DISTRIBUTION OF GLACIAL LANDFORMS IN SOUTHERN NORWAY IN RELATION TO THE THERMAL REGIME OF THE LAST CONTINENTAL ICE SHEET

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ABSTRACT. The zonation of moraines and meltwater landforms in southern Norway indicates that the ice sheet was cold-based during the deglaciation of the central areas. Flutes, drumlins, Rogen moraines and end moraines in these central areas most probably predate the late Weichselian. There is also a vertical zonation of landforms which indicate that the highest areas became cold-based at an early stage during the last glaciation. These higher areas are characterized by blockfields and other weathering phenomena, and no traces of glaciation except meltwater channels and erratic boulders. Later the cold-based zone of the glacier expanded both downwards to lower parts of the terrain and outwards to areas further away from the culmination zone. In these areas the glacier stayed cold-based throughout the deglaciation period. Flutes, drumlins and end moraines were fossilized beneath cold-based ice, while Rogen moraines were formed by ice movement in warm-based patches with trapped water beneath a glacier that was otherwise frozen to the ground. In more distal areas of southern Norway the ice sheet was warm-based, and glacial landforms therefore directly reflect the course of deglaciation.

Introduction

This paper reviews the distributional pattern of morainic and meltwater landforms in southern Norway (Fig. 1), and relates this pattern to the thermal regime of the Scandinavian ice sheet during the last part of the Weichselian glaciation. The following outline of the distributional pattern is mainly based on overview mapping of geomorphology and Quaternary geology carried out by the Department of Physical Geography, University of Oslo (Sollid and Sørbel, 1977, 1982, 1985; Sollid and Torp, 1984; Sollid and Kristiansen, 1982, 1984; Kristiansen and Sollid, 1985, 1988; Sollid and Trollvik, 1991).

The western part of southern Norway is characterized by fjords and areas of alpine relief, while the central and eastern parts have valleys and mountains with gentler relief. While the western areas were situated near the margin of the Scandinavian ice sheet during the Weichselian maximum, the eastern areas, situated near the ice divide, were covered by thick ice.

Morainic and meltwater landforms in most of Scandinavia were formed during the last part of the Weichselian glaciation. Therefore, the regional distribution of these landforms can be used to analyze the extent and dynamics of the ice sheet during this period. However, in some interior areas like the central parts of southern Norway, many morainic and meltwater landforms probably date from older periods (Sollid and Sørbel, 1982, 1984, 1988). Similiar evidence is found in central and northern Sweden (Lagerbäck, 1988a, 1988b; Rhode, 1988; Kleman and Borgström, 1990; Kleman *et al.* 1992, Kleman, 1992).

Regional distribution of glacial landforms

The regional distribution of some types of glacial landforms in southern Norway is discussed below. These landforms include ice-marginal deposits (end moraines and ice-marginal deltas), drumlinoid forms (drumlins and flutes), Rogen moraines, eskers, and marginal meltwater channels.

The many *ice-marginal deposits* in southern Norway are part of large end-moraine systems that can be traced more or less continuously over long distances (Fig. 2). These moraine systems can in most cases be correlated to climatic conditions that existed at the time of their formation, such as the Younger Dryas climatic deterioration. The innermost end moraines from which it is possible to reconstruct a continuous glacier margin are found in the Dovrefjell area and at the heads of the large western fjords. These moraines were deposited during the Preboreal. As to the general extent of

