WASTAGE FEATURES OF THE INLAND ICE SHEET IN CENTRAL SOUTH NORWAY

Kari Garnes and Ole Fr. Bergersen

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Detailed field mapping of different lateral phenomena, striae, texture and till fabric are the basis of a reconstruction of five deglaciation phases in the east Jotunheimen-Gudbrandsdalen area, a landscape with moderate relief in the vicinity of the ice divide. During the wastage, the inland ice sheet was separated into several ice lobes situated in valleys encircled by large ice-free uplands. The slope of the ice surface varied with local changes in the ice-movement pattern as well as due to breaking of ice-dams giving reversal of drainage from ice-dammed lakes. Non-climatic, large marginal moraines are thought to have been formed as a result of locally increased steepness of the ice surface. By tracing the deglaciation phases through two different valley-systems which converge in the lake Mjøsa area, deglaciation events in the ice divide zone are correlated with marginal deposits at the front of the ice lobes.

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The last years' investigation in the east Jotunheimen and Gudbrandsdalen area have brought to light a detailed view of the deglaciation events in an area around the last ice-divides of the inland ice. The area mentioned is classical ground for studies of deglaciation phenomena. Numerous papers have been published. Many of these were written already at the middle of the nineteenth century. The main topics discussed in older days were former ice-dammed lakes and the position of the ice-divide of the last inland ice (among others, Sars & Kjerulf 1860, Schiøtz 1895, Hansen 1886, 1890, 1891, 1895, Øyen 1896, 1898, 1899, Reusch 1894, 1910, Rekstad 1895, 1896, 1898, Holmsen, G. 1918). In the last decades, however, papers have been dealing very much with the problems of vertical wastage (Reusch 1901, Mannerfelt 1940, Ramsli 1947, Strøm 1956, Gjessing 1960, 1965, Samuelsen 1953, Mangerud 1963, Jørgensen 1964, Tollan 1963, Bergersen 1964. See also Vorren 1977).

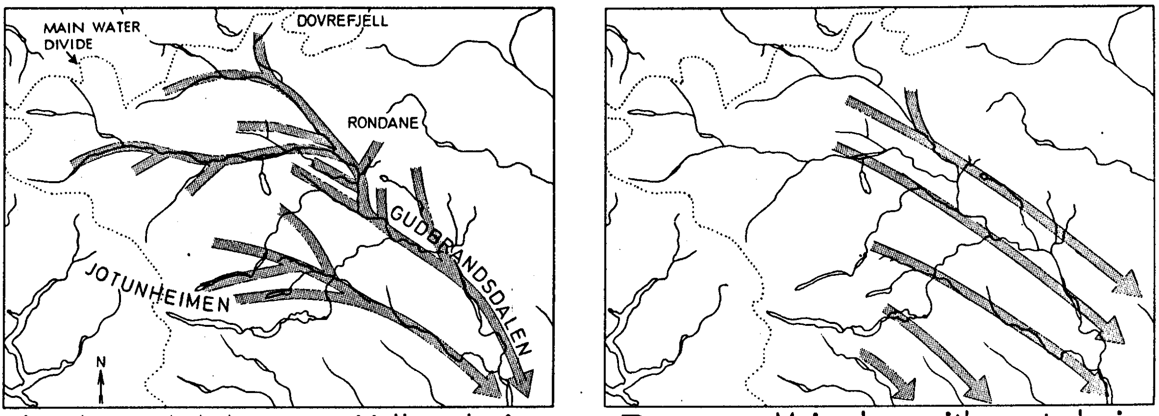
Reading the literature, it is striking that many scientists have tried to interpret the deglaciation on the basis of simple models, often making conclusions for large areas based on insufficient field-work.

Based on data collected during the years 1968 - 1978, this paper presents a picture of the deglaciation separated into five phases. The phases represent situations during a continuous downmelting of the inland ice. The separation of the different phases has been enabled by the reconstruction of some drastic changes in the catchment area of the ice. The changes locally gave large differences in the direction of flow and in the gradient of the ice surface as well.

After the period when the highest mountain area became ice-free, the inland ice seems to have melted down almost continuously without any marked stagnations or oscillations. At a relatively early stage, the inland ice was divided into different branches confined mainly to valleys and depressions without supply from any accumulation areas. This division makes it possible to relate events and phenomena in the nunatak area with (sub-)synchronous phenomena at the ice-front in the lower areas. The authors have earlier discussed parts of the deglaciation in the actual area, but no full presentation has been published yet (Bergersen & Garnes 1972, Garnes 1978). Up till now, the last ice age in the Gudbrandsdal area has been divided into four stadia (Fig. 1). The figure shows that the last culmination zones of the inland ice were situated close to the district of the river Vinstra (stage C and D). Stage D represents the deglaciation period after the highest mountains became ice-free. This stage is in the following divided into five sub-stages or phases.

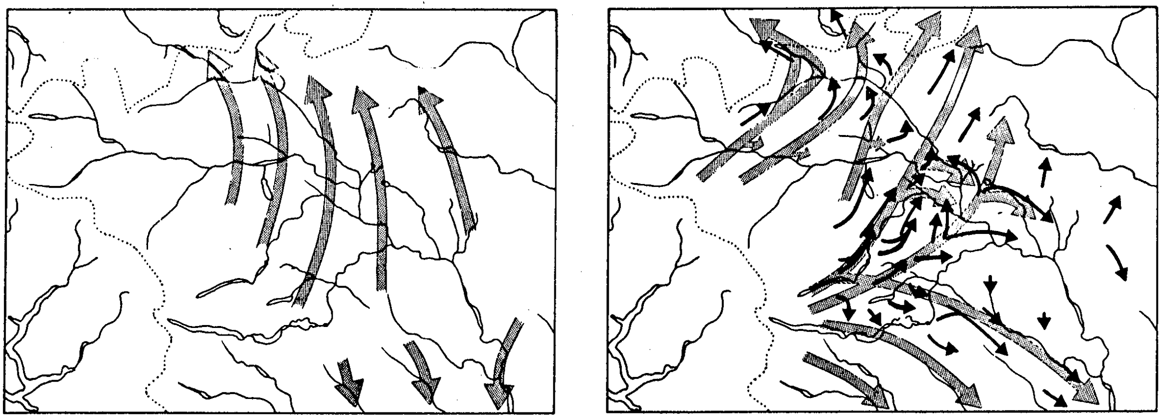
Today the river Vinstra has its uppermost sources in the higher areas of Jotunheimen, about 2,000 m a.s.l., where also a few small, recent glaciers are situated. The drainage from these mountain areas, is gathered in several big valleys. Some of these have long lakes situated at about 1,000 m a.s.l. The lakes are located at the boundary between glacially sculptured mountains in the west and a wide, mainly pre-glacial landscape further east. The latter widespread smooth-formed palaeic surface is in Norwegian termed vidde. Well-marked valleys are almost missing

LAST ICE AGE IN EAST JOTUNHEIMEN - GUDBRANDSDALEN



A Valley glaciers

B Main phase with great glacio-geological influence



C Inland-ice maximum with little glacio-geological influence

D ➡ Youngest ice movements
→ Ice-directed meltwater drainage across water divides during the last deglaciations

Fig. 1. A reconstruction of four stadia of the last ice age in the investigated area (Garnes 1978).

in the vidde-landscape. Most of the drainage from east Jotunheimen converges on Skåbu, and follows the deep, meandering valley of Vinstra towards the northeast to the Gudbrandsdal (220 m a.s.l.) (Fig. 2). From Skåbu there is also a well-developed valley-system towards the southeast, through the Espedal and the Vestre Gausdal to the lake Mjøsa. This valley-system has a low watershed between the Espedal and the Vestre Gausdal at 728 m a.s.l. During deglaciation, considerable parts of east Jotunheimen were drained through this valley-system for a period of time, thus creating important possibilities for correlation of deglaciation phenomena in the lowlying country.

The drainage through the Espedal to the Gausdal valleys has been briefly described by Rekstad (1898), Ramsli (1948), and Bergersen (1964, 1971). However, the history of the drainage is more complicated than earlier believed. In this paper the drainage history is separated in five phases, approximately equivalent to the phases that the deglaciation of the whole region is divided into. In order to facilitate understanding of the regional reconstruction, three of the phases have been simplified on Fig.2., which shows the whole area of study.

The reconstruction of the deglaciation phases is based on an evaluation of a great variety of available data. These data have been gathered by mapping, and by the study of forms, as well as of glacial sediments. The most important information has been revealed by:

a) Mapping and investigation of all types of lateral phenomena, frontal deposits and overflow-channels.

