

Ice sheet limits in Norway and on the Norwegian continental shelf

Jan Mangerud

University of Bergen, Department of Geology,
Allégt. 41, N-5007 Bergen, Norway
Jan.Mangerud@geol.uib.no

Introduction

Ice sheets and other glaciers have had a spectacular erosional impact on the Norwegian landscape, producing deep fjords, long U-shaped valleys, numerous cirques and thousands of lakes in overdeepened bedrock basins. In the central part of Sognefjorden there has been vertical glacial erosion of at least 1900 m (Andersen & Nesje, 1992; Nesje & Whillans, 1994). Glaciers in the Norwegian and Swedish mountains formed the nucleus from which the Scandinavian Ice Sheet has grown many tens of times during the Quaternary.

In this paper the author will briefly review present knowledge of the glacial history of Norway. The reconstruction of the Late Weichselian maximum and the Younger Dryas ice sheets will be discussed in some detail.

THE OLDEST GLACIAL HISTORY OF NORWAY

The strong glacial erosion by the last large ice sheets has led to scarcity of old Quaternary deposits on land in Norway. Therefore the oldest glacial history of Norway has to be deciphered from deposits in the border zone of the Scandinavian ice sheet to the south, in Denmark-Germany-Netherlands-The North Sea, and to the west, on the Norwegian continental shelf and in the deep Norwegian Sea.

The best record of the oldest glaciations is ice-rafted debris dropped from 'Norwegian ice bergs' into the deep sea beyond the coast. A review and discussion of this record has recently been given in Mangerud *et al.* (1996), who concluded that calving glaciers first appeared along the Norwegian coast at about 11 Ma. When comparing the amount of ice rafting, the global marine oxygen-isotope signal, and the stratigraphy of the Netherlands, these authors concluded that there was a major increase in the maximum size of the Scandinavian Ice Sheet after the onset of the Praetiglian in the Netherlands 2.5-3 Ma (Zagwijn, 1992).

The oldest identified and dated glacial deposits on the Norwegian shelf is the Fedje Till, that is assigned an age of about 1.1 Ma (Sejrup *et al.*, 2000). The most continuous record of the glacial/interglacial history is probably found in the large submarine fans on the continental slope, located in front of troughs where fast-moving ice streams crossed the continental shelf (King *et al.*, 1996; Laberg & Vorren, 1996; Sejrup *et al.*, 2000). However, long cores have not been obtained from these fans off mainland Norway.

On land in Norway, old glacial deposits are found in two areas. Finnmarksvidda in northern Norway (Fig. 1) is a rolling plain with thick Quaternary deposits including several till beds, interglacial deposits and soils dating back to at least Marine Isotope Stages (MIS) 8 or 10 (Olsen, 1998; Olsen *et al.*, 1996). Even thicker Quaternary deposits occur in the Jæren lowlands at the very SW corner of the country. Here glacial and interglacial deposits from MIS 10 and upwards are described from boreholes (Sejrup *et al.*, 2000). Elsewhere in Norway no glacial deposits are proven older than the Saalian (MIS 6), but till of that age has even been found (below Eemian sediments) in the fjord district, where the glacial erosion has been most intense (Mangerud *et al.*, 1981b).

Even older Quaternary formations are found in karst caves. Numerous caves are now known in Norway, many of which contain speleothems (Lauritzen, 1984). The oldest well-dated speleothem yielded non-finite (>350 ka) U series dates by alpha particle counting and had normal polarity and was therefore assumed to have an age between 350-730 ka (Lauritzen *et al.*, 1990). An age of 500 ka (MIS 13) has subsequently been obtained from this speleothem with the mass-spectrometric method (S.E. Lauritzen, written communication, 2000). Even older caves exist (Lauritzen, 1990), but most U-series dates on speleothems have yielded Eemian ages (Lauritzen, 1991; 1995).

The maximum extent of Pleistocene glaciers

As will be apparent from the above discussion, the outermost glacial limit is far beyond the Norwegian territory to the south. To the west glacial deposits are mapped using seismic methods across the entire continental shelf (H. Holtedahl, 1993; King *et al.*, 1987; Sejrup *et al.*, 2000; Vorren *et al.*, 1983). It seems quite obvious that the Scandinavian Ice Sheet would have advanced much further west if shallow water or dry land had extended in that direction. Western expansion was simply limited by the deep water beyond the shelf edge. Where the water depth exceeds some few hundred metres, the ice front generally floats, and further expansion is limited by iceberg calving. In a detailed seismic mapping of Quaternary deposits on the middle Norwegian shelf, King *et al.* (1987) mapped till tongues down to 800-1000 m below present sea level. However, these beds probably have subsided after deposition, as a result of isostatic response of the shelf to sediment loading.

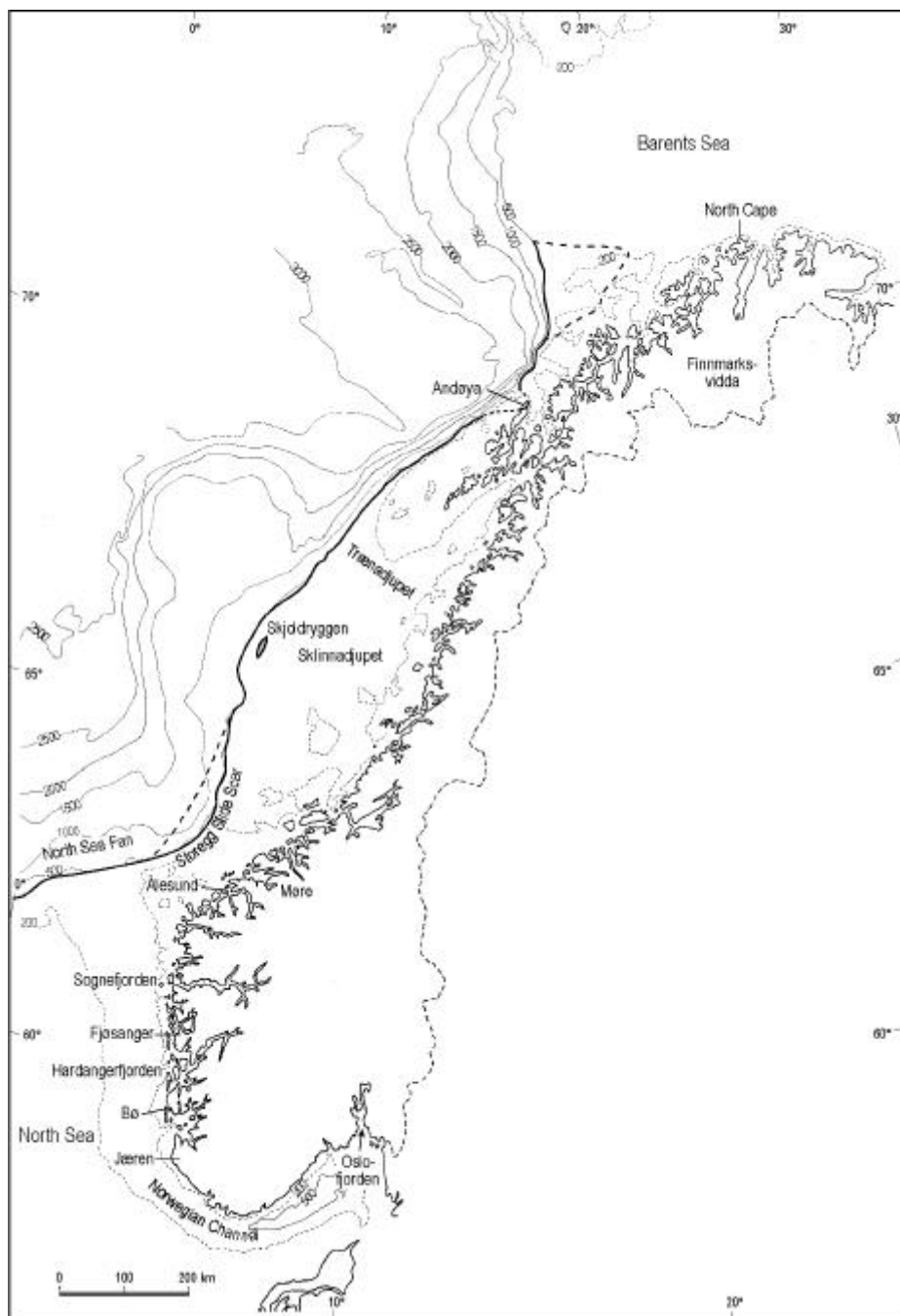


Fig. 1: Map of Norway with the continental shelf. The Late Weichselian glacial limit is marked, in accordance with the digital map on the CD. Geographical names used in the text are given, except some of those related to the discussion of the Younger Dryas which are marked on Figs 12 or 15.

The maximum Pleistocene glacial extent can be considered to be about the same as the Late Weichselian extent, or slightly beyond, as the latter is shown on the map on the CD.

THE EARLY AND MIDDLE WEICHSELIAN

The glaciation history

The Weichselian is obviously better known than the earlier glaciations. However, the Late Weichselian ice sheet also removed most of the older deposits from this period, so

only fragments of the pre-Late Weichselian history are known. Therefore, the interpretation of the older part of the Weichselian is based on observations from very few localities that provide only glimpses into this fascinating history. They are insufficient to allow any accurate mapping of ice sheet limits at different times during the Early and Middle Weichselian.

Dating of events older than the range of the radiocarbon method is also problematic. Different scientists have therefore disagreed on the age of the deposits and the correlation between different sites, and consequently also on the conclusions on the glacial history. Figure 2 shows a glaciation curve for south-western Norway slightly

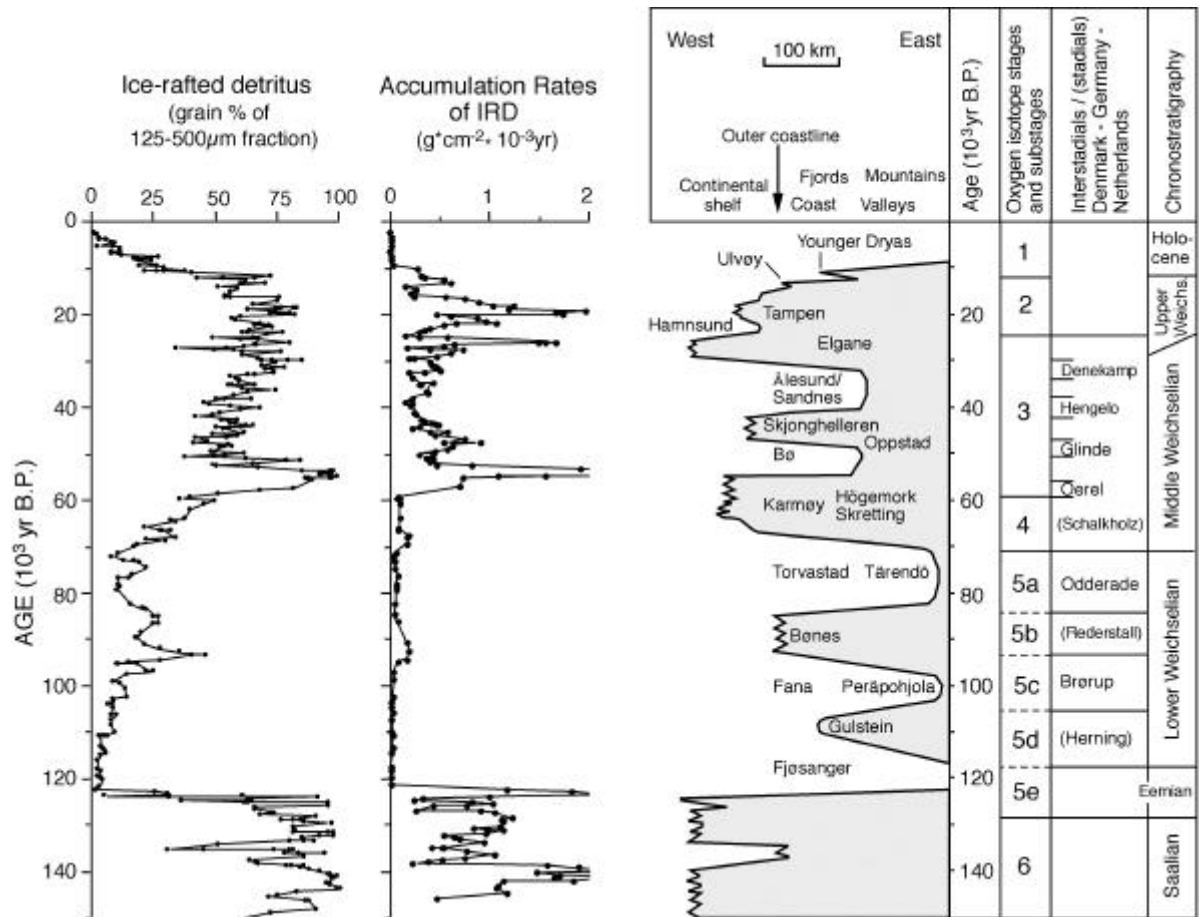


Fig. 2: The curve to the right is a glaciation curve for western Scandinavia constructed from continental data (Mangerud, 1991a), except that the advance during MIS 4 (Karmøy) has been extended into MIS 3, based on the ice-rafted detritus (IRD) curves. Note that the time scale is in calendar years. The curve to the left is a stacked record for grain % of IRD in 5 cores, and the middle curve a stacked record of accumulation rates in 3 cores; all cores collected from the Vøring Plateau west of the Norwegian coast. A three-point moving average smoothing filter was used for the IRD curves. The figure is slightly modified from Baumann *et al.* (1995). It is postulated that most of the IRD was dropped from icebergs that calved from the margin of the Scandinavian Ice Sheet, off the coast of western Norway. The stratigraphical position of the till beds on Jæren (Elgane, Oppstad, Høgemork/Skretting) are also indicated according to Larsen *et al.* (2000), except that the Høgemork/Skretting is plotted with an MIS 4-3 age, instead of an MIS 5a age, as suggested by these authors.

modified from Baumann *et al.* (1995). The curve was originally developed from the interpretation of localities on land (Mangerud, 1981; 1991a; 1991b). When comparing the curve with the record of ice-rafted detritus (IRD) off the Norwegian coast, Baumann *et al.* (1995) found a close correlation, supporting the main features of the curve. The only difference was that Mangerud (1991a; 1991b) had assumed that a major glaciation in MIS 4 ended at the transition to stage 3, whereas the IRD record suggested the deglaciation was well into stage 3 (which is adapted in Fig. 2).

Alternative interpretations of the same continental data are presented by Larsen & Sejrup (1990) and Sejrup *et al.* (2000). There is a general agreement with Mangerud (1991a, 1991b) concerning the younger part of the curve. The Skjonghelleren glacial advance is tied to the Laschamp magnetic excursion about 43 ka (in calendar years), and the younger part is based on ^{14}C dates (although note that the scale in Fig. 2 is given in calendar years). However, there are considerable differences in the older part of the curves,

which can be explained in the following way: The lowest part of the curve in Fig. 2 is based mainly on the stratigraphy at Fjøsanger (Mangerud *et al.*, 1981b). The correlation of the Fjøsangerian Interglacial with the Eemian is well established. However, the dating of the younger stadials and interstadials has been more problematic, and is partly based on correlation with the western European and deep-sea stratigraphy. The author accepts that the Brørup and Odderade interstadials should be correlated with Marine Isotope Substages 5c and 5a respectively (de Beaulieu & Reille, 1992; Behre, 1989; Lowe & Walker, 1997; Mangerud, 1989) although the boundaries probably were not exactly time parallel. The ages of the MISs are estimated to about 105-93 ka for Substage 5c and thus also for Brørup and 85-74 ka for Substage 5a/Odderade (Martinson *et al.*, 1987). This implies that the younger ^{14}C dates are disregarded (about 61 ka) for the Odderade, which have been duplicated several times (Behre & van der Plicht, 1992).