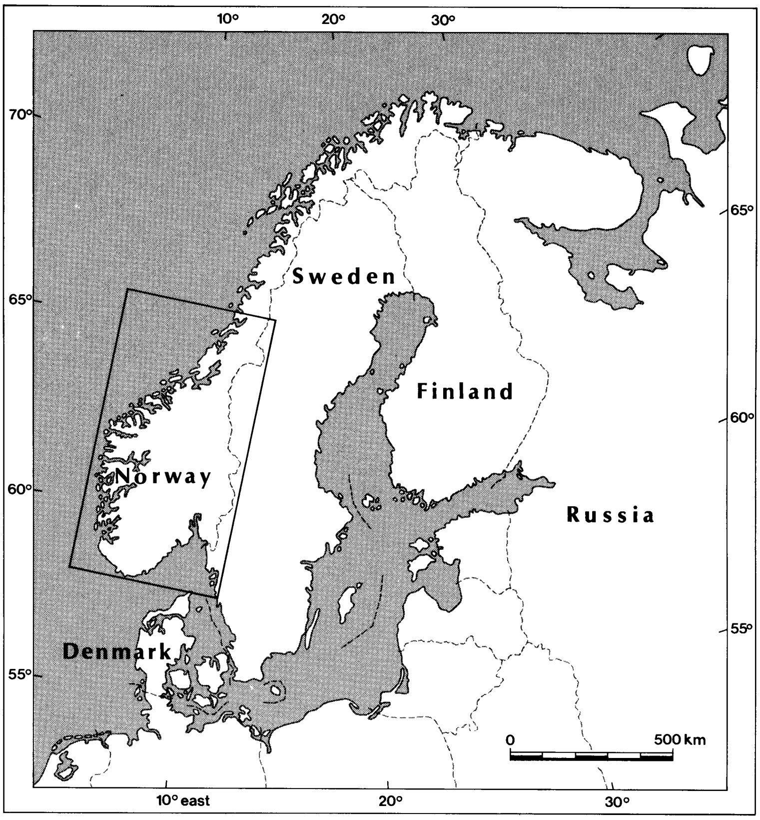

Fig. 1. Key map of the investigated area in southern Norway. Framed area corresponds to later figures showing the distribution of different glacial landforms.

the Scandinavian ice sheet in different phases of Weichsel, cf. Andersen (1981).

Some large end moraines also exist in the central areas close to the culmination zone of the ice sheet, like on the mountain of Søln (Fig. 2). These moraines predate the deglaciation period, and they are probably not related to one singel glacial advance. End moraines older than the last deglaciation are also reported from Sweden (Kleman, 1992).

Drumlinoid forms include all kinds of streamlined moraine ridges formed by basal ice movement. The long axis of the ridges parallels the direction of the ice movement at the time of their formation.

Drumlinoid forms are common in most of southern Norway, except in regions with marked fjord topography (Fig. 3). Otherwise their distribution is not restricted to particular areas, but their density of distribution varies. This seems, to a certain degree, to be related to the distribution of surficial deposits. Extensive areas of western and southernmost Norway consist of exposed bedrock, and have little surficial material available to form drumlins and flutes.

Rogen moraines are ridges with their long axis perpendicular to the ice-movement direction; the ridges are usually 100–200 metres long and 10–20 metres high, they are generally located in shallow terrain depressions, and they always occur like a field of several individual moraine ridges at each location (Fig. 4). Their mode of formation is still a subject of controversy (Lundquist, 1969, 1989; Shaw, 1979; Sollid and Sørbel, 1984; Bouchard, 1988; Aylsworth and Shilts, 1989; Fischer and Shaw, 1991). It is clear, however, that Rogen moraines are formed subglacially.

Rogen moraine fields are found in the central parts of southern Norway, relatively close to the culmination zone of the last ice sheet (Fig. 5). They have not been found in coastal areas, nor in places which have recently been uncovered by contemporary glaciers.

Eskers. Only a few eskers occur in or near coas-

Fig. 2. Distribution of ice-marginal deposits (end moraines and ice-marginal deltas) in southern Norway. D=Dovrefjell, S=Søln.

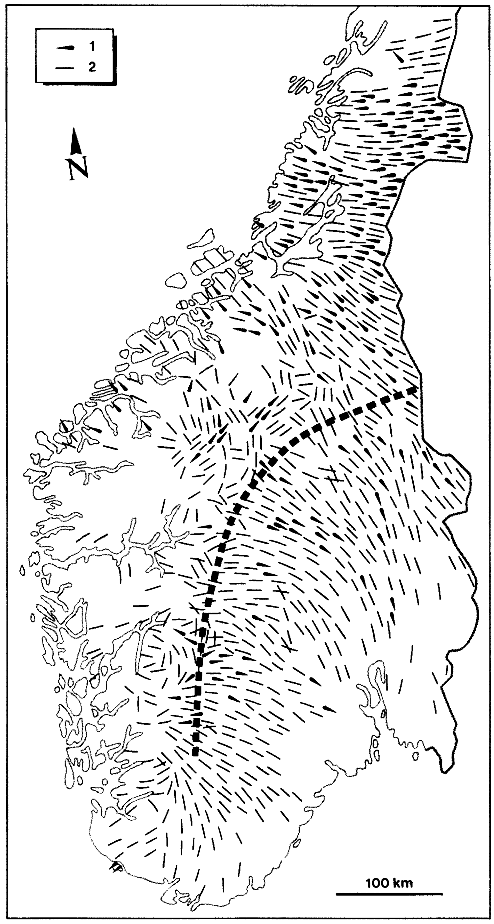

Fig. 3. Distribution of drumlinoide forms in southern Norway. 1=drumlins, 2=flutes. In addition, the main position of the ice divide is marked on the figure.

tal areas, but they are common in a broad zone further inland. Relatively few, small eskers are found in the central areas near the culmination zone of the ice sheet (Fig. 6).

