Rapid and rhythmic ice sheet fluctuations in western Scandinavia 15 - 40 Kya—a review

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The onshore record of Middle to Late Weichselian sediments and glacial history in Norway indicates a succession of four major ice advances alternating with rapid, considerable ice recessions and interstadial conditions. During all the glacial advances the ice sheet expanded from onshore / inland positions to the shelf areas. The basis for visualizing these variations in glaciation curves constructed along nine transects from inland to shelf, and for interpretation of the palaeoclimatic history, is the regional Quaternary stratigraphy, more than 300 datings, fossil content and some palaeomagnetic data. The methods applied in recent years for AMS radiocarbon dating of glacial sediments with low organic carbon content have given promising results with respect to accuracy and precision, and the results of such datings were an important tool for our reconstructions and for timing of the ice oscillations. The rapid and rhythmic ice fluctuations, as reconstructed in our new model, have been fairly synchronous in most parts of Norway. Ice advances commenced and culminated at 40, 30 - 28, 24 - 21 and 18 - 15 (^{14}C) Kya. We describe three intervening interstadials from inland sites: Hattfjelldal I, Hattfjelldal II and Trofors. Our stratigraphical record also includes many indications of high, pre-Holocene, relative sea levels, suggesting a considerable glacio-isostatic depression of western Scandinavia during the interstadials. In our glaciation model we suggest that, in addition to precipitation, the mountainous fjord and valley topography, glacial isostasy and relative sea level changes were probably more important for the size of the glacial fluctuations than were air temperature changes.

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Proxy climatic records from terrestrial and deep-sea sediments and ice cores reported during the last decade seriously challenge the view of a relatively continuous ice cover in Scandinavia during the interval 15 - 40 Kya. Seasonally open waters existed at least three times in this period, at 19, 25 and 30 - 35 Kya, along the Norwegian coast and even north to the Fram Strait in the polar North Atlantic Ocean (e.g. Hebbeln et al. 1998), as reviewed by Olsen et al. (2001a). Major ice retreat with ice-free areas reaching far into the inland of southern Norway at 32 - 37 Kya is indicated by ^{14}C dates on sub-till sediments and thermoluminescence (TL) dating of 37 - 40 Kya (calendar years) of aeolian sand. The published record showing similar glacier fluctuations at