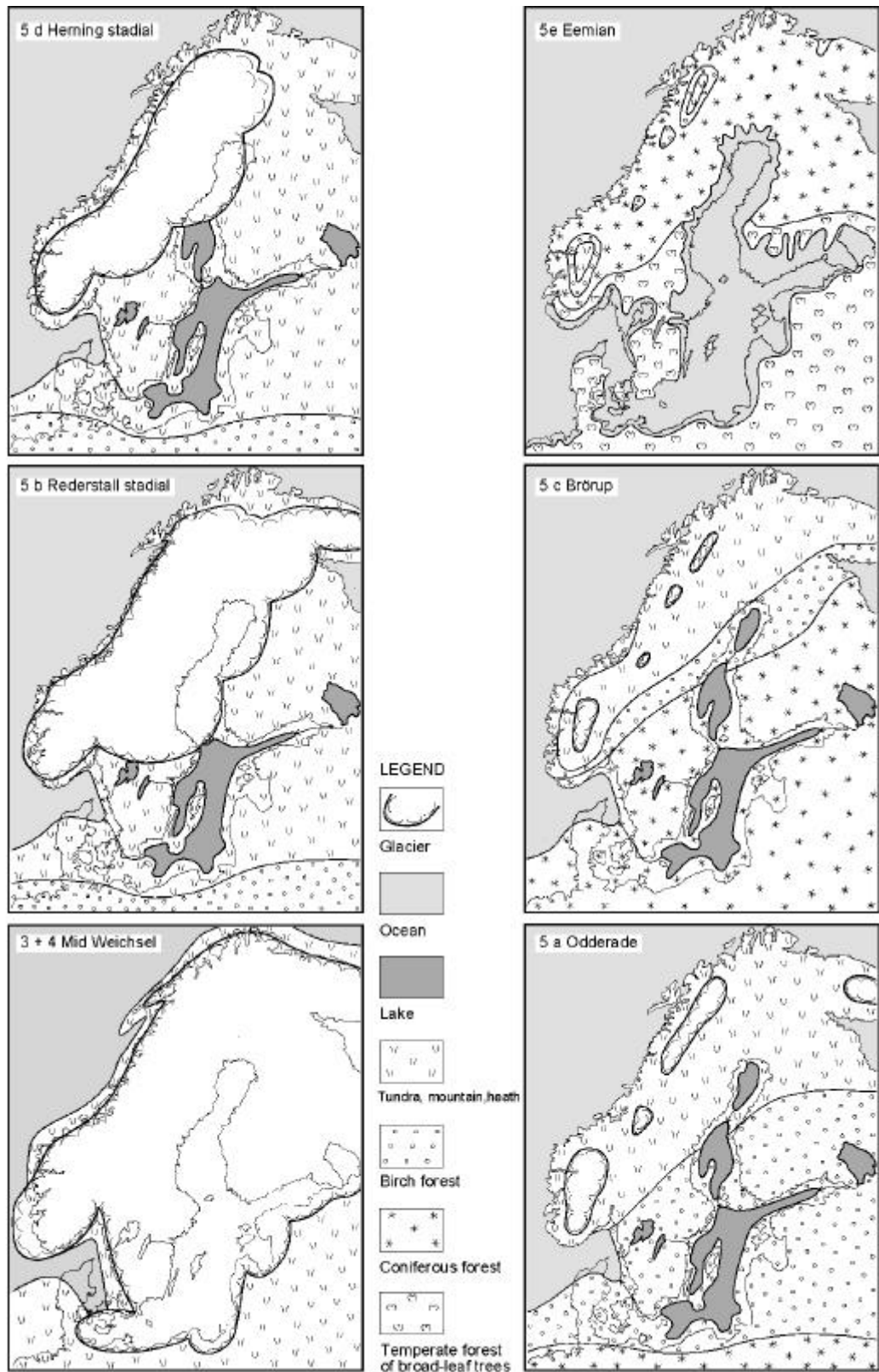


Fig. 3: Sketch maps of the Scandinavian Ice Sheet and surrounding environments during MIS 5e to 3. The data are slightly modified from Lundqvist (1992), who stated that all boundaries were hypothetical and that the maps merely illustrated an interpreted development, although he used the inter-pretations of known sites. Here more extensive glaciation in SW Norway during MIS 5d, 5b and 4 according to Fig. 2 is indicated. In northernmost Norway the ice extent during MIS 5d and 5b are reduced according to Olsen et al. (1996) and L. Olsen (written communication, 2000).

Brørup and Odderade were the last known interstadials with forests in Netherlands-Germany (Behre & van der Plicht, 1992; Zagwijn, 1989), and the author correlates them with two ice-free interstadials in northern Sweden (Lagerbäck & Robertsson, 1988; Lundqvist, 1992). Consequently, the writer postulates that Scandinavia was nearly ice free during the Brørup and Odderade interstadials (Fig. 2). These correlations and interpretations have recently been supported by the results from the Sokli site in northern Finland, which contains a nearly continuous sequence from the Eemian to MIS 3 (Helmens *et al.*, 2000). Sejrup *et al.* (2000), on the other hand, rely more directly on amino-acid dates, and they place for example a major glaciation between 85-70 ka, i.e. during the Odderade interstadial/MIS 5a in my scale, and they propose ice-free conditions in MIS 4. Another difference is that they leave Scandinavia nearly ice-free during Marine Isotope Substages 5b and 5d.

Sejrup *et al.* (2000) “.. note that the new glaciation curve (...), better matches IRD values from the Norwegian Sea (Baumann *et al.*, 1995) than glaciation curves published earlier based on different chronologies (Larsen & Sejrup, 1990; Mangerud 1991c; Baumann *et al.*, 1995)”. The dating and correlation of the individual sites by Mangerud (1991a) and Baumann *et al.* (1995) may of course be wrong. However, if one compares the published glaciation curves with the given IRD curves, the author disagrees with the cited statement from Sejrup *et al.* (2000). They have plotted the Bø Interstadial, when Norway according to their curve was almost ice-free (their Fig. 9), in the period 52-70 ka when the IRD curves (Fig. 2) show the highest peak during the entire Weichselian. In contrast Baumann *et al.* (1995) and the present paper (Fig. 2) postulate that the ice sheet reached the continental shelf during that period (Karmøy Stadial). Sejrup *et al.* (2000), on the other hand, placed this Karmøy glaciation in the period 70-85 ka when the IRD curves show minimum values. The writer will also point out that there is a small increase in IRD during Marine Isotope Substage 5b (about 90 ka), when one assumes the ice front first crossed the coast (Fig. 2), whereas Sejrup *et al.* (2000) postulated no growth of glaciers at that time.

A major new contribution to the Weichselian glacial history of Norway appeared after this paper was written in fact. In the Jæren area (Fig. 1), Larsen *et al.* (2000) demonstrate that the Norwegian Channel ice stream developed in a nearly similar fashion during two earlier Weichselian glaciations as it had during the Late Weichselian. They correlate the youngest advance, represented by the Oppstad Diamicton, with the Skjonghelleren readvance, and the oldest, represented by the Høgemork Diamicton, with the Karmøy readvance (Fig. 2). The author considers that both correlations are probably correct. However, they maintain an age of 80-70 ka for the Karmøy readvance, which the present author finds unlikely. Instead he considers an age corresponding to either MIS 5b or 4 as more probable. When comparing with the IRD curve (Fig. 2), the most probable alternative is MIS 4, extending into stage 3, as discussed above.

Early/Middle Weichselian glacial limits

It is apparent from the above discussion that there is as yet no consensus on the Early/Middle Weichselian glacial history of Norway. However, more important than the disagreement about the interpretation of the few known sites is the scarcity of sites. We simply need more sites to resolve the general stratigraphy, including the timing of the events, and even more sites to be able to map the areal extent of the ice sheets at different times.

In the first attempt to reconstruct the Early (MIS 5d and 5b) and Middle Weichselian (MIS 4) ice sheets of Fennoscandia, the limits along the more than 2000 km long Norwegian coast were based on only four sites/areas (Jæren, Bø, Fjøsanger and Ålesund) (Andersen & Mangerud, 1989). The situation has hardly improved since then. The main new information is the evidence from Jæren discussed above, which shows that in southern Norway the ice sheet twice grew so large that an ice stream developed in the Norwegian Channel (Larsen *et al.*, 2000). The area reconstructions of the ice sheets in Norway still have to be based on observations from these few sites, and on general geological evaluations. The sites are discussed and partly described in the papers cited above (Larsen & Sejrup, 1990; Mangerud, 1991a; 1991b; Sejrup *et al.*, 2000). Primary, and more extensive descriptions for the different sites are for Jæren (Andersen *et al.*, 1987; Larsen *et al.*, 2000; Sejrup *et al.*, 1998), Bø (Karmøy) (Andersen *et al.*, 1983; Sejrup, 1987), Fjøsanger (Mangerud *et al.*, 1981b), Ålesund (Larsen *et al.*, 1987; Mangerud *et al.*, 1981a; Valen *et al.*, 1996).

Figure 3 shows a slightly modified version of the reconstructions by Lundqvist (1992), where the reconstructed ice sheets are not very different from those presented by Andersen & Mangerud (1989). However, Lundqvist included reconstructions for the interstadials, and also the vegetation at different times. Therefore his maps are more instructive and also more provocative for future testing.

A key question is if the ice margin passed the coastline of western Norway during MIS 4-5. According to H. Holtedahl (1993) there is no site that can unambiguously prove whether the ice front reached the continental shelf or not during the Early or Middle Weichselian. In the present author's interpretation (Fig. 2), the ice front passed beyond the coast near Fjøsanger during MIS 5b, and it passed the coast over a wider area during MIS 4 and 3. As discussed above, an ice stream developed in the Norwegian Channel during the two latter events, demonstrating that the ice limit was well outside the coast of southern Norway (Larsen *et al.*, 2000). Within the North Sea Fan, lies a till (M/N) deposited by an ice stream in the Norwegian Channel (Sejrup *et al.*, 2000). These authors conclude that the till is of either Saalian or Early Weichselian age, and they favour the latter interpretation. If correct, it should represent the older of the two ice streams described by Larsen *et al.* (2000), for which the present writer favours a MIS 4 age.

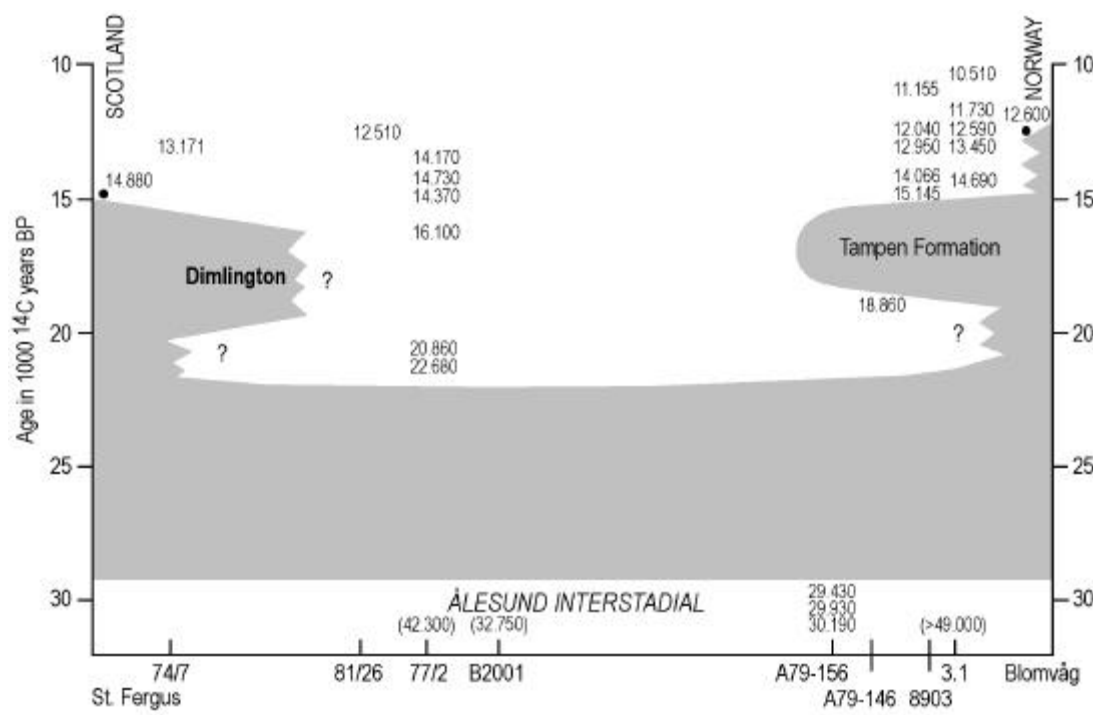


Fig. 4: Time-distance curve for the fluctuations of the ice margins of the British and Scandinavian ice sheets across the North Sea, indicating that the two ice sheets met before about 23 ka. From Sejrup *et al.* (2000). Note that the time scale is in radiocarbon years, whereas in Fig. 2 it is calibrated to calendar years.

THE LATE WEICHSELIAN GLACIAL MAXIMUM

The ice sheet limit on the Norwegian Shelf

An extensive review and synthesis of the Quaternary geology on the Norwegian shelf is given by H. Holtedahl (1993), to which the author refers for general conclusions and for references to the literature. At present there is an apparent agreement among geologists working on the Norwegian shelf that the Late Weichselian ice sheet reached the shelf edge along its entire length from the mouth of the Norwegian Channel nearly to the North Cape. The only probable exception is a segment west of Andøya (Fig. 1), where the limit according to Vorren & Plassen (2002) (and several earlier authors) was located on land. Thus the main features of the mapping of the Late Weichselian maximum by Andersen (1981) are still valid.

The glacial limit is mapped using three criteria: 1) for most of its length by the western limit of the youngest till sheets, or till tongues, mainly mapped by seismic methods; 2) end-moraine ridges; 3) submarine fans built up mainly by debris flows of glacial sediments. More detailed descriptions of the glacial limit are given in the section 'Comments to the ice sheet limit drawn on the map on the CD' below.

The age of the glacial limit

There are few radiocarbon dates that can be used to bracket the age of the glacial maximum on the western Norwegian coast or shelf. The best are probably a set from the North Sea (Fig. 4), indicating a radiocarbon age of between 29-22

ka for the maximum and 15-19 ka for a secondary readvance (Sejrup *et al.*, 1994; 2000). Similar dates were obtained from lake sediments on Andøya in Northern Norway (Alm, 1993; Vorren *et al.*, 1988). The stratigraphical sequences in these lakes have been correlated with the stratigraphy in the adjacent fjord and on the shelf (Fig. 5) (Vorren & Plassen, 2002).

Dates related directly to the ice front have been obtained by King *et al.* (1998), dating glacial debris flows deposited from the ice front onto the North Sea Fan (Fig. 6). Several dates bracketing the last main debris flow unit indicate that the ice front rested at the mouth of the Norwegian Channel from before 23 ka until 16 ka. A thinner debris flow unit above indicates that the ice margin remained close to the mouth of the Norwegian Channel until 15 ka (Fig. 6). Further north, about 64° N, a date of 15 ka was obtained from a tongue of till that almost reached the shelf edge (Rokoengen & Frengstad, 1999).

Radiocarbon dates on bones from the Skjonghelleren Cave, including more than 30 AMS dates in the range 29-35 ka, provide a maximum age for a Skjonghelleren ice advance (Fig. 2) (Baumann *et al.*, 1995; Larsen *et al.*, 1987). This advance is also dated by identification of the 28-29 ka old Lake Mungo palaeomagnetic excursion in clay deposited in a lake dammed in the cave by this ice-advance (Larsen *et al.*, 1987). Thus an ice front passed the coast near Skjonghelleren at about 29 ka. These results were supported by many dates and the palaeomagnetic stratigraphy in another cave (Valen *et al.*, 1996). In the latter cave two dates of 24.5 ka were also obtained indicating a withdrawal of the ice-front at that time.

Two radiocarbon dates of 22 and 20 ka have also been obtained on bones of polar bears in a karst cave in Nordland

(Lauritzen *et al.*, 1996; Nesje & Lauritzen, 1996). These dates also support the suggestion that the ice margin in northern Norway withdrew inside the coastline for a period around the time of the Late Weichselian maximum (Fig. 5).

Olsen (1997) has obtained more than 100 AMS dates from terrestrial organic-bearing sediments with low organic content (0.2-1.5%). A description of the individual sites and details of the dated samples will soon be published (L. Olsen, written communication, 2000). The writer is generally sceptical of dates on samples with such a low organic content. However, Olsen's conclusion is that the main glacial maximum occurred 24-21 ka, with an earlier secondary maximum at 30-29 ka and a later one at 14.5-17 ka, more or less similar to the results cited above.

