The vertical extent of the Late Weichselian ice sheet in the Nordfjord–Møre area, western Norway

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Block fields and weathering limits in the mountains around inner Nordfjord, and glacial striae, erratics, block fields and alpine mountain morphology in the outer Nordfjord–Møre area, give information about the altitude of the surface of the continental ice sheet during the Late Weichselian glaciation. The ice sheet in the accumulation zone on the northern Jostedal Plateau was relatively thin during the peak of the Late Weichselian glaciation, due mainly to effective ice-drainage through the deep fjords and valleys. A longitudinal profile for the surface of the ice sheet from the northern Jostedal Plateau through Møre to the edge of the continental shelf has been reconstructed for the Late Weichselian glacial maximum.

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Because of its peripheral position with respect to the Weichselian glaciations, the Nordfjord–Møre area (Fig. 1) is an important region for glacial-morphological studies to determine the altitude of the surface of the ice sheet during periods of maximum glaciation and early deglaciation.

The highest mountain areas around inner Nordfjord and in the Møre area are covered by in situ block fields, and some mountains have alpine morphology (Figs. 2 and 3). These areas show no evidence of overriding by an ice sheet. Autochthonous block fields have been one of the main arguments for the existence of ice-free areas and refuges in Norway during the last glaciation (see summary in Mangerud 1973 and Rudberg 1977).

A considerable discussion has continued for decades as to whether western Norway was completely ice-covered or if ice-free areas existed during the Late Weichselian maximum, 18,000 to 20,000 B.P. (Helzen 1948; E. Dahl 1949, 1955; 1961; R. Dahl 1972; Holtedahl 1955; Mangerud 1973; Mangerud et al. 1979, 1981; Sollid & Sørbel 1979; Sollid & Reite 1983).

In this paper we re-examine and summarize the data concerning the elevation of the surface of the Scandinavian ice sheet in the Nordfjord–Møre area during the Late Weichselian.

Topography and bedrock

The landscape in the Nordfjord–Møre area (Fig. 4) is extremely varied, with striking differences between inland and coastal areas. Around Nordfjord a high plateau is incised by deep valleys. The relatively flat and gently undulating mountain tops are commonly bordered by steep cliffs. The highest mountain plateaus around Nordfjord descend from about 1800 m a.s.l. at the Jostedal Plateau to 400–500 m a.s.l. near the coast.

In the coast and fjord areas of Møre, numerous cirques and jagged peaks are located in the mountains between the fjords. Deep fjords extend far inland. The bedrock is dominated by gneisses with some massive granite, amphibolite, quartzite, schist, eclogite and dunite (Hernes 1965; Bryhni 1966; Brueckner 1979; Oftedahl 1980).

Block fields and weathering limits around inner Nordfjord

Definition of block fields

The definition of block field, adhered to in this paper, is that of Fairbridge (1968, p. 351), and

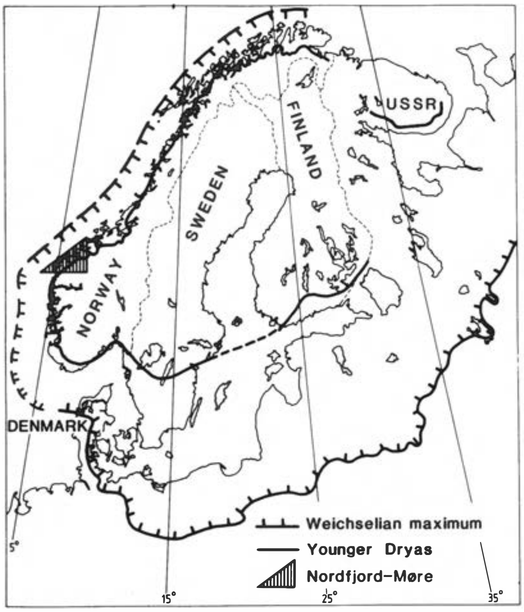

Fig. 1. The extent of the Scandinavian continental ice sheet during two different Weichselian phases. Slightly modified from Andersen (1981) and Sejrup et al. (in press).

used by Svenonius (1909), E. Dahl (1949), Embleton & King (1971), Flint (1971), Strømquist (1973), Washburn (1973). A block field consists of in situ angular blocks and stones formed through weathering of the local bedrock (autochthonous block fields). Subsequent frost sorting and slow downslope movement of the material may form allochthonous block fields.

In the discussion of possible ice-free areas during the Late Weichselian glaciation, the occurences of autochthonous block fields and alpine morphology have been one of the main arguments for the existence of ice-free areas. The sharp lower boundaries (trimlines) of these features indicate an upper limit of an ice sheet that eroded pre-existing block fields.

Many authors, however, (e.g., Høgbom 1909, 1914, 1926; Ives 1957, 1958; Lundquist 1958, 1962; Rapp & Rudberg 1960; E. Dahl 1961; Løken 1962; Markgren 1962; R. Dahl 1963, 1966; Svensson 1967; Caine 1968; Rudberg 1970, 1977; White 1976) have included frost-sorted, block-rich ground moraine in the term 'block field'. This extended definition is not used in this paper.

Fig. 2. Block field with in situ weathered quartz dike at Melheimnibba 1665 m a.s.l. See Fig. 6 for location. Photograph: S. O. Dahl.

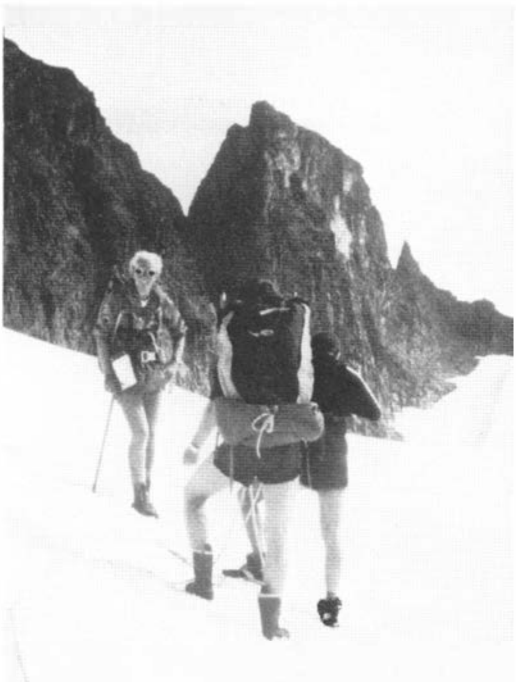

Fig. 3. Typical alpine morphology; Tindefjell between Loen and Stryn. View towards SE. See Fig. 6 for location. Photograph: O. Tveita.