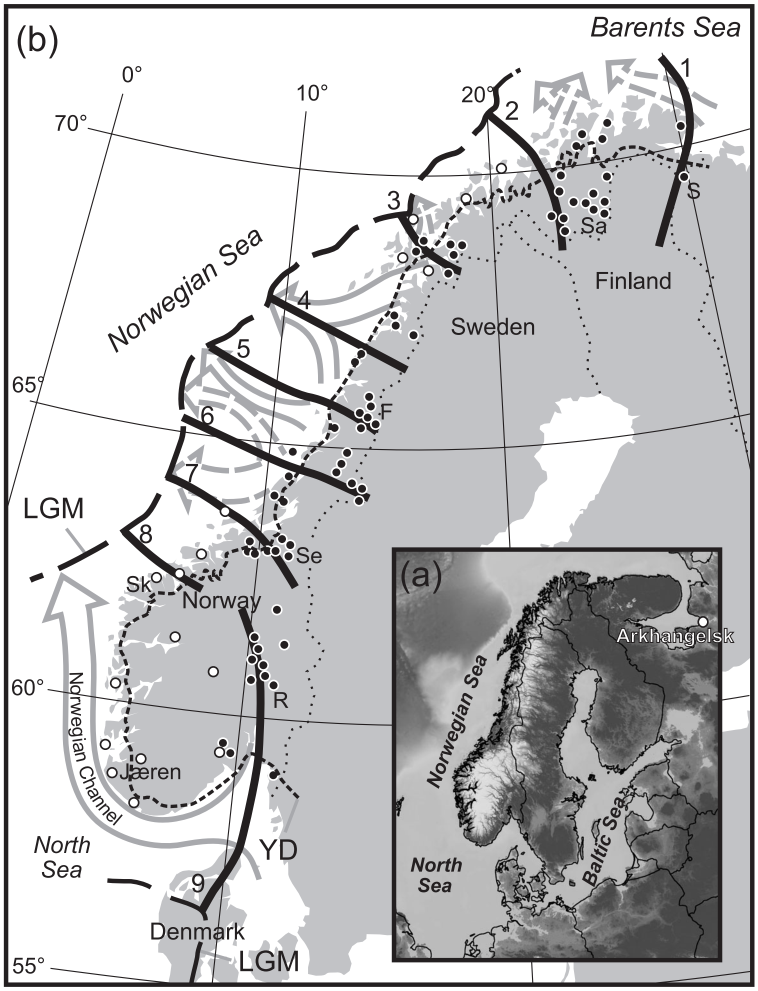

Fig. 1. (a) Topography of Fennoscandia and adjacent areas; light shading indicates higher elevations. (b) Stratigraphical sites used (filled dots) or considered for comparison (circles) in this study, the western ice margin of the Weichsel maximum (LGM) and the Younger Dryas (YD) Stadial, transects (1 - 9) for the glaciation curves (Figs. 8 and 9c), and stratigraphical sites / site areas referred to in the text: S = Skjellbekken; Sa = Sargejohka; F = Fiskelauselva; Se = Selbu area, Sk = Skjonghelleren; R = Rokoberget. Positions of the major ice-stream channels with distinct (unbroken lines) and less distinct (broken lines) ice-flow features on the adjacent shelf are also indicated. (Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* / Tapir Academic Press.)

30 - 40 Kya in northern Norway includes both U / Th dating of speleothems from inland caves in Nordland County, TL dating of glaciofluvial sand from various parts of Fennoscandia and accelerator mass spectrometry (AMS) ^{14}C dating of organic-bearing, sub-till sediments from inland Finnmark County (also reviewed by Olsen et al. 2001a). Our study confirms and extends these results, as well as previously reported interstadials of various ages from the coastal areas (Sandnes, Ålesund, Arnøya, Hamnsund and Andøya interstadials), both geographically and with regard to time (Olsen et al. 2001a, 2001b, 2001c).

The aim of this review paper is to give a brief presentation of our new glaciation model and summarize the conclusions on the 2-D reconstructions of rapid and rhythmic ice sheet variations at 15 - 40 Kya in Norway (Fig. 1), as obtained from the stratigraphic record, more than 300 dates of various kinds and some palaeomagnetic data. For details and background data, such as utilized methods, stratigraphic data, traces of high sea levels etc., see Olsen et al. (2001a, 2001b, 2001c). The present paper also includes new information on traces of high Middle Weichselian sea levels from Selbu, central Norway, supporting the regional glacial reconstructions.

Our conceptual model for glacial variations has been questioned, but has also gained considerable support from modern proxy climatic records. Hopefully, this new model will provide new motivation and inspiration for further investigations and discussions of methods, ice sheet fluctuations and their timing.

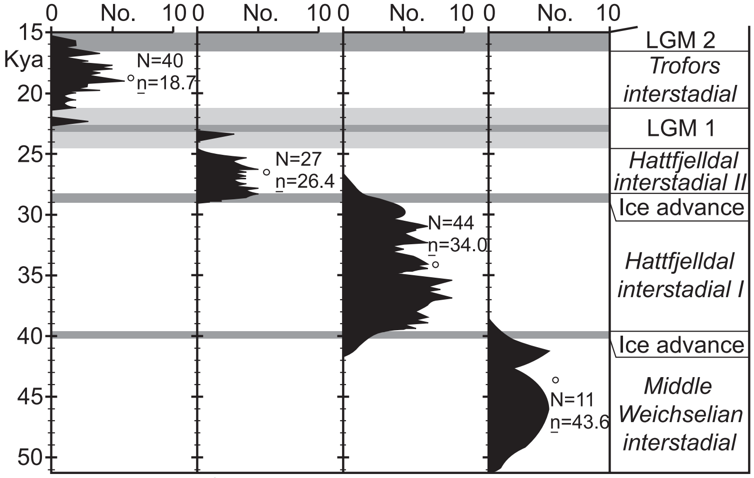

Fig. 2. Frequency distribution of radiocarbon dates (running mean ages ± 1σ) of organic-bearing sediments and shells from four ice-free intervals separated by glacial episodes during the Mid to Late Weichselian. The suggested names, the number of dates (N) and their mean age (n in ^{14}C Kya) for each ice-free interval are indicated. The difference in mean ages between these groups of dates is significant at a 99% confidence level (based on data presented in Olsen et al. 2001b).