The conclusion from these observations is that the Late Weichselian ice sheet reached its maximum extent off the coast of Norway relatively early, probably at 24-22 ¹⁴C ka. There were one or more ice front oscillations up to about 15 ka, when the main ice retreat started. However, the writer emphasises that it is highly unlikely that the ice front reacted in unison along the entire Norwegian coast. The maximum position was probably reached at different times. Many more dates distributed along the position of the ice margin will be necessary to resolve the probable asynchronicity of the glacial maximum.

Ice streams on the shelf

A major improvement in our understanding of glacier dynamics and even ice front deposits on the shelf has come from the discovery and interpretation of submarine fans at the mouth of glacial troughs, the so-called 'trough mouth fans', and the existence of distinct ice streams across the shelf during glaciations. A recent review is given by Vorren *et al.* (1998).

The longest ice stream on the Norwegian Shelf was that in the Norwegian Channel (Longva & Thorsnes, 1997; Sejrup *et al.*, 1996; 1998). It was also different from the others in that the channel runs parallel with the coast for some 6-700 km (Fig. 8). This ice stream drained much of the southern part of the Scandinavian Ice Sheet. The huge North Sea Fan was deposited beyond the Norwegian Channel ice stream (King *et al.*, 1996; 1998).

Through detailed morphological mapping of the sea floor, it has been shown that there have been a number of ice streams across the Norwegian shelf (Figs 7 and 8) (Ottesen *et al.*, 2001). There are numerous large, parallel glacial lineations (megaflutes and mega-scale lineations) in the troughs, whereas features diagnostic of glacial flow are absent from the shallow ground. The inference is that there was only slow moving ice in the shallows. However, major trough mouth fans did not form in the front of most of these ice streams. At the mouth of the Sklinnadjupet trough is the morphologically largest end moraine on the shelf, the Skjoldryggen, some 200 m high, 10 km wide and 200 km long (Ottesen *et al.*, 2001).

Comments to the ice sheet limit shown on the digital map on the CD

Whether the Norwegian and British ice sheets met in the North Sea and where the ice margins were located have been long-standing questions. It is now documented that they probably met (Carr *et al.*, 2000; Sejrup *et al.*, 1994; 2000). According to the radiocarbon dates mentioned above (Fig. 4) this maximal position was reached before about 22 ka ¹⁴C years.

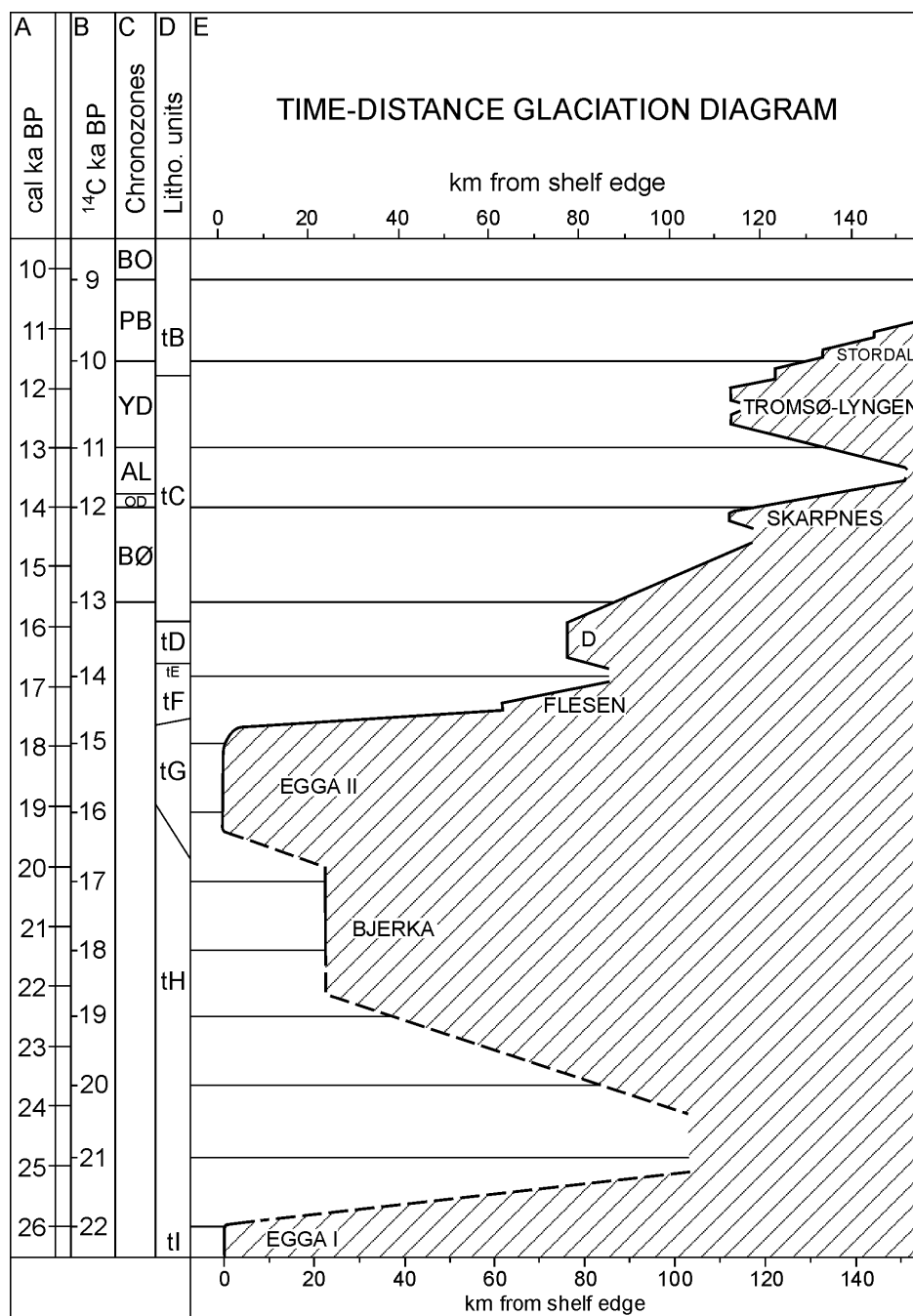
At the mouth of the Norwegian Channel, the limit is placed at the boundary between basal till in the channel and the glacial-debris flows on the North Sea Fan, as identified from seismic signatures by King *et al.* (1998) and King *et al.* (1996). As described above, King *et al.* (1998) dated this limit to 23-16 ¹⁴C ka.

The huge, post-glacial Storegga Slide is located along the shelf edge (between about 62° 30' and 64° 40') north of the Norwegian Channel (Bugge, 1980; Bugge *et al.*, 1978; Jansen *et al.*, 1987; H. Haflidason, oral communication, 2000). Its backwall extends for approximately 300 km along the shelf edge. In this area the upper formation on the shelf is a 10-40 m thick till (the Storegga Moraine) which is cut by the slide (Bugge, 1980; Bugge *et al.*, 1978). The till was probably deposited during the Late Weichselian maximum, and the outer limit of the till sheet was therefore removed by the slide. On the map the limit has been drawn as a stippled line across the slide scar.

About 64° N the western limit of the Storegga Till sheet turns eastwards (Bugge, 1980). It is there correlated with till tongue 24 (Rokoengen & Frengstad, 1999) and is underlain by the older till tongue 23. The latter is mapped to a water depth of about 500 m along the shelf edge, and radiocarbon dated to about 15 ka (Rokoengen & Frengstad, 1999). Between 64° and 67° 30'N, the author used the limit of till tongue 23, as mapped by King *et al.* (1987) and Rokoengen & Frengstad (1999). Both till tongues 23 and 24, and thus the Skjoldryggen moraine, were according to these authors deposited during the Late Weichselian glacial maximum. The Skjoldryggen moraine crosses the mouth of the Sklinnadjupet trough and was formed by an ice stream out this trough (Ottesen *et al.*, 2001).

Another major ice stream that reached the shelf edge is mapped in the Trænadjupet trough (67° N) (Ottesen *et al.*, 2001). North of the trough the thickness of Quaternary sediments is less than south of the trough, and the till tongues could not be traced there (King *et al.*, 1987). However, the youngest till sheet generally thickens towards the shelf edge, and probably this records the Late Weichselian ice sheet limit, although the till is not dated (Holtedahl, 1993; Rokoengen *et al.*, 1977). These authors placed the Late Weichselian limit along the shelf edge until the edge turns away from the coast near the southern boundary of the Barents Sea. However, an alternative interpretation is that the north-western part of Andøya, and thus the continental shelf, remained ice-free (Vorren & Plassen, 2002). On the map the author has followed the

Fig. 5: Time-distance diagram showing the ice-front variations near Andøya, Northern Norway. From Vorren and Plassen (2002).



latter view, if the former is correct, the limit should simply be drawn along the shelf break.

Vorren & Kristoffersen (1986) mapped a system of end moraines (shown with dashed line on the map) in the south-western corner of the Barents Sea that were considered candidates for the junction between the Scandinavian and Barents ice sheets. However, Sættem (1990) has subsequently mapped some glaciotectionic structures further west, where a minimum age of 13 ka was obtained. On the map the author follows the results of Landvik *et al.* (1998) and draw the limit along the shelf edge, as has also been done in the chapter on the Barents Sea (Svendsen *et al.*, this volume).

Ice thickness – Did nunataks exist in Norway?

The surface geometry, and thus the thickness, of the Scandinavian Ice Sheet are much more poorly known than its areal limits. The author will therefore discuss the problems at some length. For more than a hundred years there has been discussion as to whether mountain peaks in Norway protruded as nunataks above the ice surface during the Quaternary glaciations, especially during the Late Weichselian glacial maximum. Recent reviews of the discussion are given in Sollid & Sørbel (1979), Mangerud *et al.* (1979), Nesje *et al.* (1987; 1988) and Nesje & Dahl (1992). Earlier the main focus was whether plants had

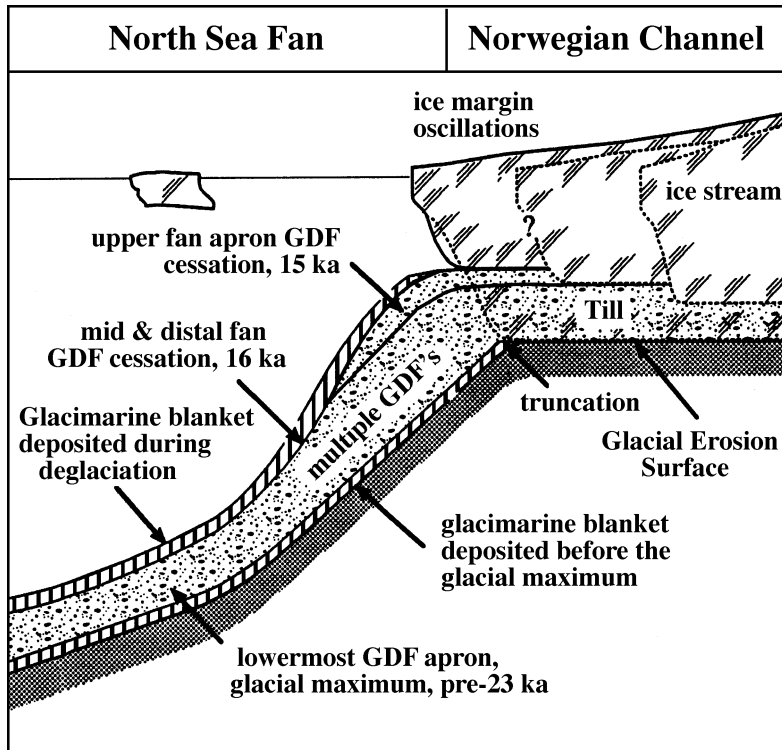


Fig. 6: Schematic diagram showing the development of the Norwegian Channel trough-mouth fan during the Late Weichselian glacial maximum, slightly modified from King *et al.* (1998). The lowermost glacimarine blanket was deposited during the glacial advance, after the Ålesund Interstadial (Fig. 2). When the ice stream in the channel reached the slope break, glacial debris flows (GDF) travelled down the fan slope, depositing most of the sediments on the fan. The start of this maximum phase is not accurately dated, but was probably about 25–27 ka (in radiocarbon years) whereas the end is dated to 16 ka. An upper GDF indicates that the ice margin had retreated only a short distance at 15 ka.

survived on nunataks or not, whereas here a three-dimensional reconstruction of the Scandinavian Ice Sheet is considered.

Nesje *et al.* (1987) and Nesje & Dahl (1992) argue that there were ice-free summits across much of southern Norway during the Late Weichselian glacial maximum, using the altitudinal distribution of autochthonous block fields as the main argument (Fig. 9). They plotted altitudes of summits with and without block fields and found a geographically consistent altitudinal boundary between the two types. They postulate that the block fields pre-date the Late Weichselian, and that the lower limit represents a glacial erosional boundary showing the maximum elevation of the Late Weichselian ice sheet surface (Fig. 9). They also maintain that their reconstruction is supported by the distribution of alpine pinnacle topography without indications of glacial moulding, and also by the distribution of 'refugia plants'. In the Nordfjord area their interpretation has subsequently been supported by cosmogenic nuclide exposure ages giving 55 ka (^{10}Be age) or 71 ka (^{26}Al age) for bedrock surfaces in the block field, and 21 ka on bedrock below the limit of block fields (Brook *et al.*, 1996). Another area with pinnacles that have traditionally been considered to have remained ice-free is western Andøya in northern Norway (Fig. 1). There this interpretation is supported by mapping of moraines and by the stratigraphy in lakes, as mentioned above (Vorren & Plassen, 2002). The hypothesis of ice-free nunataks is attractive to explain the cited observations; it is difficult to envisage an eroding glacier overriding the block fields, and for the writer even more so for the tall and narrow pinnacles. Therefore these

arguments have been used in favour of the nunatak theory for more than a century. The number of observations and the consistent pattern in the Nordfjord-Møre area in western Norway (Fig. 10) seem to favour that the interpretation might be correct in that area (Nesje *et al.*, 1987; Sollid & Sørbel, 1979). In this area it is also glaciologically reasonable because the deep fjords would efficiently drain the ice flow. However, the interpretation becomes more difficult, or rather impossible, when the limit is extended further across southern Norway, which would imply a maximum ice thickness of less than 800 m, and a maximum altitude of the ice sheet of about 1600 m a.s.l. in the eastern ice divide areas (Nesje & Dahl, 1990; Nesje *et al.*, 1988). A closer look at some of the arguments therefore seems necessary.

