Block fields in southern Norway: Significance for the Late Weichselian ice sheet

ATLE NESJE, SVEIN OLAF DAHL, EINAR ANDA & NORALF RYE

The geographical and altitudinal distribution of block fields and trimlines in southern Norway are discussed in relation to the vertical extent of the continental ice sheet during the Late Weichselian glacial maximum. Inferred from these considerations and formerly presented ice-sheet phases for the last glaciation in southern Norway, a new model on the Late Weichselian ice sheet is presented. This model indicates a low-gradient, poly-centred ice sheet during maximum glaciation with the ice divide zone located close to the present main watershed. During the deglaciation, the margin of the ice sheet retreated to the coast and fjord areas of western Norway. This induced a backward lowering of the ice-sheet surface, and the culmination zones in areas with low pass-points between eastern and western parts of southern Norway thus migrated E/SE of the present main watershed. During maximum glaciation the areas of greatest relative ice thickness were located to the central lowland areas of eastern Norway, to the Trøndelag region, and along the deeper fjords of western Norway.


The discussion of possible ice-free areas was initiated by the discoveries of endemic plant and animal species in NW Scandinavia, which induced many botanists to postulate the existence of ice-free areas throughout the Weichselian glaciation(s). In order to prove the existence of refugia, additional geological evidence was used: Areas characterized by glacial cirques surrounded by pinnacle-like mountain peaks were regarded as former nunataks. It was suggested that if an ice sheet had overridden these landforms, this cirque topography would have been smoothed out by the ice sheet(s).

In addition, autochthonous block fields ('Felsenmeere') and deep weathering of rocks, both supposed to require a long time for formation, have been considered as other evidence of non-glaciation. The absence of erratics, glacial striae and other positive evidence of ice moulding in the highest block-field areas supported the idea of unglaciated areas. However, observations of glacial striae and erratics in some 'refuge areas' were said to disprove the hypothesis in those areas. In this paper, data on the geographical and altitudinal distribution of block fields and trimlines in southern Norway are collected and discussed in a glacial geological/historical context.

The distribution of autochthonous block fields in southern Norway

General description

The definition of block fields used here is that of Fairbridge (1968:351) termed 'felsenmeere'. Block fields normally consist of in situ angular boulders and stones. They can be from a few
to several metres thick and are formed through mechanical and chemical weathering of the local bedrock (autochthonous block fields). However, intermediate layers in the block fields, characterized by organic and minerogenic fines may occur. Basal layers lying on bedrock may consist either of blocks with an in-filling of silt and sand, or silt and/or sand without blocks. The fine interstitial material in the block fields may consist of quartz, smectite and hydromicas. Occasionally occurrences of kaolinite, siderite, aluminium and ferroxide/hydroxide are also found. The latter minerals are interpreted to be the result of a preglacial weathering (e.g. Roaldset et al. 1982). A thin and in periods dynamically active ice- or snow cover (nivation), subsequent frost sorting and slow downslope movement of the weathered material may form para-autochthonous or allochthonous block fields.

**Geographical distribution**

From numerous descriptions of block fields in southern Norway (Table 1) and other available data (pictures, air photographs, oral and written communication), Nesje et al. (1987) presented a map (Fig. 1) showing the most extensive block-field areas and regions dominated by alpine morphology in southern Norway. The geographical distribution of block fields is independent of the main bedrock regions in southern Norway (Figs. 1 & 2), and the most extensive areas of autochthonous block fields and alpine morphology are located to the Jotunheimen, Rondane, Dovre, upper Hemsedal/Hallingdal, and to the inner Nordfjord–Møre regions. Along the Swedish border the block-field areas are distributed widely, while summits south of Hallingskarvet, with a few exceptions, are not covered by block fields.