Lateral meltwater channels are most common in the central regions of southern Norway. Here they often occur in large series, where several channels run more or less parallel to each other along a hillside (Fig. 7). As our geomorphological overview maps do not distinguish between different kinds of meltwater channels, the regional distribution of lateral meltwater channels is only generally known.

Landscape zonation

Based upon the distributional pattern of the different landforms described above, southern Norway can be divided into the following zones (Fig. 8):

I This zone is characterized by ice-marginal deposits, with extensive end moraines deposited mainly during the Younger Dryas and the Preboreal. In addition, drumlins and flutes are quite common, especially in the inner part of the zone. Most of the ice-marginal deposits located below the marine limit consist of glaciofluvial material transported to the ice margin in meltwater conduits. Some large eskers exist, but marginal meltwater channels are rare.

Fig. 4. Rogen moraines near the lake Fullsenn, Valdres, southern Norway. Scale of air photo, 1:35 000. For location, see Fig. 5. Air photo: Fjellanger-Widerøe A/S.

II This zone is dominated by drumlinoid forms and almost completely lacking ice-marginal deposits. Among glaciofluvial landforms, eskers are common, while lateral meltwater channels only occur in higher areas.

III This zone is characterized by Rogen moraines, always found in groups in shallow terrain depressions. Drumlinoid forms occuring in the same areas are mostly located on convex or rather flat parts of the terrain.

Zone III can be subdivided into an outer part, IIIa, and a cental part, IIIb. Eskers are common in the outer part (IIIa) but mostly absent in the central part (IIIb). The glaciofluvial landforms of this inner subzone (IIIb) are characterized by large systems of lateral meltwater channels. The glaciofluvial landforms indicate that drainage took place supraglacially or laterally in subzone IIIb. Some large end moraines are also found in this subzone, many of them occuring as broad belts of irregular mounded and ridged terrain, normally with a distinct outer boundary.

The presence of end moraines within zone I, indicates that deglaciation was interrupted by climatic deteriorations. This is well documented along other marginal parts of the Scandinavian ice sheet. Along the fjords and in deep glacial valleys, the location of ice-marginal deposits is largely controlled by topography. Landforms made by ice-directed drainage show that most of the drainage took place subglacially.

The absence of end moraines in zone II suggests that the glacier front here had a continuous retreat uninterrupted by climatic deteriorations. The many eskers show that much of the drainage was subglacial.

Within zone I and II, there is a direct connection between the distribution of landforms and the re-

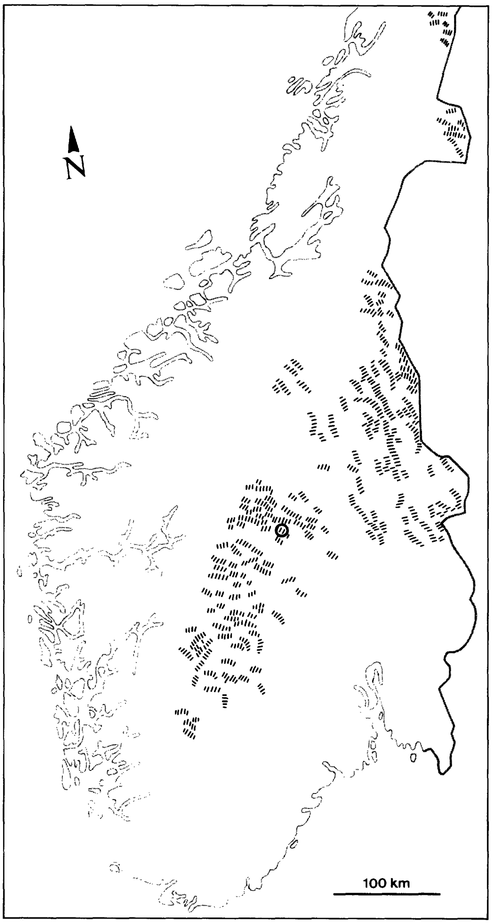

Fig. 5. Distribution of Rogen moraines in southern Norway. The circle marks the location of Fig. 4.