Definition of weathering limit

The block fields often have sharp lower limits. Rock surfaces just below the weathering limit usually show relatively fresh glacial striations and are covered by thin and discontinuous moraine and slope deposits.

Slope-related processes have in places transported block-field material below the local weathering limit. We have therefore defined the weathering limit as the level between the lowest summits *with* block fields and the highest summits *lacking* block fields and characterized by ice-eroded forms.

Location and description of the block fields

Altogether, 65 summits were examined during mapping of the weathering limit around inner Nordfjord (Tables 1 and 2). Fig. 5 shows the weathering limit parallel to the interpreted main drainage routes for the inland ice during the Weichselian maximum glaciation, from SE to NW across the inner Nordfjord area. The weathering limit descends by an average gradient of 7 m/km from about 1750 m a.s.l. at the northern part of the Jostedal Plateau to c. 1500 m a.s.l. in the mountains between inner Nordfjord and Sunnmøre (Fig. 5). As can be seen, the elevation of the weathering limit is rather uniform all over inner Nordfjord.

Large block fields are mapped in the mountains west and east of Lovatnet and south of Strynefjellet around inner Nordfjord (Fig. 6). The highest mountain plateaus around inner Nordfjord are dominated by autochthonous block fields where in situ weathering to 2–5 m has been observed in vertical cliffs.

All rock surfaces between the level of Younger Dryas lateral moraines (Fareth 1970 and in press) and the weathering limit show relatively fresh glacial erosion and scouring without any signs of block–field formation. The difference in altitude between the weathering limit and the Younger Dryas lateral moraines is about 600 m at Stryn, diminishing to 100–200 m at the northern Jostedal Plateau.

Observations from outer Nordfjord and Møre

The highest locality with glacial striae in the coastal area of Nordfjord is 433 m a.s.l.; it shows an ice-flow direction towards the NW, indicating inland ice moving towards the sea (Mangerud et al. 1979).

Below this altitude, however, chemical weathering profiles not eroded by glaciers at several low-lying localities in the coastal district of Nordfjord and Sunnmøre show high gibbsite contents. This strongly indicates chemical weathering in a warm and humid climate. Such conditions have not existed in this region since the Late Tertiary (Roaldset et al. 1982).

Holtedahl (1955) collected observations of glacial striae and erratics in the coastal areas of Møre. The highest localities with glacial striae along the coast of Sunnmøre are about 500 m a.s.l.; the highest erratics lie at about 700 m a.s.l. Farther inland, Sollid & Sørbel (1979) and Sollid & Reite (1983) mapped a weathering limit with an average gradient of about 1% towards the coast, in the mountains between Storfjorden and Romsdalsfjorden (for location, see Fig. 4).

Sollid & Sørbel (1979) and Mangerud et al. (1981) described block fields on the mountain of

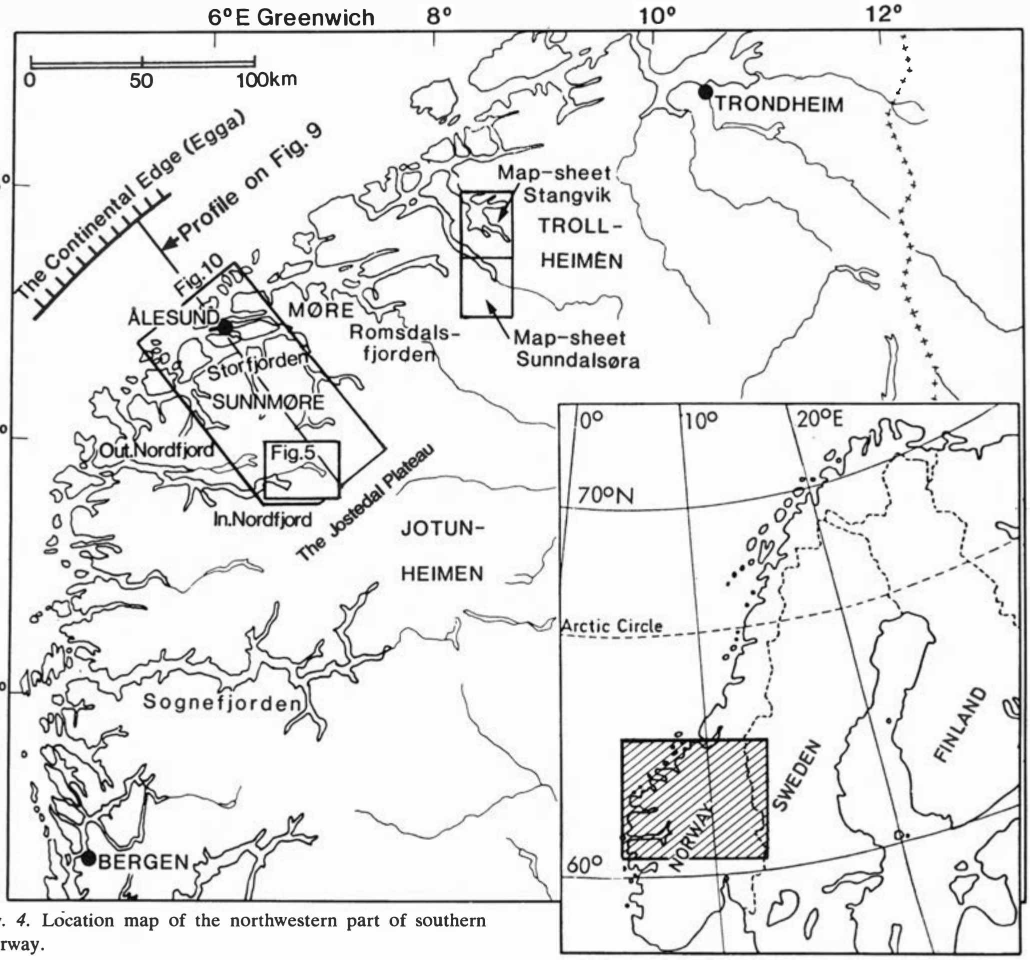

Fig. 4. Location map of the northwestern part of southern Norway.