**Altitudinal distribution**

The lower limits of block fields in southern Norway display a geographically consistent pattern. Their lower boundaries gradually slope from the central mountain range of southern Norway (Jotunheimen c. 2000 m a.s.l.) toward the coastal areas of Nordfjord–Møre (500–600 m a.s.l.). Toward the Swedish border in the east, the lower limits of block fields are located c. 1000 m a.s.l. As the autochthonous block fields are situated above certain altitudinal levels, a weathering boundary can be defined. Slope-related processes have in places transported block-field material below the actual weathering limit. Where it is difficult to determine the weathering boundary directly, we have found it most convenient to map this limit by means of the 'summit method' (cf. Nesje et al. 1987). Fig. 3

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**Table 1. References used to map the block-field areas in different parts of southern Norway.**

<table>
<thead>
<tr>
<th>Area</th>
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<td>Grønlie (1950, 1953)</td>
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<td>P. Holmsen (1951)</td>
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<td>H. Holtedahl (1955)</td>
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<tr>
<td></td>
<td>Solild &amp; Sørbel (1979)</td>
</tr>
<tr>
<td></td>
<td>Mangerud et al. (1979, 1981)</td>
</tr>
<tr>
<td></td>
<td>Solild, Carlson &amp; Torp (1980)</td>
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<td></td>
<td>Sulebak (1982)</td>
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<td></td>
<td>Solild &amp; Reite (1983)</td>
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<td>Follestad &amp; Henningsen (1983)</td>
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<td></td>
<td>Follestad (1986)</td>
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<td>Rye et al. (1987)</td>
</tr>
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<td>Nesje et al. (1987)</td>
</tr>
<tr>
<td>Hordaland</td>
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<tr>
<td>Buskerud</td>
<td>Kristiansen &amp; Solild (1985)</td>
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**Fig. 1.** Map showing the most extensive block-field areas (black spots) in southern Norway (slightly modified from Nesje et al. 1987). The location of the profile in Figs. 4 and 14 is indicated.
Fig. 2. The main bedrock regions in southern Norway.

- Late Precambrian rocks, mainly sandstone and conglomerate
- Precambrian gneiss and gabbro in Caledonian nappes
- Precambrian rocks, mainly gneisses and granites
- Permian rocks, mainly lavas
- Devonian sandstone and conglomerate
- Cambro-silurian rocks, mainly phyllite and mica schist
shows the main criteria for determining the upper ice limit in southern Norway.

By plotting summits with and without block fields along a longitudinal profile from the Møre coast across the water divide at Lesja, and extended to the central area of eastern Norway, the lower summits covered by block fields show a geographically consistent vertical distribution (Figs. 1 & 4). Similarly, a north–south profile along the central mountain range of southern Norway (Fig. 5) shows an undulating lower boundary of block fields, with the highest elevation of the weathering limit in the Jotunheimen mountains (c. 2000 m a.s.l.). Deviations from the altitude of the weathering boundary may be recorded if moving too far aside from the profile.

Possible relationships between autochthonous block fields and the Late Pleistocene glaciations

Several mechanisms for the formation of autochthonous block fields with consequences for the age relationships have been proposed:
The block fields have no relationship to the Weichselian glaciation(s), and have been developed during postglacial time in a high-altitude climatic zone.

A possible connection between a high-altitude periglacial climate and the weathering boundaries in Scandinavia has been suggested (e.g. Rudberg 1977). However, the sharp and regionally consistent weathering boundary suggests that this postulate is unlikely. If postglacial high-altitude periglacial weathering had explained the occurrence and distribution of the block fields, a close relationship between modern temperature conditions and the weathering limit should have been expected. The altitude of the present (1931–1960) annual 0°C isotherm descends gradually southeastward from the coastal areas of Møre, across the central mountain range of southern Norway (Fig. 4). The serrate pattern of the 0°C isotherm is due to local climatic effects at the meteorological stations along the profile (e.g. different exposure and altitude above valley bottom). The altitudinal zonation of the present 0°C isotherm, which shows no correlation with the altitude of the weathering boundary, is in agreement with the altitudinal distribution of permafrost in southern Norway. King (1986) found that the lower limit of discontinuous permafrost rises from about 1000 m a.s.l. in the Rondane mountains to c. 1200 m a.s.l. in Jotunheimen, with the highest elevation approximately 1600 m a.s.l. at the coast of western Norway.

Similarly, annual mean temperature (1931–1960) fluctuations at meteorological stations along the profile from the Møre coast extended across the central mountain range of southern Norway, do not show any significant relationship with the altitudinal distribution of the block fields along the profile (Fig. 6).