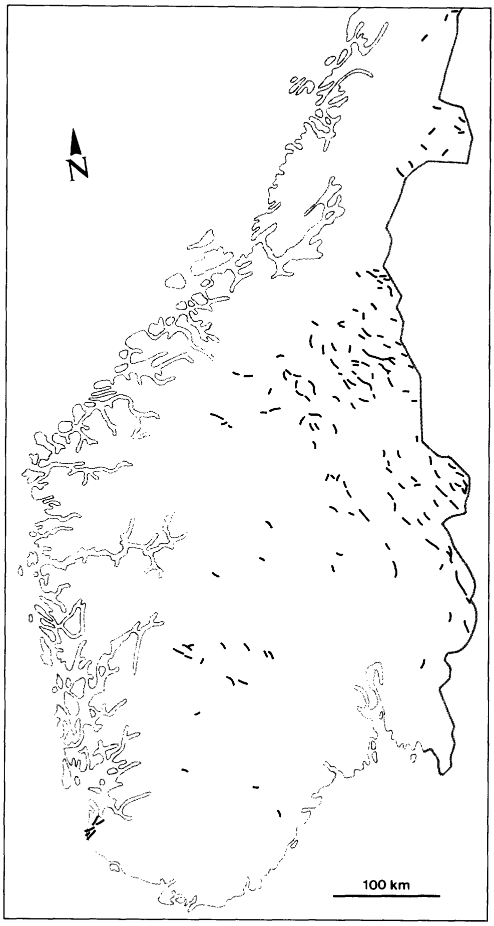

Fig. 6. Distribution of eskers in southern Norway.

treat mode of the ice sheet during the last deglaciation. The meltwater landforms indicate extensive subglacial drainage. This demonstrates that the glacier was warm based during the deglaciation of the distal parts of southern Norway, including both zones I and II.

In the central regions, or zone III, the many occurences of drumlins, flutes and Rogen moraines indicate warm-based ice at the particular place at the time of their formation. On the other hand, the meltwater landforms often indicate extensive supraglacial or lateral drainage at the same locations where drumlins, flutes and Rogen moraines occur. This indicates cold-based ice conditions during the deglaciation of large parts of zone III, as proposed by the authors earlier (Sollid and Sørbel, 1982, 1984, 1988). The subglacial moraine forms, however, indicate warm-based conditions at an earlier stage. The large end moraines in subzone IIIb, which are interpreted to be much older than the last deglaciation, were later preserved beneath a cold-based glacier.

A glacier with subzero temperatures in its upper layers, normally shows an increase in temperature with depth. In some areas, the temperature at depth could reach the pressure melting point; in other areas the glacier may be cold all the way down. It is therefore most likely that in some areas

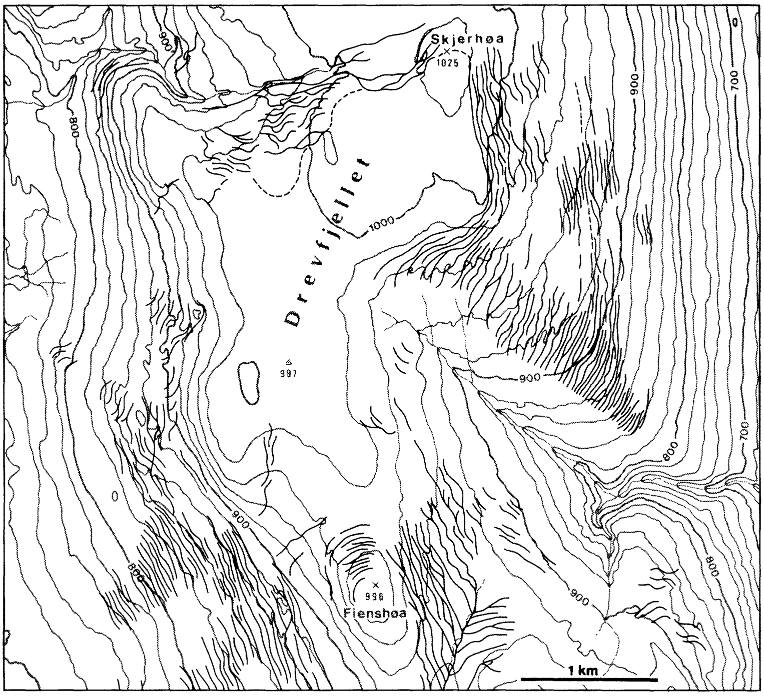

Fig. 7. Series of meltwater channels in the Drevfjellet mountain in the eastern part of southern Norway, close to the Swedish border. For location, see Fig. 8.

the ice sheet was cold-based in higher parts of the terrain, and warm-based in the lower parts, especially within zone III.

