THE DISAPPEARANCE OF THE LAST ICE SHEET FROM CENTRAL NORWAY*

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ABSTRACT. The lecture was a review of the research work carried out by the author and his collaborators, as well as by J. Gjessing and students working for their final degree. Attention is called to the existence of local centres in western regions even during the maximum of the last glaciation, as well as the transition from down-wasting of dead ice near the ice divide to backward melting of partly active glacier tongues in the high mountains near the sea. Regional reconstructions of the waning of the glacier ice are attempted.

ZUSAMMENFASSUNG. Der Vortrag ist eine Übersicht der Untersuchungen die vom Verfasser und seine Mitarbeiter, sowie von J. Gjessing und Gradualstudenten vorgenommen sind. Das Vorhandensein von Lokalzentren im westlichen auch während des Maximums der letzten Vereisung wird betont, sowie der Übergang von dem Toteisabschmelzen nahe der Eisscheide zu dem Rückschmelzen teilweise aktiver Gletscherzungen im meeresnahen Hochgebirge. Versuche regionaler Rekonstruktionen des Verschwindens des Gletschereises sind vorgenommen.

FOR the last fifty years or more it has been realized that the final phase in the disappearance of the last ice sheet in the Swedish mountains and in the eastern parts of the central mountain region of Norway, was almost entirely one of down-wasting, with a firn line elevated above even the mountain summits. This was a great advance upon the views of an older generation of geologists who did not imagine such a rise in the firn line, and believed that even at a very late stage active glaciers descended the valleys from the high mountain *massifs*.

Such glaciers may have come down in the west where high altitudes combine with a heavy snowfall. The supposed late activity of glaciers within the eastern valleys of the central region was, however, founded upon a misconception probably inevitable at the time. The ablation moraines and sometimes very curious glaciofluvial deposits found on the bottom of these valleys were interpreted as terminal moraines.

How much a change in snow line altitude would affect the glaciation of the more or less level surface at 700 to 1200 m., the *vidde*, which extends over a vast area in central Norway, was realized more than a hundred years ago by Forbes[1], who expressed it in a masterly way:

> ". . . any change of climate tending to contract the limits of permanent snow and ice, must have acted with simultaneous energy over the greater part of the vast *plateau*, which maintains a nearly uniform level of between 3000 and 4000 feet, which, in the colder conditions of climate assumed, must have been entirely *above* the snow-line, and after even a moderate relaxation of the rigour of the climate, entirely *below* it. Supposing such a change to have occurred at all suddenly, the overwhelming torrents of water to which it must have given rise would more than suffice to annihilate any definite constructions of moraine."

By "moraines" Forbes would mean terminal moraines.

He imagined a thin ice cover, and could have had no notion that the summit of the ice divide at times lay some 1500 m. or more above the *vidde* level.

I think that in spite of down-wasting having been postulated for so long a time, Mannerfelt [2] about 1940 was the first person who applied to the eastern parts of the central mountain region a really full and comprehensive understanding of how wasting ice and its melt water behave. The actual basis for all dead ice research is, of course, Tarr's work on Alaskan glaciers [3] during the first decade of this century.

My personal field work on the deglaciation of central Norway was mainly carried out in the years 1941–47, that of my immediate assistants in 1946–51. Since 1952 a very large amount of work has been done by Mr. J. Gjessing [4] and people working for degrees under his direction (Fig. 1, p. 748).

* Substance of a lecture given by Professor Strøm to the British Glaciological Society at Cambridge, 25 February 1955.

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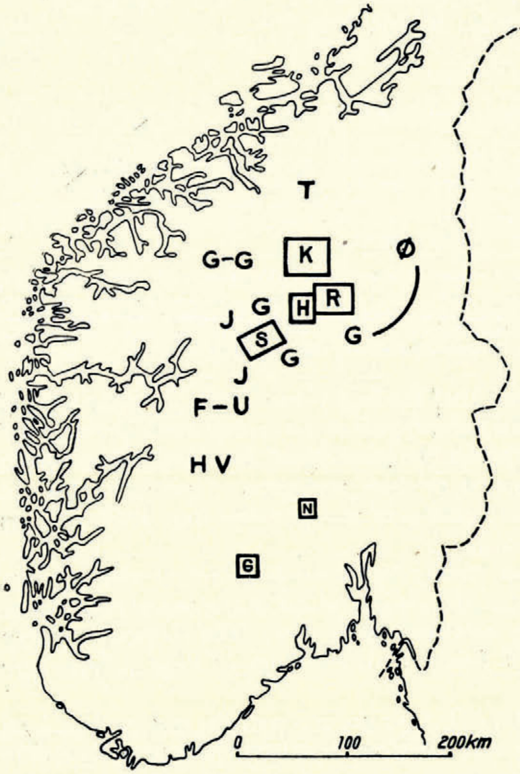