Frost-shattering is considered the most important mechanical weathering process in periglacial climates (e.g. Washburn 1973, 1979). The number of freeze/thaw cycles and the amplitude of the temperature variations are important factors controlling the effectiveness of various kinds of frost action.

In order to test the present intensity of frost-shattering in periglacial climates and thereby the...
### Block fields in southern Norway

<table>
<thead>
<tr>
<th>No.</th>
<th>Met. station</th>
<th>m a.s.l.</th>
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<td>Skodje</td>
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**LEGEND**
- Mean annual temperature 1931–1960
- Minimum
- Maximum
possibility that the block fields may have been formed during the Late Weichselian deglaciation and the Holocene, laboratory experiments have been carried out by several investigators to quantify frost-shattering as a function of climatic conditions, bedrock and time (for references, see Lautridou & Sepplilli 1986). The intensity of frost-shattering and the amount of debris produced from quartzite, granulite and Rapakivi granite samples from northern Finland were studied with laboratory experiments run for 1103 temperature cycles from +1.5 to −8°C (Lautridou & Seppälä, op. cit.). Their laboratory experiments demonstrate that Precambrian rocks are very resistant to weathering under existing climatic conditions. From southern Norway, this is also supported by glacial striations on rock surfaces in high-altitude climatic zones above the reconstructed Younger Dryas glacier surface, which are well preserved and have been exposed without significant alteration for more than 10,000 years. This is also demonstrated by the extensive block fields on top of Reineskarvet 1730 m a.s.l. (Fig. 7), which strongly contrast the well-preserved glacial striations on bedrock exposures 1740 m a.s.l. west of Hallingskarvet (Fig. 8).
Consequently, an actively occurring block-field formation related to the present climatic conditions would probably have created more uniform altitudinal weathering levels all over southern Norway. In addition, the lowest-lying weathering zonation would probably have been located to the central and eastern mountains of southern Norway, and not along the coast of Møre. (For further discussion concerning the relationship between block fields and climate in southern Norway, see E. Dahl 1955, 1961; Nesje et al. 1987).

(2) The block fields are younger than the Late Weichselian glacial maximum, and are developed on nunataks that were deglaciated during the early Late Weichselian

P. Holmsen (1951) and H. Holteidal (1955) argued for a post-Late Weichselian age for the weathering products at Gjevilvasskammene in Trollheimen (Fig. 1). However, N. A. Sørensen (1949), Grønlie (1950, 1953) and E. Dahl (1961) suggested that these weathering products were formed prior to the Late Weichselian.

(3) The block fields are older than the Late Weichselian glaciation, but have been covered by a cold-based, non-erosive ice sheet

The sharp and regionally consistent altitudinal pattern of summits with and without block fields in southern Norway suggests that the summits were not totally covered by a huge and dynamically inactive frozen ice sheet. If the ice sheet had been frozen in the upper part, the regional weathering boundary would probably not have been so regular over the mountain regions. Gently undulating mountain plateaus covered by block fields may, however, have been covered by dynamically inactive local snow fields or minor ice caps. These can have been either too thin, or periodically/permanently frozen to the substratum, and therefore not able to erode the block fields already formed. In parts of central and eastern Norway, however, the existence of erratics above transitional weathering boundaries indicates that these areas have been covered by one or more temporarily/permanently cold based ice sheet(s). Thus the upper boundary of erratics gives the minimum altitudinal extent of the ice sheets, and not necessarily the upper Late Weichselian ice limit. It is, however, suggested that these summit areas were covered by relatively thin ice sheets only.

Sollid & Sørbel (1979) and Sollid & Reite (1983) argued that the block fields in Møre were formed prior to the Late Weichselian and that the lower limit of block fields could be used to delineate the upper limit of the Late Weichselian ice sheet.

From studies in the Møre-Nordfjord region, E. Dahl (1961), Sollid & Sørbel (1979), Sollid & Reite (1983), Rye et al. (1987), and Nesje et al. (1987) concluded that the regional weathering boundary is erosive and represents the upper limit of one or more ice sheets.

Inferred from the large altitudinal difference between the weathering boundary and the Younger Dryas lateral moraines in inner Nordfjord, Rye et al. (1987) and Nesje et al. (1987) concluded that the upper limit of the maximum Late Weichselian ice sheet, or a pre-Late Weichselian glaciation, was responsible for the formation of the weathering boundary.

