The glacial History of the Barents and Kara Sea Region

John Inge Svendsen [1], Valery Gataullin [2&4], Jan Mangerud [3] and Leonid Polyak[4]

1) Centre for Studies of the Environment and Resources, University of Bergen, Høyteknologisenteret, N-5007 Bergen, Norway
John.Svendsen@smr.uib.no

2) Oil and Gas Research Institute, 5 Exporta Street, LV-1226, Riga, Latvia.

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

4) Byrd Polar Research Center, Ohio State University, 1090 Carmack Rd., Columbus, Ohio 43210, USA
polyak.1@osu.edu

Introduction

The Barents and Kara seas, fringing the northern rim of the Eurasian continent, cover one of the widest continental shelves in the world (Fig. 1). Geological investigations reveal that this vast area has been repeatedly affected by major glaciations during the Quaternary (e.g. Elverhøi *et al*., 1998a). From time to time the ice sheets expanded onto the Russian Lowland blocking the north-flowing rivers on the continent (Grosswald, 1980; Arkhipov *et al*., 1995; Astakhov *et al*., 1999; Mangerud *et al*., 2001).

The ice sheet extent during the Last Glacial Maximum (LGM) has been much debated over the past decades, and was considered to represent one of the largest uncertainties in the global distribution of glaciers. According to one extreme view, much of northern Eurasia was covered by an enormous shelf-centered ice sheet at the LGM (Grosswald, 1993; 1998) whereas others visualise more localised ice caps over the Arctic islands (e.g. Velichko *et al*., 1997). Based on comprehensive investigations, it has now been demonstrated that a major ice sheet did exist in the Barents Sea region at this time (e.g. Landvik *et al*., 1998). However, this ice sheet did not expand onto the Russian Lowland and there was no major ice dispersal centres over the Kara Sea shelf during the LGM (Astakhov, 1998; Svendsen *et al*., 1999; Forman *et al*., 1999). It has also become clear that the glacier distribution has been more variable through time than previously thought and that the large ice sheets represent rather short-lived events. During the last 150,000 years as many as 4 major glaciations have been recorded, but most of the time the glacier coverage was limited (Mangerud *et al*.,1998; 2001).

Here we summarise current knowledge of the Quaternary ice sheet history in the Barents and Kara Sea region. A reconstruction of the ice sheet extent during the LGM (21-18 ka) is presented (Fig. 2). The authors have also drawn interpreted ice limits for two periods during the last deglaciation, at around 13 ka and during the Younger Dryas Chron (11-10 ka). The reconstructions are based on a review of published geological and geophysical data from the shelf and adjacent islands and have also taken into account unpublished results. The ice-sheet limits on land are discussed in other chapters.

Physiography and general sediment cover

The sea floor topography in the Barents and Kara seas is relatively uneven with several banks and plateaux and is characterised by a series of deep transverse troughs opening to the Arctic Basin and the Norwegian Sea (Fig. 1). Typically the water depths in the troughs range from 300-500 m whereas most of the shelf is shallower. This region also includes several archipelagos on the shelf, which are partly glaciated at present; Svalbard, Franz Josef Land, Novaya Zemlya and Severnaya Zemlya.

The stratigraphical records on the islands are fragmentary because of glacial erosion and long periods of non-deposition. Interpretations of glacial variations are mainly based on investigations of exposed tills and glacioisostatically-uplifted marine sediments. The best studied area is Svalbard which has been the focus of intensive investigations for several decades (e.g. Landvik *et al*., 1998; Mangerud *et al*., 1998).

Seismic surveying and coring show that there is a continuous, mainly thin, draping of Quaternary sediments on the sea floor consisting of marine sediments underlain by one to several till sheets. The base of the Quaternary deposit is normally recognized as an erosional boundary, the so-called Upper Regional Unconformity (URU) (Solheim & Kristoffersen, 1984). In the central part of the Barents Sea, the thickness of the Quaternary sediment cover is normally less than a few tens of metres whereas much thicker sequences occur near the continental slope and in the southeast. Along the western margin, large prograding fans are located at the mouth of glacially-eroded troughs. These trough-mouth fans are dominated by glacially-derived debris flow deposits, and are interpreted as depocentres of sediments transported by ice streams (Laberg & Vorren, 1995; Dowdeswell *et al*., 1998; Elverhøi