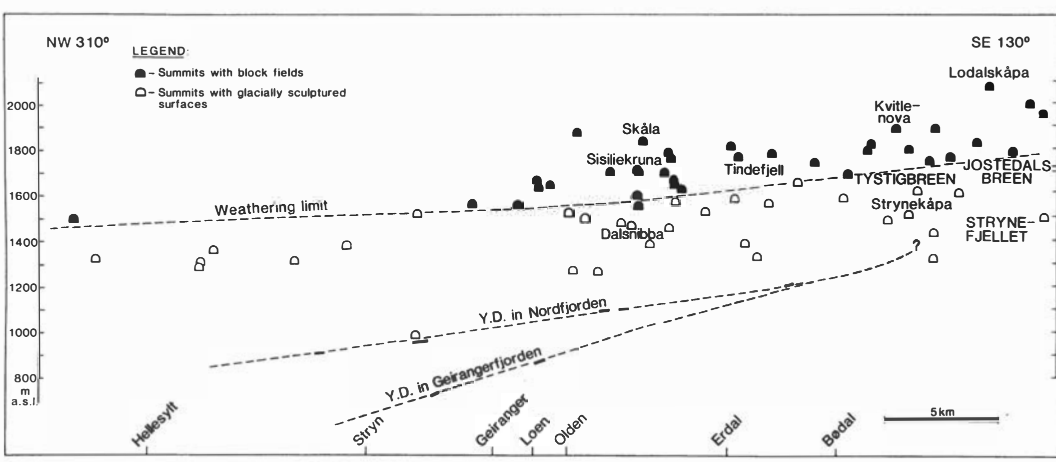

Fig. 5. Summit areas between Stryn and the northern Jostedal Plateau/Strynfjellet. Block fields and summits with glacially sculptured surfaces lacking block fields plotted on a SE–NW profile, parallel to the main drainage direction for the inland ice during maximum glaciation. The elevation of the glacier surfaces along Nordfjorden and Geirangerfjorden during the formation of Younger Dryas lateral moraines are indicated.

Table 1. Summit areas with block fields around inner Nordfjord.

Name	m.a.s.l.	UTM	Map-sheet (M 711)
1. Skarsteinfjellet	1566	808577	1318 I (Stryn)
2. Melheimnibba	1564	873561	1318 I (Stryn)
3. Sisiliekruna	1717	826519	1318 I (Stryn)
4. Skåla	1843	930614	1318 I (Stryn)
5. Ramnefjellet	1779	910537	1318 I (Stryn)
6. Tindefjell	1775	976609	1418 IV (Lodalskåpa)
7. Skålfjellet	1756	044552	1418 IV (Lodalskåpa)
8. Lodalskåpa	2083	054524	1418 IV (Lodalskåpa)
9. Brenibba	2018	488495	1418 IV (Lodalskåpa)
10. Tverrfjellet	1888	065534	1418 IV (Lodalskåpa)
11. Stornosa	1804	095547	1418 IV (Lodalskåpa)
12. Tomefjellet	1851	022577	1418 IV (Lodalskåpa)
13. Fedalsnibba	1609	944740	1418 IV (Lodalskåpa)
14. Stolshyrna	1648	047729	1418 IV (Lodalskåpa)
15. Reindalshyrna	1680	004724	1418 IV (Lodalskåpa)
16. Sandskarhyrna	1689	045750	1418 IV (Lodalskåpa)
17. Nuken	1730	105674	1418 IV (Lodalskåpa)
18. Midtstolhyrna	1771	052710	1418 IV (Lodalskåpa)
19. Stolhyrna	1852	010753	1481 IV (Lodalskåpa)
20. Snønipa	1827	779408	1318 II (Brigsdalsbreen)
21. Gjerdeaksla	1845	895476	1318 II (Brigsdalsbreen)
22. Høgste breakulen	1957	963401	1418 III (Jostedalen)
23. Kjenndalskruna	1830	984460	1418 III (Jostedalen)
24. Kvitlenova (west)	1805	134672	1418 I (Skridulaupen)
25. Kvitlenova	1898	155680	1418 I (Skridulaupen)
26. Nokkenibba	1380	932863	1219 II (Geiranger)
27. Rindalseggene	1489	889909	1219 II (Geiranger)
28. Ljosurdegga	1556	001825	1219 II (Geiranger)
29. Hammarsnibba	1608	019782	1219 II (Geiranger)
30. Hammarsnibba	1612	020787	1219 II (Geiranger)
31. Vollsetskåla	1644	997765	1219 II (Geiranger)
32. Vollsetskåla	1713	013769	1219 II (Geiranger)
33. Vollsetskåla	1759	010769	1219 II (Geiranger)
34. Rundegga	1615	118805	1319 III (Tafjord)
35. Fossfjellet	1574	115821	1319 III (Tafjord)
36. Storbarden	1742	134825	1319 III (Tafjord)

Gamlemsveten (791 m a.s.l.), north of Ålesund (for location see Fig. 10). From a 3-m-deep excavation there, J. Mangerud and collaborators obtained a radiocarbon date of 19,900 ± 210 B.P. (T-4384) from organic material in brownish grey sandy silt 2 m below the surface (J. Mangerud, pers. comm.). The organic content of the material is only 2.5%, and therefore the date should be interpreted cautiously. According to Mangerud, the sediment is a weathering product, later disturbed by frost and slope processes. Glacial striations on stones or other positive indications of glacial transport or deposition were not found. The interpretation of the stratigraphy in the excavation is, however, somewhat problematic; conclusive evidence for whether this summit was ice-covered or not was not found (J. Mangerud, pers. comm.).

Mangerud et al. (1981) also cored sediments beneath several lakes of three coastal islands at Ålesund, above the extrapolated weathering limit described by Sollid & Sørbel (1979), but only Late Glacial and Holocene sediments were found. They reexamined the weathering limit at Gamlemsveten and found that it should have been placed higher up the slope because the material had moved downslope from its point of formation (Mangerud et al. 1981).

The islands, however, show no block fields on the mountain peaks and all the lakes may therefore have lain below the weathering limit in this area. Mangerud et al. (op.cit.) also pointed

Table 2. Summit areas with ice-eroded forms around inner Nordfjord.

Name	m.a.s.l.	UTM	Map-sheet (M 711)
1. Gulkoppen	1304	754721	1318 I (Stryn)
2. Årheimsfjellet	1007	819645	1318 I (Stryn)
3. Løkenfjellet	1274	823539	1318 I (Stryn)
4. Gjerdanibba	1400	868487	1318 I (Stryn)
5. Klovane	982	841513	1318 I (Stryn)
6. Kyrkjenibba	1400	836703	1318 I (Stryn)
7. Neslenibba	1359	853461	1318 II (Brigsdalsbreen)
8. Flatefjellet	1291	867420	1318 II (Brigsdalsbreen)
9. N. of Bødalen	1589	986566	1418 IV (Lodalskåpa)
10. Strynekåpa	1530	059578	1418 IV (Lodalskåpa)
11. Klubben	1603	118551	1418 IV (Lodalskåpa)
12. Sandskardhyrna	1395	059754	1418 IV (Lodalskåpa)
13. Sandskardhyrna	1471	061741	1418 IV (Lodalskåpa)
14. Svartaksla	1525	997744	1418 IV (Lodalskåpa)
15. Sætreskardsfjellet	1606	101745	1418 IV (Lodalskåpa)
16. Raudnova	1665	117724	1418 IV (Lodalskåpa)
17. Hurklutefjellet	1323	941823	1219 II (Geiranger)
18. Furneshornet	1335	962905	1219 II (Geiranger)
19. Rindalseggene	1344	890896	1219 II (Geiranger)
20. N. of Sandskardhyrna	1488	043761	1219 II (Geiranger)
21. At Nautbreen	1518	035775	1219 II (Geiranger)
22. Middagsnibba	1531	963760	1219 II (Geiranger)
23. S. of Hammarsnibba	1542	023773	1219 II (Geiranger)
24. Djupvassegga	1546	112778	1319 III (Tafjord)
25. Oppljosegga	1571	136763	1319 III (Tafjord)
26. Dalsnibba	1476	097810	1319 III (Tafjord)
27. Kvitenova	1563	138734	1418 I (Skridulaupen)
28. Sætrehyrna	1618	138643	1418 I (Skridulaupen)
29. Langvassegga	1651	162730	1418 I (Skridulaupen)