Geological setting

Norway is characterized by a highly irregular mountainous terrain with a densely dissected coastline and deeply incised fjords and valleys (Fig. 1), ideal for rapid ice growth and decay. Considering the westerly position of the mountain areas above 1000 m a.s.l. in Fennoscandia, the initial ice growth during glaciations must have started in central southern Norway, in the highest mountains along the coast and along the Norwegian–Swedish national border in the north. Conditions favourable for glaciation are enhanced by the short distances to principal moisture sources: the North Atlantic and the Norwegian Sea. However, the long coastline and deep fjords may also have functioned in the opposite sense, with ice flow mainly concentrated along the fjords and at many "entry" points for the sea to destabilize an extensive ice sheet.

Methods

The stratigraphical methods employed were the standard ones (clast fabric, grain-size analysis, etc.) used by the Geological Survey of Norway. Some of the more important for the present study are summarized below.

AMS radiocarbon dating of sediment samples with a low organic content and some marine molluscs has been carried out at the R. J. Van de Graaff Laboratory, University of Utrecht. For samples of sediments, dates were obtained from one of four organic fractions, with the majority performed on the *NaOH-insoluble* fraction (97 of a total of 136). Conventional radiocarbon dating and most AMS datings of shell samples were performed at the Radiological Dating Laboratory in Trondheim, Norway, and at the T. Svedborg Laboratory, Uppsala University, Sweden, respectively. All dates used for glaciation curve reconstructions are presented by Olsen et al. (2001a, 2001b). If not otherwise indicated, all ages cited in this paper are in radiocarbon years before the present.

Considering the controversial character of our data compared with previously published data from fjord and inland areas of Norway, first we had to evaluate the dating methods and the established chronology. Statistical treatment of the dates indicated that the mean ages of the four, major, Middle to Late Weichselian interstadials (Fig. 2) were significantly different at 99% confidence level (Olsen et al. 2001b). We concluded that the best argument for the reliability of the chronology was the similarity of ages, within a precision of 1 - 3 Ky, for the phases of ice advance and retreat along the nine transects (Fig. 1; see also Figs. 8, 9c). Therefore, we consider the radiocarbon dating of sediments with a low content of organic carbon, which has been important for the established chronology, to be a useful and reliable tool for the timing of glacial fluctuations in areas where macrofossils are scarce.

To identify marine sediments older than the Holocene at localities situated far inland and high

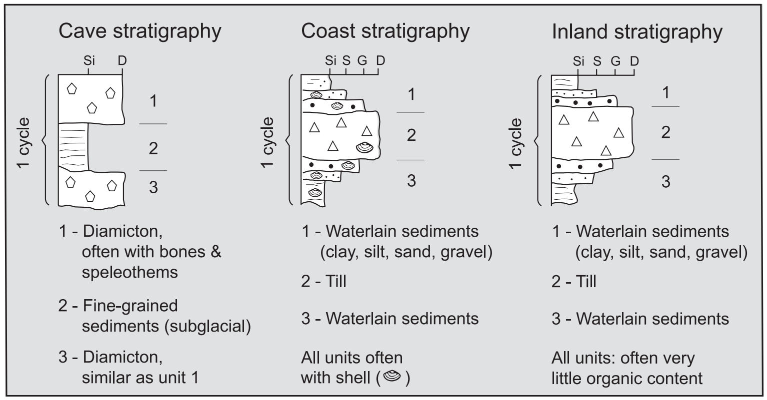

Fig. 3. Simplified logs of generalized stratigraphical successions of sedimentary units which indicate alternating ice-free—ice-covered—ice-free conditions. Each succession has a thickness ranging from less than 1 to more than 5 m and represents one cycle of glacial events with a total duration of 5 - 10 Ky. The sediment successions illustrate stratigraphies (i) in caves (e.g. Larsen et al. 1987), (ii) subaerially at the coast, and (iii) inland. (Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* / Tapir Academic Press.)

above the present sea level, and even well above the post-glacial marine limit, we have searched for marine fossils, but only seven localities (along transects 3, 6, 7 and 9) have been identified so far. In addition, several such sites close to the coast are reported from south-west Norway (e.g. Larsen et al. 2000). As alternative methods, we have used residues of marine organisms extracted with hexane, and we have determined the content of La and Ce to find a Ce-deficient, lanthanide abundance pattern, which is indicative of a marine depositional environment.