The vertical distribution of glacial landforms in the central areas

So far we have considered only the regional distribution of the landforms. In a dicussion of landforms related to the thermal conditions of the ice sheet, it is also of interest to look at their vertical distribution, especially in areas with high relief like in great parts of southern Norway. We focus especially upon zone III (Fig. 8), where many indicators of cold ice during the deglaciation are found. Fig. 9 shows the vertical distribution of glacial landforms within a profile through central southern Norway.

The distribution of drumlinoid forms (mostly flutes) has a distinct upper limit rising from about 1000 m a.s.l. near the Swedish border, to about 1700 m a.s.l. in the mountain areas north of Jotunheimen (Fig. 9, line 1). The upper limit of drumlinoid forms corresponds roughly to the lower limit of block fields and other weathering phenomena.

In the eastern areas, Rogen moraines exist from the lowest parts of the terrain (500–600 m a.s.l.) up to a limit of about 900 m a.s.l. (Fig. 9, line 2). This upper limit rises westward, but the highest altitude of the Rogen moraines is always situated 100–200 metres below the highest altitude of the drumlinoid forms. The Dovrefjell mountains are the westernmost areas in which Rogen moraines are found. Here they occur at elevation between 1100 and 1300 m a.s.l.

Only a few, small eskers exist in the inner areas. Larger eskers are found some tens of kilometres out from the ice divide at altitudes up to 600–700 m a.s.l. Further west, the eskers are found up to progressively higher levels, but seldom above 1200 m a.s.l. (Fig. 9, line 3).

Lateral meltwater channels are found within a wide zone from above the highest limit of drumlinoid forms (Fig. 9 line 1), to somewhat below the highest limit of eskers (Fig. 9, line 3). In the easternmost areas, these channels are found up to a height of a little more than 1100 m a.s.l. In the Rondane and Dovrefjell mountains further west, the highest meltwater channels are located at 1550–1600 m a.s.l.

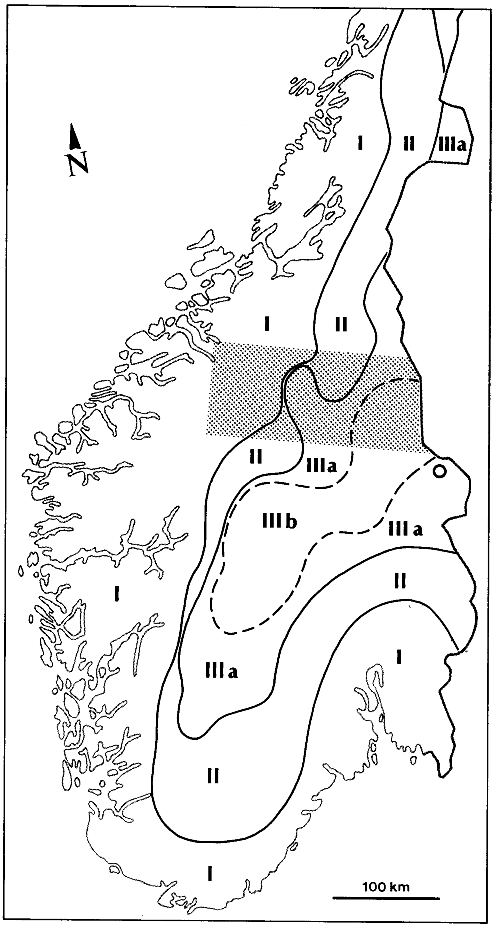

Fig. 8. Zonation of southern Norway based upon the distributional pattern of glacial landforms. The vertical distribution of glacial landforms within the shaded area is shown in Fig. 9. The circle marks the location of Fig. 7.

The thermal regime of the ice sheet

The distribution of cold and temperate ice within a continental ice sheet is determined by many factors, including the climatic conditions throughout the glaciation period, and changes in the ice sheet extent and dynamics. Though the causal relations are very complex, the distribution of cold and temperate ice may be quite simple. This is because the temperature regime in an ice sheet is an extremly conservative system. Temperature changes at the surface of an ice sheet take thousands of years to affect the temperature at the base of the ice sheet (Zotikov, 1986).