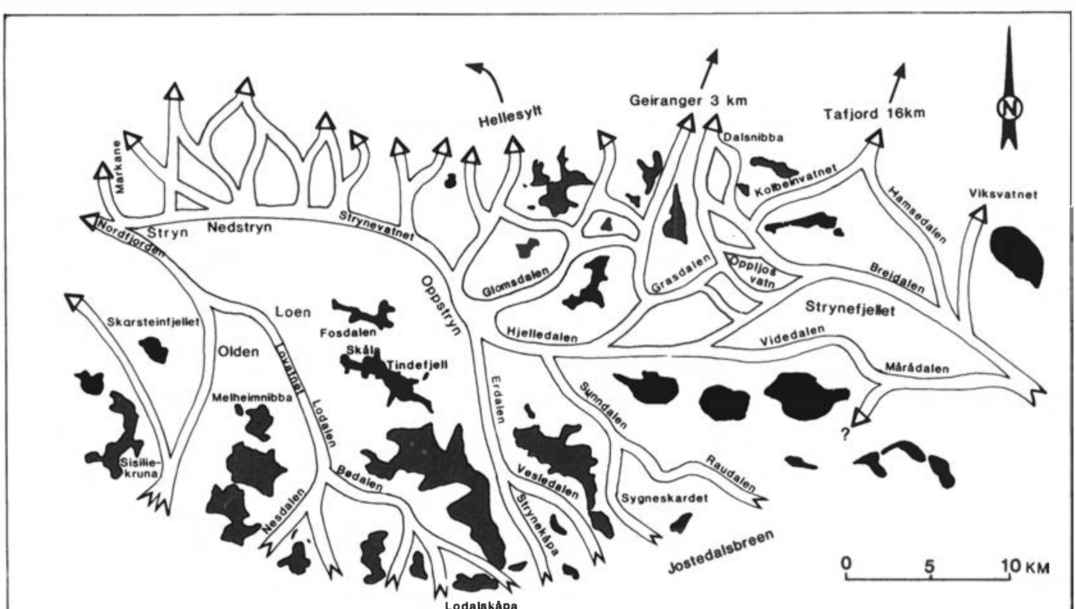

Fig. 6. Summit areas between Stryn and the northern Jostedal Plateau/Strynefjellet covered with block fields, in places with alpine morphology (black areas). The arrows indicate drainage routes for the inland ice during maximum glaciation.

Fig. 7. Alpine morphology at Kolåstind (1463 m a.s.l.), Ørsta, Sunnmøre. See Fig. 10 for location.

out that if the inland ice reached the continental edge, as claimed by Andersen (1979), Rokoengen (1979) and Bugge (1980), the glacier surface, according to theoretical profiles (Sugden & John 1976, Fig. 4.4), would have been above the weathering limit of Sollid & Sørbel (1979). The problem therefore, remained unsolved by Mangerud et al. (1981).

Other relevant observations include trimlines (Sulebak 1982) at Kolåstind (Fig. 7), about 1000 m a.s.l. in the mountains at Ørsta (Sunnmøre). The mountain areas in inner parts of Sunnmøre ('Sunnmørsalpene') are dominated by alpine morphology, where the highest summits show no signs of overriding by an ice sheet (Fig. 8).

Follestad & Henningsen (1983) and Follestad (1984) mapped the superficial deposits on two map-sheets in Møre (for location, see Fig. 4). The highest mountain areas in this region are covered by block fields, whereas lower summits are not. Plotting mountain peaks with and without block fields on a longitudinal profile parallel to the main ice flow direction, a somewhat irregular zone between weathered and non-weathered mountains appears. This zone slopes gradually down toward the NW, indicating that a glacier surface or an upper zone of the inland ice sheet was responsible for it.

Recently, the Geological Survey of Norway mapped the superficial deposits on map-sheet 1220 III Brattvåg, NE of Ålesund. The highest mountain tops in this area are covered by rather extensive block fields; lower mountains are not (O. Klakegg, pers. comm.).

Theories for the formation of the weathering limit

The distribution of block fields, and in particular their lower limits, are important factors to be taken into consideration in determining their origin and age. Furthermore, a discussion of the formation of the weathering limit is closely related to hypotheses regarding glaciation and deglaciation. Four different theories for the formation will be discussed in the following.

(1) A total lack of evidence exists for overriding by the inland ice sheet above the weathering limit, and there is abundant evidence for glaciation below the limit in the inner Nordfjord area (Fig. 5). We conclude that the limit was caused by erosion of the inland ice sheet.

Fig. 8. Alpine morphology at Jønshorn (1419 m a.s.l.) west of Hjørundfjorden, Sunnmøre. View towards SW. See Fig. 10 for location. Photograph: Fjellanger/Widerøe A/S.

The lower limit of the block fields in inner Nordfjord lies well above the Nor lateral moraines of Younger Dryas age described by Fareth (1970 and in press) and Mangerud et al. (1979). Rock surfaces between the Younger Dryas lateral moraines and the weathering limit all show signs of relatively fresh glacial erosion, without any signs of block-field formation, despite the fact that they have been exposed to weathering from before 11,000 yrs B.P. The weathering limit thus seems to correspond with the upper level of regional glaciation in this area. Also, the large altitudinal difference between the weathering limit and the Younger Dryas lateral moraines, up to 600 m, indicates a much more extensive glaciation during the formation of the weathering limit than during the Younger Dryas. The large altitudinal difference indicates that the glaciers were much larger and thicker when the weathering limit was formed than when the Younger Dryas lateral moraines were formed.