Fig. 1. Some areas surveyed or reconnoitred

F-U	*Flåm-Ustaoset* (*K.S.*)
G	*Gausta* (*Telemark, southernmost point surveyed*) (*K.S.*)
G G	*Gudbrandsdal* (*various collaborators*)
G—Ø	*Gudbrandsdal-Østerdal* (*Gjessing project*)
G-G	*Grotli-Geiranger* (*K.S.*)
H	*Høvringen* (*K.S.*)
HV	*Hardangervidde crossing*
J	*Jotunheimen* (*K.S. with collaborators*)
K	*Kongsvoll-Snøhetta-Fokstua* (*K.S.*)
N	*Norefjell* (*K.S.*)
R	*Rondane* (*T. Sund*)
S	*Sjodal area*
T	*Trollheimen* (*A. Grønlie*)

Regional Reconstructions of Former Ice Cover

The full publication of my work will, I hope, take place in the near future with the necessary illustrations, many of which were shown as slides accompanying the lecture. Space permits here only the reproduction of two series of block diagrams, constructed after the original maps, and showing the deglaciation of the Høvringen (western Rondane) and the Sjodal (eastern Jotunheim) areas.

Each stage is reconstructed from definite markings in the field, which I have correlated using all the material collected from the area in question. I would like to emphasize this, as of course one can always construct a map based upon probable general levels and gradients of the ice surface.

Something of an exception is Stage I in eastern Jotunheim, as a still active glacier leaves so few traces. This is largely an extrapolation from Stage II.

The deglaciation of the Høvringen area (Fig. 2, p. 749) is of the now classical dead ice type, and comes out very clearly in the map and block diagrams with explanations (Figs. 3, 4, 5, 6, pp. 750–51). The highest dead ice feature is that of a real marginal watercourse. The traces reach 1525 m., but probably the ice was inactive even when lying higher.