Block fields are not unambiguous proof that ice has not overridden the site. On the contrary, it has been demonstrated that both block fields and other unconsolidated sediments have survived below the Scandinavian Ice Sheet and yet show little evidence of glacial overriding (Kleman, 1994; Kleman & Borgström, 1990; Kleman & Hättestrand, 1999; Lagerbäck & Robertsson, 1988). In fact, it is just as difficult to understand how sharp-ridged eskers have survived below glaciers (Lagerbäck & Robertsson, 1988), as it is the pinnacles discussed above. Meltwater channels from the last deglaciation cut through block fields at many localities in the Norwegian and Swedish mountains demonstrating that the ice-sheet surface was above the lower limit of block fields (Borgström, 1999; Sollid & Sørbel, 1994). All of the cited authors argue that the unconsolidated deposits, in most cases, survived beneath

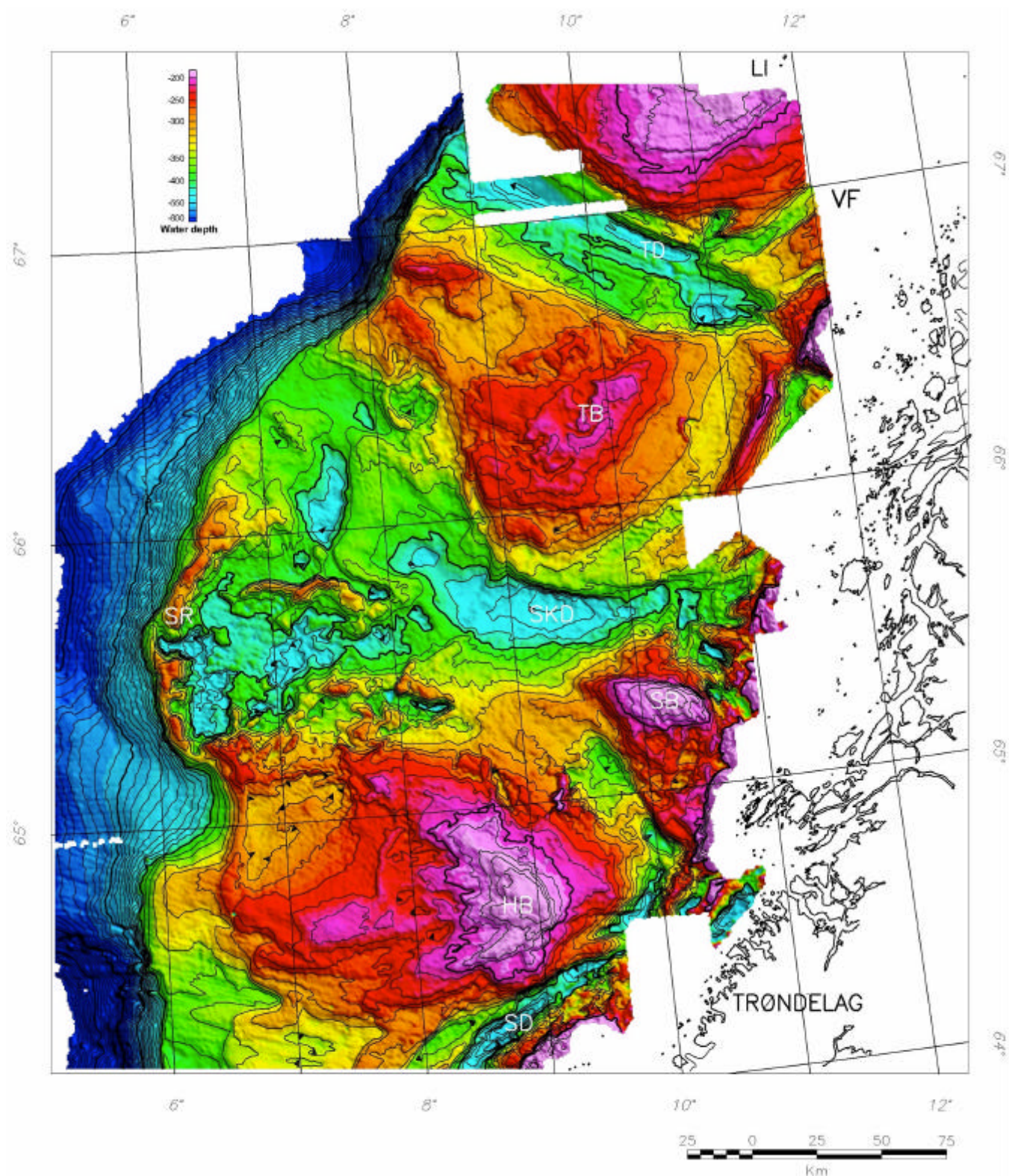


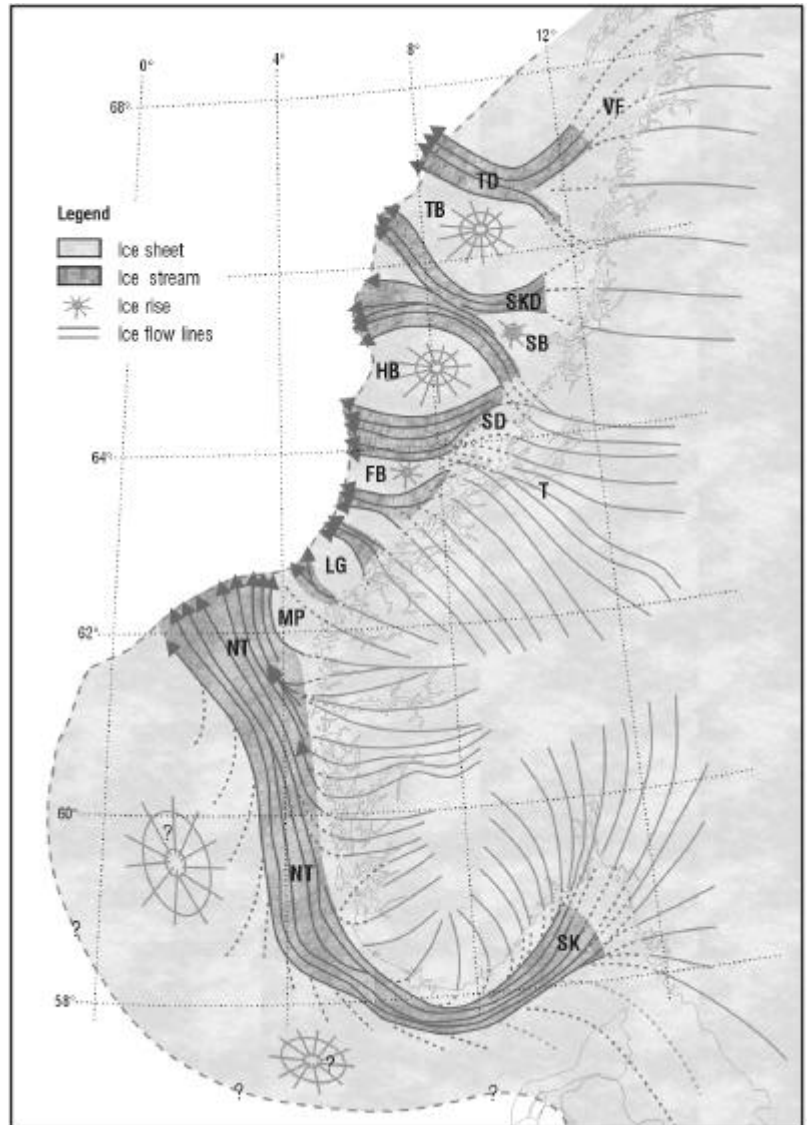
Fig. 7: Relief map from the Norwegian shelf from 64° to 67° N from Ottesen et al. (2001). Contour interval 20 m. LI- Lofoten Islands, VF- Vestfjorden, TD- Trænadjupet, TB- Trænabanken, SKD- Sklinnadjupet, SR- Skjoldryggen, SB- Sklinnabanken, HB- Haltenbanken, SD- Suladjupet.

cold-based ice. In addition the summits with block fields would certainly have lain in the cold-based zone if they were covered by glacial ice. In reply to this Nesje & Dahl

(1990) argue that the limit between cold and warm-based ice should not be parallel to the ice surface, and as mentioned above, this could be a valid argument for the

Fig. 8: Interpreted ice-flow model during Late Weichselian glacial maximum from Ottesen *et al.* (2001).

VF-Vestfjorden,
HB-Haltenbanken,
SKD-Sklinnadjupet,
TD-Trænadjupet,
SB-Sklinnabanken,
SD Suladjupet,
FB-Frøyabanken,
MP-Måløydjupet,
NT-Norwegian Trench (also translated as the Norwegian Channel),
TB-Trænabanken,
LG-Langgrunna,
SK-Skagerak,
T-Trondheim.



Nordfjord-Møre area where this limit is very consistent. However, an alternative explanation could be that the block fields were covered by cold-based ice, and that the lower limit does not show the boundary to warm-based ice, but a later erosion limit formed at a younger and lower ice-surface.

The botanical argument, first presented around 1890, was in fact the one that started the discussion about ice-free nunataks (Birks, 1993; Mangerud, 1973). The main argument is that some mountain plants, with particular emphasis on endemics and West-Arctic species, have a bi-centric distribution in Norway, which suggests that they survived the glaciation close to these centres. However, it has recently been demonstrated that this distribution pattern can be explained by other factors, and it has no weight as argument for ice-free nunataks (Birks, 1993).

Fjeldskaar (2000) has tested the thin ice sheet interpretation by isostatic modelling. Using the ice sheet of Nesje & Dahl (1990) he found that the predicted tilt of deglacial shorelines was less than 50% of the observed tilt,

and he concluded that the results "seem to rule out the thin ice model as a viable option". Lambeck *et al.* (1998; 2000), on the other hand, obtain moderate ice thickness from reverse modelling based on observed sea level curves.

Most glaciological models (e.g. Boulton *et al.*, 1985; Dowdeswell & Siegert, 1999; Holmlund & Fastook, 1993) predict considerably thicker ice than that reconstructed by Nesje & Dahl (1990; 1992), especially in central areas. However, the ice thickness in climate-driven models are very dependent on the amount of precipitation and the duration of ice build up, and both factors are partly dependent on assumptions in the models. All models are also so simple that they cannot be used to reconstruct the regional ice thickness in any detail. Certainly, they cannot be used as an argument against empirical reconstructions in the fjord areas, such as Nesje *et al.*'s reconstruction in Nordfjord.

The writer concludes that the lower limit of block fields is not a unique criterion that can be used to map the ice sheet surface during the Late Weichselian glacial maxi-

Fig. 9: Map showing block-fields in southern Norway (black spots). The main flow lines and tentatively con-structed contour lines of the ice sheet during the Late Weichselian glacial maximum in southern Norway are also indicated (adapted from Nesje et al., 1988). The present author assumes that the ice sheet was thicker and covered all the block-fields in the eastern part.

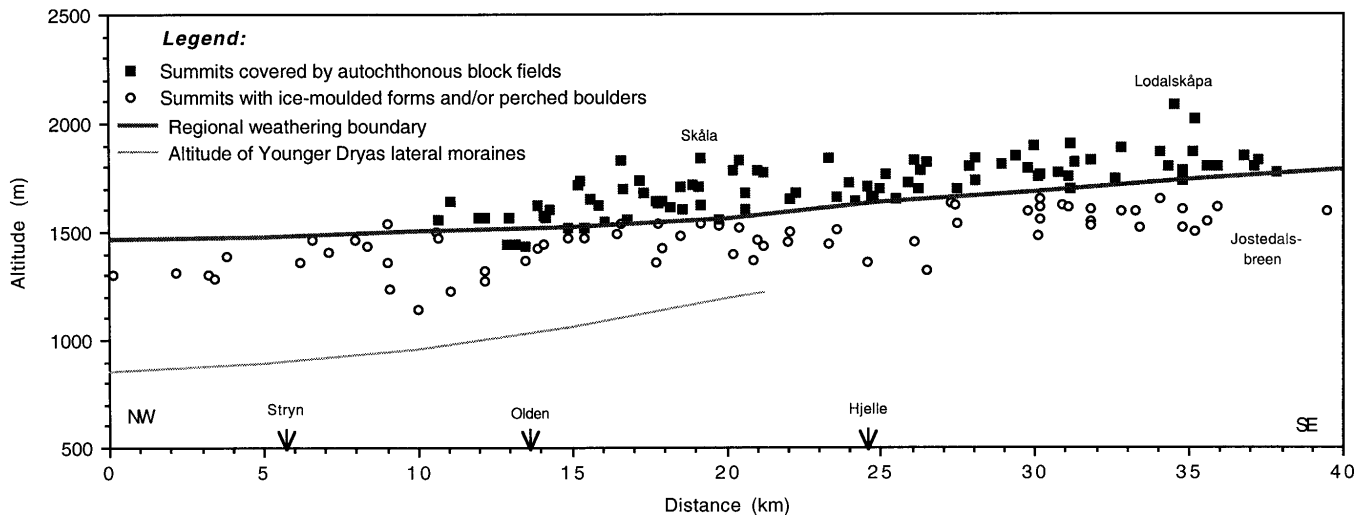
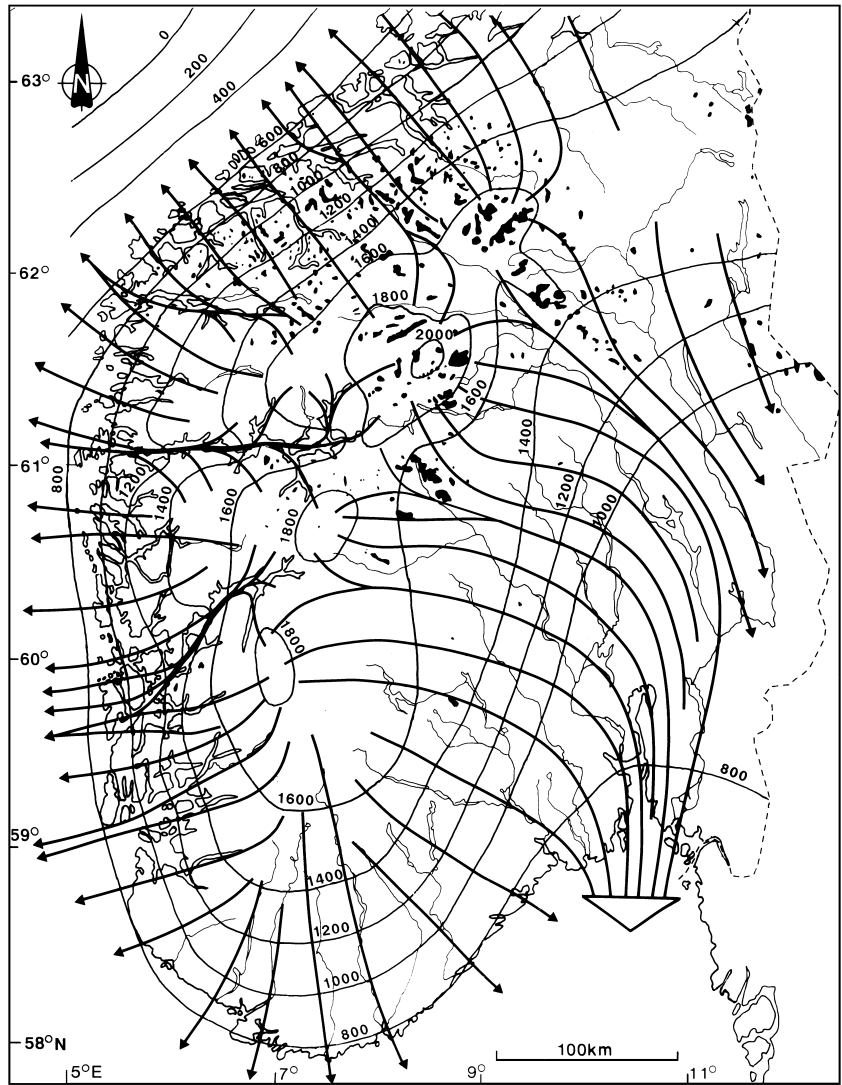


Fig. 10: The distribution of summits, with and without blockfields are plotted in a NW-SE cross section across inner Nordfjord. The lower boundary of the blockfields is assumed to represent the Late Weichselian glacial limit. The Younger Dryas moraines are also shown. Taken from A. Nesje (written communication, 2000), updated from Brook et al. (1996).