b) Mapping and interpretation of striae and other indicators

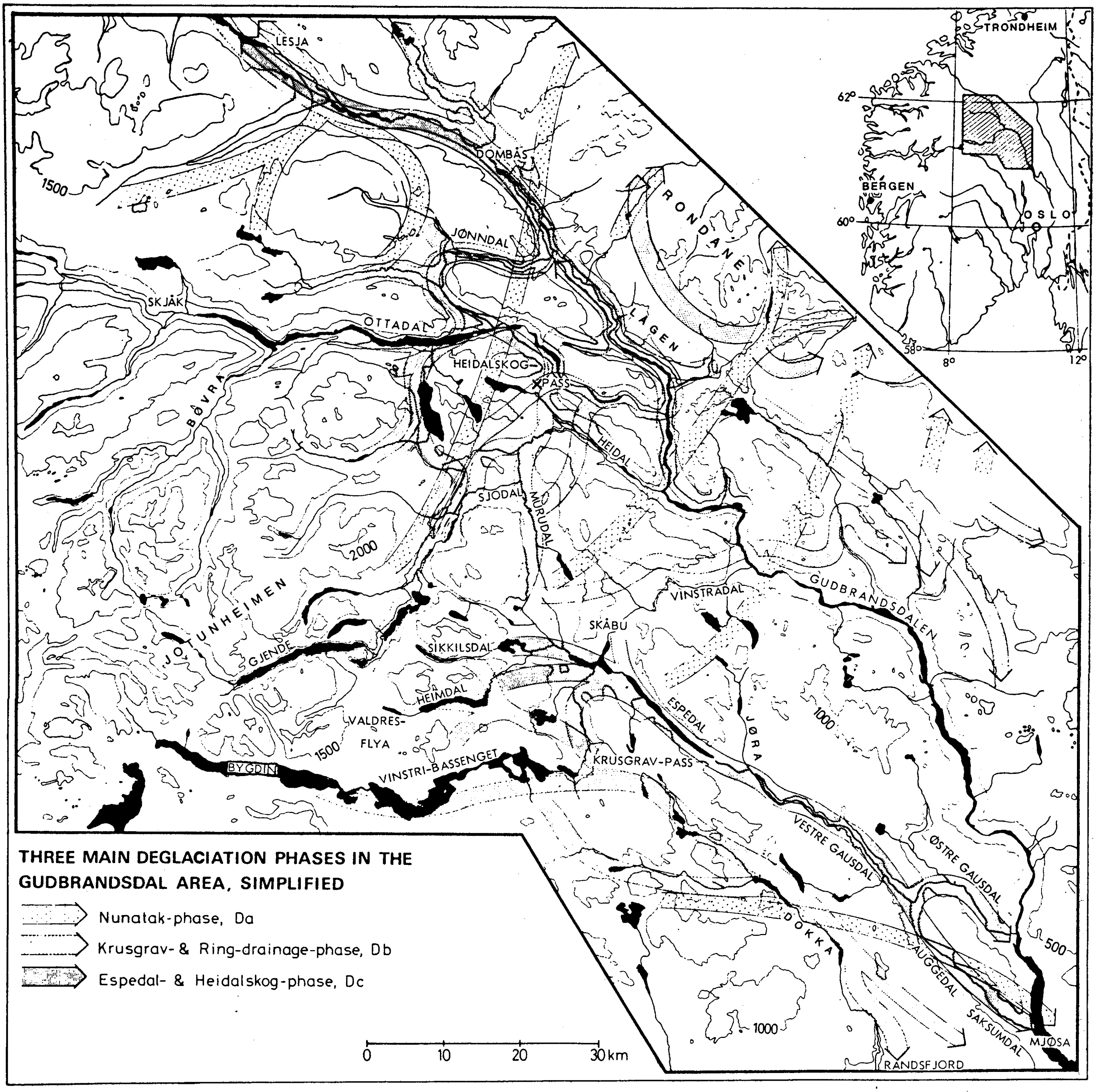


Fig. 2. *The investigated area, showing the most important melt-water routes during the three oldest drainage phases. As can be seen, the drainage during the oldest phase, Da, is almost independent of the topography. Later, the ice movements, as well as the melt-water routes became more and more topographically controlled. During the youngest phase drawn, the thickest remnant of the ice sheet was situated in Mid-Gudbrandsdalen. It directed all drainage in areas north of Vinstradalen up the main valley slope. The contour interval is 500 m.*

of direction (drumlins, fluted surface).

c) Studies of sediments, especially different types of ablation till. However, glacio-fluvial material and basal tills have also been studied.

d) Establishing a till stratigraphy.

A certain danger of placing phenomena in the wrong phase, or correlating non-synchronous phenomena, applies for all these criteria. Therefore, it is necessary to use as many different criteria as possible. This is specially important in the investigated area, as its stratigraphy is thought to be more varied than is common elsewhere in Norway (Garnes 1978). In other areas, similar problems are discussed by e.g. Lundqvist (1973), Fulton (1967).

THE NUNATAK-PHASE, Da.

It has been found that, at the beginning of phase D (Fig. 1), there was an ice-culmination zone across the Vinstra and the Gudbrandsdal valleys, in a 60^{o}-240^{o} direction. The ice-divide zone sloped towards the northeast. This may be a result of the fact that the ice melted down more rapidly in the eastern part than in the western part. At the same time, however, the inland ice in the east of South Norway sloped towards the northwest. This is shown by the deglaciation course in north Østerdalen and in Rondane (e.g. G. Holmsen 1915, Mannerfelt 1940, Gjessing 1960). The convergence area between the northeast and the northwest-sloping ice moved during deglaciation. However, a great amount of ice and water drained towards Dovrefjell and Drivdalen at the time when the ice-surface had sunk to c. 1100 m a.s.l. at Dovrefjell (P. Holmsen 1964, Sollid 1964).

From the investigated area, ice and water drained nearly radially away from a culmination zone in the southwest, as shown on Fig. 2. At the same time, ice flowed from another culmination center in the northwest. The drainage of ice and water away from the investigated area through numerous passes north and east to Gudbrandsdalen, is therefore the most characteristic trait of phase Da, see Fig. 2. During this phase, only the highest mountain areas were free of ice. As the ice surface melted down to the same levels as the northeastern and eastern gaps, i.e. about 1100 m a.s.l., the ice surface 60 - 70 km to the west-southwest reached up to about 1400 m a.s.l. The gradients of the inland ice were therefore small. Between the mountain sides and the ice margin the melt-water drainage caused numerous lateral channels. Some of these can be traced continuously for several kilometers as erosion channels in the till deposits. Sometimes they are even seen as canyons in the bedrock. When followed over long distances the phenomena are considered to be almost strictly laterally eroded. It is therefore assumed that the channels show an almost correct picture of the position of the ice surface. Such channels have been found to have a gradient of less than 0,5% proximally. The gradients are even less distally, and the lateral channels indicate an asymtotic approach towards zero at the draining gaps. Fig. 3 illustrates examples of general wastage phenomena which are found in the area between the ice divide crossing Gudbrandsdalen and the main watershed in the north.

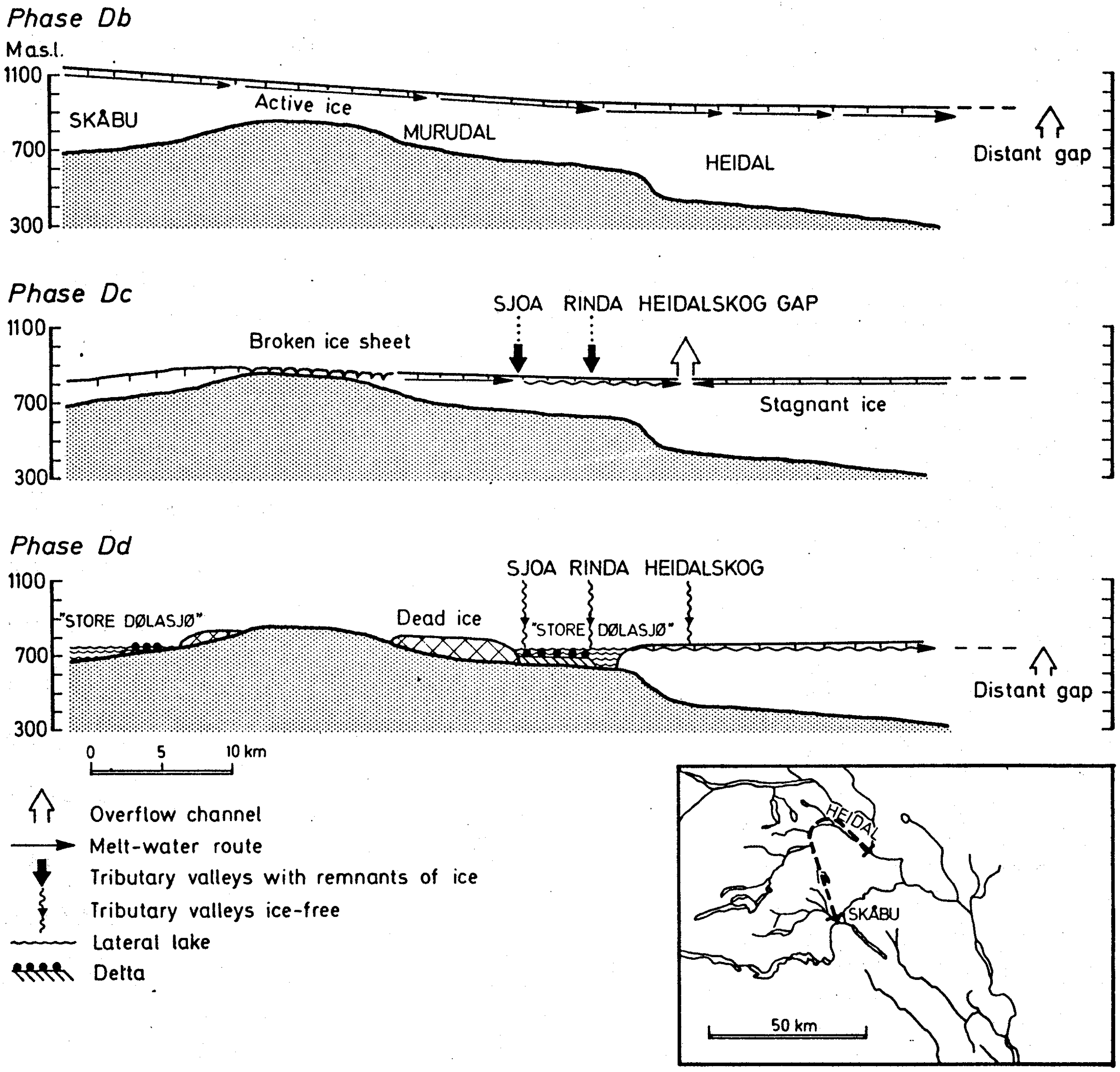


Fig. 3. *Longitudinal profile showing some characteristic phenomena during the wastage of the northern branch of the ice sheet, approximately in the direction of flow. In phase Db (or Da) the gradient of the ice surface close to overflow passes approached zero. Phase Dc shows the situation around a pass when the ice surface had melted down further. The drainage now converged on the Heidalskog gap and flowed down the valley, as well as up the valley slope. The height of the different lateral deposits shows very small differences in value, lateral lakes therefore probably also existed. When the ice sheet broke up over a pass or a watershed the surface of the ice adjusted to the slope of the terrain (to the left, phase Dc). Phase Dd, following shortly after phase Dc, shows the situatin in large tributary valleys, namely the Vinstra valley (Skåbu) to the left and the Sjoa valley (Heidal) to the right, during the "Store Dølasjø" phase. Ice several hundred meters thick was still lying in Gudbrandsdalen while uplands and upper parts of tributary valleys were free of ice, or covered with remnants of dead ice.*

Typical of the nunatak phase is that some zones along the mountain sides became washed completely clean. The zones are usually only 10 - 30 m wide. They may completely lack till, even though there may be several meters of till-layers on both sides. The zones may often have a well-defined boundary to the thick till below, while the border above may be more diffuse. Accumulation terraces are common where the mountain sides curve inward, as well as close to drainage passes. The outlet areas themselves are somewhat differently formed, due to the magnitude of the drainage and to what time the next, lowerlying gap was opened. If the drainage continued untill the gap was free of ice and a subaerial drainage occurred, the outlet area became washed. Typical for these are distinct kame terraces leading into the pass. If the drainage stopped, - or turned, - while there was still ice in the gap, both till and glacio-fluvial deposits can be found in the pass area, often as eskers. If the drainage stopped at a very early stage, it may be difficult to find any traces of the drainage through the gap at all. In these cases it is therefore difficult to evaluate the importance of the pass. When ice and water no longer could pass through one gap, and a lowerlying outlet was opened, the ice surface gradient adjusted itself to the new one. This often changed the drainage pattern for ice and water to a great extent, depending on the position, the size and the elevation of the new pass. The consequences of this will be discussed further in connection with the next phase.

