till is thin.

PLATE XIV

Fig. 27. Artesian wells bring water into the river flowing outside the visible margin of Svinafellsjökull (Hoffelsjökull). The hydrostatic pressure is due to the stagnant ice under the glacial drift. The wells seen in the picture are about one meter in diameter.

Fig. 28. A miniature esker has been formed on ground moraine at Breidamerkurjökull. It represents a direct extension of the superglacial stone row presented in Fig. 15 p. 38.

PLATE XV

Fig. 29. The bottom sediments of the ice-dammed lake (Efstafellsvatn at Hoffelsjökull) seen in a river bank. The fresh wall in the picture is about 2 m high.

Fig. 30. A typical shore line of an ice-dammed lake (Gjánupsvatn). The spade and a small remnat of a floated ice block indicate the water level before the outburst. The shore becomes more distinct seen from a distance.

PLATE XVI

Fig. 31. The border of Fláajökull (top left) covers melted but wet till in immediate contact with water. After being released from the glacier the till is thus reworked, washed and sorted, which changes its character.

Fig. 32. Coarse material on an outwash plane at Breidamerkurjökull. It has been carried from the glacier by a glacier outburst. Among the stones there appears a chunk of peat (left of the spade).