Nesje et al. (1987) suggested on the basis of the present knowledge of glacial extent during the Weichselian glaciations in southern Norway (Bergersen & Garnes 1971, 1981, 1983; Miller & Mangerud 1980; Mangerud 1981, 1983; Miller et al. 1983; Sejrup 1987) that summits covered by autochthonous block fields had probably not been overridden by an ice sheet since the Saalian glaciation (before c. 130 ka).

(4) The block fields are older than the Pleistocene glaciations, and have never been overridden by continental ice sheets.

The areas of most extensive and deeply weathered block fields in southern Norway are located to the paleic, pre-Quaternary land surface of Norway, as described by Reusch (1901) and Gjessing (1967). Together with the clay mineral content, this indicates that parts of the block fields may have been formed by chemical weathering and that they have been under formation since at least Tertiary time, as also previously suggested by E. Dahl (1961, 1987).

In its widest consequence, some of the highest and most extensive block fields may never have been eroded/covered by the Pleistocene ice sheets.

Relatively fresh glacial striations of possibly Late Weichselian age are frequently recognized just below the weathering boundary, suggesting
that the Late Weichselian ice sheet may have reached an altitude at, or just below the possible maximum Pleistocene ice limit. Therefore, the weathering boundary in different parts of southern Norway may not have been formed contemporaneously, or by the same ice sheets since a similar state of dynamic stability may have been achieved during previous maximum glaciations. East of the main water divide, horizontal glacier expansion was probably the main mechanism of equalization and adaption of some significance for the ice excess. The excess or deficiency of glacier mass may therefore be recorded as differences in the ice-front position along the southern and eastern margins of the Scandinavian ice sheets. Off western Norway, however, the margins of the ice sheets never reached outside the edge of the continental shelf due to calving processes (Flint 1971; Weertman 1973; Schytt 1974). This may have induced more or less the same altitudinal distribution of the ice sheets along the fjords in western Norway during periods when the margin of the ice sheets reached the edge of the continental shelf.

Other evidences for the existence of nunataks during the Late Weichselian glacial maximum

**Botanical evidence**

In Scandinavia, several plant species are located to isolated high-altitude mountain regions. Outside Scandinavia, many of these plants are located to distant regions like the Alps, Kaukasus, Ural, Greenland and North America. To solve this plant geographical problem, botanists at the end of the nineteenth century introduced the ‘refuge theory’ (Blytt 1876a, 1876b, 1882; Sernander 1896). Instead of having immigrated after the Late Weichselian glacial maximum, several of these plant species were thought to have survived at localities (‘refuges’) not covered by the continental ice sheet along the western coast of Norway. The present dispersal was therefore explained by a preglacial distribution across the northern Hemisphere.

The refuge plants in Scandinavia are located within two main regions; North of the polar circle and in the southern Norway areas: Jotunheimen, Dovre, Trollheimen, and the northern part of Jotunheimen. Plant species located within both main regions are called bicentric, while species growing in only one of them are called northern/southern unicentric. In southern Norway they are restricted to the central mountain areas and the southern unicentric plants were therefore thought to have immigrated from coast-/foreland refuges along the western coast after the Weichselian glaciation. The geographical distribution of block fields (Fig. 1), however, indicate ice-free areas in the central mountain regions of southern Norway where the refuge plants are located. An immigration of refuge plants from the coastal to the central mountain areas to explain the very restricted distribution of the southern unicentric species, is therefore not necessary.

Except the refuge plants found elsewhere in the world, some unique Scandinavian species exist. Knaben (1959a, 1959b) distinguished six endemic poppy species (Papaver sp.) in southern Norway. The different species and subspecies were thought to have developed their own characteristics in different isolated populations (Fig. 9).

Nordhagen (1936) suggested that the mountain poppies are old species in the Norwegian flora because of the long time needed for separating reproductive species. Nordal (1985a, 1985b, 1987) discussed evolution rates of endemic species, and...
suggested that the potential evolution rates may have been underestimated. In addition, she did not find the prevailing arguments for rejecting the alternative 'tabula rasa' theory, involving total postglacial immigration, biological convincing.