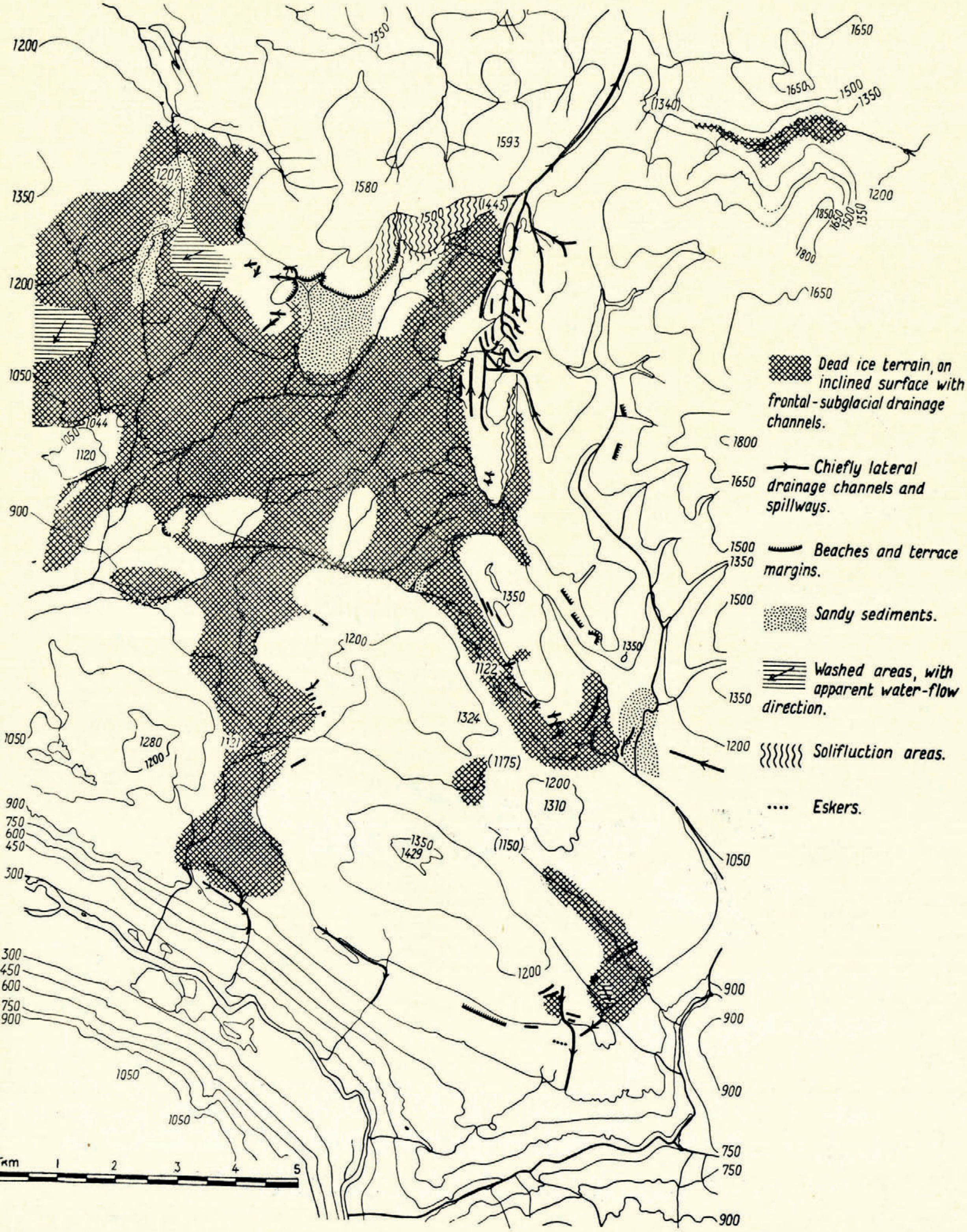

Fig. 2. Part of the Høvringen map, reduced and simplified. (Altitudes in metres)

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In the Jotunheim there was active glacier cover at a fairly late stage, as is to be expected with such high mountains not very far from the sea. There is evidence of Stage I round Bessvatn, and Stage II is marked by one of the longest apparently strictly lateral lines that I have ever followed; it stretches uninterruptedly for some 8 km. to the north-west of the Sjodal (Figs. 7, 8, 9, pp. 752–53).

The HØVRINGEN AREA (Figs. 3–6)
Orientation north-east, altitude of viewpoint 2500 m.

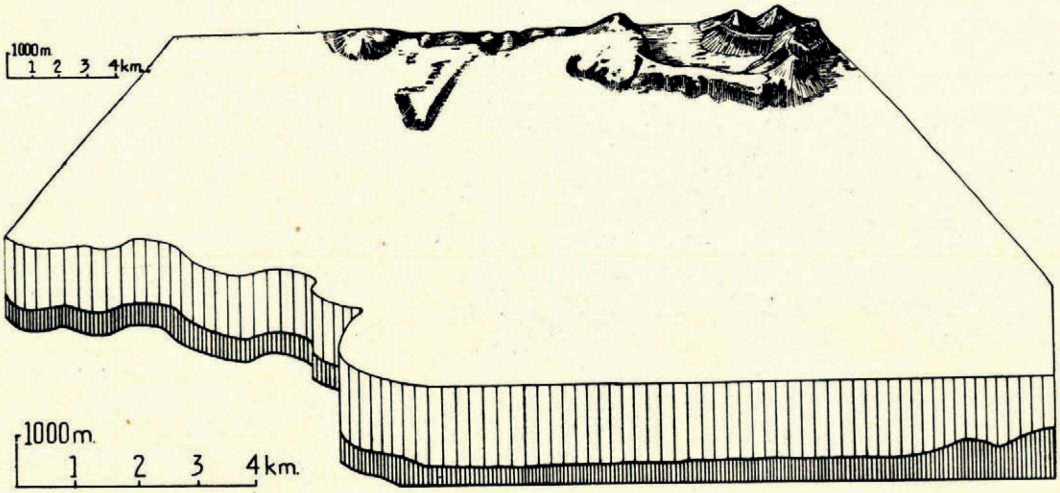

Fig. 3. Stage 1. Drainage towards north with the higher summits clear above the ice. Plateau ice on high-level flats. The ice is climatically dead