THE KRUSGRAV-PHASE, Db.

When all the gaps east of the Gudbrandsdal were closed (the lowest at 1080 m a.s.l.) because the ice surface had melted down to a lower level, there occurred an important drainage divide over the middle part of the valley. This divide caused a bifurcation of ice and water in east Jotunheimen (Fig. 2 and 4). The ice was still flowing away from the former culmination center, but the flow diminished when the ice surface was c. 1200 m a.s.l. From the beginning of phase Db deglaciation proceeded differently on the northern side of the ice divide from the southern side. In the northern area, as far north as the Ottadal, the slope of the ice surface changed slightly towards the east. This was followed by considerable lateral drainage that curved along the eastern boundary of the inland ice, to the east of the Gudbrandsdal. The northern branch of phase Db is therefore named "Ring-drainage-phase" (see Fig. 2). The drainage pattern during the continued deglaciation of this phase, was determined by a complicated interaction between the ice surface (which continued to flatten out) and a number of transfluent valleys. During this phase the runoff increased considerably along the lower Gudbrandsdal because of sudden supply from the mid-Gudbrandsdal area, cf. Fig. 2. The deflection of ice and melt-water along the lower part of the Gudbrandsdal are thought to have given increased frontal accumulations. A presumed gradient of the ice surface of c. 1%, indicates that the front of the ice sheet during this phase was situated may be 20 - 30 km south of Lillehammer. It has not been proved, but it is postulated that the increased runoff along Gudbrandsdalen may have caused the deposition of a large, subaquatic end-moraine crossing lake Mjøsa at Moelv. This ridge, wellknown from soundings and drillings, is tentatively named the Moelv moraine.

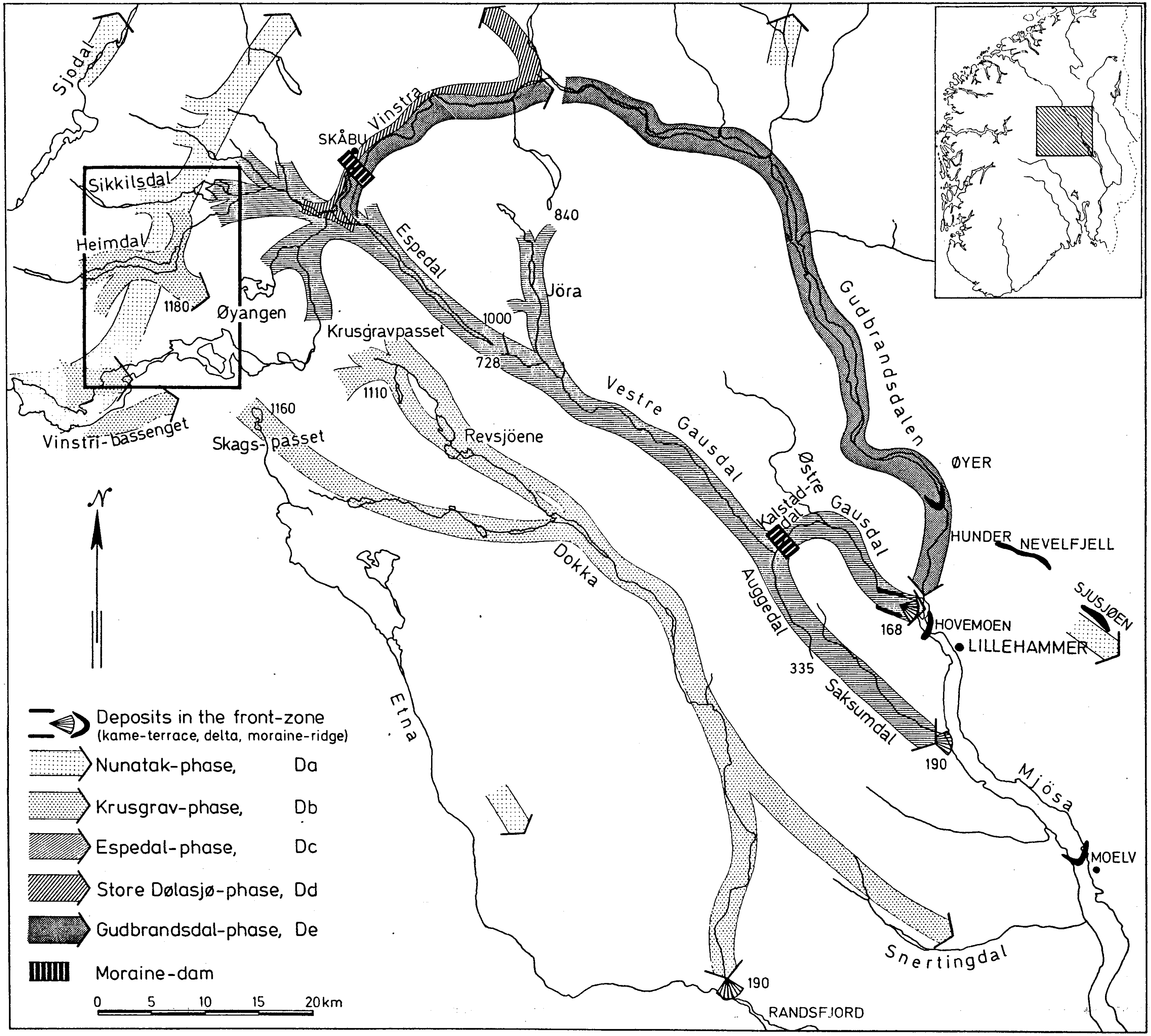


Fig. 4. *The history of the river Vinstra during deglaciation, separated into five phases. Framed area is location map for Fig. 8.*

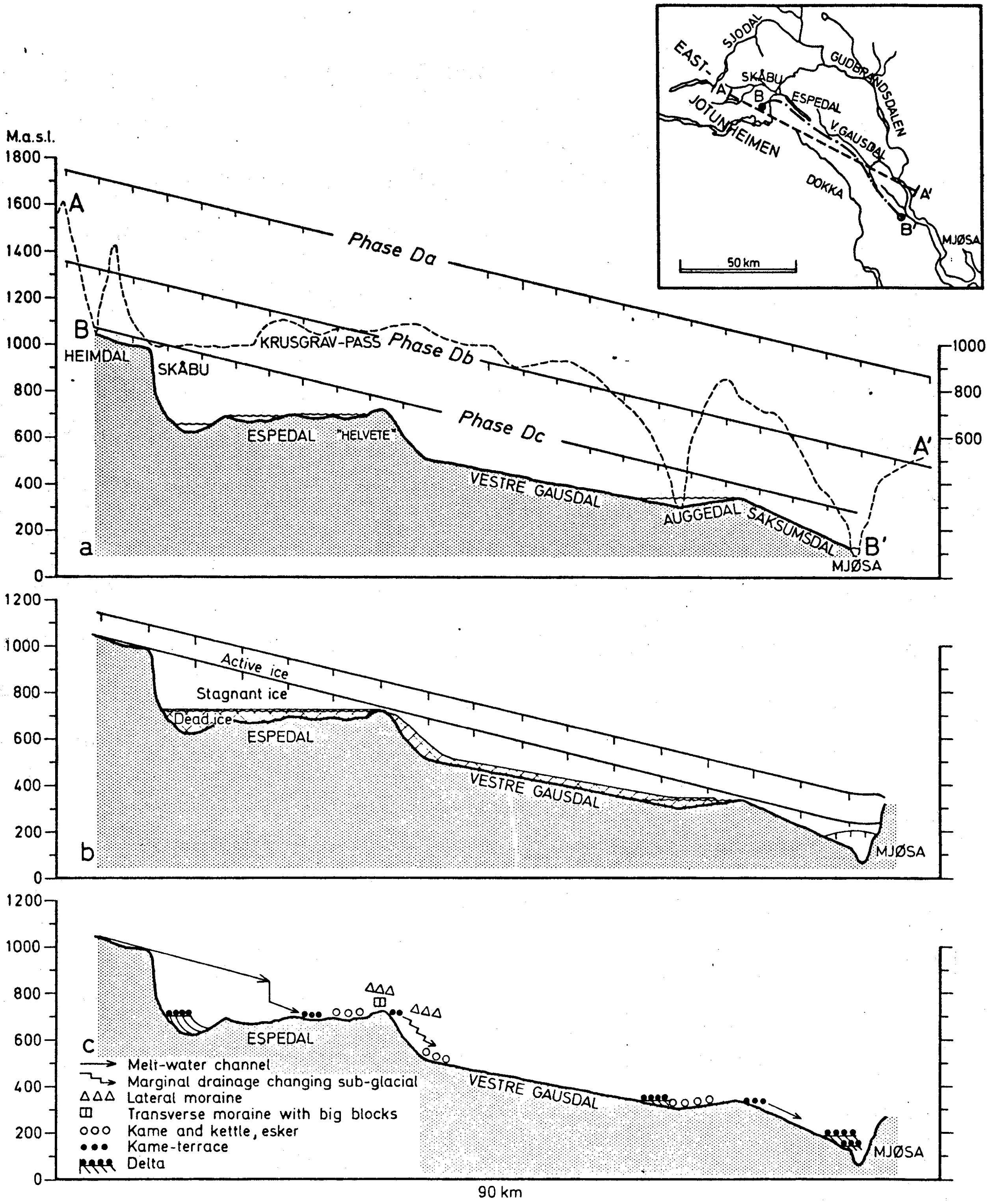


Fig. 5. *Two longitudinal profiles from east Jotunheimen to lake Mjøsa, straight (A-A') and along the valleys (B-B') showing three phases of down-wastage (b). The surface of the ice sheet is presumed to have had a gradient during phases Da, Db, and the first part of Dc of about 1% in the direction of ice flow. After being separated into several ice bodies during phase Dc, the ice gradually sank in conformity with the valley bottom slope (b). At the same time, the ice bodies in the valleys, became stagnant, and at last dynamically dead. The lowermost valley profile (c) shows the most characteristic deposits from the Espedal-phase Dc.*