Since it was first presented, the refuge theory has been strongly debated between biologists and geologists, the majority of the latter group being sceptical (e.g. Mangerud 1973). However, the strong overlap between the endemic species and the distribution of autochthonous block fields does not need to imply immigration, neither from coastal foreland refuges nor from areas outside the marginal ice limit to the central mountain regions. This strongly supports the 'refuge theory' as presented by botanists at the end of the nineteenth century, despite recent objections.

**Geomorphological evidence**

The geographical distribution of cirques and alpine morphology in southern Norway (Fig. 10) shows a strong concurrence with the mountain regions covered by block fields. Alpine morphology in southern Norway is mainly located to western Jotunheimen and Møre–Romsdal (Gjessing 1978). In the eastern part of southern Norway (eastern Hallingskarvet, Hemsedalsfjel­lene, eastern Jotunheimen, Dovre, Rondane), however, the cirques are commonly not so closely spaced and the undulating and rounded pre-Quaternary land surface is in general better preserved. In areas with well-developed cirques, the surrounding mountain peaks are commonly covered by block fields and/or are dominated by pinnacle topography in a highly dissected landscape. The most extensive cirques are therefore suggested to have been formed where cirque glaciers were able to erode throughout the ice ages, and not only at the beginning and end of each glacial cycle. In areas totally overridden by the Pleistocene ice sheets, however, extensive cirques are in contrast either lacking or poorly developed.

Based on the previous considerations, we postulate that autochthonous block fields without erratics or other positive evidence of ice moulding on summit areas in southern Norway represent ice-free areas during at least the Late Weichselian glacial maximum. Inferred from the geographical and altitudinal distribution of autochthonous block fields, we have constructed a model for the continental ice sheet covering southern Norway during its maximum extent. The model is also discussed against data concerning the lateral distribution of the ice sheet on the continental shelf off western Norway.

The reconstructed ice-sheet model describes a relatively thin ice sheet controlled by the regional topographical features within southern Norway (Fig. 11).

During the maximum glaciation, the ice surface at the main ice divide zone, which was located approximately along the main water divide, formed several ice domes and saddles. The most prominent centre of ice dispersal existed in the Jotunheimen mountains, where the ice sheet reached its maximum altitude of about 2000 m a.s.l. (relative to present sea level). The ice dome over SW Hardangervidda is reconstructed.
Fig. 11. Main flow lines and tentatively reconstructed contour lines (relative to present sea level) of the ice sheet during Late Weichselian glacial maximum in southern Norway. The reconstruction is based on weathering boundaries (suggested nunataks are indicated by black spots), glacial striation and reconstructed ice-sheet profiles. Local deviations from the contour lines may, however, be recorded. The main flow lines of the supposed Late Weichselian maximum ice sheet in southern Norway are compiled from: G. Holmsen (1915); Gjessing (1960); O. Holtedahl & Andersen (1960); P. Holmsen (1964); Vorren (1973, 1977); Bergstrøm (1975); Vorren & Roaldset (1977); Garnes (1978, 1979); Carlson & Torp (1980); Andersen et al. (1981); Hamborg & Mangerud
indirectly from the eastward sloping weathering boundary along Hallingskarvet and from NE/ENE ice movements on the eastern part of Hardangervidda (Rye & Follestad 1972; Vorren 1977).

The presented model suggests that the ice surface was considerably lowered along the deeper fjords of western Norway. This is well documented from autochthonous block fields at the southern part of Hardangerfjorden, and in the inner part of Sognefjorden. These observations are also consistent with the strongly convergent ice movements toward the inner part of Sognefjorden during the supposed Late Weichselian glacial maximum (Vorren 1973, 1977; Aa 1982). Effective ice drainage along the deeper main fjords is suggested to have prevented vertical build-up of greater ice thickness in the surrounding mountain areas, as also concluded by Nesje et al. (1987) from studies in the Nordfjord–Møre region.

At Sørlandet (Fig. 1), divergent ice movements parallel to the main valleys dominated. In the central lowland areas of eastern Norway, however, an extremely flat ice sheet (approximately 3–5 m/km), with convergent ice movements toward the outer Oslofjord–Skagerrak area, are in agreement with the reconstructed ice movements (e.g. O. Holtedahl & Andersen 1960; Sørensen 1983).