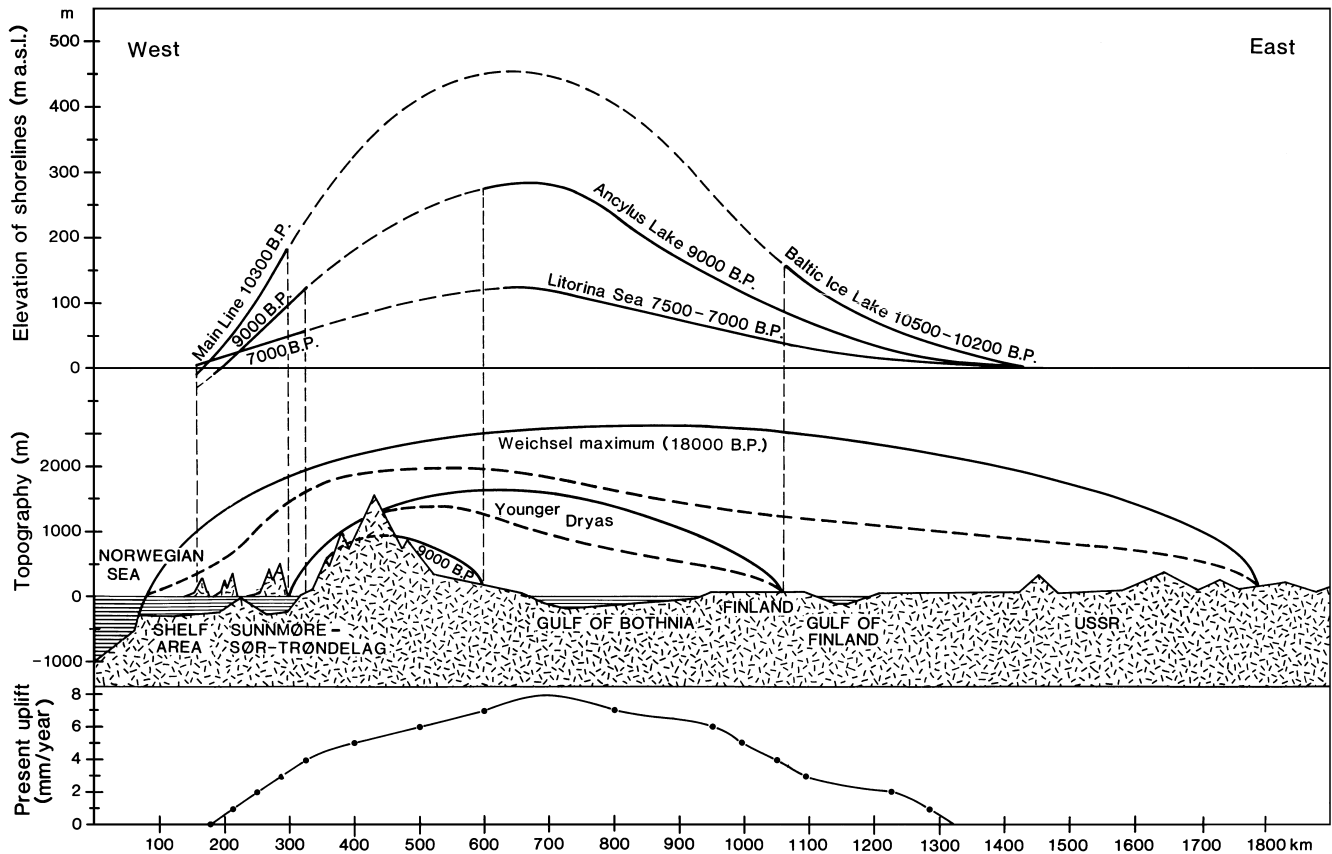


Fig. 11: A profile across Fennoscandia adapted from Svendsen and Mangerud (1987). Upper panel: Shore lines of different ages. Middle panel: Alternative ice-sheet profiles for the Late Weichselian maximum and the Younger Dryas. Full lines show maximum thickness, stippled lines minimum thickness. Lower panel: Present day uplift.

imum, although the interpretation presented for Nordfjord and some other coastal areas may, nevertheless be correct. The conflict with the results based on isostatic modelling has made this problem even more urgent to solve, because isostatic modelling, beside glaciological modelling, is the most used technique to determine past ice sheet thickness world wide (e.g. Dowdeswell & Siegert, 1999; Lambeck *et al.*, 2000; Peltier, 1994).

Here the writer supports and further develops an hypothesis proposed by Longva & Thorsnes (1997). For a century it has been accepted that the first Late Weichselian glacial advance to northern Denmark was from Norway (Sjørring, 1983), an interpretation supported by all recent studies (Houmark-Nielsen, 1999). This conclusion, mainly based upon numerous Norwegian erratics in the north Danish tills, was also supported by till fabric and glaciotectionic deformation features, which showed flow from the north. It is difficult to envisage an ice flow carrying erratics from Norway to Denmark if there was an active ice stream in the Norwegian Channel. In fact it appears impossible if that ice stream was developed as far upstream, as shown on Fig. 8, because flow from Norway would simply be 'cut off' and drain into the ice stream. Longva & Thorsnes (1997) described three generations of ice flow directions based on the sea-floor morphology in

the outer part of Oslofjorden. Deep, diffuse furrows with a direction showing that the ice crossed the Norwegian Channel represent the oldest generation. It is interpreted to show the ice flow to the Late Weichselian ice limit in northern Denmark (Longva & Thorsnes, 1997). Deep furrows, with a more south-westerly direction represent the next generation. This change in direction was likely the result of ice culmination over Central Norway-Sweden moving eastwards. The youngest flutes show a very plastic ice flow along the Norwegian Channel, and are interpreted to represent an ice stream in the channel (Longva & Thorsnes, 1997).

The observations cited from Oslofjorden are compatible with a hypothesis that there first developed a thick Scandinavian ice sheet, for example as the one shown by Kleman & Hättestrand (1999). This ice sheet may have developed without peripheral ice streams, or at least without an ice stream in the Norwegian Channel. Ice from Norway could then move across the Norwegian Channel to Denmark and the North Sea. This ice sheet could have had a steeper surface slope, although it still moved on deformable beds in peripheral areas. In Denmark and the shallow part of the North Sea, there was probably permafrost during the advance, favouring a steeper ice surface (Clark *et al.*, 1999), although that could not have



Fig. 12: The Younger Dryas moraines around Fennoscandia slightly modified from Andersen *et al.* (1995a). The names on the moraines are given with bold letters. Other geographical names used in the discussion of the Younger Dryas moraines are marked with normal text.

been the case in the deep Norwegian Channel. All summits in Central Norway could in this early phase have been covered by frozen-bed ice. Subsequently the ice streams developed, probably from the shelf edge and propagating upstream. That would lead to a major drawdown of the ice-sheet surface, and possibly to a situation similar to that reconstructed by Nesje & Dahl (1990; 1992) (Fig. 9).

Cross-profiles across the Scandinavian Ice Sheet according to Svendsen & Mangerud (1987) are shown in Figure 11. The writer considers that the pattern of the profile of the minimum model for the Late Weichselian maximum probably is correct, showing low surface slopes on deformable beds across the shelf in the west and in eastern areas. However, it is assumed that ice thickness was closer to the maximum model over Scandinavia. The Younger Dryas ice surface profile was probably closer to the shown minimum model.

THE YOUNGER DRYAS

The Younger Dryas moraines constitute the backbone of reconstructions of the deglaciation history of Norway, and indeed of all of Fennoscandia. End moraines from this period have been mapped more or less continuously around

the entire former Scandinavian Ice Sheet (Fig. 12) (Andersen *et al.*, 1995a). One of the Younger Dryas moraines in southern Norway was interpreted as an end moraine by the Norwegian geologist Esmark already in 1824 (Andersen *et al.*, 1995b), and that was the first time it was concluded that there had been a major ice sheet over Scandinavia. The large Ra moraines around Oslofjorden were recognised in the middle of the 19th century. However, mapping along the long western and northern coasts was not completed until about a decade ago. As shown below, many problems still remain for the course of the main moraines, but even more so for their accurate dating, the distance of the readvances, and the geometry of the ice surface.

Dating problems

There are three main problems with ¹⁴C dates that are relevant for the accurate dating of Younger Dryas glacial events in Norway. First, the calibration scale to calendar years is not well established through the Younger Dryas and Allerød. Secondly, there are plateaux in the radio-carbon scale during the Younger Dryas, including one at the Younger Dryas/Preboreal boundary, so that the

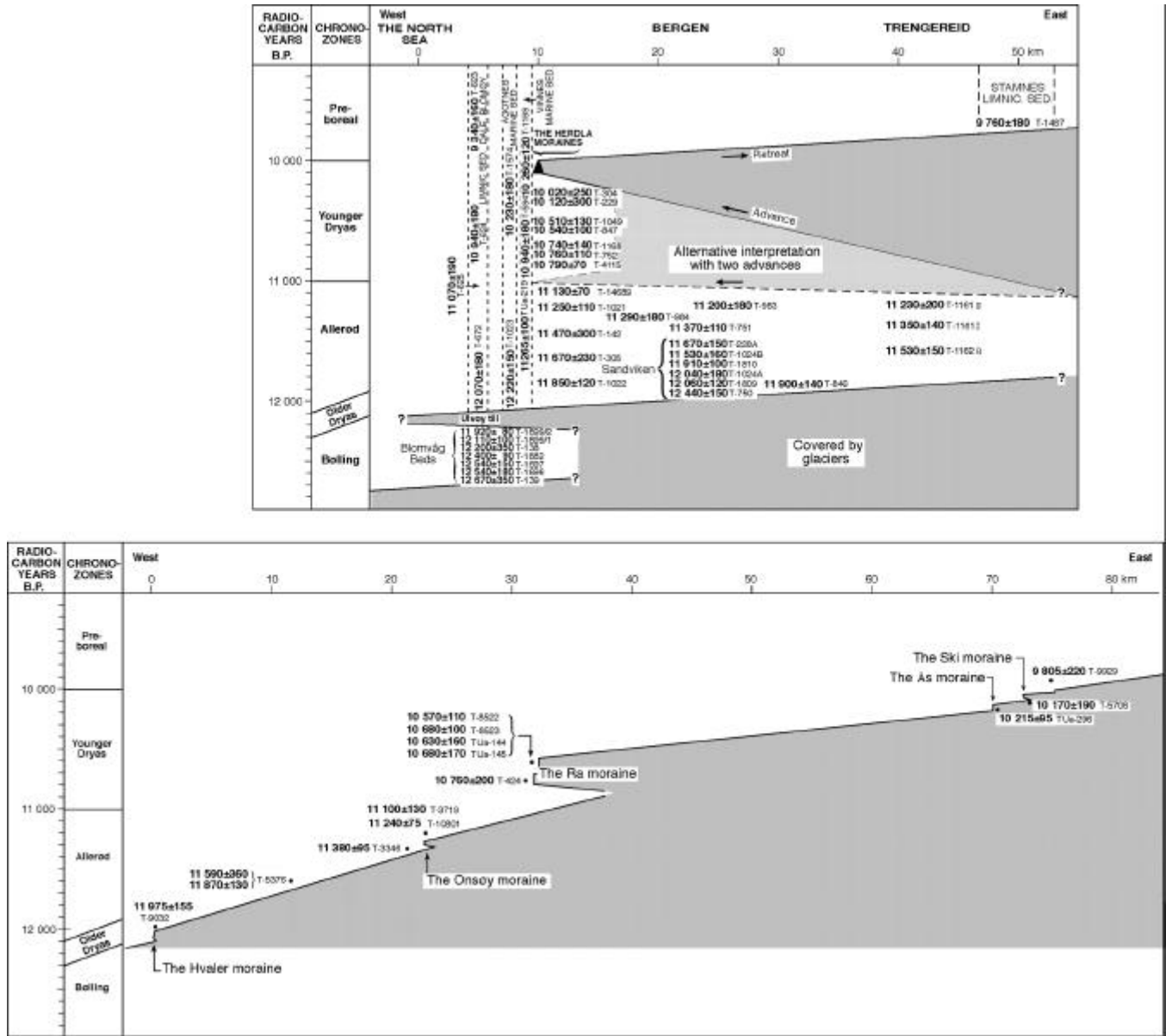


Fig. 13: Upper panel: Ice-front fluctuations in the Bergen district, from Mangerud (2000). Lower panel: Ice-front fluctuations on the east shore of Oslofjorden, redrawn from Andersen *et al.* (1995b). The location and details about the radiocarbon dates are provided by R. Sørensen (written communication, 2000). Most of the dates are given in Andersen *et al.* (1995b) and Sørensen (1999). The minimum date for the Hvaler Moraine is from Bergstrøm *et al.* (1992). The two diagrams are drawn with the same scale and placed so that the main Younger Dryas moraines (Herdla and Ra) are aligned.

boundary is difficult to identify using dates (Gulliksen *et al.*, 1998). Thirdly, and most important, is the uncertainty related to the marine reservoir age, because most ^{14}C dates of the Younger Dryas moraines in Norway are performed on marine molluscs. Uncertainties in the reservoir age hamper precise comparison between dates on marine and terrestrial materials. Conventionally all dates of marine fossils from the Norwegian coast are corrected for a reservoir age of 440 years (Mangerud & Gulliksen, 1975), although it has been known for a long time that the reservoir age could have varied backwards in time (Mangerud, 1972). Until recently, however, the magnitude of this variation has been unknown. For the Allerød, the

marine reservoir age is about 380 years for western Norway, identical to the present day reservoir age, if both are calculated the same way (Bondevik *et al.*, 1999). For the Younger Dryas, the reservoir age is so far only estimated for the time of the Vedde Ash fall (Mangerud *et al.*, 1984). For benthic forams from the floor of the Norwegian Channel, Haflidason *et al.* (1995) obtained a reservoir age of 800 years at Vedde Ash time, whereas Bondevik *et al.* (2001) obtained 610 ± 55 years for shallow marine shells at the coast. The latter value is considered most relevant for dates on uplifted marine deposits. If this value is correct, it implies that further 170 years should be subtracted from the ^{14}C age of molluscs of mid-Younger

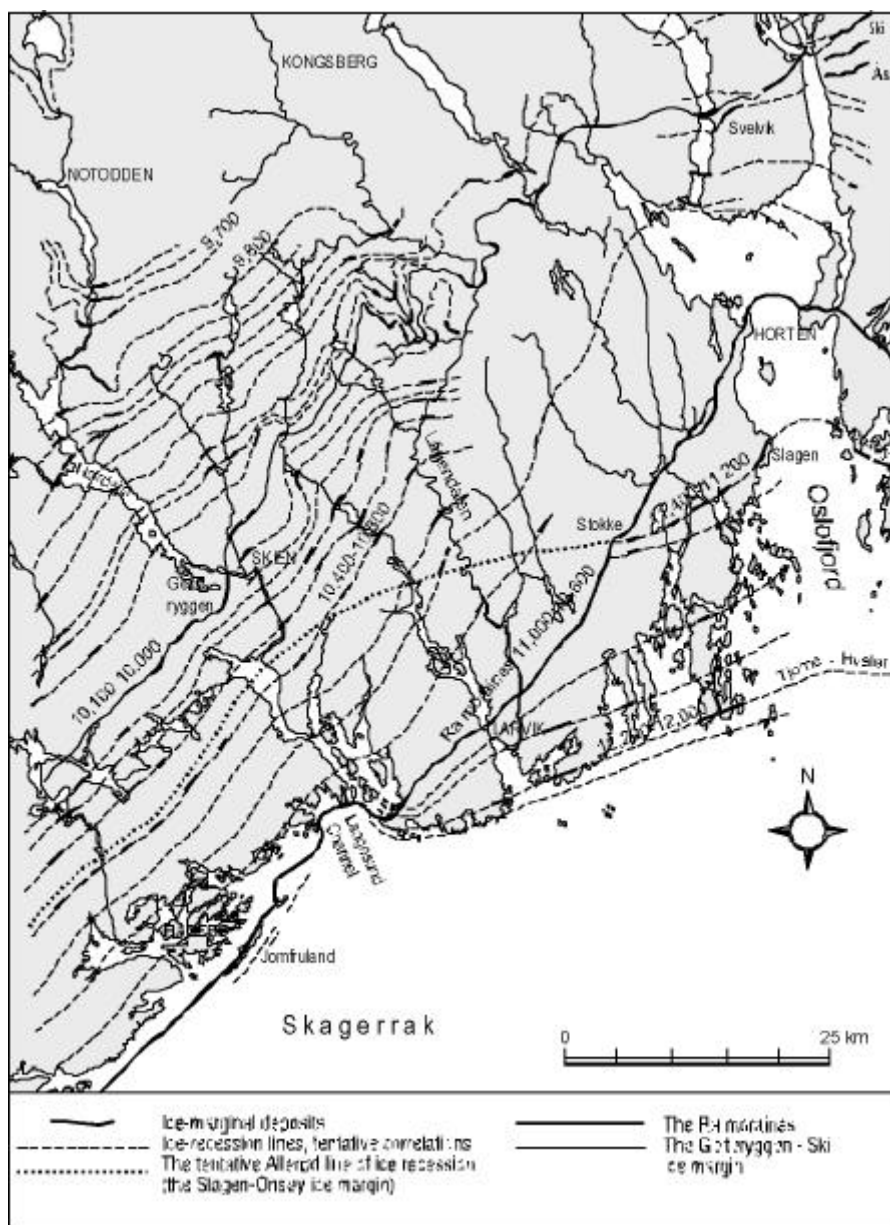


Fig. 14: Map of moraines and constructed retreat lines west of Oslofjorden, slightly modified from Bergstrøm (1999).

Dryas age in order to make them comparable with the ^{14}C age of terrestrial fossils. This is certainly only little, but still enough that some moraines that have during the last decades been considered to be of late Younger Dryas age, based on mollusc dates, might in fact be of early Pre-boreal age.