The ice surface of the inland ice south of the ice divide is found to be practically conformal to the general slope of the land surface . However, the details of the course of deglaciation were to large extent controlled by local topography (Fig. 5). The "vidde" area around the upper part of the river Dokka is particularly interesting. This area was the recipient of large amounts of meltwater during this phase, notably from extensive mountain and "vidde" areas to the west through the Krusgrav gap, 1110 m a.s.l. This drainage was especially heavy when the ice surface was at about 1150-1200 m a.s.l. in the Vinsrti basin when the outlets to the south, towards the Etna valley, became closed to drainage. The ice surface in the Vinstri basin was then almost horizontal. Large flows of water were led laterally and supraglacially through different gaps towards the east, and further towards the southeast along the Dokka valley. It is important to note that the drainage, which at the end went subaerially through the Krusgrav gap, encountered thicker ice in the east, and there again took an essentially lateral, supraglacial course (Figs. 6 and 7). East of the pass, the ice surface dipped towards the east-southeast, and the drainage was therefore led to Snertingdal and to Mjøsa lake, and later out through the Dokka valley into Randsfjord lake. On the basis of erosion marks and accumulations in Snertingdal, one can assume that the ice surface here, and at Mjøsa, lay at 400 m a.s.l. in an early stage of the phase. However, a large delta at Randsfjord indicates a Randsfjord level at approximately 190 m a.s.l. at the end of phase Db (see Fig. 4).

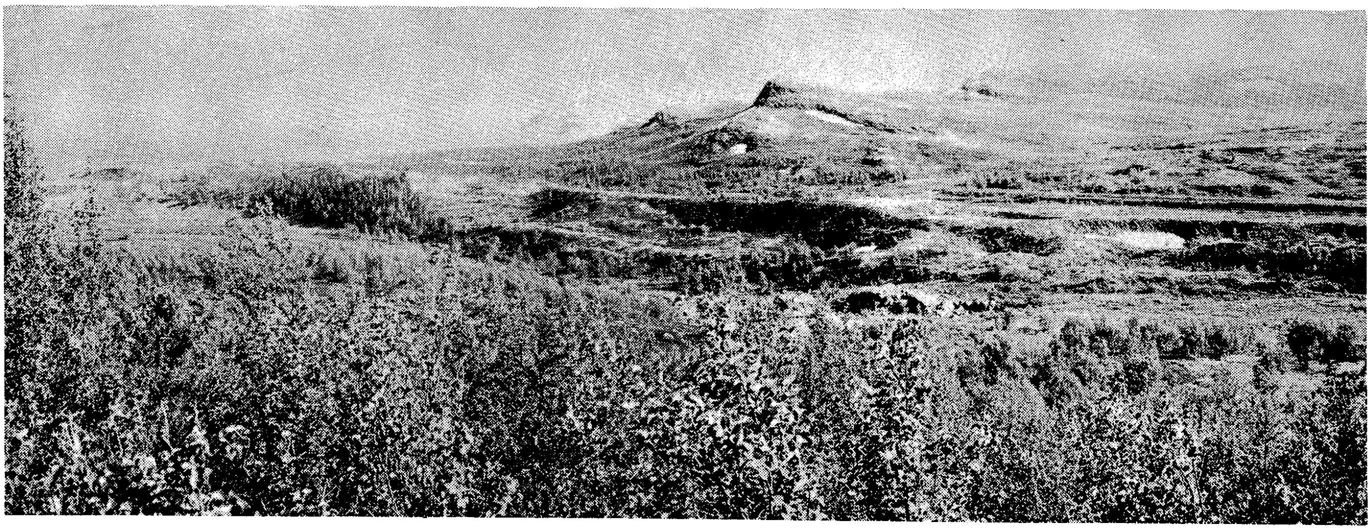


Fig.6. *Glacio-fluvial deposits on the distal side of the Krusgrav-pass, viewed towards the southeast. The kame-terraces seen to the right are built up to approximately the same height as the pass (outside the picture to the right). The deposits continue several kilometers to the left and were evidently deposited in a lateral position as the drainage gradually encountered thicker ice. The surface of the deposits shows fine examples of dead ice topography.*

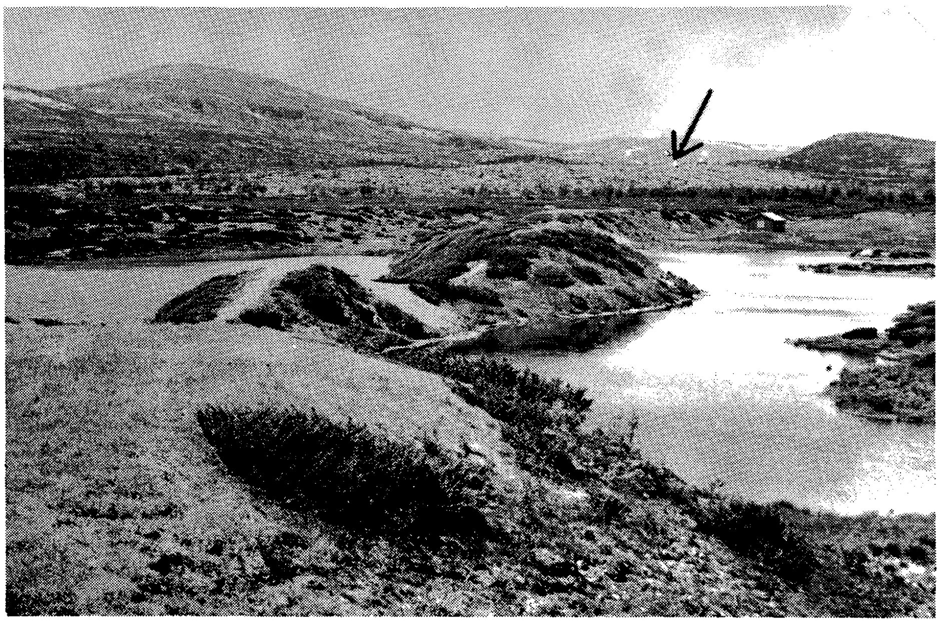


Fig.7. *Traces of two sub-phases of strong lateral, sublateral drainage at Revsjøen in the upper catchment area of Dokka river, viewed to the northwest. The light zone in the background along the valley side became washed completely clean by lateral drainage coming through the arrowed pass. The esker in the center of the photo was deposited when the melt-water later found its way along the valley, from the right to the left.*

Observations of lateral marks, and the mapping of deposits assumed to correlate with these, indicate that the gradient of the ice surface in the area between east Jotunheimen and Mjøsa was approximately 1% during most of the deglaciation period. As seen on Fig. 5, most of the upland (vidde) became ice-free simultaneously. Thus very large areas became ice-free in a short period of time. The inland ice was comparatively rapidly divided into different ice-bodies, which were connected in vallyes and depressions.

In the wide "vidde" basins isolated remnants of the ice sheet remained over large areas. These melted away as dead-ice, often preserving older deposits and forms as well. In certain areas nearly all older deposits were removed by glacio-fluvial erosion along the routes of the melt-water. Large accumulations of ablation till and glaciofluvial material somtimes line these routes. In other places older deposits were covered by glacio-fluvial material. The Vinstri basin shows good examples of all these types of phenomena. It is evident that the widespread, dead-ice sheets in the "vidde" basins yielded enormous amounts of melt-water which, from this stage onwards, mainly followed the valleys. While the ice sheet in the upland areas gradually became dynamically dead, there was several hundred metres thickness of ice in the valleys. When the upland areas (approximately 900 m a.s.l.) around the Gudbrandsdal were almost ice-free the ice was still c. 700 m thick in the main valley. Even if there was practically no supply of ice to the valleys, the masses there were still dynamically active. Striae and lateral moraines indicate this particularly clearly.

LATERAL MORAINES

In east Jotunheimen there are strikingly many large lateral moraines at the altitude where the surface of the inland-ice was situated during phase Db, i.e. 1500 - 1200 m a.s.l. They have been known for a long time. Reusch (1894) for example mentioned two of them, one in the Heimdal and one in the Sikkilsdal valleys. Reusch (op.cit.) suggested that both examples might be shorelines formed in local ice-dammed lakes. However, further studies have shown that the ridges consist mostly of till and that they, without doubt, often are true lateral moraines. On the other hand, many examples show that such lateral moraine ridges can be followed into kame-terraces consisting of sorted material. Other ridges continue as melt-water channels or washed zones. The slope of the most typical lateral moraines varies considerably, but it is usually 0 - 2 %. Many of the morphologically clear examples can be found on only one of the valley sides. They may occur on a north- as well as on a south-facing slope, seemingly independent of aspect. The ridges have been found to be more than ten meters thick, and there are evidently several types with different origins. Garnes (1978) has given examples of lateral moraines in the area that she considers to have been deposited at the beginning of the last ice age, as well as of moraines from the deglaciation formed independent of climatic conditions.