During the Late Weichselian glacial maximum, the margin of the Fennoscandinian ice sheet was previously supposed to have been situated along the edge of the continental shelf seaward off western Norway and Britain (Boulton et al. 1977, 1985; Andersen 1979, 1981). This in contrast to the proposal of Jansen (1976), who suggested ice-free areas in the southern North Sea, while areas north of 60°N were ice covered.

Boulton et al. (1985) presented two alternative models for the ice extent. In their minimum model of the Scandinavian and the British ice sheets they took into consideration basal shear stress conditions according to the substratum. Their resulting model implies two separate ice sheets which did not coalesce in the central North Sea. In Jutland, Denmark, the northern part of the Main Stationary Line has an east–west direction and strikes toward the Lille Fiskebank Moraine (see Fig. 13). A correlation of the two moraines therefore seems likely. Furthermore, the maximum Late Weichselian ice limit along the shelf break outside Møre (Andersen 1979, 1981) has been generally accepted. Data from Scotland (summarized by Sutherland 1984) and the central North Sea (Sejrup et al. 1987) suggest that the Scandinavian and the Scottish ice sheets did not coalesce in the central North Sea, indicating areas of dry land and an open embayment in this area.

These latter ideas of a smaller extent of the Late Weichselian ice sheet in the North Sea, compared to previous reconstructions, fit well with our model for the ice sheet over the mainland areas, and make it possible to tentatively reconstruct the Scandinavian ice sheet over southern Norway and in the North Sea (Fig. 12).

Fig. 13 shows a tentative profile for the glacier surface from central south Norway across Skagerrak toward the Main Stationary Line in Jylland, Denmark. The profile follows the reconstructed flow lines from striations. In the Skagerrak area, however, the flow lines of the ice sheet are not evident. A relatively thin ice sheet above the overdeepened, glacially shaped Norwegian Trench in the Skagerrak, with water depths exceeding 700 m (e.g. Thiede 1987), may suggest that the ice movements at least in the basal parts of the ice sheet were deflected more or less parallel with the Norwegian Trench. For this reason, the ice-sheet profile may have deviated from the supposed flow lines in the Skagerrak, as indicated in Fig. 13.

Important causes for the shape of the ice-sheet surfaces may have been:

1) The growth of the Late Weichselian Scandinavian ice sheet caused an increasing dominance of high atmospheric pressure zones above the central parts of the ice sheet. At the same time, a more or less seasonally permanent sea-ice cover was probably established in the Norwegian Sea. As a result, the eastbound Atlantic cyclone tracks moved southward during expansion of the ice sheet (Liljequist 1974; Gates 1976). Thus deficiency of precipitation in the central and northeastern regions of southern Norway probably prevented the ice sheet from achieving a 'steady state' ice-sheet profile. (See also the recently developed model for the Late Weichselian ice sheet in southern Sweden (Lagerlund 1987)).

(2) Due to the short time span (c. 10,000 years) between the Ålesund Interstadial (Mangerud et al. 1981; Larsen et al. 1987) and the Late Weichselian glacial maximum, the build-up of the ice sheet may have stagnated before its potential vertical extent was attained.

(3) Effective ice drainage along the deeper valleys and fjords of western Norway prevented vertical build-up of the ice sheet.

(4) Fast and low-friction glacier movement due to low basal shear stress in areas covered by sediments, and especially across deformable sediments on the shelf.

Consequences for the ice movement phases in southern Norway inferred from the ice-sheet model

The presented model has important consequences for the age of the meltwater- and ice drainage phases in southern Norway during the Late Weichselian deglaciation.

So far, the prevailing model describes a main ice drainage phase prior to the Late Weichselian maximum with ice movements controlled by an ice divide approximately along the main water divide of southern Norway (Phase II of Vorren 1977; phase B of Garnes & Bergersen 1980).