Asynchronous moraines and the major re-growth of ice in SW-Norway

In spite of the uncertainties with dates indicated above, it appears quite clear that the outermost and largest Younger Dryas moraines are asynchronous around Fennoscandia (Mangerud, 1980). In Finland, Sweden and eastern Norway the main moraines were formed during the early or middle part of the Younger Dryas. In these eastern

areas, the readvances were relatively small and there was a net retreat during the Younger Dryas (Fig. 13, lower panel). In the Bergen area, western Norway, the ice sheet readvanced during the entire Younger Dryas, and formed the Herdla moraines at the very end of the Younger Dryas (Fig. 13, upper panel). Therefore, although the Younger Dryas moraines are mapped morphologically continuously around Scandinavia (Fig. 12), these moraines represent an asynchronous line.

It is apparent from Fig. 13 that the asynchronicity of the Younger Dryas moraine in southern Norway mainly results from a long-lasting readvance in the western areas. This problem will be discussed in some detail, partly because it has interesting implications, and partly because the author is familiar with the observations.

The dynamics of the ice front are well documented on the two shores of the Oslofjorden (Andersen *et al.*, 1995b;

Bergstrøm, 1999; Sørensen, 1992) (Fig. 14). On the east shore there was a nearly continuous retreat of the ice front, interrupted only by minor readvances or halts (Fig. 13, lower panel). Between 12 and 10 ka there was a net retreat of more than 70 km, and during the Younger Dryas alone, a net retreat of 30 km. The retreat on the east shore was mirrored on the western shore between 12-11 ka. However, from about 11 ka the ice front on the west shore readvanced with increasing amplitude towards southwest. At Horten, where the Ra moraines cross the Oslofjorden, there was only a minor readvance, whereas at Stokke the Ra crosses the Slagen-Onsøy moraines (Fig. 14). Around the Langesund Channel, the ice front readvanced at least 10 km and at the Ra-time (about 10.6 ka) had the same position as at 12.2-12 ka. This latter reconstruction is similar to the reconstruction in the Bergen area, where the ice front during the Younger Dryas also reached its 12-ka position (Fig. 13, upper panel). However, near Langesund the ice front retreated some 25 km, to the Geiteryggen-Ski moraine, during the later part of the Younger Dryas (from 10.6 to 10.0 ka). In contrast, in the Bergen district, the readvance to the Herdla moraine continued until the very end of the Younger Dryas. If correct, this means that moraines corresponding to the Geiteryggen-Ski moraine somewhere further to the SW had to cross the Ra moraine and connect with the Herdla moraine. This crossing point is yet to be identified.

The readvance in the Bergen area is only documented for a length of about 40 km, although from the fauna at the easternmost site it is thought to have been larger (Andersen *et al.*, 1995b). The readvance occurred along fjords several hundred metres deep, so that the ice reached a thickness of 800-1200 m in fjords that had been ice free during the Allerød (Andersen *et al.*, 1995b). Thus the net accumulation of snow during the Younger Dryas must have been considerable, despite the estimate that winter precipitation was only 60% of the present (Dahl & Nesje, 1992).

The distance of a glacial readvance is difficult to plot, because the mapping requires that some datable sediment survived glacial erosion during the readvance. Therefore our knowledge about the Younger Dryas readvance is certainly incomplete. However, the major readvance which culminated in late Younger Dryas, was apparently confined to the southwestern coast of Norway, from the southern tip to somewhat north of Sognefjorden (Fig. 12). A rise in relative sea level (transgression) of up to 10 m is recorded in an area which coincides with the area of the Late Younger Dryas readvance (Anundsen, 1985). The interpretation has been that the relative sea level rise was caused by the combined effect of three factors. 1) The ice growth slowed or halted the glacio-isostatic uplift, 2) eustatic sea level rise and 3) the change in the geoid due to the gravity effects of the advancing ice sheet (Anundsen & Fjeldskaar, 1983; Fjeldskaar & Kanestrøm, 1980). In the Bergen area, relative sea level at the end of the Younger Dryas was as high, or higher, than during the deglaciation about 12 ka (Anundsen, 1985; Krzywinski & Stabell, 1984). At the position of the Younger Dryas ice margin

near Bergen, relative sea level was close to 60 m above the present sea level at both 12 and 10 ka (Lohne, 2000). The implication is that the ice load during the Younger Dryas was almost the same as the load during the deglaciation, including the isostatic 'memory' of the glacial maximum load. Certainly, much of the isostatic rebound after the glacial maximum occurred during thinning and retreat of the ice sheet, before the area became ice-free. However, the rising relative sea level during the Younger Dryas in these areas is certainly consistent with considerable ice growth across large mountainous areas in south-western Norway.

It was earlier explained that the large readvance in western Norway, compared to the smaller glacial fluctuations in eastern areas and also in Trondheimsfjorden, mainly as a result of topographic and glaciological effects (Mangerud, 1980). However, here it should be stressed that there must also have been considerably more (snow) precipitation in south-western areas compared to other parts of the ice sheet. This was probably a result of dominant south-westerly winds (Larsen *et al.*, 1984).

Comments to the Younger Dryas moraines on the digital map on the CD

A detailed description of the Younger Dryas end moraines in Norway was given in a recent review paper (Andersen *et al.*, 1995b), to which is referred for descriptions and also for more complete references to the literature. In the following the writer mainly comments on new observations and disagreements from the results presented by Andersen *et al.* (1995b), starting in the southeast and following the coast westwards and northwards. The digital map on the CD is much more detailed than the map in Andersen *et al.* (1995b). A number of scientists have therefore examined and improved the map according to published maps and in many cases also unpublished new results. The author has mentioned through the area descriptions below who has examined and contributed to the respective areas, but the writer is certainly responsible for any errors.

The classical view for the Oslofjorden area was that the Ra moraines represented the Younger Dryas, and that the Ås, Ski and younger moraines were of Preboreal age (O. Holtedahl, 1960). New radiocarbon dates subsequently indicated that the Ås and Ski moraines were of (late) Younger Dryas age (Sørensen, 1979), a view that has prevailed until today (Andersen *et al.*, 1995b; Bergstrøm, 1999). However, the moraines are dated mainly by means of marine molluscs and if the reservoir age for the Younger Dryas is larger than 440 years, as discussed above, the Ås-Ski moraines would possibly be of Preboreal age. This will probably not be resolved without an accurate correlation of the moraines, or the corresponding shorelines with well-dated lacustrine sequences. Intuitively, the writer finds it probable that the Ski moraine indeed represents the end of the Younger Dryas, because even with a higher reservoir age, the ice withdrew from the Ra moraine well before the end of the Younger Dryas. The Ski moraine is a relatively

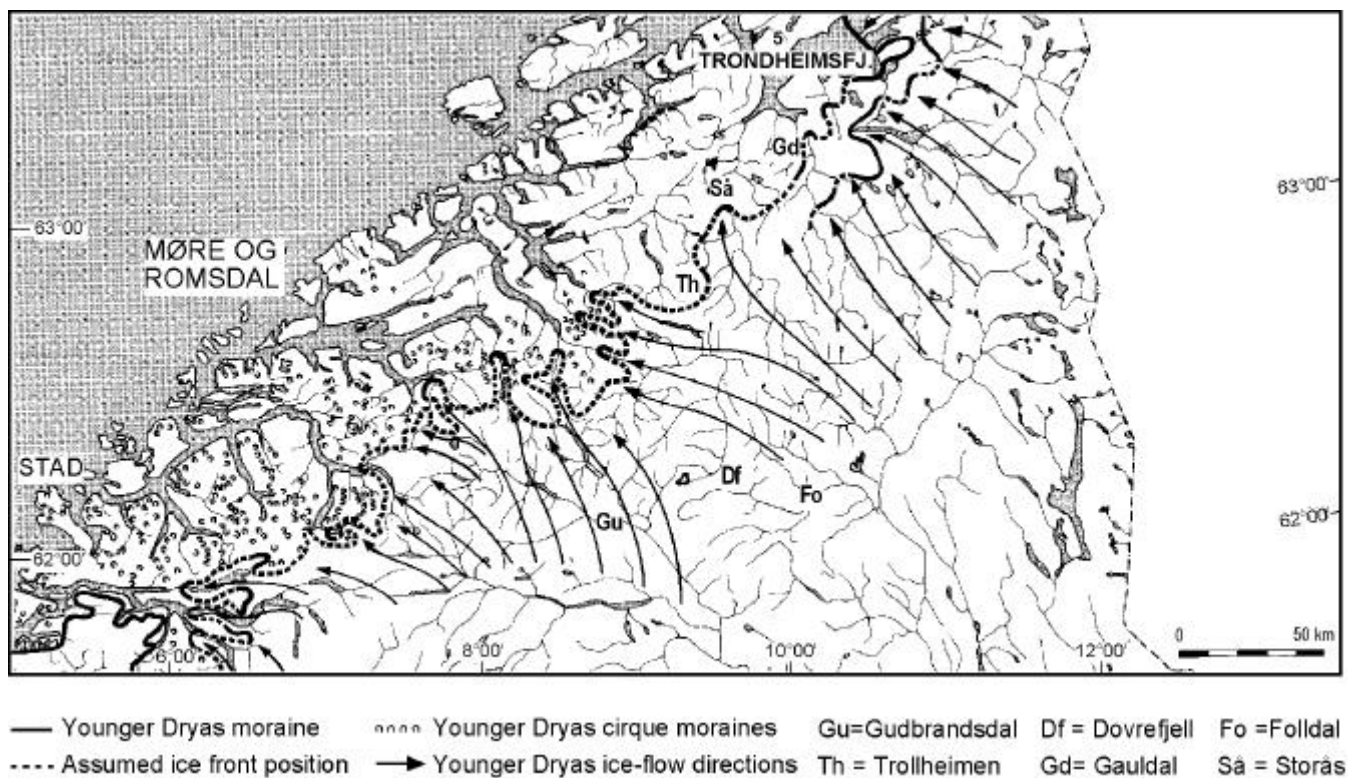


Fig. 15: Map of the Younger Dryas moraines in the Trollheimen - Trondheimsfjord district, modified from Sollid & Reite (1983).

distinct moraine that probably corresponds in time to the Herdla moraine in western Norway (Fig. 13). On the map, for this area controlled by B. Bergstrøm and R. Sørensen, the Ås and Ski moraines are therefore retained. In Sørlandet, the moraine is drawn according to the detailed map in Andersen (1960).

For western Norway, new descriptions and interpretations have been published for the submarine moraines crossing the fjords (Aarseth, 1997; Aarseth *et al.*, 1997). Several scientists also recently have suggested that Hardangerfjorden remained ice free from the Allerød and throughout the entire Younger Dryas (Bakke *et al.*, 2000; Helle *et al.*, 1997; Helle *et al.*, 2000). This is in contrast to the interpretation given in Andersen *et al.* (1995b), where the Halsnøy Moraine across the mouth of Hardangerfjorden, was mapped as the late Younger Dryas moraine. That problem is discussed in depth in Mangerud (2000), who concluded that the latter interpretation is correct and it is therefore shown on the map. The conclusion that the readvance ended close to 10 ka in the Bergen district (Fig. 13) is mainly based on dates from marine molluscs. Therefore, if the marine reservoir age was larger one should consider if the readvance continued into the very early Preboreal. It is now shown that the readvance certainly ended after deposition of the Vedde Ash, and in fact at the *Betula* increase at the Younger Dryas/Preboreal boundary (Bondevik & Mangerud, 2001; Bondevik & Mangerud, 2002).

Sønstegaard *et al.* (1999) mapped the marginal deposits of two large coalescing plateau glaciers of Younger Dryas

age in the Ålfoten area (Fig. 12). These glaciers were located west of, and separate from the Younger Dryas Scandinavian Ice Sheet. It is interesting to note that the plateau glaciers reached their maximum before the deposition of the Vedde Ash, whereas the Scandinavian Ice Sheet reached its maximum after the Vedde Ash in the Bergen district somewhat south of Ålfoten.

There is a distinct boundary for the style of glaciation around the Ålfoten area: south of that line no local glaciers existed outside the limit of the Scandinavian Ice Sheet, whereas along the coast further north there were numerous local glaciers. The change is an effect of topographical differences, in the southern area there are no high mountains beyond the Younger Dryas ice limits, whereas between Ålfoten and Trondheimsfjorden (and also in several areas in northern Norway) there are alpine landscapes with high peaks along the coast (Mangerud, 1980). The local glaciers are not marked on the digital map, but some are seen in Fig. 15. It can be mentioned that it has been demonstrated that some of the local glaciers did not survive during the Allerød, and were formed at the onset of the Younger Dryas (Larsen *et al.*, 1984; Mangerud *et al.*, 1979), whereas others survived the Allerød (Larsen *et al.*, 1998).

The mapped course of the moraine between Hardangerfjorden and Storfjorden (Fig. 12) are controlled and corrected by A.R. Aa, I. Aarseth and E. Sønstegaard.

Conflicting interpretations have recently been presented for the area surrounding the Trollheimen mountain region (Th on Fig. 15) and the Dovrefjell plateau (Df on Fig. 15). The Scandinavian Ice Sheet limit was previously drawn

west of Trollheimen, which is a massif located west of the main mountain chain, although continuous marginal moraines have not been found there (Andersen *et al.*, 1995a; 1995b; Sollid & Reite, 1983). Recently Follestad, based on mapping of Quaternary deposits, presented a completely different view (Follestad, 1994a; 1994b; written communication, 2000). He claims that there were only local glaciers in and surrounding Trollheimen. On the digital map the author has partly used the western limits indicated by Follestad to the south of Trollheimen (written communication, 2000), whereas through Trollheimen and towards the north, a limit drawn by A. Reite when he corrected the map is used. Reite emphasises that the limit across Trollheimen is uncertain. In practice, the map does not look very different from the earlier reconstructions south of Trollheimen. However, a major controversy is hidden in this drawing. In Andersen *et al.* (1995b) it was assumed that the moraines were formed by outlet glaciers from the main ice sheet, which is still postulated as correct for most of them. Follestad, on the other hand, postulated that the Trollheimen glaciers were dynamically separated from the Scandinavian Ice Sheet, the only connection being a zone of stagnant ice in northern Gudbrandsdalen (Gu in Fig. 15).

Follestad (written communication, 2000) and Dahl *et al.* (2000; 1997) further propose that mountain plateaux (including Dovrefjell, Df in Fig. 15) in the central part of Norway, and even in the Folldalen valley (presently below 700 m a.s.l.) (Fo in Fig. 15) were ice free during the Younger Dryas. The main arguments are that cirque moraines of postulated Younger Dryas age were mapped down to 1100 m a.s.l., and radiocarbon dates of Allerød and Younger Dryas age were obtained from Grimsmoen in Folldal for example (Dahl *et al.*, 2000). All earlier Younger Dryas ice reconstructions assumed these areas were covered by thick ice flowing towards Trondheimsfjorden, a view supported by geologists currently working in the area (Sveian *et al.*, 2000; A. Reite, oral communication, 2000). They have also mapped the Hoklingen moraine (see below) up to about 1000 m a.s.l. along Gauldalen, which is a large valley to the south of Trondheimsfjorden. That would indicate an ice surface above 1400–1500 m a.s.l. in Folldalen (Sveian *et al.*, 2000). It is concluded that some mountain peaks in Central Norway probably protruded through the ice sheet during the Younger Dryas. However, it is glaciologically very unlikely that the ice surface was below some 1400 m a.s.l., not to speak of 700 m a.s.l. in Central Norway, at a time when there were major glacial readvances out along Trondheimsfjorden and Oslofjorden. It is postulated that the cited radiocarbon samples (Dahl *et al.*, 2000) are from Early Holocene sediments which were contaminated with old carbon (Sveian *et al.*, 2000). On the map the classical view has therefore been retained and the view postulated that Folldalen and Dovrefjell were ice covered.