In the following, examples will be given from a smaller area at the mouths of the Heimdal and the Sikkilsdal valleys. These examples will show the genesis of the ridges as well as give important information about the course of deglaciation itself. In the eastern parts of Sikkilsdalen and Heimdalen, there are distinct lateral moraines and other lateral phenomena at several levels. By studying these, one has been able to reconstruct the ice-flow pattern, e.g. during the two phases drawn on the maps (Fig. 8). On the north side of Heimdalen, as well as on the west side of Dørådalen, distinct moraine ridges are situated at 1300 m a.s.l. They are found only on one side of the valley, and both slope at about 2 %. The moraine in Dørådalen indicates that the ice masses in the Vinstri basin flowed out to Heimdalen at this stage (Fig. 8, map a). At the same time, ice moved from Sikkilsdalen to Heimdalen as well. This can be concluded from the direction and aspect of different lateral erosion and accumulation forms in the eastern part of Heimdalen, situated between c. 1250 m and 1180 m a.s.l. As there is clear evidence of synchronous northerly movements in the Sikkilsdal area, ice flowed both northwards and southwards from Sikkilsdalen at this stage. While the Vinstri basin and Sikkilsdalen were supplied with ice each from their own large basin (the fingerlakes Bygdin and Gjende), the supply to Heimdalen was gradually reduced. Leirungsdalen, a much smaller valley than Bygdin and Gjende, is the continuation of Heimdalen westwards. After having converged from the Vinstri basin and the Sikkilsdal, the ice flowed from Heimdalen over Flatstranda towards the outer part of the Vinstri basin (see Fig. 8, map a). The gap is situated at the continuation of Heimdalen. The ice surface probably sloped further towards the south-east, with large runoff through the Krusgrav-pass.

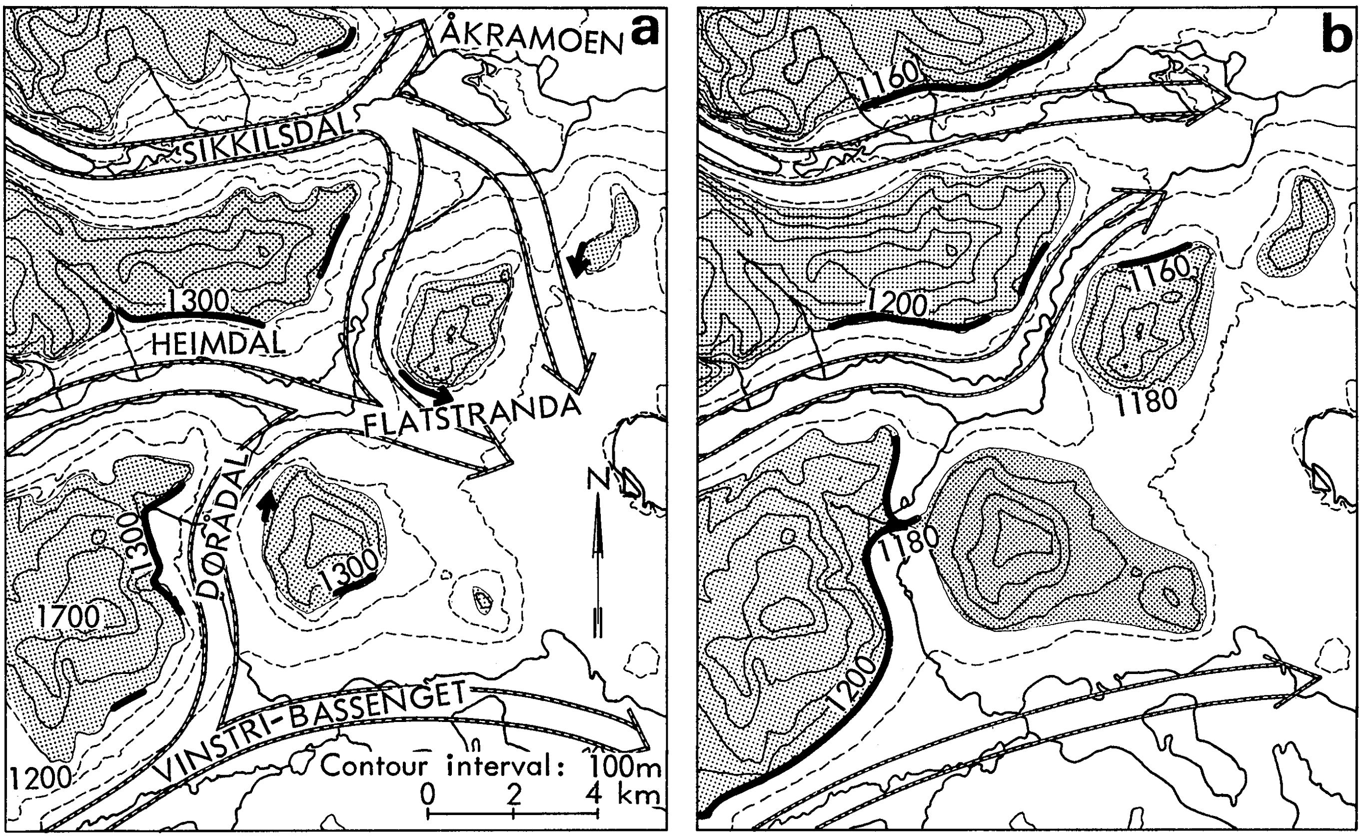


Fig. 8. *Sketch-maps showing two phases with different ice movements patterns in a small area of east Jotunheimen. For location, see Fig. 4. The situation shown on Maps a) and b) corresponds to phase Db and Dc respectively. Large moraine ridges (heavy line) and important cannels (arrow) are pointed out. The ice surface in the situation shown on Map a) is about 1300 m a.s.l. with a gradient near 2%. The ice surface on map b) is close to horizontal and it lies at about 1200 m a.s.l. The lateral moraines marked on Map b) are presumed to have been formed when the ice movements shifted from the situation seen on Map a) to that on Map b).*

The ice movements through the Dørådal valley ceased when the ice surface had melted down close to the level of the outlet, 1180 m a.s.l. Small lateral moraines were formed at this level on both sides of the pass. Lateral phenomena (both erosion and accumulation forms) can be traced along the 1200 m contour line in the Vinstri basin westwards to Bygdin, presumably controlled by the level mentioned. These forms show that the ice surface had now levelled out, with a gradient in the basin approaching zero. At the same time, the ice movement from Sikkilsdalen to Heimdalen was also decreasing (cf. Fig. 8, map b). After this stage, the melt-water drainage lined the valleys. For the area studied the drainage was confined to the Espedal valley. Ice masses from Sikkilsdalen, Heimdalen and the Vinstri basin as well, converged therefore on Espedalen (cf. the Espedal-phase, Dc). The ice surface adjusted in general to the valley profile, giving steeper gradients again (see Fig. 5).

On the southern valley side of Heimdalen, there are large moraine ridges situated between 1280 and 1160 m a.s.l. The highest situated ridges have no well defined dip. They are, however, found to slope up the valley westwards. The largest ridges lie at about 1160 m a.s.l. The western part of these is also found to slope westwards. The eastern part, however, clearly slopes eastwards (Fig. 9). These ridges, mainly consisting of till, are partly eroded by melt-water. As their altitude correlates well with the changes of the ice movements mentioned above, the authors' interpretation is that the moraines were formed due to these changes. Such moraines are often situated close to the same level as that of important overflow passes or transfluent valleys. In a few cases, however, ridges of this type seem to have no relation to distinct passes at all.

As shown, distinct marks indicate that the ice surface was adjusting to the slope of the terrain during this late stage of the deglaciation. As a result of locally increased steepness of the ice surface, lateral moraines could be formed independently of climate. Several examples of such non-climatic moraines are presented on Table 1 (i.e. the Hovemoen, and the Øyer- and Moelv-moraines).

THE ESPEDAL PHASE, Dc.

As already emphasized, enormous quantities of melt-water were concentrated in the larger valleys when the ice surface had melted down below the 1200 m contour line. Melt-water channels show that the drainage from the Vinstri basin and Øyangen flowed mainly to the Espedal valley when the Krusgrav gap (1110 m a.s.l.) became too high. During this phase, therefore, Espedalen drained the whole area that today is the catchment area of the river Vinstra. As shown on Fig. 4, the Gausdal valleys also received supplies from the north, i.e. from the lower part of the Vinstra valley, to the river Jøra. Thus the Gausdal valleys were the recipients of drainage from an area almost 2.5 times larger than the catchment area of the river Gausa today. Because the Espedal drainage can be followed to and correlated with different levels in the Mjøsa lake, it is important to reconstruct the main events of this phase. As shown on Fig. 5, the ice surface is found to have had a mean gradient of about 1 % during this phase. The topography exercised an increasing

Fig. 9. *The eastern part of a lateral moraine at 1.160 m a.s.l. on the southside of the valley in the outer part of Heimdalen. The irregularity of the surface which is easily seen, is due mainly to melt-water erosion and in a lesser degree to the burying of dead ice. The moraine is thought to have been formed as a result of a sudden shift in ice movement pattern (see text).*

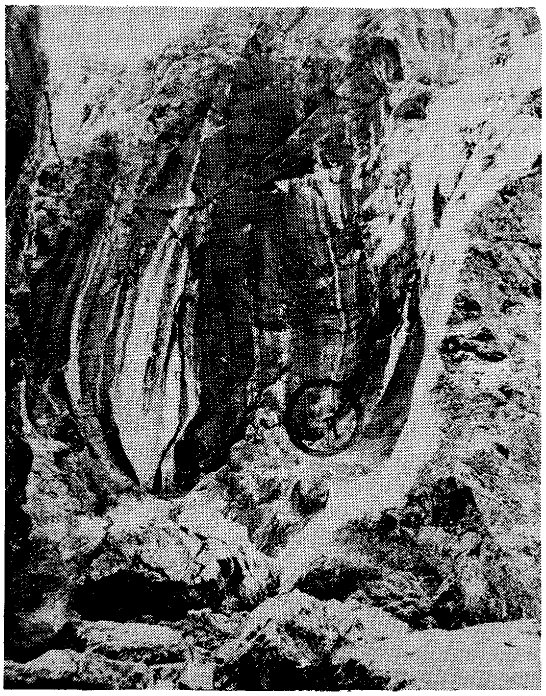


Fig. 10. *Large pot-holes near the pass between the Espedal and Vestre Gausdal valleys. The scale is indicated by a person. The pot-holes, eroded in homogenous anorthosite, are thought to have been excavated sub-glacially during an early stage of deglaciation.*

control over the movements of the ice. The gradienst, therefore, varied somewhat down through the valley. The pass area between Espedalen and Vestre Gausdal shows evidence of this. In the distal part of the pass well developed lateral moraines indicate a local dip of 2 - 4 %. Lateral moraines are seldom found elsewhere in the vicinity.