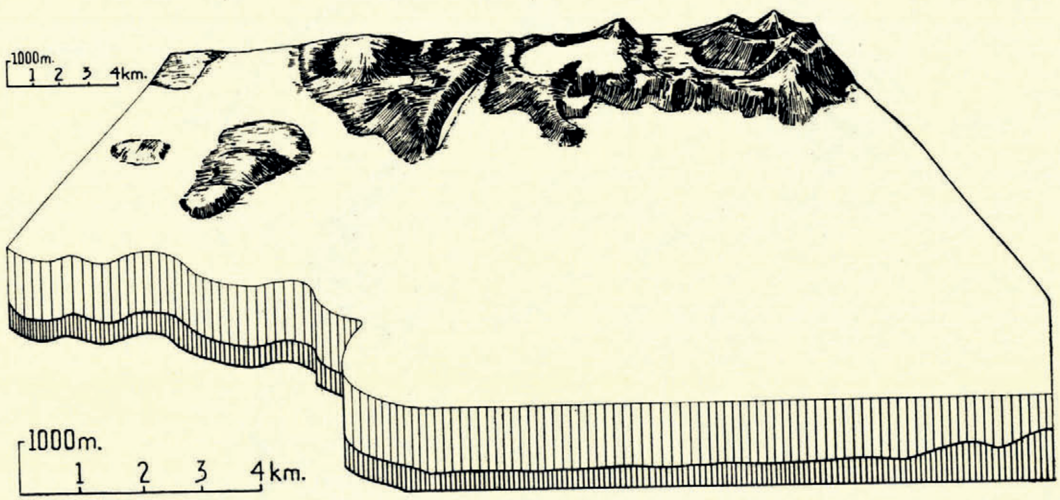

Fig. 4. Stage 2. Subglacial drainage towards south (see Fig. 1) to Gudbrandsdalen (foreground valley). Marginal lake. Plateau ice still lying on one high-level flat

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Kongsvoll-Snøhetta-Fokstua is an important area. The down-melting was very regular from north-west towards south-east with no conspicuous traces of late active local glacierization even at the Snøhetta (2286 m.) (Fig. 10, p. 746), but the most interesting fact is that here a large part of the glacier surface could be reconstructed at the last "live" stage, being marked by lateral moraines with distal drainage channels. Below this surface the usual dead ice phenomena were met with in large numbers.

It is pleasant to imagine the interglacial plants of the "Dovre flora" following the retreating ice boundary from their refuges on or off the Møre coast to their present habitat near Kongsvoll.

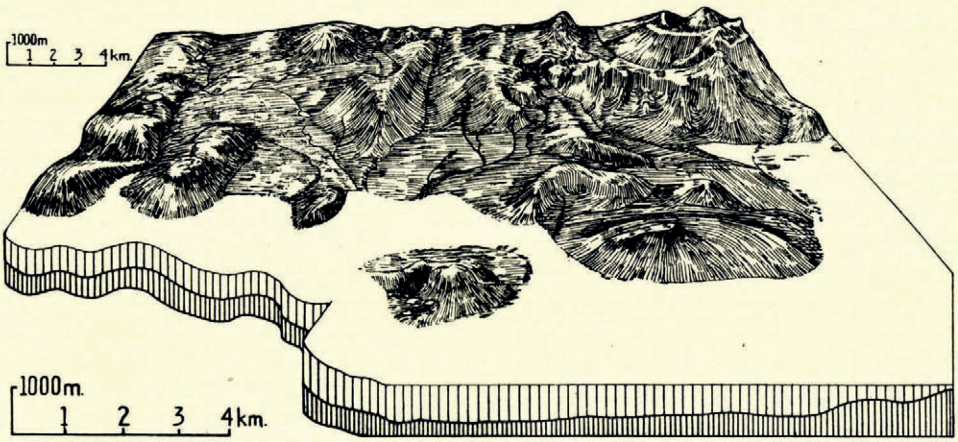

Fig. 5. Stage 3. Western part of glacier surface slopes towards Gudbrandsdalen. High level free of ice. Marginal lakes in eastern part of area