Ice sheet fluctuations, sediments and high relative sea levels

Our reconstruction of the ice sheet fluctuations is based on sediment sequences which include a variety of sedimentary facies and a range of depositional environments. The most frequent and qualitatively most important of these comprise sediments deposited in proglacial environments, which is essential for the ice sheet reconstructions. Sediment successions occurring in caves (e.g. Larsen et al. 1987), and subaerially at the coast or in the inland parts of Norway, are illustrated in a series of idealized logs (Fig. 3). Fine-grained laminated cave sediments appear to preserve palaeomagnetic signals, and show evidence of a palaeomagnetic excursion considered to equate with the Mono Lake / Lake Mungo excursion (28 Kya). This is recorded in Skjonghelleren (Fig. 1; Larsen et al. 1987) and in other cave sequences. It is also possible that the same excursion is represented in fine-grained sediments in subaerial positions at Fiskelauselva and Sargejohka. A review of this, including a geographic overview with examples of sediment successions from each of the nine regions studied, is presented by Olsen et al. (2001a, 2001b, 2001c).

Sub-till sediments with marine fossils are mainly found at moderately uplifted sites along the coast. However, some of these are located high above the previously known post-glacial marine limits, such as those recorded from the Hinnøya and Grytøya islands (transect 3). Similar sediments have recently been found in the inland of central Norway (Selbu) at altitudes 10 - 15 % higher than the post-glacial marine limit (Figs. 4, 5). This means that the glacio-isostatic component during the last glaciation was much more pronounced in several places than hitherto realized.

We have also recorded traces of a marine environment based on secondary indications (e.g. Ce deficiency), as described before, at a number of places both close to the coast and farther landward, and at elevations high above the marine limits from the last deglaciation period (Fig. 6), e.g. at Rokoberget where marine microfossils have also been recorded recently. This further strengthens the argument for a considerable glacio-isostatic component during most of the Mid to Late Weichselian, because these records of inferred marine sediments encompass most of the ice retreat intervals during the 15 - 40 Kya period.

Conceptual model

Based on the geographical distribution of dated sub-till sediments (subglacial sediments

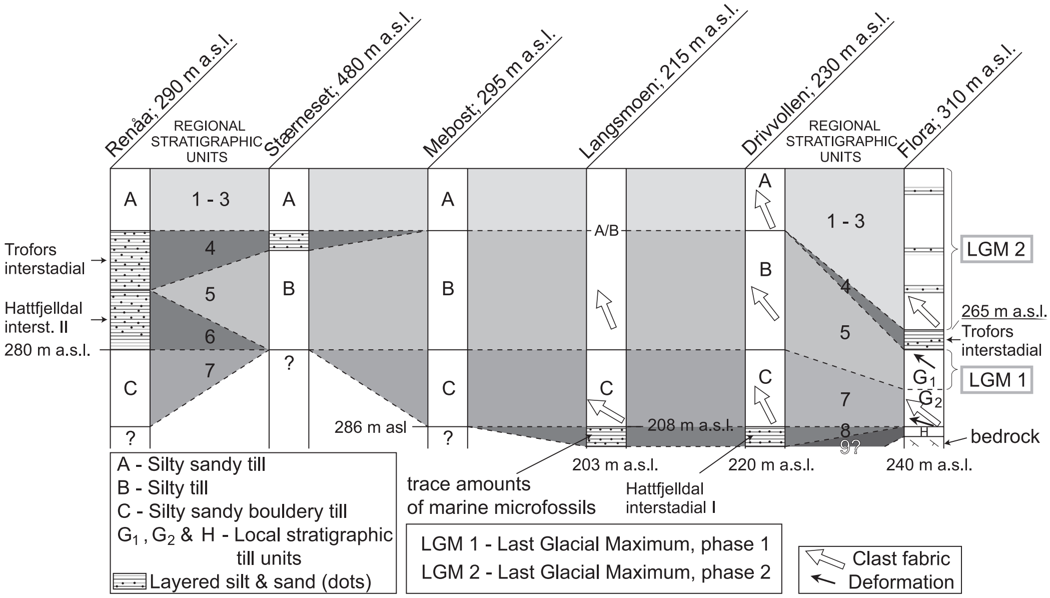

Fig. 4. Simplified stratigraphic columns from three sites in inland central Norway, Selbu area, correlated to three previously reported sites in the same area. The regional stratigraphic units represent the interval 40 - 15 Kya from the base to the top. Trace amounts of foraminifers have been recorded in unit 8 (30 - 39 Kya) at Drivvollen and Langsmoen, well above the post-glacial marine limit at 200 m a.s.l.