The reconstruction of the drainage history of the Espedal phase can bes be based on two criteria, i.e. morphology and the texture of the glacial sediments. The most important morphological traces in Espedalen are erosion channels. In Vestre Gausdal and Auggedal accumulation forms dominate. From the lower part of the valley system some of these deglaciation phenomena have already been described by Rekstad (1898), Bergersen (1964, 1971), Enger (1973).

In the accumulations deposited from the Espedal drainage, there occur high percentages of rocks with a characteristic origin. West of a north-south line, approximately along the river Jøra, the so-called Jotun rocks (anorthosite, gabbro, and other crystallines) dominate the bedrock. East of this line the bedrock consists of different sedimentary rocks only. The percentage of Jotun rocks in glacio-fluvial deposits is higher than 30 in the pebble fraction (usually quite a bit higher) as far down the valley as 60 km east of the bedrock border, In other glaciofluvial deposits along the valley such rocks form a far smaller share, normally 2 - 5 % (Bergersen 1964, 1971). The stones deposited by the Espedal drainage also have a considerably higher degree of roundness than other glacial sediments in the area (Bergersen 1973).

When the Espedal drainage started, the ice sheet was probably near the breaking point above the passes at Espedal - Vestre Gausdal and Auggedal - Saksumdal (cf. Fig. 5). Therefore the drainage through these passes evidently encountered thicker ice. On the distal part of the two watersheds there occur characteristic kame terraces at the same height as the passes. The accumulations that at first appear as terraces along the valley sides, continue as ridges several hundred meters distally to the watershed-gaps. Eventually, the accumulations, consisting of coarse glacio-fluvial material, assume a small gradient down the valley, but this is less than the slope of the valley floor. It is not possible to follow the deposits continuously any further than about one kilometer. A blanket of ablation material with characteristic elements of Jotun rocks and with a sharp upper boundary, however, can be followed along the whole valley system to the Mjøsa lake.

The connecting valley from Espedalen to Vestre Gausdal declines 200 m from the watershed (728 m a.s.l.) to the confluence with the river Jøra (Gausa), a distance of 5 km. In the confluence area large glacio-fluvial masses showing magnificent dead-ice topography have been accumulated on the southwest side of the valley up to 80 m above its floor. Further down the valley glacio-fluvial accumulations are only found along the valley floor and up to 20 - 30 m above it. The areas around the Mjøsa lake, where the base level at that time was up to 70 m higher than today, are exceptions. In these areas deltas were formed at different levels to above 190 m a.s.l.

The pass areas between Espedal - Vestre Gausdal and Auggedal - Saksumdal both have distinct signs of lateral, as well as subaerial melt-water drainage. In the former pass there are 10 - 12 exceptionally well developed potholes, up to 40 m deep, in the strongly washed valley floor. These are named Helvete (Hell) (Fig. 10). The connecting valley from Espedalen is clearly polycyclical, having obviously been eroded during many periods. The potholes, evidently belonging to the youngest generation, are situated in a superimposed canyon on the side of the "Talweg". As there existed an extensive, lateral, melt-water drainage through the valley during most of the Espedal phase, the potholes were probably due to sub-glacial erosion before the ice broke up over the pass. The potholes are therefore thought to be from the very beginning of this phase, or they may originate from an older phase.

As already shown, there are different erosion forms, as well as different types of depositional forms, that originated from the Espedal phase. Well developed melt-water channels and kame-terraces dominate the northwestern part of the Espedal valley. Otherwise few traces can be found, except in the watershed area where several eskers occur proximally and distinct kame-terraces distally . Evidence of sub-glacial drainage cannot be found until the melt-water drainage reached Vestre Gausdal where it encountered thinner ice. From Fig. 5 c it can be seen how accumulations of presumed sub-glacial origin are to be found mainly in areas proximal to the watersheds. Here the melt-water was ice-directed under hydrostatic pressure against the slope of the valley bottom. Distally, however, where the melt-water was confronted with gradually thicker ice, lateral terraces dominate. Accumulations can also be found elsewhere, especially where the drainage managed to take a sub-glacial course and at the ice front.

The Espedal phase has two succesive sub-phases. First the drainage can be followed, as described, across the watershed (335 m a.s.l.) between Auggedal and Saksumdal and to lake Mjøsa. A delta was built up at Mjøsa, somewhat higher than 190 m a.s.l. The extent of the delta towards the south indicates an accumulation in a lateral lake, probably due to an ice lobe in Mjøsa. The melt-water drainage also continued for some time after the watershed was free of ice. At that time, a lateral lake dammed against the watershed (335 m a.s.l.), existed in Auggedal. The lake grew to a length of 13 km, but the depth was never more than 30 m. The whole lake was probably filled with fine-grained sediments and dead-ice remnants when the break-through to Kalstaddalen and Østre Gausdal occurred (Fig. 4).

The second sub-phase of the Espedal drainage started as the water made its way through the transverse Kalstaddal valley to Østre Gausdal . Distinct lateral channels at an altitude of 270 - 200 m a.s.l. in Østre Gausdal show that ice still remained in this valley (Bergersen 1964, Enger 1973). At the beginning of this sub-phase, kame-terraces were built up in Østre Gausdal to a height of 168 m a.s.l. - the level of Mjøsa at that time.

In the northern part of Mjøsa, outside the mouth of Gausdalen there exists a large transverse ridge, called Hovemoen. The deposit is thought to be of importance to the understanding of the sequence of deglaciation in this area (Vogt 1943, Bergersen 1975, Østmo 1972). Hovemoen, which is situated east of the delta area, has a concave form towards Østre Gausdal . Both its surface and outline are formed by glacio-fluvial erosion. Characteristic dead-ice topography has nevertheless been preserved, and it covers almost the whole surface. The accumulation, which lies at 181 m a.s.l. consists of a 10 - 30 m thick cover of coarse, glacio-fluvial material with an assembly of rocks that cannot have arrived from Vestre Gausdal . The feature is probably derived from older deposits (mostly basal till) in the delta area. The till seems to originate mostly from Gudbrandsdalen. This coarse accumulation rest upon thick layers of lacustrine sediments, maybe 100 meter thick (Østmo 1972).

A general survey of available information shows that the Hovemoen was probably built up in the vicinity of the ice margin, at a base level in the Mjøsa close to 170 m a.s.l. as the result of a catastrophic flood. The lake level correlates well with the altitude of the kame-terraces in Østre Gausdal that correspond to a base level of 168 m a.s.l. It is therefore possible that Hovemoen was formed by a flood wave caused by the tapping of the ice-dammed lake in Auggedalen (Østmo 1972). However, a study of the rock content suggests that the drainage came from Gudbrandsdalen (Bergersen 1964, 1975). This apparent contradiction in views may be explained in the following way. When huge amounts of melt-water, resulting from tapping of the lake, reached the outer part of Østre Gausdal , the water eroded old basal tills derived from Gudbrandsdalen in earlier phases of glaciation. It can be concluded from this description that the transition between the first and second Espedal sub-phases occurred when Mjøsa had subsided to 170 - 168 m a.s.l.

At the mouth of Østre Gausdal there is also a large delta built up to about 140 m a.s.l. (Jørstadmoen). Between the 168 m terraces and this delta, no distinct level of deposition has been found. The delta is so extensive that it most probably originated during the Espedal phase, when the whole Vinstra river-catchment area drained into Østre Gausdal. Since no ice-contact phenomena have been found on the delta, the area was probably ice-free during deposition. Hence, the Espedal phase lasted at least until Mjøsa had subsided to 140 m a.s.l. Between the 140 m delta, and today's delta at 122 m a.s.l., no distinct levels have been established.

Towards the end of the Espedal phase, a big lake was dammed up between the ice remnants in Espedal - Vinstradal and the watershed between Espedal and Vestre Gausdal. When this watershed had become ice-free, the ice lobe in Espedalen lost its gradient, at the same time as the ice probably was gradually broken up (Fig. 5b). This lake eventually became 26 km long, and Ramsli (1948) called it "Storsjøen" (The great lake). Normal deltas were built in this lake at the mouth of the tributary valleys. This fact indicates that it at least partly was an ice-free lake. During the Espedal phase "Storsjøen" was drained to the southeast through Vestre Gausdal. Later, during the phases Dc and Dd, it drained along the Vinstra valley. ^{14}C-dating of the bottom layers of a c. 0.7 m deep bog at the watershed Espedal-Vestre Gausdal gave the result 6050 ± 90 years B.P. (T-855). Another two datings from the bottom layers of a bog at Skåbu at 695 m a.s.l., i.e. 33 m below the level of "Storsjøen", gave the results 8787±210 years B.P. (T-2525) and 9080± 140 years B.P. (T-2875) (Alstadsæter 1979). The latter bog lies on bedrock of calcarious micashists. Therefore, the dates may be somewhat too old due to the so-called hard-water effect. However, if the dates are approximately correct, the "Storsjøen" must have existed for only a very short time, and the Espedal phase must have ended more than 9.000 years ago.

THE STORE DØLASJØ PHASE, Dd.

The authors have previously shown that large remnants of the inland ice lay in the central parts of Gudbrandsdalen after the upland areas were almost ice-free. The ice masses comprised a gigantic dam to consequent drainage down the main valley (e.g. Garnes 1978). By follwoing different types of lateral phenomena (so-called "seter" or "parallel roads") a marginal lake has been reconstructed. This lake is called "Store Dølasjø", and, at its latest stage, it stretched from Skåbu to the main watershed between East and West Norway, at Lesja (612 m a.s.l.), a distance of 140 km. In addition, the lake had up to 80 km long branches in the tributary valleys. Many scientists have discussed the northern part of this north-flowing lake (older works reviewed by Øyen 1896, also G. Holmsen 1918, Gjessing 1960). In all the earlier works, the lake dam was thought to have been located at Selsrosten, a narrow part of Gudbrandsdalen just south of the mouth of Jønndalen (Fig. 2). Continuation of the synchronous "seter" also far to the south of this area, shows that this assumption was incorrect (Garnes 1978, Lie 1974, Hole 1979, Skjerven 1978). Because of isostatic down-warping, probably caused by the remaining ice-bodies, the reconstructed level of the lake is found at c. 670 m a.s.l. in the Vinstra valley. Traces of the lake are scarce as far south as the Vinstra area, but even here the level is marked by small lateral deltas and erosion terraces. Several small moraine ridges are of interest in this context. They are thought to have been formed as the ice-dam broke and the lake drained southwards. The sudden reversal of the drainage direction is thought to have been followed by a locally increased gradient of ice lobes left in the tributary valleys. This phenomenon can be observed in the upper part of the Vinstra valley, for example. The formation of several moraine ridges in east Jotunheimen can be explained in the same way (see p. 10-13).