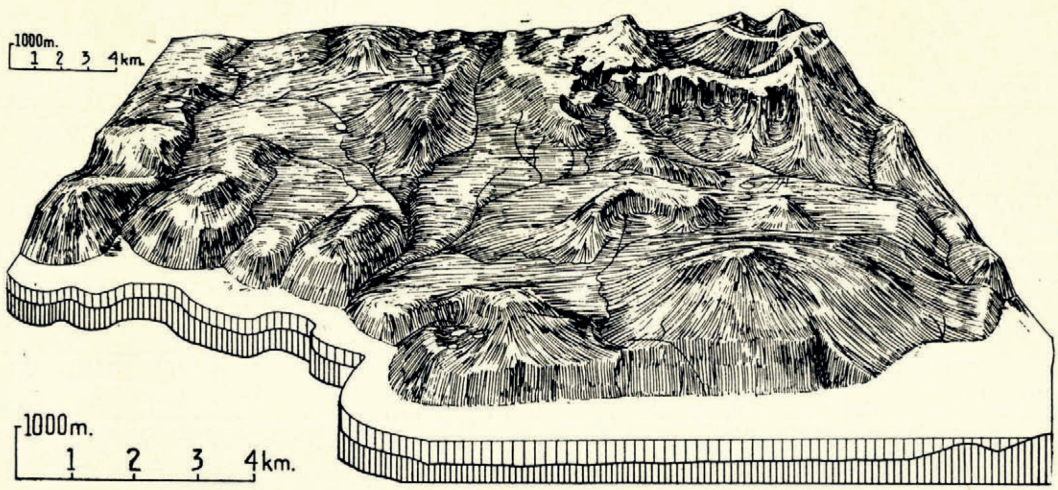

Fig. 6. Stage 4. Ice only in the valley (Gudbrandsdalen)

Deductions

From work in the different areas marked on Fig. 1 it is possible to essay some generalizations of importance.

There can hardly be any doubt that during the whole of the last glaciation the Jotunheim mountains were an active centre, not overridden by the main Scandinavian ice. Not only do striae, etc., radiate from the Jotunheim area, but a complete transformation of landscape with large rocky hills transformed more or less to *roches moutonnées*, clearly indicate the long duration of a glaciation centre here. However, Jotunheimen is not the only centre of glaciation from which streams radiated onto the inland ice sheet.

Lateral moraines and drainage channels in Geiranger indicate that during deglaciation there must have been an ice surface there sloping to the north, forming part of an ice cap with its centre in the Jostedalsbre high plateau. Here as in Jotunheimen, sufficiently large areas are found at a sufficient altitude, and with a sufficient snowfall.

Other high parts of the land surface in western Norway have also formed glacierization centres for which there is positive evidence in many cases. Even for the maximum of the last ice cover the concept of a smoothly sloping ice shield must be superseded by a more varied picture.

Generally speaking, wherever there are important glaciers to-day, and even on some high plateaux now unglaciated, *e.g.* in Sogn, there seem to have been local centres during the last glaciation. A notable exception is the Hardangerjøkul (Fig. 11, p. 746), to-day covering 95 km.^{2} (Flåm-Ustaoset area).

EASTERN JOTUNHEIM (SJODAL AREA) (Figs. 7–9)
Orientation west, altitude of viewpoint 2500 m. Stages are not synchronous with those of the Høvringen area