(2) The weathering limit may, however, also be explained in terms of vertical differences in erosive properties of an inland ice sheet. The block fields in summit areas may have been protected against erosion beneath a cold-based, non-erosive zone toward the higher, thinner part of the inland ice sheet, as described by Goldthwait (1960), Holdsworth & Bull (1970) and Boulton (1979), while the lower deeper parts, below the weathering limit, were under a warm-based glacier and thus erosive. In accordance with this hypothesis the highest mountain areas may have been completely covered by a cold-based inland ice sheet during the Weichselian maximum without eroding the block fields formed earlier. Rasmussen (1984) proposed this possibility for weathered mountain areas on the Vesterålen islands of northern Norway.

(3) Malmstrøm & Palmér (1984), in detailed investigations of block fields on the Varanger peninsula, northern Norway, concluded that the block fields were autochthonous and formed by weathering in a periglacial environment, mainly during the latter part of the Middle Weichselian and the Late Weichselian, but also during the early Holocene. Tor-like remnants, which they observed, were explained as the results of pre-

glacial weathering. The remnants survived the Weichselian glaciation under a thin ice cover, which had an insignificant geomorphological effect on the substratum.

The observed position of the weathering limit in inner Nordfjord can hardly be explained as a lower limit of a periglacial weathering. Mountain areas typically exhibit irregularities in the weathering limit because of variations in microclimates, in terms of vertical differences in erosive properties of the ice sheet or variations in the height of the inland ice sheet, as ice-flow directions changed in response to different locations of accumulation zones through one or more glaciation cycles.

(4) Another possibility is that the weathering products are post-Late Weichselian in age. Holmsen (1951) and Holtedahl (1955) argued for this view concerning the weathering at Gjevilvasskammene in Trollheimen, southern Norway (for location, see Fig. 4). Sørensen (1949), Grønlie (1950, 1953) and E. Dahl (1961), however, postulated that these weathering products were formed prior to the Late Weichselian. R. Dahl (1966), on the other hand, suggested that some mountain areas covered by block fields in Nordland, northern Norway, were developed entirely during the postglacial period and therefore could not be used to delineate ice-free areas during the last glaciation.

Mountains to the east of the northern Jostedal Plateau, with altitudes around 1700 m a.s.l. have no block fields. These mountains are dominated by bare rock surfaces with fresh glacial striae. In addition, erratics have been found at and around these summits. If the block fields are of Holocene age, these observations reveal a marked difference in the rates of weathering on summits at approximately the same altitude in inner Nordfjord compared to the area east of the northern Jostedal Plateau, only 10 km apart. The weathering in the mountain areas of inner Nordfjord cannot, therefore, be of Holocene age. Consequently, the mountain areas east of the Jostedal Plateau were probably ice-covered during a later phase than the mountain areas at the same altitude in inner Nordfjord. This may be explained in terms of a glacier surface gradually rising towards the E-SE during maximum glaciation. Both areas belong to the same bedrock complex (the Jostedal Complex, e.g., Bryhni 1966; Skjerlie 1984).

One of the arguments used earlier, favouring a Holocene age for the formation of block fields, is that freeze/thaw cycles at high altitude would lead to a more effective mechanical weathering than in lower areas. Data from the Norwegian Meteorological Institute (pers. comm.) show, however, that the meteorological station at Oppstryn (201 m a.s.l.) (inner Nordfjord) experiences about the same number of freeze/thaw cycles per year than that at Fanaråken (closed 1978) (2068 m a.s.l.) (western Jotunheimen) (Fig. 4); on average 74 and 72 days per year, respectively. For Oppstryn, the data cover the period from 1957 to 1984 and for Fanaråken the period from 1957 to 1978.

Frost-shattering has for some time been considered the most important process in mechanical weathering in periglacial climates, and laboratory experiments have been carried out by several researchers to demonstrate and quantify frost-shattering as a function of climatic conditions, bedrock and time.

The number of freeze/thaw cycles and the amplitudes of the temperature variations are an important control on the effectiveness of various kinds of frost action, including frost wedging (Washburn 1973). However, the purely climatic factor of the number of times the air temperature passes through the freezing point is not in itself an adequate measure of frost action. The insulating effect of snow and vegetation, the characteristics of rock material and the rapid attenuation of temperature fluctuations with depth must all be taken into account in evaluating the frequency and effect of freeze/thaw cycles in rock material (Washburn op. cit.).

Large discrepancies between air and ground-surface temperatures are possible as a result of insolation on dark surfaces. A difference of over 30°C has been observed in northeast Greenland, (cf. Washburn 1969:45–46). In the Antarctic, thawing of snow or ice adjacent to rock has been reported at air temperatures as low as −16.5°C (Taylor 1922, p. 47) and −20°C (Souchez 1967, p. 295). Freeze/thaw cycles in bedrock joints during negative air temperatures have also been reported from the Antarctic (Aughenbaugh 1958; Andersen 1963). On the other hand, because of thermal radiation, ground frost is also possible at positive air temperatures, as reported from Iceland (Steche 1933).

Although large discrepancies in the number of freeze/thaw cycles in air and rock surfaces have been recorded in polar climates, it is believed that these differences could not have been responsible for the post-Weichselian formation of deep and continuous block fields on summit areas around inner Nordfjord because the block fields have sharp lower limits, as if truncated (see Fig. 5).

We therefore conclude that the weathering limit must represent an ice limit, and we infer from the large altitudinal difference between the weathering limit and the Younger Dryas lateral moraines that the upper limit of the maximum Late Weichselian ice sheet was most probably responsible for formation of the weathering limit.

The sharp and geographically consistent altitudinal pattern of summits with and without block fields suggest that the summits were not totally covered by an upper inactive frozen part of the ice sheet. If this had been the case, the weathering limit would probably not have been so consistent over the inner Nordfjord region.

It is possible, however, that the gently undulating mountain plateaus above the weathering limit were covered by dynamically inactive local snowfields or minor ice-caps too thin to erode the block fields already formed.

The age of the block fields

If we accept that the weathering limit represents the upper limit of the Late Weichselian ice sheet, it is inferred from the present knowledge of the Weichselian glaciations (Miller & Mangerud 1980; Miller et al. 1983; Mangerud 1981, 1983; Bergersen & Garnes 1971, 1981, 1983) that the summits were probably not covered by an ice sheet during the Weichselian prior to the Late Weichselian glacial maximum.

As a consequence, the summits may not have been covered by an ice sheet since the Saalian glaciation (before 130 ka), which gives a minimum age for the formation of the block fields. However, occurrences of isolated pockets or minor areas of deeply weathered rocks are reported from Norway (for references, see Roaldset et al. 1982).

Roaldset et al. (op. cit.) found from studies of three sites with in situ weathered gabbroic and granitic rock material, remnants of preglacial weathering in western Norway.