The authors believe that, when the ice surface in Gudbrandsdalen had been sufficiently lowered, "Storsjøen" drained northwards, up Gudbrandsdalen for a short period of time before draining northeastwards through the Vinstra valley. This happened during a period when the "Storsjøen" surface sank from 728 m to about 670 m a.s.l. and resulted in a drastic reduction of the extention and volume of the lake. Already in 1898, Rekstad mentioned three levels, thereby indicating that "Storsjøen" was drained at different stages. Ramsli (1948) found by levelling that the two highest surfaces of two deltas at the western part of the former lake lay at 728 m and 695 m a.s.l. He also mentioned a surface at about 680 m a.s.l.

At Skåbu, the Vinstra valley has probably been filled with waterlaid sediments and overlaid till up to a level of at least 720 m a.s.l. This assumtion is based on erosion terraces found at different levels in the thick deposits still remaining on both valley sides. It has previously been suggested that these deposits were the real dam of "Storsjøen, or part of it (Rekstad 1898, Mangerud 1963, Bergersen 1971). The reconstruction of the large ice dam in mid-Gudbrandsdalen, the ^{14}C-datings already mentioned, and the step by step-drainage, are all strong evidence against such an interpretation. Furthermore, the lower part of these deposits, consisting of coarse glacio-fluvial material, is very permeable. The deposits, therefore, are thought to have a low damming effect.

THE GUDBRANDSDAL PHASE, De.

Phase De represents the last phase in the deglaciation of the Gudbrandsdal valley system. The phase started as the ice lobe in the main valley allowed the "Store Dølasjø" to be drained southwards. From then on, the drainage followed the valley as it does today. However, the ice remnants, still almost 500 m thick in the main valley, controlled to a large extent the routes of the melt-water. The authors have not so far compiled all the details concerning this last reconstructed phase of deglaciation. In this paper, therefore, only a few events important to the correlations between deglaciation phenomena in mid-Gudbrandsdalen with those at the ice front will be dealt with. The reversal of melt-water drainage represents an important event in the deglaciation history. As long as the drainage was directed to the north, the lower Gudbrandsdal received drainage from areas south of the Vinstra valley only. The catchment area then was less than 1700 km^2. When the drainage reversed southwards the catchment area suddenly became six times larger than it had been before (c. 11,000 km^2), i.e. almost the present size. In addition the water stored in the ice-dammed lake, "Store Dølasjø", had to be drained along the same route. Extensive washed zones on some exposed valley sides north of the former ice-dam are thought to be the result of the reversed drainage (Fig. 11). In the southern area, only a few phenomena have been identified that could have been formed in connection with the catastrophic flood. Some of these (canyons and eskers, all transverse to the valley sides) indicate that the drainage very soon became sub-glacial or englacial.

The reversal of drainage is correlated with large frontal deposits consisting of coarse glacio-fluvial material, called the Øyer moraines. These moraines are situated about ten kilometers north of Mjøsa, showing that the front of the ice lobe had melted back to this position when the "Store Dølasjø" ceased to exist. Both the frontal deposits and a sheet of ablation material also correlated with the reversal of drainage towards the south, contain a characteristically large amount of rocks transported over long distances, especially gabbroid rocks of the Jotun type from the Vinstra and the Sjoa areas. The reconstruction shows that the ice surface, also in the lower parts of Gudbrandsdalen, had a gradient of about 1 % during this phase.

Important features of phase De, was that the ice remnants in the main valley still dammed the drainage from the tributary valleys. Therefore, local ice-dammed lakes occurred in some of the tributary valleys. The accumulations there were exposed to heavy erosion when the lakes drained, as well as during intensive postglacial slope development on the steep valley sides. Slope processes have buried many signs of deglaciation on the floor of the main valley as well.

A large deposit of sorted material is located at the mouth of

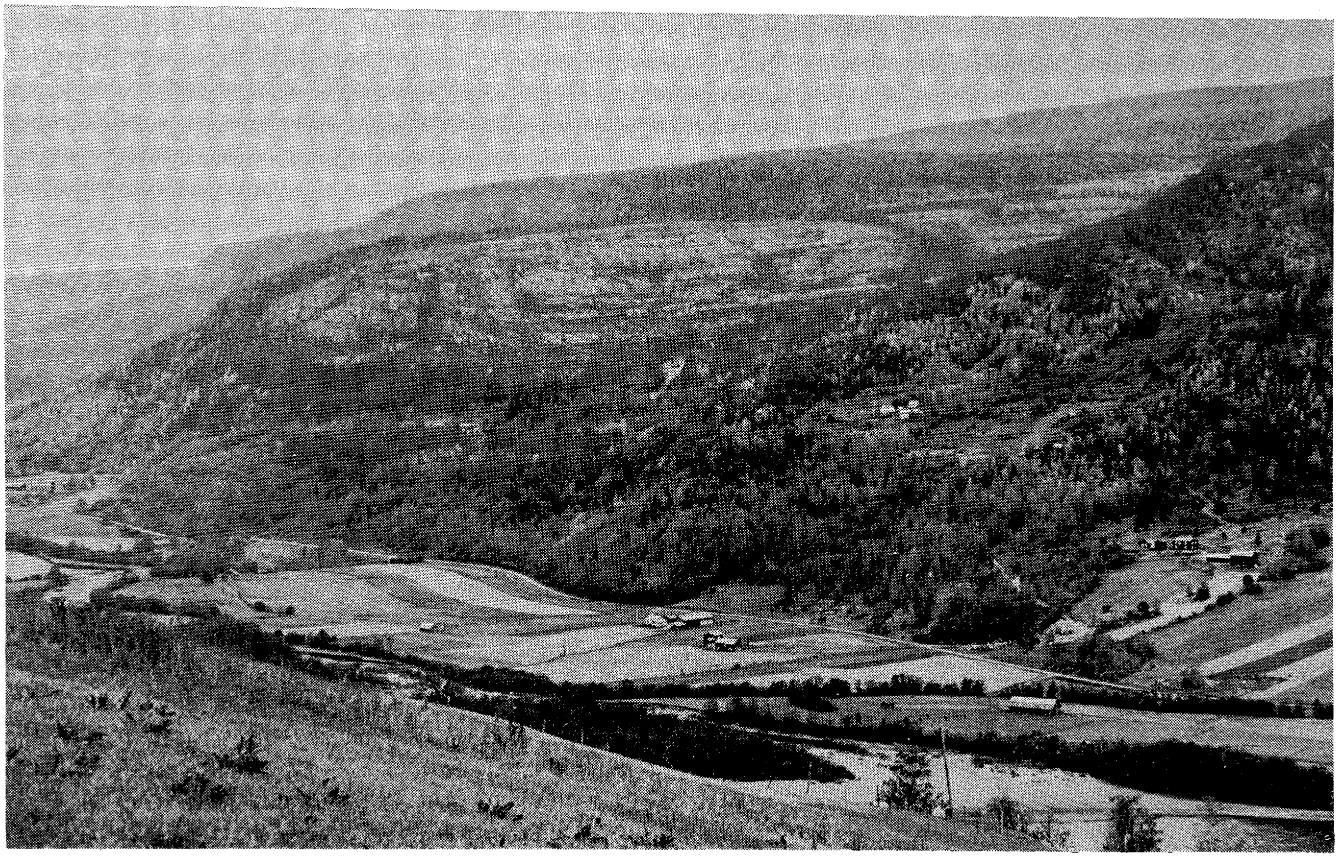


Fig.11. *Example of washed zone in the valley side presumed being stripped by the melt-water after the reversion of the drainage in Gudbrandsdalen. The actual zone, situated about 600 m a.s.l. just north of the mouth of the Vinstra valley, is completely free of deposits. (Viewed to the southwest).*

the Vinstra valley in Gudbrandsdalen. Mangerud (1963) interpreted this as a fan deposited by water from "Storesjøen" pouring through the Vinstra valley when the postulated dam at Skåbu was broken. Sections in this deposit show normal delta formations (Fig. 12). The boundary between the foreset and topset layers is at 250 m a.s.l. All observations indicate that the delta was built by the river Vinstra during post-glacial time, when all the ice had disappeared. Similar young deltas or fans are situated in front of all larger tributary valleys in Gudbrandsdalen. The authors believe therefore that the delta has no connection with "Storsjøen".

CORRELATION

To outline the most important events and phenomena that can be correlated at the present stage, the main features are shown in tableform. The drainage through east Jotunheimen has been traced, both through the Espedal - Gausdal valleys and through the Vinstra - Gudbrandsdal valleys. It converges at the northern end of Mjøsa. The most important correlations and relative dating can be found on Table 1. Some main features will be commented upon.