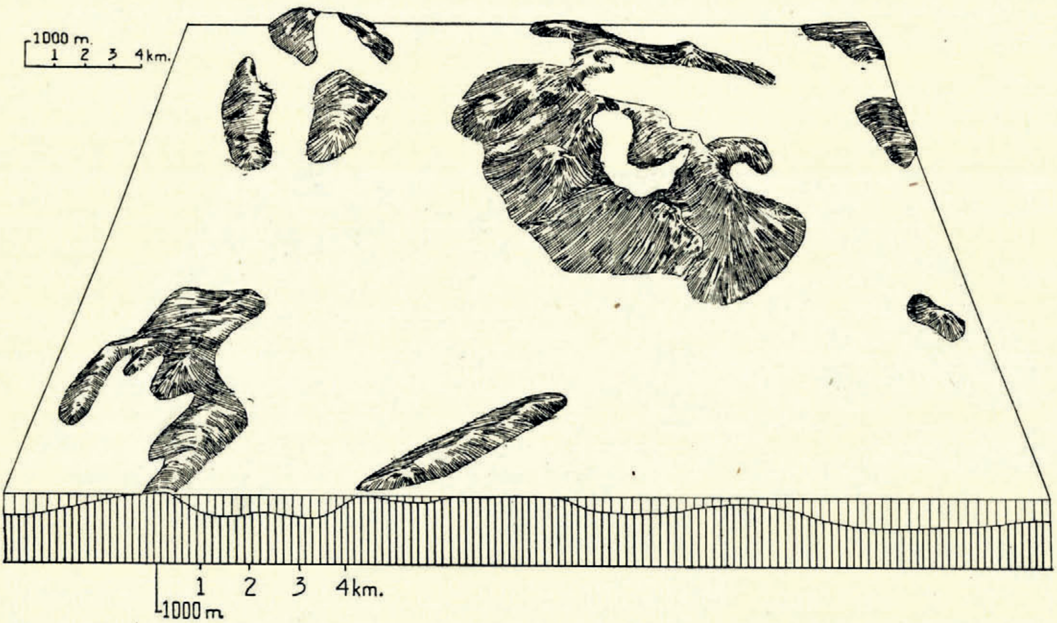

Fig. 7. Stage I. Active glaciers spreading from the Jotunheim glaciation centre. Local glaciers descend from Besshø (2258 m. left) and the Nautgardstind massif *(up to 2257 m. centre) where there is also an isolated local glacier*

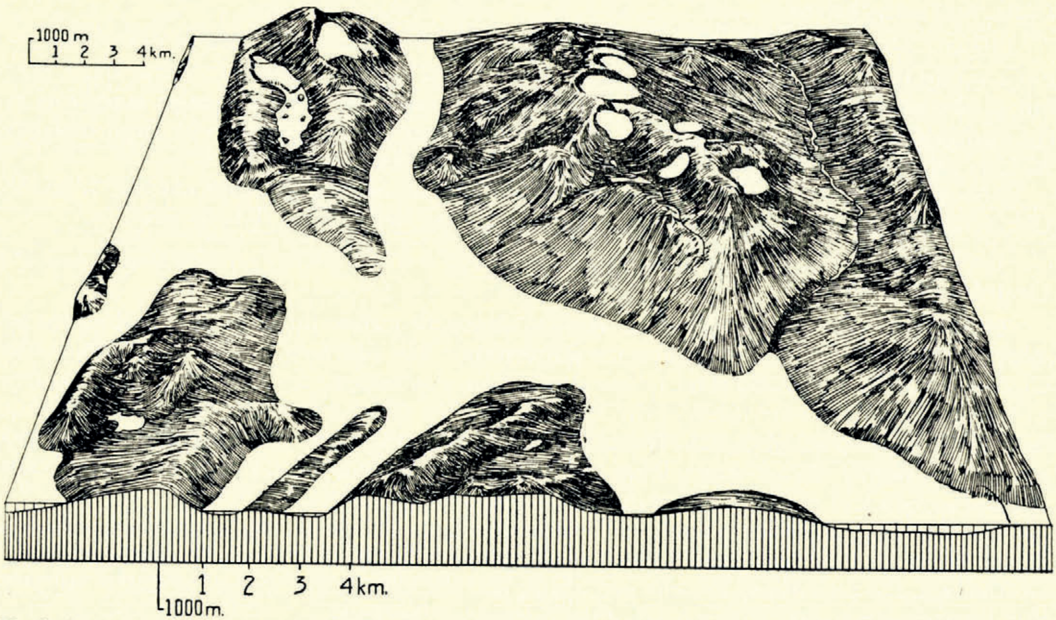

Fig. 8. Stage II. The main ice climatically dead. Cirque glaciers in Bessvatn (lake), on Besshø and the Nautgardstind massif. *Enormous marginal terraces and channels are being formed in Veogjelet (where the river at the right meets the ice)*