The areas of most extensive and deeply weathered block fields in inner Nordfjord are located on the gently undulating mountain plateaus, interpreted to be parts of the pre-Quaternary land surface of Norway: the paléic surface (Reusch 1901; Gjessing 1967).

Thus, most parts of the block fields in this area may have been under formation, caused by mechanical and chemical disintegration, since at least Tertiary time. In its widest consequence, this may indicate that parts of the highest and heavily weathered mountain areas of the Nordfjord–Møre region may not have been covered by inland ice sheets at any time during the Quaternary.

A model for the shape and build-up of the Late Weichselian ice sheet

Accepting that the block fields on Gamlemsveten are of pre-Weichselian maximum age, they may also indicate the maximum elevation of the Late Weichselian inland ice sheet in the coastal areas of Møre. In contrast, the highest elevations at which Holtedahl (1955), Mangerud et al. (1979) and Longva et al. (1983) observed erratics and glacial striae in the coastal areas of Nordfjord and Møre indicate the minimum estimate of the vertical extent of of the continental ice sheet during the same period. By considering the weathering limit in inner Nordfjord, the distribution of block fields, trimlines, erratics and glacial striae in the Møre area, it is possible to reconstruct a profile for an inland ice sheet.

On Fig. 9 we have made some simple assumptions concerning the shape of the Late Weichselian ice sheet. During the maximum glaciation there was a topographically controlled, mainly N to NW ice-drainage in inner Nordfjord from a probable accumulation zone on the Jostedal Plateau, towards Sunnmøre (Vorren 1977; Rye et al. 1984; Nesje 1984; Hole 1985; Blikra 1986; Rye et al. 1987). From this area the inland ice drained towards the NW over Sunnmøre (Mangerud et al. 1979; Longva et al. 1983; Henningsen & Hovden 1984) to an ice terminus at the continental edge about 70 km seaward of the Møre coast (Andersen 1979, 1981; Rokoengen 1979; Bugge 1980). The main ice-drainage routes for the ice sheet during the Late Weichselian maximum in parts of the Nordfjord–Møre area are shown on Fig. 10 (see also Rye et al. 1987).

Parallel to their general SE–NW direction, theoretical glacier profiles have been constructed (Fig. 9) using the formula $H = kL\ 1/2$, where H

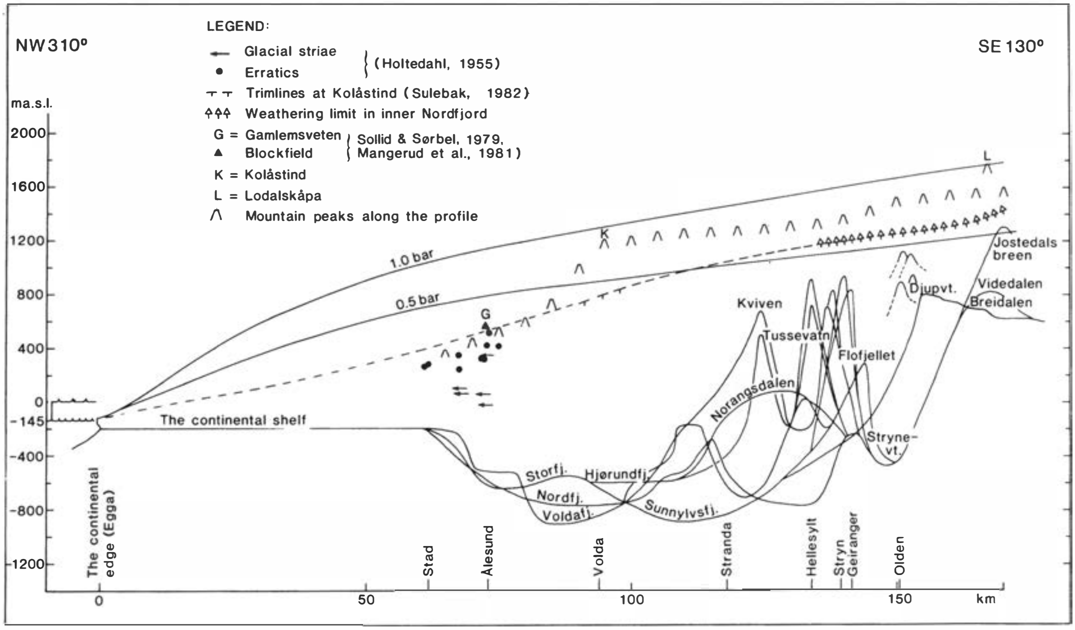

Fig. 9. Longitudinal profile from the continental edge NW of Møre to the northern Jostedal Plateau/Strynefjellet, showing the topography along the main drainage routes for the inland ice sheet. Theoretical glacier profiles for basal shear stresses of 1.0 and 0.5 bar are indicated (solid lines). The postulated glacier profile during Late Weichselian maximum is indicated on the basis of observed weathering limits in inner Nordfjord and observations from Møre (dashed line). The profile is corrected for a glacio-eustatic sea level 145 m below the present and a glacio-isostatic depression of c. 300 m in inner Nordfjord. The location of the profile is shown on Fig. 4.

is the height of the glacier surface at distance L from the glacier front, in metres (Orowan 1949). The constant k is often 4.7, assuming a basal shear stress of 1 bar (100 kPa). However, observed values of basal shear stress vary between 0 and 1 bar with an average of 0.5 bar, giving $k=3.4$ (Paterson 1981). Both values for k are used, giving two alternative profiles (Fig. 9). The profiles are adjusted for a sea-level 145 m lower than at present (Gascoyne et al. 1979) and a glacio-isostatic depression of c. 300 m in inner Nordfjord, a value based on Walcott's (1970) calculations from Canada, and Svendsen's (1985) calculations of isostasy and eustacy for the last 12,000 years in the Møre area.

The weathering limit in the mountain areas between inner Nordfjord and Sunnmøre is steeper north of the watershed toward inner Sunnmøre than between the Jostedal Plateau and the watershed. The most important topographic obstacle for the inland ice from the northern Jostedal Plateau towards Sunnmøre was the mountains forming the present watershed between inner Nordfjord and Sunnmøre. These are, however, cut by several high-lying passes (Fig. 9). The increasing slope of the weathering limit along the fjords in Sunnmøre was probably caused by a steeper gradient of the inland ice sheet resulting from these topographic obstacles. Between the watershed and the Jostedal Plateau the surface of the inland ice had a more gentle slope. However, the relatively steeper gradient of the weathering limit closer to the Jostedal Plateau may indicate that the subglacial plateau had a limited but significant topographic effect on the surface of the inland ice sheet.