As the ice sheet expanded to its maximum extent, the ice divide migrated E/SE, accompanied by W/NW ice movements toward...
Fig. 13. Tentatively reconstructed ice-sheet profile for the Late Weichselian glacial maximum from Hallingskarvet via Oslofjord and extended to the Main Stationary Line in Jylland, Denmark. The Younger Dryas glacier profile is also indicated (from S. O. Dahl 1987). If the main ice flow from the Oslofjord area was conducted by the Norwegian Trench along the coast of Sørlandet, the Lille Fiskebank Moraine (Andersen 1979) should be regarded as a lateral moraine to this ice flow. The location of the profile from the central North Sea to Hardangervidda in Fig. 15 is indicated.
the main water divide (Phase III of Vorren 1977; phase C of Garnes & Bergersen 1980).

However, according to the presented model, west/northwestern ice movements could not have been possible E/SE of the watershed before the glacier surface at the present watershed had been lowered relative to the areas in E/SE (Fig. 14). As a result, phase II/B and not phase III/C may represent the period of maximum glaciation. Phase B, with great glaciogeological influence, is also called the 'Main Phase' in the Gudbrandsdalen region (e.g. Garnes & Bergersen 1980).

The model presented in this paper therefore suggests that phase III of Vorren (1977) is from a period of marginal retreat from the edge of the continental shelf to the fjords and inner valley areas of Møre, during which the ice divide was lowered rapidly. This late glacial retreat may have led to a backward lowering of the ice-sheet surface, causing a migration of the culmination zone(s) c. 100 km toward S/SE over the northern Gudbrandsdalen region. The ice marginal retreat may have been caused by a slight initial withdrawal from the grounding line at the edge of the continental shelf. This may have resulted in a break-up accompanied by a rapid terminal retreat to the next anchor points at shoals, headlands or constrictions along the coast of western Norway (Fig. 14). The same process also prevailed along the southern margin of the ice sheet (Thiede 1987), but had in this area less influence on the ice thickness in the central mountain regions of southern Norway. This was mainly due to the longer distance between the accumulation zone and the calving area in Skagerrak and Oslofjord (e.g. Högboom 1885).

During phase D of Garnes & Bergersen (1980) and Bergersen & Garnes (1983), a culmination zone was located across Vinstra in Gudbrandsdalen (Fig. 1). During this phase, the ice divide zone sloped toward NE, most probably caused by a more rapid lowering of the ice surface in the eastern than in the western parts. In addition, however, glacier supply from eastern Jotunheimen during this phase may have contributed to this gently sloping glacier surface toward NE. This is demonstrated by the ice and meltwater flow patterns, which show drainage nearly radially from a culmination zone in the SW (Jotunheimen), contemporaneously with ice drainage from a culmination area in NW (Skjåk).

In the NE parts of southern Norway the surface of the continental ice sheet sloped toward NW, as shown by the sequence of deglaciation in northern Østerdalen and in Rondane (G. Holmsen 1915; Mannerfelt 1940; Strøm 1956; Gjessing 1960). When the ice surface had lowered to 1100 m a.s.l. at Dovrefjell and Drivdalen, a great amount of ice and water drained toward Dovrefjell and Drivdalen (Fig. 1) (P. Holmsen 1964; Sollid 1964). This shows that the main culmination zone
of the continental ice sheet had migrated south of the present water divide at that period (see Fig. 14).

According to the presented model, the continental ice sheet during the Late Weichselian glacial maximum sloped with average gradients of c. 9 m/km toward W/NW in the Møre area and approximately 3 m/km from the culmination zone at Tafjordfjella–Lesja–Dovre toward the SE (Fig. 14). The highest-lying lateral drainage systems in the upper Gudbrandsdalen region (the Nunatak phase of Garnes & Bergersen 1980) are parallel to the reconstructed surface of the ice sheet during the Late Weichselian glacial maximum and are mapped to approximately two hundred metres below the regional weathering boundary. As a result, the NW meltwater drainage could have started when the margin of the ice sheet had retreated to the fjord areas of Møre. Consequently, the highest-lying meltwater channels may have been formed during the initial deglaciation in the later part of the Late Weichselian, and not in the Preboreal Chronozone, as previously proposed by Garnes & Bergersen (1980). In the high-altitude areas of the Gudbrandsdalen region, lateral meltwater channels close to the pass-points show that the gradients of the inland ice sheet during the early or middle phase(s) of the deglaciation were lower than 0.5% proximally, and even less distally. This flat surface of the inland ice sheet strongly supports a low-gradient ice-sheet surface during the Late Weichselian glacial maximum too.