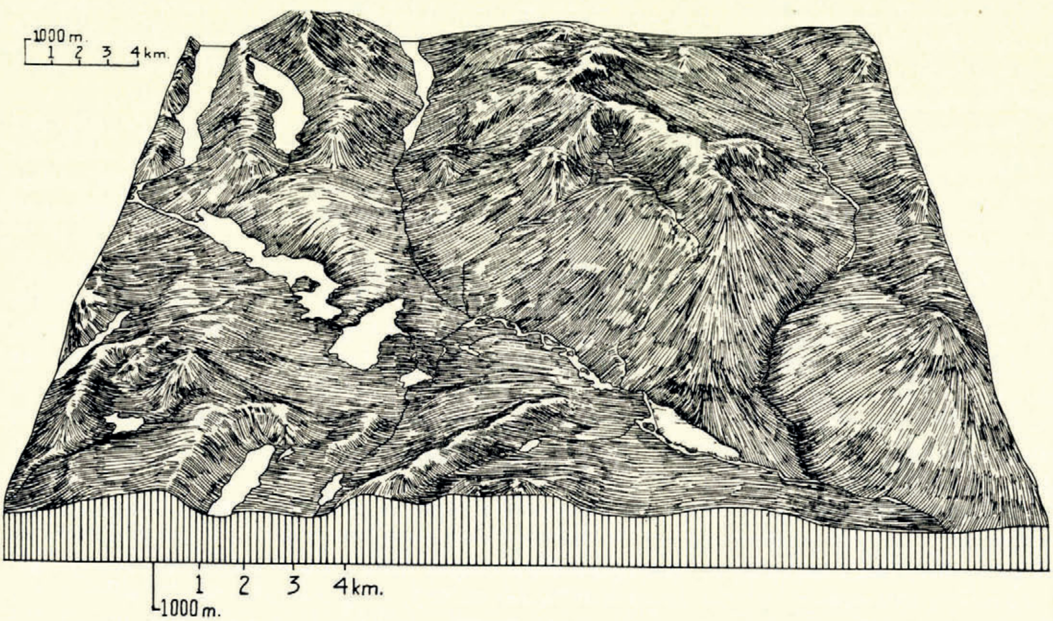

Fig. 9. Stage III. The whole area is ice-free except a small remnant of dead ice covered by gravel in the main valley (Sjodal). No cirque glaciers, in contrast to one to-day in Besshø and several in the Nautgardstind massif

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Climatic Fluctuations

Climatic deviations must have tended to interrupt or reverse the course of down-wasting. Even within Rondane there are traces of some late climatic change, evidently but a slight one; but in two other places I have found evidence of a forward push from mountain *massifs* on to the surrounding *vidde*. In both cases a clear terminal moraine was found, with large boulders sticking out of the old moraine formed into *roches moutonnées* with striae.

There was evidently a kind of thin piedmont glacier involved, issuing in the one case from the Gjende-Bygdin massif on to Valdresfly, in the other from Heddersfjell (Gausta area).

Dead Ice Phenomena

These phenomena may be found everywhere above the marine limit, as there will always be some stagnant ice cut off, even when the glacierization was active to the last. But only in the Gudbrandsdal-Dovrefjell-Østerdal region are dead ice phenomena very evident. This is the area where there was least movement in the ice sheet and the thickest morainic cover, partly dating back to the penultimate glaciation. Here also was the last occurrence of a fairly thick shield, and a maximum supply of melt water. Thus the best conditions for magnificent glaciofluvial phenomena of erosion and deposition were present, and also plenty of ice to be buried.

The dead ice phenomena occur equally on both sides of the ice divide, and not only between the ice divide and the watershed. Indeed when approaching the watershed, for instance in the Grotlid area, the phenomena become very sparse and the uplands are covered with the ordinary thin bottom moraine found over most of the Norwegian highlands.

Dating of the Stages

Over the Gudbrandsdal-Rondane-Dovrefjell region the deglaciation process has been exclusively one of down-wasting of the Mannerfelt type.

It is the same all over the Gudbrandsdal-Østerdal areas surveyed by Gjessing and his collaborators, but they have found new and important phenomena at the stage when the dead ice remained in the valley bottoms, with water (the ice-dammed lakes of earlier authors) and glaciofluvial deposits from tributary streams upon and within it. Through future research these late stages may be connected with the melting-back from the coast.