In the central parts of a continental ice sheet, surface temperatures are far below the melting point even in the summer, and as a consequence there is no melting. Today's temperatures in the culmination zones of the Antarctic and Greenland ice sheets are normally about 20 degrees below zero or colder. Cold snow and firn accumulate, and the temperature of the upper part of the glacier stays close to the mean annual air temperature. Glacier temperatures normally increase with depth, partly due to geothermic heat flux, and partly because of frictional heat generated by the ice deformation.

Whether the basal temperature is at the pressure melting point or not depends mainly on the following factors: (1) the thickness of the glacier, since the temperature increases continuously downwards; (2) the rate of accumulation, which determines how fast the cold snow and ice is transported from the surface downwards; and (3) the rate of ice movement, which determines the quantity of frictional heat produced. For a more comprehensive discussion of basal ice temperatures, cf. for example Hooke (1977).

In a vertical profile through an ice sheet, the transition line between cold and temperate ice theoretically lies deepest in central parts of the ice sheet, and then increases in height towards the equilibrium line (Denton and Hughes, 1981). The primary reason for this gradient is that the rate of ice movement increases in the same direction.

Based upon the general, thermal characteristics of ice sheets mentioned above, we here propose a model to describe the general trends of the development of the thermal regime of an ice sheet (Fig. 10). We assume this model to be valid for an east-west profile through a mid-latitude ice sheet, like the southern part of the last Scandinavian ice sheet. We assume permafrost conditions in higher areas from the beginning of the glaciation, but no permafrost at lower levels.

During the development and growth of the ice sheet (phase a), the elevation of the equilibrium line must necessarily be rather low. The higher, central parts of the ice sheet have temperatures below the pressure melting point (Fig. 10a).

When the ice sheet is close to its maximum (phase b), the equilibrium line is probably even lower than during phase a. The transition line between cold and temperate ice is also lower (Fig. 10b). Contributing factors include the higher elevation of the glacier surface, which leads to colder firn accumulation and transportation of colder ice downwards in the glacier, as well as the long term establishment of a cold, continental climate.

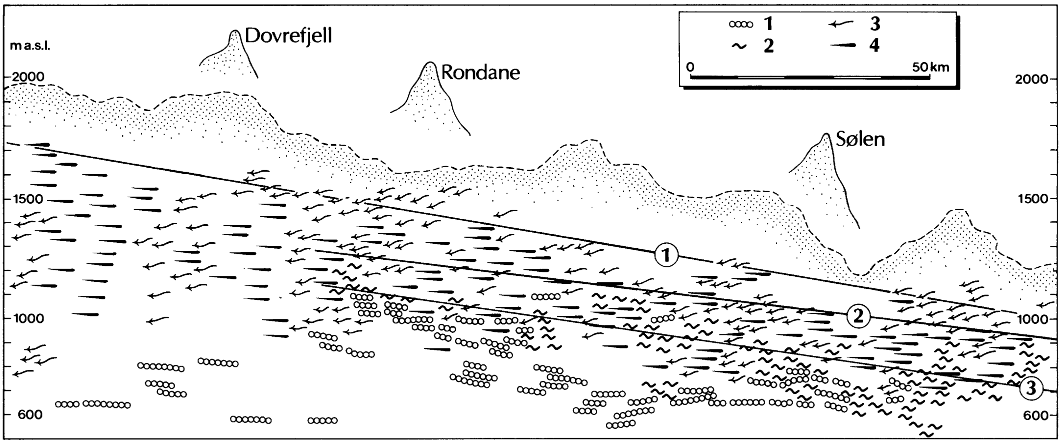

Fig. 9. Vertical distribution of glacial landforms in central part of southern Norway (corresponding the shaded area in Fig. 8). 1=eskers, 2=Rogen moraines, 3=lateral meltwater channels, 4=drumlinoid forms. Line 1 marks the upper limit of drumlinoid forms, line 2 marks the upper limit of Rogen moraines and line 3 marks the upper limit of most of the eskers.

During deglaciation (phase c), the position of the equilibrium line is much higher than during the two previous phases. The transition line between cold and temperate ice is, however, situated even lower in the glacier (Fig. 10c). Crucial to this development is the very low heat conductivity of ice. Since surficial temperature changes are transmitted very slowly downwards in the ice, the basal temperature of the glacier is influenced by climatic conditions tens of thousand years earlier. The climatic warming during the relatively short deglaciation period had no effect on the basal temperature in the thicker part of the ice sheet.