Over the last decades the area around Trondheimsfjorden has been mapped in detail by the Norwegian Geological Survey and many radiocarbon dates related to the Younger Dryas moraines have been obtained e.g. (Ander-

sen *et al.*, 1995b; Reite, 1994; Sveian & Solli, 1997). The map for this area has been corrected and modified by H. Sveian and A.R. Reite. In the Trondheimsfjorden area there are two major and sub-parallel Younger Dryas moraines. The outer, named the Tautra Moraine, is the larger and is dated to 10.8–10.4 ka; the younger Hoklingen Moraine is dated to 10.3–10.4 ka (Andersen *et al.*, 1995b). Again, most of the dates are from marine shells, and the final results will depend on the marine reservoir age. It is interesting to note that both the glaciation curve (Andersen *et al.*, 1995b; Reite, 1994) for the Trondheimsfjorden area and the picture with two Younger Dryas moraine systems are similar to the Oslofjorden area discussed above. Such distinct double moraines have not been described from elsewhere in southern Norway. Oslofjorden and Trondheimsfjorden are the only fjords in Norway surrounded by wide lowlands, so the similar responses are possibly a result of the similar topography and relation to the ice culminations far inland (Mangerud, 1980). The Tautra Moraine can be mapped nearly continuously towards the north, as shown on the map (Andersen *et al.*, 1995b; Reite, 1994). The Hoklingen Moraine is more distinct than the Tautra Moraine south of the fjord. This moraine is also a result of a readvance and is mapped as a continuous line. On the map it is drawn to the south, as far as it was mapped by Reite (1994). Concerning the age, the situation is again as in the Oslofjorden area: Hoklingen is close in age to the Herdla Moraine in western Norway, therefore its extension has to cross the extension of the Tautra Moraine somewhere between Trondheimsfjorden and Bergen.

In the area from the Trondheimsfjorden to southern Nordland (Fig. 12) B. Bergstrøm and H. Sveian have drawn the results of their recent mapping (Sveian & Solli, 1997). The main difference from the maps in Andersen *et al.* (1995b) is that the Hoklingen Moraine is mapped much further north than previously.

In the southern and northernmost part of Nordland (Fig. 12), the moraine mainly follows Andersen *et al.* (1995b), and the central part it is shown mainly according to Andersen (1975) and Rasmussen (1981). The entire stretch is corrected and somewhat modified by T. Bargel and L. Olsen, according to their recent mapping. On and around Hinnøya Olsen *et al.* (2001) have proposed a re-interpretation. They found that the main ice sheet inundated Hinnøya during an early phase of the Younger Dryas. Subsequently the glaciers in the fjords broke up, and late in the Younger Dryas the ice sheet terminated east of the island, and a small ice cap formed on Hinnøya. Both Olsen *et al.* (2001) and Vorren & Plassen (2002) have concluded that there was a major Younger Dryas readvance of at least some 30 km in this area.

The Tromsø-Lyngen Moraines are indicated mainly according to Andersen *et al.* (1995b), with corrections from B. Bergstrøm, H. Sveian and T. Vorren. In this area, there were numerous local glaciers on the islands outside the ice sheet limit. The two largest of these, Senja (Vorren & Plassen, 2002) and Ringvassøy (Andersen *et al.*, 1995b), are shown on the map.

In Finnmark, the moraines are generally very distinct. They are plotted according to Sollid *et al.* (1973), and the map was corrected by L. Olsen.

Acknowledgements

Øystein Lohne assisted enthusiastically in drawing the map of the Late Weichselian glacial limit, in correctly drawing all the details in the course of the Younger Dryas moraine, finding literature, etc. Terje Finnekås assisted in the first compilation of the Younger Dryas moraine. An earlier draft of the manuscript was sent to a number of geologists. I have received comments to that draft or other scientific information from A.R. Aa, I. Aarseth, B.G. Andersen, T. Bargel, B. Bergstrøm, S. Bondevik, S.-O. Dahl, B. Follestad, H. Haflidason, J. Kleman, E. Larsen, S.E. Lauritzen, L. Olsen, D. Ottesen, A. Nesje, A.J. Reite, K. Rokoengen, J.L. Sollid, E. Sønstegeard, R. Sørensen, H. Sveian and T.O. Vorren. The drawings were made by E. Bjørseth and J. Ellingsen. The English language was corrected by M.R. Talbot. I thank all of these people for their friendly help.

References

- Aarseth, I. (1997). Western Norwegian fjord sediments: age, volume, stratigraphy, and role as temporary depository during glacial cycles. *Marine Geology*; **143**, 39-53.
- Aarseth, I., Austbø, P.K. & Risnes, H. (1997). Seismic stratigraphy of Younger Dryas ice-marginal deposits in western Norwegian fjords. *Norsk Geologisk Tidsskrift*; **77**, 65-85.
- Alm, T. (1993). Øvre Årsvatn - palynostratigraphy of a 22,000 to 10,000 BP lacustrine record on Andøya, northern Norway. *Boreas*; **22**, 171-188.
- Andersen, B.G. (1960). Sørlandet i sen- og postglasial tid. *Norges geologiske undersøkelse* 210, 1-142.
- Andersen, B.G. (1975). Glacial Geology of Northern Nordland, North Norway. *Norges geologiske undersøkelse*; **320**, 1-74.
- Andersen, B.G. (1981). Late Weichselian Ice Sheets in Eurasia and Greenland. In: Denton, G.H. & Hughes, T.J. (eds), *The Last Great Ice Sheets*, John Wiley & Sons, New York, pp. 3-65.
- Andersen, B.G., Lundqvist, J. & Saarnisto, M. (1995a). The Younger Dryas margin of the Scandinavian Ice Sheet - an introduction. *Quaternary International*; **28**, 145-146.
- Andersen, B.G. & Mangerud, J. (1989). The last interglacial-glacial cycle in Fennoscandia. *Quaternary International* 3/4, 21-29.
- Andersen, B.G., Mangerud, J., Sørensen, R., Reite, A., Sveian, H., Thoresen, M. & Bergstrøm, B. (1995b). Younger Dryas ice-marginal deposits in Norway. *Quaternary International*; **28**, 147-169.
- Andersen, B.G. & Nesje, A. (1992). Quantification of Late Cenozoic glacial erosion in a fjord landscape. *Sveriges Geologiska Undersökning*; **Ca 81**, 15-20.
- Andersen, B.G., Sejrup, H.-P. & Kirkhus, Ø. (1983). Eemian and Weichselian Deposits at Bø on Karmøy, SW Norway: A Preliminary Report. *Norges geologiske undersøkelse*; **380**, 189-201.
- Andersen, B.G., Wangen, O.P. & Østmo, S.-R. (1987). Quaternary geology of Jæren and adjacent areas, southwestern Norway. *Norges geologiske undersøkelse, Bulletin*; **411**, 1-55.
- Anundsen, K. (1985). Changes in shore-level and ice-front position in Late Weichsel and Holocene, southern Norway. *Norsk Geografisk Tidsskrift*; **39**, 205-225.
- Anundsen, K. & Fjeldskaar, W. (1983). Observed and theoretical Late Weichselian shore-level changes related to glacier oscillation at Yrkje, South-West Norway. In: Schroeder-Lanz, H. (ed.), *Late- and Postglacial oscillations of glaciers: Glacial and Periglacial forms*, Rotterdam, A.A. Balkema, 133-170.
- Bakke, J., Dahl, S.O. & Nesje, A. (2000). Reconstruction of Younger Dryas and Holocene glacier fluctuations and paleoclimate at Folgefonna, southwestern Norway. *Geonytt*; **1**, 2000, 36.
- Baumann, K.-H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf-Welling, T.C.W., Henrich, R. & Kassens, H. (1995). Reflection of Scandinavian Ice Sheet fluctuations in Norwegian Sea sediments during the last 150,000 years. *Quaternary Research*; **43**, 185-197.
- de Beaulieu, J.-L. & Reille, M. (1992). The last climatic cycle at La Grande Pile (Vosges, France): A new pollen profile. *Quaternary Science Reviews*; **11**, 431-438.
- Behre, K.-E. (1989). Biostratigraphy of the last glacial period in Europe. *Quaternary Science Reviews*; **8**, 25-44.
- Behre, K.-E. & van der Plicht, J. (1992). Towards and absolute chronology for the last glacial period in Europe: radiocarbon dates from Oerel, northern Germany. *Vegetation History Archaeobotany*; **1**, 111-117.
- Bergstrøm, B. (1999). Glacial geology, deglaciation chronology and sea-level changes in the southern Telemark and Vestfold counties, southeastern Norway. *Norges geologiske undersøkelse Bulletin*; **435**, 23-42.
- Bergstrøm, B., Olsen, K.S. & Sørensen, R. (1992). *Tjøme 1813 II, Kvartærgeologisk kart 1:50 000, med beskrivelse*. Norges geologiske undersøkelse.
- Birks, J. (1993). Is the hypothesis of survival on glacial nunataks necessary to explain the present-day distributions of Norwegian mountain plants? *Phytocoenologia*, **23**, 399-426.
- Bondevik, S., Birks, H.H., Gulliksen, S. & Mangerud, J. (1999). Late Weichselian marine ¹⁴C reservoir ages at the western coast of Norway. *Quaternary Research*, **52**, 104-114.
- Bondevik, S. & Mangerud, J. (2001). Tidfesting av innlandsisen si maksimale utbreiing på Vestlandet i yngre dryas. *Geonytt*, **2001**, 33.

- Bondevik, S. & Mangerud, J., (2002). A very late Younger Dryas ice sheet maximum in western Norway. *Quaternary Science Reviews* (in press).
- Bondevik, S., Mangerud, J. & Gulliksen, S. (2001). The marine ^{14}C age of the Vedde Ash Bed along the west coast of Norway. *Journal of Quaternary Science*, **16**, 3-7.
- Borgström, I. (1999). Basal ice temperatures during late Weichselian deglaciation: comparison of landforms assemblages in west-central Sweden. *Annals of Glaciology*, **28**, 9-15.
- Boulton, G.S., Smith, G.D., Jones, A.S. & Newsome, J. (1985). Glacial Geology and glaciology of the last mid-latitude ice sheet. *Journal of the Geological Society London*, **142**, 447-474.
- Brook, E.J., Nesje, A., Lehman, S.J., Raisbeck, G.M. & Yiou, F. (1996). Cosmogenic nuclide exposure ages along a vertical transect in western Norway: Implications for the height of the Fennoscandian ice sheet. *Geology*, **24**, 207-210.
- Bugge, T. (1980). Øvre lags geologi på kontinentalsokkelen utenfor Møre og Trøndelag. *Continental Shelf Institute Publication*, **104**, 44 pp.
- Bugge, T., Lien, R. & Rokoengen, K. (1978). Kartlegging av løsmassene på kontinentalsokkelen utenfor Møre og Trøndelag. *Continental Shelf Institute Publication*, **99**, 55 pp.
- Carr, S., Haflidason, H. & Sejrup, H. (2000). Micromorphological evidence supporting Late Weichselian glaciation of the northern North Sea. *Boreas*, **29**, 315-328.
- Clark, P.U., Alley, R. & Pollard, D. (1999). Northern Hemisphere ice-sheet influences on global climate change. *Science*, **286**, 1104-1111.
- Dahl, S.O., Follestad, B.A., Nesje, A. & Lie, Ø. (2000). Age and climate when cirque glaciers and ice-dammed lakes existed during the deglaciation in east-central Norway. *Geonytt*, **1** 2000, 54.
- Dahl, S.O. & Nesje, A. (1992). Paleoclimatic implications based on equilibrium-line altitude depressions of reconstructed Younger Dryas and Holocene cirque glaciers in inner Nordfjord, western Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **94**, 87-97.
- Dahl, S.O., Nesje, A. & Øvstedahl, J. (1997). Cirque glaciers as morphological evidence for a thin Younger Dryas ice sheet in east-central southern Norway. *Boreas*, **26**, 161-180.
- Dowdeswell, J.A. & Siegert, M.J. (1999). Ice-sheet numerical modelling and marine geophysical measurements of glacier-derived sedimentation on Eurasian Arctic continental margins. *Geological Society of America Bulletin*, **111**, 1080-1097.
- Fjeldskaar, W. (2000). An isostatic test of the hypothesis of ice-free mountain areas during the last glaciation. *Norsk Geologisk Tidsskrift*, **80**, 51-56.
- Fjeldskaar, W. & Kanestrøm, R. (1980). Younger Dryas geoid-deformation caused by deglaciation in Fennoscandia. In: Mörner, N.-A. (ed.), *Earth Rheology, Isostasy and Eustasy*, New York, Wiley, 569-574.
- Follestad, B.A. (1994a). *Eresfjord 1320 II. Kvartærgeologisk kart med beskrivelse*. Norges geologiske undersøkelse.
- Follestad, B.A. (1994b). *Snota. Kvartærgeologisk kart M 1:50 000 med beskrivelse*. Norges geologiske undersøkelse.
- Gulliksen, S., Birks, H.H., Possnert, G. & Mangerud, J. (1998). A calendar age estimate of the Younger Dryas-Holocene boundary at Kråkenes, western Norway. *The Holocene*, **8**, 249-259.
- Haflidason, H., Sejrup, H.-P., Klitgaard Kristensen, D. & Johnsen, S. (1995). Coupled response of the late glacial climatic shifts of NW-Europe reflected in Greenland ice cores: Evidence from the northern North Sea. *Geology*, **23**, 1059-1062.
- Helle, S.K., Anundsen, K., Aasheim, S. & Haflidason, H. (1997). Indications of a Younger Dryas marine transgression in inner Hardanger, West Norway. *Norsk Geologisk Tidsskrift*, **77**, 101-117.
- Helle, S.K., Rye, N. & Stabell, B. (2000). Shoreline displacement and fault activity in the Hardangerfjord, western Norway, after deglaciation. *Geonytt*, **1** 2000, 82.
- Helmens, K.F., Räsänen, M.E., Johansson, P.W., Jungner, H. & Korjonen, K. (2000). The Last Interglacial-Glacial cycle in NE Fennoscandia: a nearly continuous record from Sokli (Finnish Lapland). *Quaternary Science Reviews*, **19**, 1605-1623.
- Holmlund, P. & Fastook, J. (1993). Numerical modelling provides evidence of a Baltic Ice Stream during the Younger Dryas. *Boreas*, **22**, 77-88.
- Holtedahl, H. (1993). Marine geology of the Norwegian continental margin. *Norges geologiske undersøkelse. Special publication*, **6**, 1-150.
- Holtedahl, O. (1960). Geology of Norway. *Norges geologiske undersøkelse*, **208**, 1-540.
- Houmark-Nielsen, M. (1999). A lithostratigraphy of Weichselian glacial and interstadial deposits in Denmark. *Bulletin of the Geological Society of Denmark*, **46**, 101-114.
- Jansen, E., Befring, S., Bugge, T., Edvin, T., Holtedahl, H. & Sejrup, H.-P. (1987). Large submarine slides on the Norwegian Continental Margin: Sediments, transport and timing. *Marine Geology*, **78**, 77-107.
- King, E.L., Haflidason, H., Sejrup, H.-P. & Løvlie, R. (1998). Glacigenic debris flows on the North Sea Trough Mouth Fan during ice stream maxima. *Marine Geology*, **152**, 217-246.
- King, E.L., Sejrup, H.-P., Haflidason, H., Elverhøi, A. & Aarseth, I. (1996). Quaternary seismic stratigraphy of the North Sea Fan: Glacially fed gravity flow aprons, hemipelagic sediments, and large submarine slides. *Marine Geology*, **130**, 293-315.
- King, L.H., Rokoengen, K. & Gunleiksrud, T. (1987). *Quaternary seismostratigraphy of the Mid Norwegian Shelf, 65°-67°30'N - A till tongue stratigraphy*. IKU Sintef Group 114 (ISSN 0332-5288), 1-58 and 7 map enclosures.