On the Hardangervidda plateau, an eastward migration of the ice divide zone of c. 50 km recorded between phases II and III (Fig. 15), was explained by Vorren (1977) as a result of a possible glacial surge along Hardangerfjorden. However, according to the presented ice-sheet model, the shift of the culmination zone can be explained by an ice-marginal retreat from the maximum position in the central North Sea to the coast- and fjord areas of western Norway (Fig. 15). The marginal retreat of the ice sheet accelerated 14 000–13 000 B.P. (Mangerud et al. 1979; Jansen & Bjørklund 1985), while the coast of western Norway was deglaciated during the Bølling Chronozone (Mangerud 1977). The climatic deterioration during the Younger Dryas led to a build-up of an accumulation zone along the main watershed, causing a migration of the ice divide to the west (e.g. Vorren 1977), and an extensive glacier readvance took place along the western part of southern Norway (Mangerud et al. 1979).

Summary and conclusions
(1) Autochthonous block fields in southern Norway are located to the Jotunheimen–Dovre–Rondane–upper Hemsedal/Hallingdal areas, and to the inner Nordfjord–Møre regions. The lower
boundaries of block fields and trimlines show a regionally and altitudinally consistent pattern, and describe an erosive weathering boundary indicative of the upper limit of one or more ice sheets. The autochthonous block fields were probably not overridden by at least the Late Weichselian ice sheet. It is, however, possible that some allochthonous and para-autochthonous block-field areas above the regional weathering boundary were covered by local snow fields or minor ice caps. These may have been either too thin to erode the block fields already formed, or have been periodically/permanently frozen to the substratum, and therefore not able to erode the already existing block fields completely. However, this can explain the existence of locally derived blocks within para-autochthonous block fields, which are transported either by local plateau/cirque glaciers or by nivation processes.

(2) The presented ice-sheet model suggests a low-gradient, poly-centred ice sheet with the main ice divide zone located close to the main watershed, and with local domes above plateau areas between valleys and fjords. The highest ice-sheet surface was located to central Jotunheimen and along the central mountain range. However, the regions of maximum relative ice thickness were located to the central lowland area of eastern Norway, to the Trøndelag region, and along the deeper fjords of western Norway. Undoubtedly, this must have had a significant effect on the pattern of glacio-isostatic depression in southern Norway.

(3) The model explains the distribution of alpine landscapes and cirque topography in southern Norway.

(4) The geographical location of refuge plants shows a remarkable overlap with the distribution of the supposed ice-free areas covered by autochthonous block fields. Therefore, the distribution of these species does not need to imply an immigration to the central mountain regions of these plants neither from coastal foreland refuges nor from areas outside the marginal ice limit. This strongly favours the ‘refuge theory’ as presented by botanists at the end of the nineteenth century.

(5) As a result of a backward lowering of the ice sheet during the ice marginal retreat to the coast and fjord areas of western Norway, the main culmination zones migrated toward SE and E in the Gudbrandsdalen and Hardangervidda regions, respectively. This induced glacier and meltwater transport toward the main watershed. In a four-phase model for southern Norway, the ice drainage phases II/B and III/C of Vorren (1977) and Garnes & Bergersen (1980) are most probably from the Late Weichselian glacial maximum, and from the early deglaciation period, respectively.

By considering the areas which are included in the model, regions with E and SE migrating ice divides are undoubtedly closely related to low pass-points between eastern and western parts of southern Norway.

The result of the presented model for the deglaciation postdating the Late Weichselian glacial maximum is in agreement with slightly modified ideas as presented by Hansen as early as 1886 and 1890. Since the presented model only gives a regional overview, there might be local deviations from the proposal. More detailed field work is therefore required to date the weathering boundary more accurately, and to verify the model in different parts of southern Norway.

Acknowledgements. – We thank all those who provided information through oral and written communication about the areal distribution of block fields in southern Norway. E. Irgens and J. Ellingsen are acknowledged for drawing the Figures.

Manuscript received December 1987

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NORSK GEOLOGISK TIDSSKRIFT 68 (1988)