excluded), it is inferred that the Middle to Late Weichselian glaciation in Fennoscandia started at 30 Kya from glaciers located along the Scandinavian mountain chain (Fig. 7). Glacier fluctuation curves along all transects (Fig. 1), of which four are shown in Fig. 8, show a high regional consistency. An attempt to reconstruct the 2-D glacier extent in western Scandinavia during alternating major stadial and interstadial episodes in the period 15 - 40 Kya, using all these data, is illustrated in Fig. 9. The results indicate multiple glacial advances across the coast to the continental shelf alternating with ice retreats to the inland areas (the Hattfjelldal I, Hattfjelldal II and Trofors interstadials), on which we have based our conceptual model. The importance of this reconstruction is its emphasis on ice instability, with rapid shifts between ice growth and ice recession during the studied time interval.

It is presumed that rapidly fluctuating ice streams, which occurred in many fjord-valleys, fjords and their extension seawards to the adjacent shelves, also had a significant upstream influence on the land-based parts of the ice sheet, and that the major destabilization component was the abrupt changes of ice surface gradients towards the rapidly oscillating ice streams. Even minor changes in sea level, therefore, could have triggered a sequence of processes, which, together

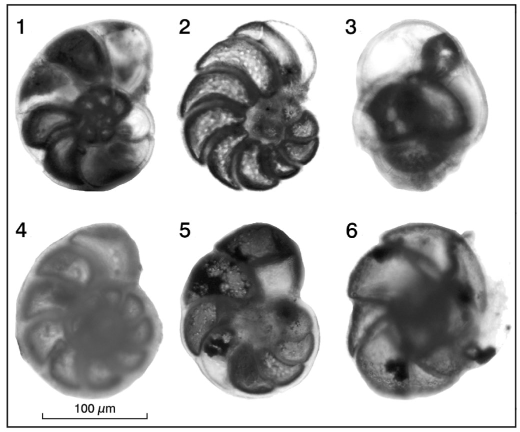

Fig. 5. Photographs of foraminifers from unit 8 at Langsmoen. These are all corroded and probably mainly boreal species (e.g. 1: *Hyalinea balthica?*; 2: *Planulina araminensis?*; 3: *Bulimina marginata?*), but uncorroded forms of the cold species *Elphidium excavatum* are also recorded in these sediments (D. Bøe, pers. comm. 2001). Similar microfossils also occur in unit 8 at Drivvollen.

Fig. 6. Locations (dots) and numerical values showing the altitude (in m a.s.l.) of high-lying sediments, or traces of environments, thought to be of marine origin from the period 15 - 40 Kya. The interpretation is, in several cases, based on chemical and other secondary indicators (underlined numbers—see the main text). For comparison, the post-glacial marine limit in each area is shown in parentheses. G = Grytøya; H = Hinnøya; R = Rokoberget. (Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* /Tapir Academic Press.)