The fjords in Sunnmøre, presumably, were effective drainage routes for the inland ice sheet during maximum glaciation. In addition, the submarine channel, Breisunddjupet (Fig. 10), extending about 60 km NW from the coast south of Ålesund as an extension of Storfjorden and Sulafjorden, was probably a drainage channel for the glaciers flowing from Storfjorden, Sunnylvsfjorden, Norddalsfjorden and Hjørundfjorden, the major drainage routes for the inland ice

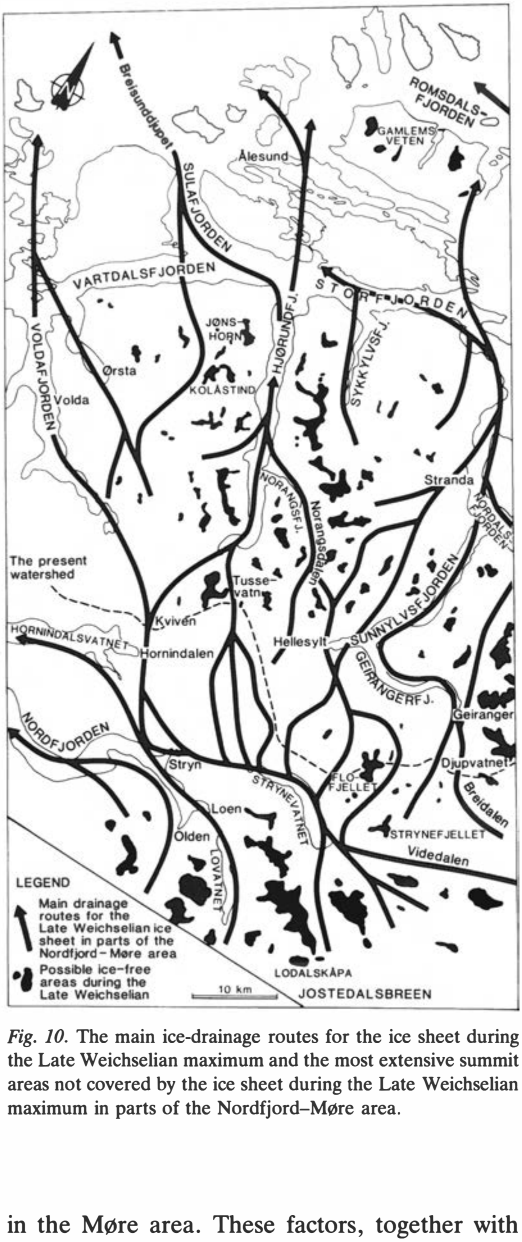

Fig. 10. The main ice-drainage routes for the ice sheet during the Late Weichselian maximum and the most extensive summit areas not covered by the ice sheet during the Late Weichselian maximum in parts of the Nordfjord–Møre area.

in the Møre area. These factors, together with divergent ice-flow in the outer coastal areas, may explain the relatively gentle slope of the glacier surface on the proposed glacier profile in relation to theoretical profiles in the outer fjord areas and on the continental shelf (Fig. 9).

Boulton & Jones (1979) postulated that low basal shear stresses result from subglacial, deformable, water-saturated sediments which increase a glacier's response rate to mass balance changes and consequently lead to a relatively low ice-surface slope. In general, their model predicts steep, 'normal' profiles over bedrock areas, and gentler slopes over areas underlain by sediments.

It is known that large thicknesses of Quaternary sediments exist on the continental shelf (e.g., Bugge 1980). If there were water-saturated sediments on the continental shelf during maximum glaciation, there should have been a low-gradient glacier in this area. Such a low-gradient glacier profile would also affect the glacier profile farther inland. Along the coast of Møre, the continental shelf is relatively narrow (c. 70 km), making the distance from the maximum position of the Late Weichselian ice sheet at the continental edge to the central accumulation zones relatively short (170–200 km).

Assuming the weathering limit at 1750 m a.s.l. on the northern Jostedal Plateau represents the upper limit of the inland ice sheet during the Late Weichselian glacial maximum, and if the glacio-isostatic depression was c. 300 m, sea-level 145 m below the present and the ice front at the continental edge, the constant k in the formula $H = kL\ 1/2$ (Orowan 1949) has the value of 3.6, a reasonable value according to Paterson (1981).

This model for the vertical extent of the inland ice sheet suggests a multi-centred ice sheet with a concave ice sheet profile along the fjords during maximum glaciation. The maximum ice thicknesses are concluded to have been in the central and inner fjord areas of Møre and Nordfjord and not along the mountain range in central south Norway (Fig. 9). As a result, this would probably have affected the centre of maximum glacio-isostatic depression, too.

According to the interpreted longitudinal profile of the Late Weichselian ice sheet in the Nordfjord–Møre area (Fig. 9), a large number of isolated mountain areas were not covered by the inland ice sheet during maximum glaciation. The most extensive areas not covered by the continental ice sheet in parts of the Nordfjord–Møre area parallel to the profile on Fig. 9 are indicated on Fig. 10. As can be seen, only a few summit areas are presumed to have been ice-free NW of Storfjorden. SW of Storfjorden, however, a large number of isolated mountain peaks probably were nunataks throughout the Late Weichselian maximum. This area ('Sunnmørsalpene') is also one of the postulated refuge areas (e.g., Mangerud 1973). The ice-free areas on Fig. 10 are mainly coincident with the dissected, jagged mountains, showing alpine morphology in that district (Figs. 7 and 8).