- Kleman, J. (1994). Preservation of landforms under ice sheets and ice caps. *Geomorphology*, **9**, 19-32.
- Kleman, J. & Borgström, I. (1990). The boulder fields of Mt. Fulufjället, west-central Sweden - Late Weichselian boulder blankets and interstadial periglacial phenomena. *Geografiska Annaler*, **72 A**, 63-78.
- Kleman, J. & Hättestrand, C. (1999). Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. *Nature*, **402**, 63-66.
- Krzywinski, K. & Stabell, B. (1984). Late Weichselian sea level changes at Sotra, Hordaland, western Norway. *Boreas*, **13**, 159-202.
- Laberg, J.S. & Vorren, T.O. (1996). The Middle and Late Pleistocene evolution of the Bear Island Trough Mouth Fan. *Global and Planetary Change*, **12**, 309-330.
- Lagerbäck, R. & Robertsson, A.-M. (1988). Kettle holes - stratigraphical archives for Weichselian geology and palaeoenvironment in northernmost Sweden. *Boreas*, **17**, 439-468.
- Lambeck, K., Smither, C. & Johnston, P. (1998). Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophysical Journal Int.*, **134**, 102-144.
- Lambeck, K., Yokoyama, Y., Johnston, P. & Purcell, A. (2000). Global ice volumes at the Last Glacial Maximum and early Lateglacial. *Earth and Planetary Science Letters*, **18**, 513-527.
- Landvik, J.Y., Bondevik, S., Elverhøi, A., Fjeldskaar, W., Mangerud, J., Salvigsen, O., Siegert, M.J., Svendsen, J.I. & Vorren, T.O. (1998). The last glacial maximum of Svalbard and the Barents Sea area: Ice sheet extent and configuration. *Quaternary Science Reviews*, **17**, 43-75.
- Larsen, E., Attig, J.W., Aa, A.R. & Sønstegeard, E. (1998). Late-Glacial cirque glaciation in parts of western Norway. *Journal of Quaternary Science*, **13**, 17-27.
- Larsen, E., Eide, F., Longva, O. & Mangerud, J. (1984). Allerød - Younger Dryas climatic inferences from cirque glaciers and vegetational development in the Nordfjord area, western Norway. *Arctic and Alpine Research*, **16**, 137-160.
- Larsen, E., Gulliksen, S., Lauritzen, S.-E., Lie, R., Løvlie, R. & Mangerud, J. (1987). Cave stratigraphy in western Norway; multiple Weichselian glaciations and interstadial vertebrate fauna. *Boreas*, **16**, 267-292.
- Larsen, E. & Sejrup, H.-P. (1990). Weichselian land-sea interaction; western Norway - Norwegian Sea. *Quaternary Science Reviews*, **9**, 85-97.
- Larsen, E., Sejrup, H.-P., Janocko, J., Landvik, J.Y., Stalsberg, K. & Steinsund, P.I. (2000). Recurrent interaction between the Norwegian Channel Ice Stream and terrestrial-based ice across southwest Norway. *Boreas*, **29**, 185-203.
- Lauritzen, S.-E. (1984). A symposium: arctic and alpine karst. *Norsk Geografisk Tidsskrift*, **38**, 139-143.
- Lauritzen, S.-E. (1990). Tertiary caves in Norway: a matter of relief and size. *Cave Science*, **17**, 31-37.
- Lauritzen, S.-E. (1991). Uranium series dating of speleothems: A glacial chronology for Nordland, Norway, for the last 600 ka. *Striae*, **34**, 127-133.
- Lauritzen, S.-E. (1995). High-resolution paleotemperature proxy record for the Last Interglacial based on Norwegian speleothemes. *Quaternary Research*, **43**, 133-146.
- Lauritzen, S.-E., Løvlie, R., Moe, D. & Østbye, E. (1990). Paleoclimate deduced from a multidisciplinary study of a half-million-year-old stalagmite from Rana, Northern Norway. *Quaternary Research*, **34**, 306-316.
- Lauritzen, S.-E., Nese, H., Lie, R.W., Lauritsen, Å. & Løvlie, R. (1996). Interstadial/interglacial fauna from Norcemgrotta, Kjølpsvik, north Norway. In: Lauritzen, S.-E. (ed.), *Climate change: The karst record*, 89-92. Charles Town, West Virginia, The Karst Waters Institute.
- Lohne, Ø. (2000). Sen-weichsel og holosen strandforskyvning i Os-området, Hordaland. Unpublished Cand. scient. (Master) Thesis, Department of Geology, University of Bergen.
- Longva, O. & Thorsnes, T. (1997). Skagerak in the past and the present - an integrated study of geology, chemistry, hydrography and microfossil ecology. *Norges geologiske undersøkelse, Special Publication*, **8**, 1-100.
- Lowe, J.J. & Walker, M.J.C. (1997). *Reconstructing Quaternary environments*. Harlow, Longman.
- Lundqvist, J. (1992). Glacial stratigraphy in Sweden. *Geological Survey of Finland, Special paper*, **15**, 43-59.
- Mangerud, J. (1972). Radiocarbon dating of marine shells, including a discussion of apparent age of recent shells from Norway. *Boreas*, **1**, 143-172.
- Mangerud, J. (1973). Isfrie refugier i Norge under istidene. *Norges geologiske undersøkelse*, **297**, 1-23.
- Mangerud, J. (1980). Ice-front variations of different parts of the Scandinavian Ice Sheet, 13,000-10,000 years BP. In: Lowe, J.J., Gray, J.M. & Robinson, J.E. (eds), *Studies in the lateglacial of North-West Europe*, 23-30. Oxford, Pergamon.
- Mangerud, J. (1981). The Early and Middle Weichselian in Norway: a review. *Boreas*, **10**, 381-393.
- Mangerud, J. (1989). Correlation of the Eemian and the Weichselian with deep sea oxygen isotope stratigraphy. *Quaternary International*, **3/4**, 1-4.
- Mangerud, J. (1991a). The Scandinavian Ice Sheet through the last interglacial/glacial cycle. *Paläoklimaforschung*, **1**, 307-330.
- Mangerud, J. (1991b). The Last Interglacial/Glacial Cycle in Northern Europe. In: Shane, L.C.K. & Cushing, E.J. (eds), *Quaternary Landscapes*, 38-75. Minneapolis, University of Minnesota Press.
- Mangerud, J. (2000). Was Hardangerfjorden, western Norway, glaciated during the Younger Dryas? *Norsk Geologisk Tidsskrift*, **80**, 229-234.
- Mangerud, J. & Gulliksen, S. (1975). Apparent radiocarbon ages of recent marine shells from Norway, Spitsbergen, and Arctic Canada. *Quaternary Research*, **5**, 263-273.
- Mangerud, J., Larsen, E., Longva, O. & Sønstegeard, E. (1979). Glacial history of western Norway 15,000-10,000 B.P. *Boreas*, **8**, 179-187.

- Mangerud, J., Gulliksen, S., Larsen, E., Longva, O., Miller, G.H., Sejrup, H.-P. & Sønstegeard, E. (1981a). A Middle Weichselian ice-free period in Western Norway: the Ålesund Interstadial. *Boreas*, **10**, 447-462.
- Mangerud, J., Sønstegeard, E., Sejrup, H.-P. & Haldorsen, S. (1981b). A continuous Eemian-Early Weichselian sequence containing pollen and marine fossils at Fjøsanger, western Norway. *Boreas*, **10**, 137-208.
- Mangerud, J., Lie, S.E., Furnes, H., Kristiansen, I.L. & Lømo, L. (1984). A Younger Dryas ash bed in Western Norway, and its possible correlations with tephra in cores from the Norwegian Sea and the North Atlantic. *Quaternary Research*, **21**, 85-104.
- Mangerud, J., Jansen, E. & Landvik, J. (1996). Late Cenozoic history of the Scandinavian and Barents Sea ice sheets. *Global and Planetary Change*, **12**, 11-26.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C.J. & Shackleton, N.J. (1987). Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300 000 year chronostratigraphy. *Quaternary Research*, **27**, 1-29.
- Nese, H. & Lauritzen, S.-E. (1996). Quaternary stratigraphy of the Storsteinshola cave system Kjølsvik, north Norway. In: Lauritzen, S.-E. (ed.), *Climate change: The karst record*, 116-120. Charles Town, West Virginia, The Karst Waters Institute.
- Nesje, A., Anda, E., Rye, N., Lien, R., Hole, P.A. & Blikra, L.H. (1987). The vertical extent of the Late Weichselian ice sheet in the Nordfjord-Møre area, western Norway. *Norsk Geologisk Tidsskrift*, **67**, 125-141.
- Nesje, A. & Dahl, S.O. (1990). Autochthonous block fields in southern Norway: implications for the geometry, thickness, and isostatic loading of the Late Weichselian Scandinavian ice sheet. *Journal of Quaternary Science*, **5**, 225-234.
- Nesje, A. & Dahl, S.O. (1992). Geometry, thickness and isostatic loading of the Late Weichselian Scandinavian ice sheet. *Norsk Geologisk Tidsskrift*, **72**, 271-273.
- Nesje, A., Dahl, S.O., Anda, E. & Rye, N. (1988). Block fields in southern Norway: Significance for the Late Weichselian ice sheet. *Norsk Geologisk Tidsskrift*, **68**, 149-169.
- Nesje, A. & Whillans, I.M. (1994). Erosion of Sognefjord, Norway. *Geomorphology*, **9**, 33-45.
- Olsen, L. (1997). Rapid shifts in glacial extension characterise a new conceptual model for glacial variations during the Mid and Late Weichselian in Norway. *Norges geologiske undersøkelse, Bulletin*, **433**, 54-55.
- Olsen, L. (1998). Pleistocene paleosols in Norway: implications for past climate and glacial erosion. *Catena*, **34**, 75-103.
- Olsen, L., Bergstrøm, B. & Sveian, H. (2001). New data indicates considerable Allerød-Younger Dryas ice-front fluctuations across Hinnøya and in the adjacent Ofotfjorden-Vestfjorden area, northern Norway. *Geonytt*, **2001**, 88.
- Olsen, L., Mejdahl, V. & Selvik, S.F. (1996). Middle and Late Pleistocene stratigraphy, Finnmark, North Norway. *Norges geologiske undersøkelse Bulletin*, **429**, 1-111.
- Ottesen, D., Rise, L., Rokoengen, K. & Sættem, J. (2001). Glacial processes and large-scale morphology on the mid-Norwegian continental shelf. In: Martinsen, O. & Dreyer, T. (eds), *Sedimentary environments offshore Norway - Palaeozoic to Recent*, Norwegian Petroleum Society.
- Peltier, R.W. (1994). Ice Age Paleotopography. *Science*, **265**, 195-201.
- Rasmussen, A. (1981). The Deglaciation of the coastal area NW of Svartisen, Northern Norway. *Norges geologiske undersøkelse*, **369**, 1-31.
- Reite, A.J. (1994). Weichselian and Holocene geology of Sør-Trøndelag and adjacent parts of Nord-Trøndelag county, Central Norway. *Norges geologiske undersøkelse Bulletin*, **426**, 1-30.
- Rokoengen, K., Bell, G., Bugge, T., Dekko, T., Gunleiksrud, T., Lien, R., Løfaldli, M. & Vigran, J.O. (1977). Prøvetakning av fjellgrunn og løsmasser utenfor deler av Nord-Norge. *Continental Shelf Institute (IKU) Publication*, **91**, 67 pp.
- Rokoengen, K. & Frengstad, B. (1999). Radiocarbon and seismic evidence of ice-sheet extent and the last deglaciation on the mid-Norwegian continental shelf. *Norsk Geologisk Tidsskrift*, **79**, 129-132.
- Sejrup, H.-P. (1987). Molluscan and foraminiferal biostratigraphy of an Eemian-Early Weichselian section on Karmøy, southwestern Norway. *Boreas*, **16**, 27-42.
- Sejrup, H.-P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D. & Rokoengen, K. (1994). Late Weichselian glaciation history of the northern North Sea. *Boreas*, **23**, 1-13.
- Sejrup, H.-P., King, E.L., Aarseth, I., Haflidason, H. & Elverhøi, A. (1996). Quaternary erosion and depositional processes: western Norwegian fjords, Norwegian Channel and North Sea Fan. *Geological Society of London*, **117**, 187-202.
- Sejrup, H.-P., Landvik, J.Y., Larsen, E., Janocko, J., Eiriksson, J. & King, E. (1998). The Jæren area, a border zone of the Norwegian Channel ice stream. *Quaternary Science Reviews*, **17**, 801-812.
- Sejrup, H.-P., Larsen, E., Landvik, J., King, E.L., Haflidason, H. & Nesje, A. (2000). Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the North Sea region. *Quaternary Science Reviews*, **19**, 667-685.
- Sjørring, S. (1983). The glacial history of Denmark. In: Ehlers, J. (ed.), *Glacial deposits of North-West Europe*, 163-179. Rotterdam, A.A. Balkema, pp.
- Sollid, J.-L. & Reite, A.J. (1983). The last glaciation and deglaciation of Central Norway. In: Ehlers, J. (ed.), *Glacial deposits in north-west Europe*, 41-60. Rotterdam, A.A. Balkema.
- Sollid, J.-L. & Sørbel, L. (1979). Deglaciation of western Central Norway. *Boreas*, **8**, 233-239.

- Sollid, J.-L. & Sørbel, L. (1994). Distribution of glacial landforms in southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler*, **76A**, 25-35.
- Sollid, J.-L., Andersen, S., Hamre, N., Kjeldsen, O., Salvigsen, O., Sturød, S., Tveitå, T. & Wilhelmsen, A. (1973). Deglaciation of Finnmark, North Norway. *Norsk Geografisk Tidsskrift*, **27**, 233-325.
- Sveian, H., Reite, A.J. & Olsen, L. (2000). The elevation of the Younger Dryas ice surface in the Røros-Folldal area; two contradiction models. In: NORPAST, Past climates of the Norwegian Region, Abstracts, Botanical and Geological Institutes, University of Bergen.
- Sveian, H. & Solli, A. (1997). Tid og form - geologisk historie. In: Dahl, R., Sveian, H. & Thoresen, M. (eds), *Nord-Trøndelag og Fosen*, 111-130. Trondheim, Norges Geologisk Undersøkelse.
- Svendsen, J.I. & Mangerud, J. (1987). Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of Quaternary Science*, **2**, 113-132.
- Sættem, J. (1990). Glaciotectonic forms and structures on the Norwegian continental shelf: observations, processes and implications. *Norsk Geologisk Tidsskrift*, **70**, 81-94.
- Sønsteegaard, E., Aa, A.R. & Klagegg, O. (1999). Younger Dryas glaciation in the Ålfoten area, western Norway; evidence from lake sediments and marginal moraines. *Norsk Geologisk Tidsskrift*, **79**, 33-45.
- Sørensen, R. (1979). Late Weichselian deglaciation in the Oslofjord area, south Norway. *Boreas*, **8**, 241-246.
- Sørensen, R. (1992). The physical environment of Late Weichselian deglaciation of the Oslofjord region, south-eastern Norway. *Sveriges Geologiska Undersökning*, **Ca 81**, 339-346.
- Sørensen, R. (1999). En ^{14}C datert og dendrokronologisk kalibrert strandforskyvningskurve for søndre Østfold, Sørøst-Norge. *AmS-Rapport*, **12A**, 227-242.
- Valen, V., Mangerud, J., Larsen, E. & Hufthammer, A.K. (1996). Sedimentology and stratigraphy in the cave Hamnsundhelleren, western Norway. *Journal of Quaternary Science*, **11**, 185-201.
- Vorren, T.O., Hald, M., Edvardsen, M. & Lind-Hansen, O.-W. (1983). Glacigenic sediments and sedimentary environments on continental shelves: General principles with a case study from the Norwegian shelf. In: Ehlers, J. (ed.), *Glacial deposits in North-West Europe*, 61-73. Rotterdam, A.A. Balkema.
- Vorren, T.O. & Kristoffersen, Y. (1986). Late Quaternary glaciation in the south-western Barents Sea. *Boreas*, **15**, 51-59.
- Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Ruhmohr, J. & Werner, F. (1998). The Norwegian-Greenland Sea continental margins: morphology and Late Quaternary sedimentary processes and environment. *Quaternary Science Reviews*, **17**, 273-302.
- Vorren, T.O. & Plassen, L. (2002). Deglaciation and palaeoclimate of the Andfjord-Vågsfjord area, North Norway. *Boreas*, **31**, (in press).
- Vorren, T.O., Vorren, K.-D., Alm, T., Gulliksen, S. & Løvlie, R. (1988). The last deglaciation (20,000 to 11,000 B.P.) on Andøya, northern Norway. *Boreas*, **17**, 41-77.
- Zagwijn, W.H. (1989). Vegetation and climate during warmer intervals in the Late Pleistocene of western and central Europe. *Quaternary International*, **3/4**, 57-67.
- Zagwijn, W.H. (1992). The beginning of the ice age in Europe and its major subdivisions. *Quaternary Science Reviews*, **11**, 583-591.

MS submitted 2001