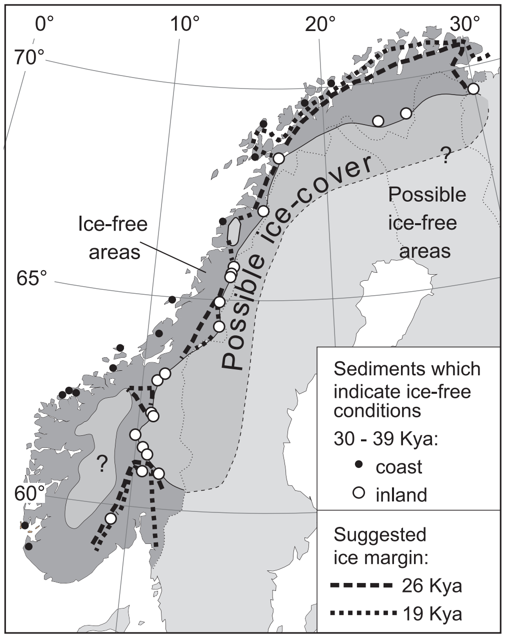

Fig. 7. Map showing the supposed maximum glacial extent (medium grey) and ice-free areas (dark grey) of western Scandinavia during the supposed climatic optimum of the interval 30 - 39 Kya. The glacial extent during this interval in some areas, particularly in eastern Fennoscandia and the Baltic Sea area, is considered uncertain in this reconstruction. The suggested ice extent during interstadials at 26 and 19 Kya in Norway is included for comparison. (Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* /Tapir Academic Press.)

with climatic variations, led to synchronized ice sheet fluctuations and rapid alternations between intervals with extensive glaciation and ice-free conditions in Norway 15 - 40 Kya.

Discussion and conclusion

Our glaciation model, as reviewed here, fits well with a proposed "minimum model" of the geometry and thickness of the Late Weichselian Fennoscandian ice sheet, which suggests a relatively thin, multidomed ice sheet with several minor ice-free areas. The evidence for general ice movement patterns indicates more than one major ice dome. With a typical average net growth rate of 0.1 m/yr (as typifies the summit area of Greenland during the Holocene), the available time during each ice build-up phase is not sufficiently long to achieve the ice thickness of the classical "maximum model."

This new record of glacier fluctuations on land in Norway during the last Fennoscandian glaciation seems to fit well with recently published information for glacier fluctuations along the west coast of Norway and the North Sea area. However, our data are in even better agreement with ice-rafted debris (IRD) peaks from the Norwegian Sea, and with ice-core data from Greenland, which indicate rapid changes from stadial to interstadial conditions in 500 - 2500 and 5000 - 7000 year intervals during the entire period from 40 - 45 Kya to the Holocene (Fig. 9a–c).

The relative sea level, thought to be driven mainly by glacial isostasy, was probably very high along the western Fennoscandian ice sheet margins during the ice retreat intervals between 40 and 15 Kya (Fig. 6). The relative sea level in the North Sea area was very low at 30 Kya.

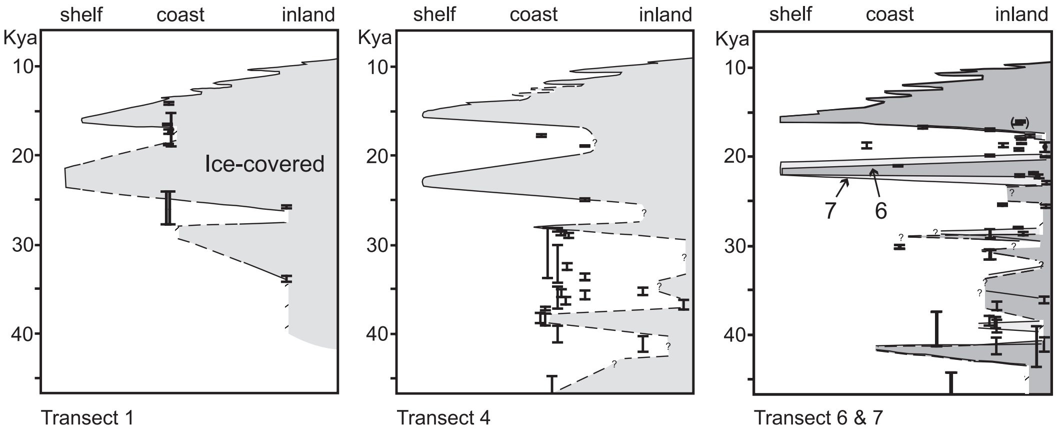

Fig. 8. Glaciation curves (time–distance diagrams) along transects 1, 4, 6 and 7. All transects are shown with normalized lengths, i.e. all transects have been given equal length. Dates used for these reconstructions are indicated within ± 1σ precision, as vertical rods. The majority of the dates are AMS ^{14}C datings of sediments (uncalibrated to calendar years). Other dates also included are ^{14}C dates from shells, bones and calcareous concretions, luminescence dates of sediments and U/Th dates of calcareous concretions. See Fig. 9c for comparison between the glaciation curves.(Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* /Tapir Academic Press.)