Discussion

The model of the development of the thermal regime of an ice sheet outlined above, can probably explain the vertical distribution of glacial landforms in the central parts of southern Norway (Fig. 9).

The uppermost drumlinoid forms indicate by their orientation that they were formed by ice movement independent of topography. Therefore they must have been formed by a thick ice sheet with surface elevations much higher than the upper limit of drumlins and flutes (Fig. 9, line 1). Such drumlinoid forms, made by an ice sheet that moved independently of topography, clearly were not formed during deglaciation. After their formation beneath a thick ice sheet, they must have been preserved despite later ice flow.

The presence of meltwater channels and erratic boulders confirms that the glacier at some time reached a higher altitude than the upper limit of drumlinoid forms. In these high terrain the glacier could have been cold-based from the very beginning of the last glaciation, and even during earlier glacial periods.

If the basal temperature of the ice sheet gradually became cold at lower levels, morainic landforms would have been fossilized. A transition like this is in accordance with the model of changing thermal regimes outlined above. This model can explain why drumlinoid forms and Rogen moraines are found in the same areas where meltwater landforms indicate cold ice during the final deglaciation. The morainic landforms are then much older than the meltwater landforms in the same area.

From Arctic Canada, Dyke (1993) describes landscape and landform assemblages related to cold-centret Late Wisconsinan ice caps. These landform assemblages are quite similiar to what we have found in southern Norway. The only exception is that Rogen moraines are missing. The reason for this difference could be that in high Arctic areas the glaciers were initially underlain by thick, continuous permafrost. As the permafrost dissipated in the peripheral zone, the thermal conditions changed from cold-based to warm-based (Dyke op. cit.), and not from warm-based to cold-based like in southern Norway.

From Prince of Wales Island, however, Dyke *et*

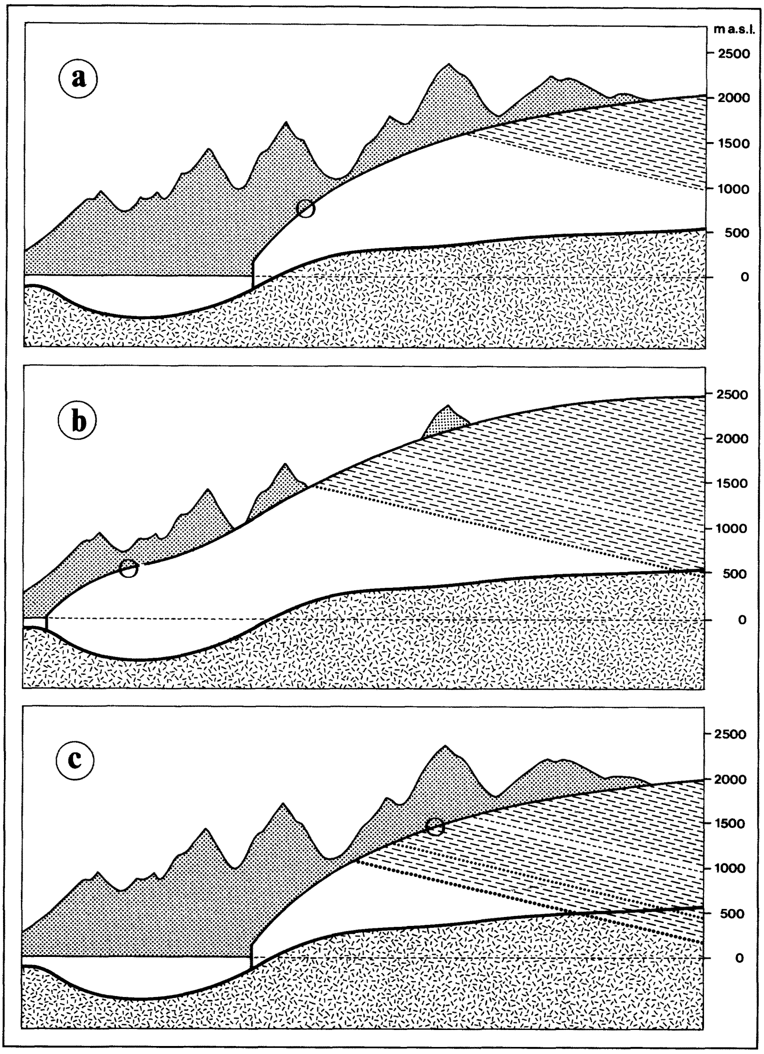

Fig. 10. The thermal condition of the continental ice sheet sketched during three phases, (a) an initial phase of glaciation, (b) the ice sheet close to its maximum phase and (c) in a late phase of the deglaciation. The shaded part of the ice sheet has subzero temperatures, while the lower part is at the pressure melting point. The position of the equilibrium line is marked with a circle.

al. (1992) assume that the basal thermal conditions changed from warm-based to cold-based during the last phase of the Wisconsian glaciation. Here, Rogen moraines (ribbed moraines) are located to the contact zone between warm-based and cold-based ice.