It is not even permissible to fix a definite relative age upon any one stage at present, and comparatively sure datings will certainly be very difficult to obtain. It is easy enough to find out the general features of the story, especially from marginal phenomena, but a correlation in time even of very clear markings within a small area is not easy owing to the interrupted nature of all the features.

In the future, radiocarbon datings from the first organic lake deposits laid down in areas just left bare may fix the general chronology. Even so they cannot help much in a local analysis, as the down-melting has been so very rapid. To judge from distances between lateral drainage channels, vertical wastages of more than 10 m. yearly seem frequent, and compare well with present-day ablation during a warm summer. However, with the slight gradient of an ice surface in late stages this corresponds to large yearly regressions of the ice border. Some stages in the process must have been very rapid, and the corresponding enormous volumes of melt water have left their mark everywhere.

Indeed if only some 5 m. of yearly downward wastage is assumed, 1000 m. would be lost within 200 years! But of course stages with intense melting may have been interrupted by intervals of quiescence, and I am afraid we have as yet not even the framework of an absolute chronology.

Finally I may mention, mainly because of its accessibility, one glacier that has "died" recently, the Omnsbre. On a miniature scale it affords several parallelisms to conditions during the deglaciation period.

The Omnsbre is a kind of "sheet" glacier (Fig. 11, p. 746) with its southern snout only some 5 km. north of Finse on the Bergen–Oslo railway. The highest part of the glacier is at 1600 m., it descends to 1500 m. to the south, and to 1350 m. to the north. At the time of the topographical survey of 1923–29 (Map D. 33, Hardangerjøkulen 1 : 100,000, stereophotogrammetric original 1 : 50,000) the glacier, as defined by the surveying party, covered some 10 km.^{2}.

The Omnsbre was thus an extremely flat glacier of considerable extent. Slight alterations in the firn line will work out much more sensationally than in an alpine glacier with perhaps 1000 m. altitudinal differences. Once the firn line rises above 1600 m., the Omnsbre is climatically dead.

Vertical wastage during the last few years has been very great. There are all kinds of marginal phenomena on a small scale, exactly like the dead inland ice in miniature. The ice is generally speaking very clean, and the melt water issuing from the glacier is now always quite clear. This is in enormous contrast to the melt water from the living glacier, which, when I worked on the lakes of the district in 1933, was frequently a real mud stream, blackish from the Ordovician shale below the glacier.

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THE DETERMINATION OF THE THICKNESS OF A GLACIER FROM MEASUREMENTS OF THE VALUE OF GRAVITY

Cambridge University Austerdalsbre Expedition 1955, Paper No. 2

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Abstract. A method is described of determining the thickness of a valley glacier from measurements of gravity. On a Norwegian glacier approximately 4 km. long and 1½ km. wide values of gravity were measured at points on four transverse lines. For comparison, values were measured at points on three lines in the valley below the snout of the glacier. The positions and altitudes of these gravity stations were determined by triangulation. After making corrections for the altitudes of stations and for the effect of the valley walls, the differences between the gravity values obtained on the glacier and those obtained in the valley below the glacier are attributed to the thickness of the ice. Four transverse sections of the glacier, obtained in this way, are given. Errors in the estimates of ice thickness should not exceed 20 per cent on the two lower cross-sections, nor 40 per cent on the upper two.

Résumé. On décrit une méthode pour calculer la profondeur d'un glacier de vallée en partant de mesures de gravité. En Norvège, sur un glacier long de 4 km et large de 1½ km environ, on a determiné des valeurs de gravité sur quatre lignes transversales. Et, par comparaison, on a mesuré des valeurs sur trois lignes en aval du front du glacier. La situation et l'altitude de ces stations de gravité ont été déterminées par triangulation. Quelques corrections faites, vu l'altitude de ces stations et l'effet des parois latérales, on a attribué à la profondeur de la glace la différence entre les valeurs calculées sur le glacier même et celles qui ont été calculées en aval. Par ce moyen on peut ainsi établir quatre sections transversales. Les erreurs des estimations de l'épaisseur de la glace ne devraient pas excéder 20% sur les deux sections transversales inférieures et 40% sur les deux sections supérieures.