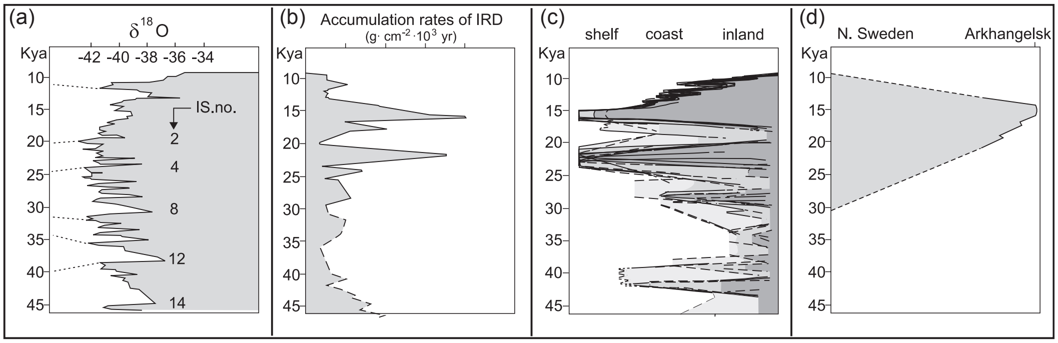

Fig. 9. Comparison between our Norwegian glacial record and various data which indicate proxy glacial and climatic variations in the vicinity of Norway. (a) $\delta^{18}O$ data from the Summit ice core from Greenland (the GISP project; Dansgaard et al. 1993); (b) IRD accumulation data from the Norwegian Sea (Baumann et al. 1995). (c) Composite diagram with glaciation curves along nine transects from inland to coast/shelf in Norway; all transects are normalized with respect to length; dark grey shading—all 9 glaciation curves; medium grey—at least four curves; and light grey or no shading—1 - 3 curves (Olsen 1997). (d) Tentative glaciation curve representing the eastern part of the Fennoscandian ice sheet during the last glacial maximum (Larsen et al. 1999). (Modified from Olsen et al. 2001a and used with permission of *Norsk Geologisk Tidsskrift* /Tapir Academic Press.)

However, this may be explained by very little glacio-isostatic depression close to the margin of the former ice sheet and at the end of an interstadial, and that the global eustatic sea level was low during the entire 15 - 40 Kya interval. Given that the ice recession, which was strongly influenced by calving in the fjord areas, took place at a similar rate during each deglaciation phase, the effect of glacial isostasy indicates that the ice thickness was considerable during all the major ice advances. The glacio-isostatic depression was greatest and, therefore, the ice was thickest during the 21 - 24 Kya interval (Last Glacial Maximum [LGM] 1) and prior to 39 Kya.

We suggest that the ice sheet responded to a westerly dominated climate regime during the first part of the last glacial maximum (LGM 1) by building major domes only in the west. This changed to a configuration with a more easterly position for the ice domes and ice divides during the second major Fennoscandian ice sheet extension (LGM 2), which is a well-documented general trend during ice build-up both in northern and southern Fennoscandia and along the southern margins of the Baltic Sea. In the Arkhangelsk area of Russia, the glacial record indicates a single last glacial maximum advance at 16 Kya towards the eastern margins of the Fennoscandian Ice Sheet (Fig. 9d; Larsen et al. 1999). The difference in glacial development in the west compared to the east (Fig. 9c, d) may result from several factors, such as different distances to the ice-divide / dome areas and moisture sources, as well as differences in topography. The natural termination of all westward-trending ice advances at the shelf break in the west, compared to the free ice flow on the flat-lying land areas in the east, is another important factor. The record of the glacial history during the late Mid Weichselian (25 - 40 Kya) in the eastern parts of Fennoscandia (Sweden and Finland), briefly reviewed by Olsen et al. (2001a), is not well known. New data from the Sokli area in northern Finland, with three in situ Weichselian interstadial organic beds separated by tills, and with at least one of the interstadials of Mid Weichselian age (Helmens et al. 2000), as well as a new compilation by Arnold et al. (2002) of previously published data, seriously challenge the previous interpretations of a continuous ice cover throughout the Mid and Late Weichselian and call for a reconsideration of the ages and character of the Early and Middle Weichselian glacial fluctuations in eastern Fennoscandia.

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