According to our model, Rogen moraines occur at lower elevations in the zone where the glacier gradually changed from warm-based to cold-based. Basal freezing began in drier patches on convex parts of the subglacial terrain. At the same time, water accumulated in terrain depressions at some lower elevation where the ice was still temperate.

In the convex parts of the terrain, drumlinoid forms were fossilized by the freezing glacier, while in depressions the glacier was still warm based due to the existence of water. Freezing of water-filled depressions probably took a very long time, perhaps thousands of years, depending on the quantity of water trapped in the depressions. This is due to the low conductivity of ice, which inhibits dispersion of latent heat released during the freezing of the water.

Rogen moraines are found in such depressions where water could accumulate and strongly inhibit freezing. Due to their location, we assume that Rogen moraines are formed in isolated patches of trapped water bodies or watersoaked debris in areas where the ice sheet was elsewhere frozen to the ground. This can explain both the regional and the local distribution of Rogen moraines. Regionally, the distribution corresponds to areas which experienced a transition from warm-based to cold-based ice, and locally the distribution corresponds to topography, which controlled the distribution of unfrozen patches. However, the actual mechanism which formed the Rogen moraines in such isolated temperate wet-based depressions is still not clear, and will here not be discussed further.

The distribution of lateral meltwater channels probably corresponds to areas with cold ice during the final period of deglaciation. In this case, the lower limit of lateral melt water channels corresponds to the transition between cold and temperate ice during deglaciation (Fig. 10). At lower levels large, continuous eskers are found, indicating warm-based ice during the deglaciation.

The temperature condition in the ice could also explain the large end moraines that are found in the eastern central areas (zone IIIb, Fig. 8). These moraines are broad zones of chaotic mound, ridge and depression filled terrain, indicating a genesis as ice-cored moraines formed initially under permafrost conditions. This disorderly terrain is caused by the melting of the ice cores. End moraines of this kind are typical in front of contemporary glaciers at Svalbard, which belongs to the zone of continuous permafrost. They are also well known as fossil forms in northern Norway, where ice-cored moraines and other kinds of permafrost landforms were formed during the deglaciation of the last ice sheet (Sollid and Sørbel, 1988, 1992, Kverndal and Sollid, 1993). Climatic conditions during the last deglaciation would most likely not have permitted an advancing, subpolar glacier to exist in areas close to the ice divide.

Conclusion

In the distal areas, the last ice sheet in southern Norway was largely warm-based, and the distribution of morainic and meltwater landforms is closely related to climatic fluctuations during deglaciation.

In higher mountain areas in the central parts of southern Norway, there has been no glacial erosion. This is due to cold-based conditions in the upper part of the ice sheet. Here, lateral meltwater channels and erratic boulders are the only landforms connected to the former ice sheet. In these high areas, the ground is mostly covered by block fields or other types of weathering features. Meltwater channels cutting through the block fields at many places clearly indicate that the weathering landforms are older than postglacial time (cf. Kleman and Borgström, 1990).

At a lower level in the central mountain areas, drumlinoid landforms are characteristic features. These forms were made by an ice sheet that moved more or less independent of the topography. The drumlinoid forms were formed by a thick glacier, probably in a relatively early phase of glaciation, and then fossilized beneath cold-based ice. The high frequency of lateral meltwater channels clearly indicates the existence of cold ice during the last phase of Weichsel. This means that a zone with cold-based ice expanded both downwards in the glacier and outwards from the culmination areas during the last part of the Weichselian glaciation.

The upper limit for the distribution of Rogen moraines lies somewhat lower than the upper limit of drumlinoid forms. Rogen moraines are located in terrain depressions where water could exist beneath an ice sheet that was elsewhere frozen to the ground. Rogen moraines are assumed to be made by ice movement in this kind of environment.

Large end moraines found in mountain areas close to the last ice culmination zone were formed in front of subpolar glaciers during an early phase of glaciation, and were later fossilized beneath cold-based ice.

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