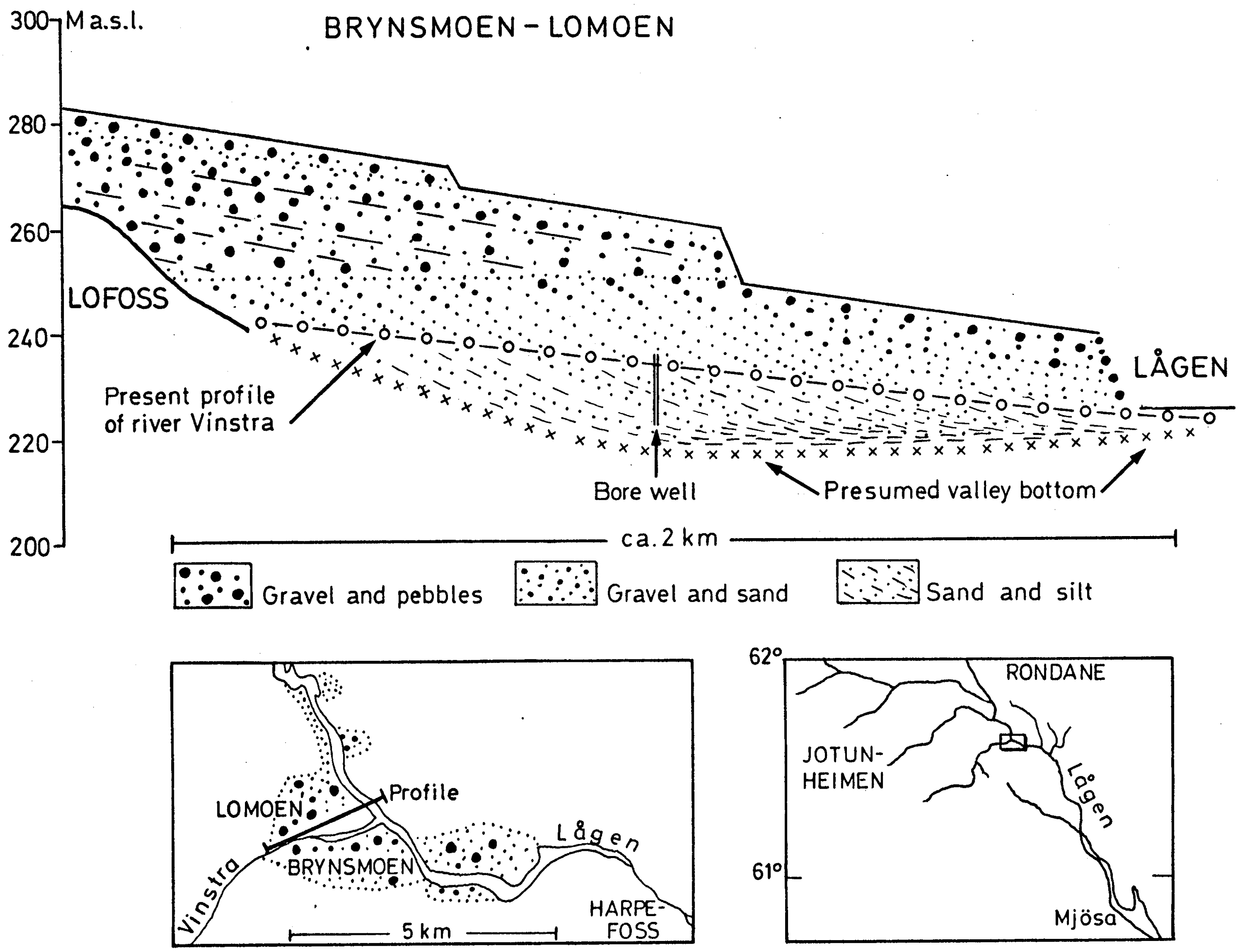


Fig. 12. *Longitudinal section through the delta at the mouth of the Vinstra valley in Gudbrandsdalen. The deposition shows normal delta formations.*

Da. During the Nunatak-phase, the inland ice in the Mjøsa area was increasingly affected by the fjord-lake, Mjøsa, which is about 500 m deep in its southern part. Very rapid retreat probably occurred here due to calving. This is comparable to the retreat of the ice lobes in the large fjords in West-Norway (among others,H.Holtedahl 1975). The rapid retreat presumably led to a steeper gradient, at least on the outer parts of the inland ice. This may have resulted in the formation of the distinct lateral moraines east of Lillehammer. Here considerable moraines can be traced more or less continuously from Nevelfjell to Sjusjøen c. 13 km to the southeast (Fig. 4) e.g. O.Holtedahl 1953 p.782-786). The position of the moraines agrees very well with the change in the ice-flow pattern that had to occur as the inland ice was deflected towards Mjøsa due to calving. Therefore, these lateral moraines were probably not determined by climatic conditions.

Db. The Krusgrav-phase to the south and the Ring-drainage-phase to the north of the ice divide are not entirely synchronous. The heavy drainage of melt-water along Gudbrandsdalen during this phase may have contributed to the formation of the sub-aquatic, front deposit across Mjøsa at Moelv mentioned on page . The break-up of the ice as it floated in Mjøsa probably happened rather quickly up as far as Moelv. This is indicated by soundings in Mjøsa. However, further north, things may have happened more slowly. The ice front could have lingered at Moelv during a greater part of phase Db, when the Mjøsa level was approximately 190 m a.s.l.

Dc. During the Espedal phase, the last remnants of the inland ice melted in the Mjøsa area. The level of Mjøsa sank very rapidly from 190 m to about 140 m a.s.l. This may be attributed to the rapid breaching of the large frontal deposits at the southern end of the lake (Minnesund) due to quick regression of the sea in the Oslofjord area during Preboreal time (e.g. Hafsten 1960).

Dd and De. Considerable ice masses still remained in Gudbrandsdalen. However, the large amounts of water coming from icefree areas caused rapid deglaciation here too, especially during the phase De.

Until detailed investigations are carried out along Mjøsa itself, the exact age of the phases and of the most important events cannot be determined accurately enough. The hitherto ^{14}C-datings are few and far between, and they are associated with a certain degree of inaccuracy. At least two important questions concerning the Mjøsa area must be resolved in the future:

1. Correlation of synchronous levels, and correlations of these with marine levels south of the lake.

To accomplish this we must also:

2. Determine the isobase directions and the rate of up-heaval in the Mjøsa area during this period.

SUMMARY

1. The history of the wastage of the last ice sheet in a land scape with a relief up to 1000m, shows that downmelting of the ice was of a greater importance than frontal retreat. The ice surface is found to have melted down with very small gradients

in the area between the ice divide zone across Gudbrandsdalen and the main watershed in the north. This was specially the case when the ice sheet was no longer supplied by ice from the former culmination areas. This happened when the ice surface was situated about 1200 m a.s.l. in east Jotunheimen. During the further deglaciation, until the last ice masses in central Gudbrandsdalen no longer dammed the drainage and the drainage reversed, the slope of the ice surface was very close to zero. The reversion took place when the ice lobe was lowered to a level adjusted to the lowermost pass in the north (612 m a.s.l.).

In the area south of the ice divide zone it is found that the gradient of the ice surface during most of the deglaciation was c. 1 %. However, during the very last phases the ice lobes probably were in close conformity with the relief. The descending angle of 1 % is of the same value as the inclination of the general land slope. Therefore, very large areas became free of ice almost simultaneously. While the ice movement to a high degree was independent of the relief at an early stage of the deglaciation, the movements and the drainage as well, became more and more topographically controlled. The interaction between the ice movements and the topographical conditions caused large differences in local gradients. Small gradients (0 - 2 %), caused erosion of terraces as well as their accumulation by melt-water, gradients exceeding c. 2 % locally caused the formation of lateral moraines. When the supply of ice from the former culmination centers in the Jotunheimen ended, the ice sheet was already separated into several lobes, situated in the valleys. The partition of the ice sheet into different bodies gave the result that the front areas of the ice existed as retreating lobes in the valleys with large ice-free areas between the valleys. This picture of the last ice sheet differs from older views where the last remnants of the inland ice are drawn as a plateau-like glacier with a straight-lined boundary.

2. Due to the down-wasting there existed simultaneously active ice in the valleys, stagnant ice in upper areas, and dead ice in many high-level basins. The last remnants of the ice sheet in central South Norway seems to have existed in the Gudbrandsdal.

3. In attempting to reconstruct the level of the ice surface, different phenomena presumed to have formed laterally or sublaterally, should be used very carefully. Nevertheless, by following and correlating terraces step for step over a large region, combined with other methods, it is concluded that the study of lateral phenomena often gives important and adequate information about the ice sheet's gradients.

4. During the downmelting, the inland ice sheet is believed to have been climatically dead from the time of the Nunatak-phase or at least from the later part of it. In mountain areas as well as in lowlands in the investigated region there occur distinct and surprisingly large marginal moraines. These moraines are believed to have been formed by sudden changes in the ice-flow pattern, causing increased steepnes of the ice surface and faster ice movements. There are different reasons for drastic changes like this. Many moraines are found at the same height as

important overflow passes, deflection of the ice streams is probably the reason for their existence. The lobes often dammed the melt-water drainage, large quantities of water being stored in lateral lakes. When dams broke, large frontal deposits were built up as a consequence of renewed activity in the ice lobe as well as of the greater runoff with a heavy sediment load.

5. The melt-water drainage have been traced through two different valley-systems which converge at the northern end of Mjøsa, namely the Espedal - Gausdal valleys and the Vinstra - Gudbrandsdal valleys. When linked together, it is possible to correlate different deglaciation phenomena in the ice divide zone with those at the ice front in the Mjøsa area. A relative correlation table showing the preliminary results, is presented in Table 1. Absolute age dates are few in the investigated area. However, all available information suggests that the four oldest phases reconstructed all belong to the Preboreal chronozone, the youngest one probably being of Boreal age.

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Phase	Ice surface at Skåbu, m a.s.l.	Frontal deposition	Level in the northern part of Mjøsa, m a.s.l.	Remarks
Da Nunatak-phase	1900 - 1300	Nevelfjell-Sjusjøen-moraine		Starting of the break-up of the ice along Mjøsa?
Db Krusgrav-phase Ring-drainage-phase	1300 - 1000	Moelv-moraine	c. 190	Calving along Mjøsa
Dc Espedal-phase	1000 - 800	Saksumdal-delta Hovemoen-moraine Kame-terraces in Gausdal Jørstadmoen-delta	c. 190 c. 170 168 c. 140	Calving decreased and ended. Down-wasting of all ice lobes.
Dd Store Dølasjø-phase	Ice-free	Øyer-moraine	< 140	C. 9000 years B.P. Down-wasting continued.
De Gudbrandsdal-phase	Ice-free	Smaller glaciofluvial deposits in Gudbrandsdalen	< 140	Reversed drainage along Gudbrandsdalen. Ice left in the main valley only.

Table 1.

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