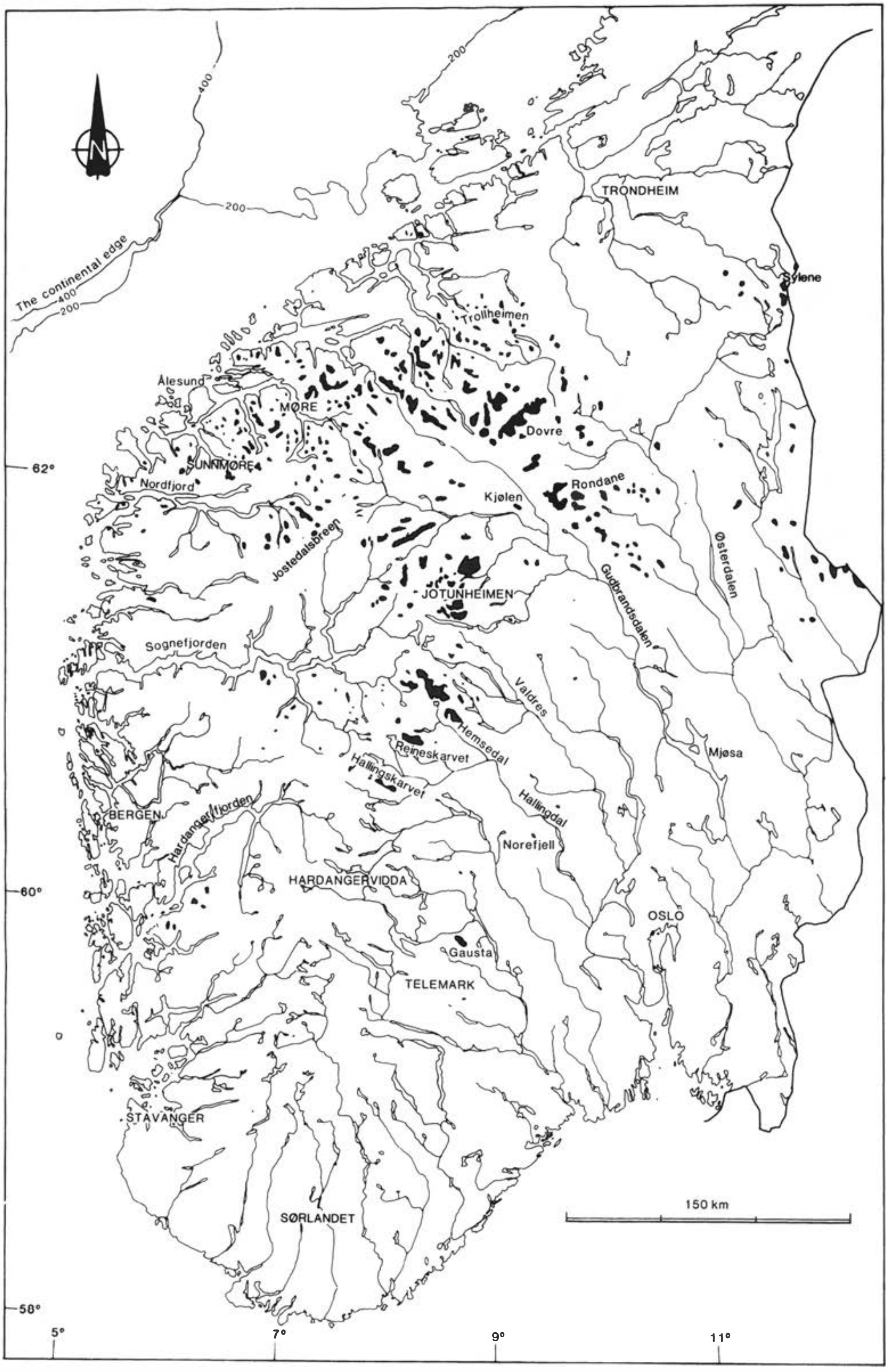

Fig. 11. The areas of the most extensive block fields in southern Norway.

In inner Nordfjord the summit areas covered by block fields, in places with alpine morphology, are interpreted not to have been covered by the continental ice sheet at any time during the Late Weichselian (Figs. 6 and 10).

The theoretical glacier profiles discussed above presuppose, however, that the inland ice sheet was in a state of climatic and dynamic equilibrium. The time required for inland ice sheets to attain the state of equilibrium is about 25,000 years (Paterson 1981). It is supposed that an ice sheet in climatic and dynamic equilibrium would not deviate considerably from the reconstructed ice sheet profile, taking into consideration the relatively short distance from the edge of the continental shelf, the topography and the composition of the substratum along the profile.

From the Ålesund Interstadial, ^{14}C-dates of 28,000 to 38,000 B.P. were obtained (Mangerud et al. 1981). During recent stratigraphic investigations in the Skjonghelleren cave at Ålesund, two ^{14}C-dates on fossil bones and three U/Th dates on speleothems from the upper interstadial bed were obtained, giving ages of c. 30,000 B.P. (Larsen et al. 1984). Therefore, the time span between the Ålesund Interstadial and the Late Weichselian maximum was so short that the glaciation culminated before the glaciers achieved equilibrium.

The glaciation postdating the Ålesund Interstadial may, therefore, have started with local glaciations in the central and the coastal mountain areas, later coalescing to glacier fields covering large areas with relatively limited vertical extent. The advance of the local coastal and inland glaciers to the continental edge may also have taken place in a relatively short time as a result of larger accumulation on the coastal, marginal parts of the ice sheet as the water on the continental shelf dropped in step with the glacio-eustatic fall in sea-level.

The presented model for the surface of the Late Weichselian ice sheet in the Nordfjord–Møre area fits fairly well with an alternative minimum model for the Weichselian European Ice Sheet during its maximum (Boulton et al. 1985, p. 471), allowing for changes in the basal boundary conditions resulting from the composition of the substratum.

According to our model, the Late Weichselian maximum ice cover, represented by weathering limits, trimlines, and upper limits of erratics and glacial striae, represents a minimum age for the formation of the block fields. As evidence exists for restricted Middle and Early Weichselian glaciations in western Norway (e.g., Miller et al. 1983), the summits may not have been covered by an ice sheet since the Saalian glaciation, providing a minimum age of >130 ka for the formation of the block fields. However, the areas of most extensive and deeply weathered block fields in inner Nordfjord are located on the undulating summit areas interpreted as belonging to the Paléic surface.

Summary and conclusions

Based on field observations of 65 summits, the weathering limit in the mountains between Sunnmøre and the northern Jostedal Plateau has a gradient of 7 m/km, and descends from about 1750 m a.s.l. at the northern Jostedal Plateau/Strynefjellet to about 1500 m a.s.l. in the mountain areas between Sunnmøre and inner Nordfjord.

Field observations of block fields, alpine morphology, trimlines and glacially sculptured landforms in the Nordfjord–Møre region and theoretical considerations of ice extent during the Weichselian maximum demonstrate that the highest summits were not completely covered by inland ice during maximum glaciation in this area. Sollid & Sørbel (1979) reached a similar conclusion. Based on the altitude of the weathering limit, the inland ice in the accumulation zone above the Jostedal Plateau is interpreted to have been relatively thin, due mainly to effective ice-drainage through the deep fjords and valleys surrounding the area.

The block-field areas may have been under formation since at least the Ålesund Interstadial (30 ka) or possibly since the Saalian glaciation (>130 ka). However, as the deeply weathered autochthonous block fields are located up to the summits interpreted to belong to the Paléic surface, the block fields may have undergone formation since the Tertiary.

If deeply-weathered autochthonous block fields can be used to indicate areas not overridden by ice during the Late Weichselian, their lower boundaries can be used for modelling the Late Weichselian maximum ice sheet in southern Norway. Based on previously published papers, geological maps, aerial photos, pictures, and some recent field observations, the most extensive block fields in southern Norway are shown in Fig. 11 (see also E. Dahl 1955). Documentation and discussion of the significance of the regional distribution of block fields will be discussed in a later paper.

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