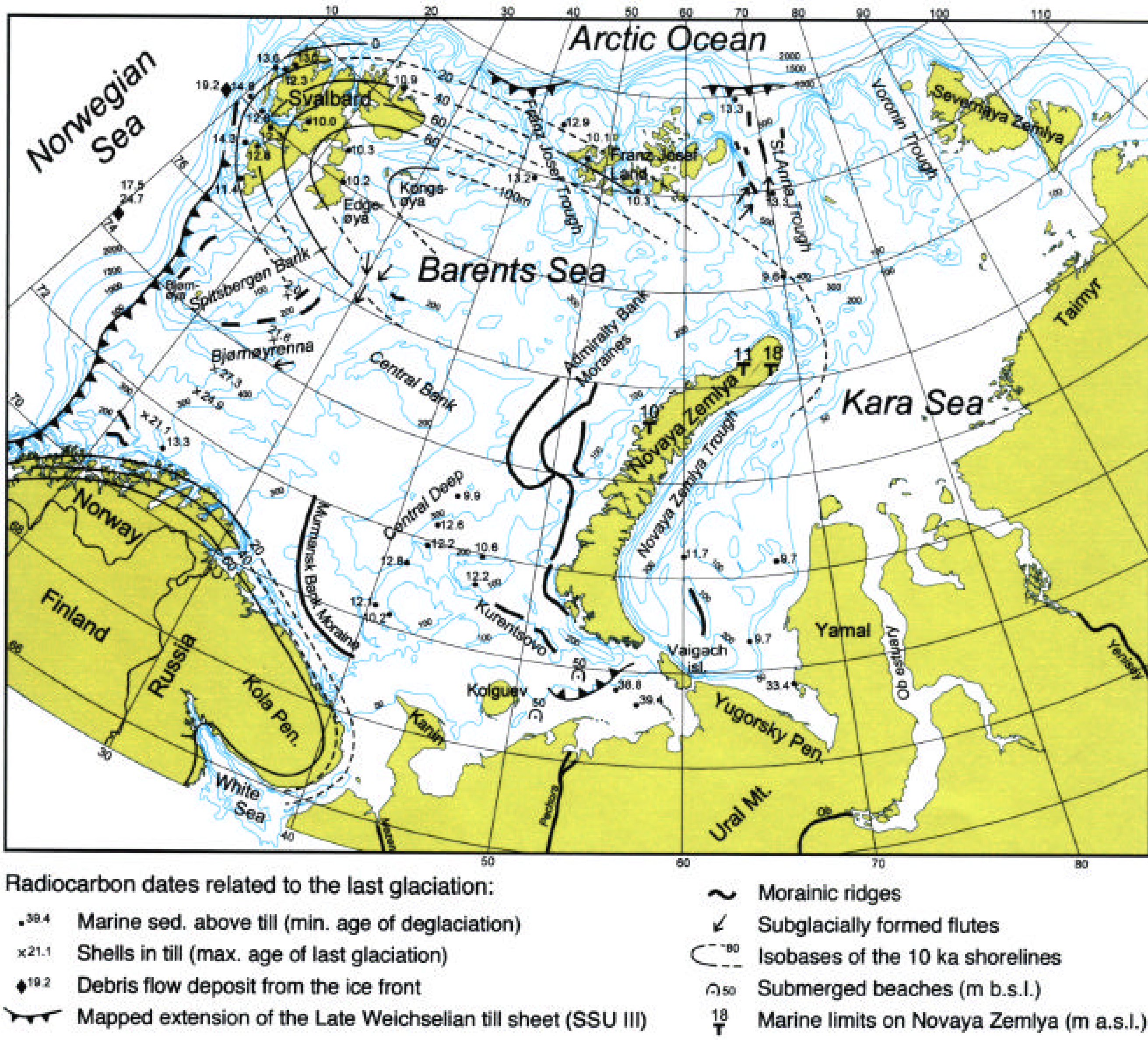

Fig.1. The Barents- and Kara Sea Region showing some of the evidence used for reconstructing the Late Weichselian ice sheet extent (Fig. 2). Most of the data from the western part of the study area were presented in a compilation by Landvik et al. (1998). Glacial features and dates from the eastern Barents Sea and from the Kara Sea are discussed in the text. The reconstructed isobases of the10 ka shoreline in the northern Barents Sea region and along the Norwegian coast are slightly modified from Landvik et al. (1998). The corresponding isobases around the Kola Peninsula in Russia are simplified from Koshechkin (1979) 1978 or 1979?. Marine limits on Novaya Zemlya are taken from Forman et al. (1999).

et al., 1998b; Vorren *et al*., 1998). In some areas end moraines also occur locally along the outer shelf margin.

The long term ice sheet history

The earliest occurrence of ice rafted debris (IRD) in the Norwegian Sea is found in the middle Miocene suggesting that incipient glaciations occurred on adjacent land areas some 12-14 Ma ago (Thiede *et al*., 1998). The increased supply of IRD at approximately 3.2-2.7 Ma reflected a strengthening of northern hemisphere large-scale glaciations (Jansen & Sjøholm, 1991; Mangerud *et al.*, 1996). In the Barents Sea region, the initial glacial growth is seen in a pronounced increase in the general sedimentation rate along the Svalbard margin from around 2.3-2.5 Ma (Faleide *et al.*, 1996; Butt *et al.* 2000). The volume of thick wedges of glacigenic sediments along the western continental slope suggest that there has been as much as 1000-1500 m of erosion over the Barents Sea region since the onset of glaciations (cf. Solheim *et al.*, 1998). During the oldest glaciations, the physiography of the Barents Sea region was very different from the present and the shelf area was probably well above sea level.

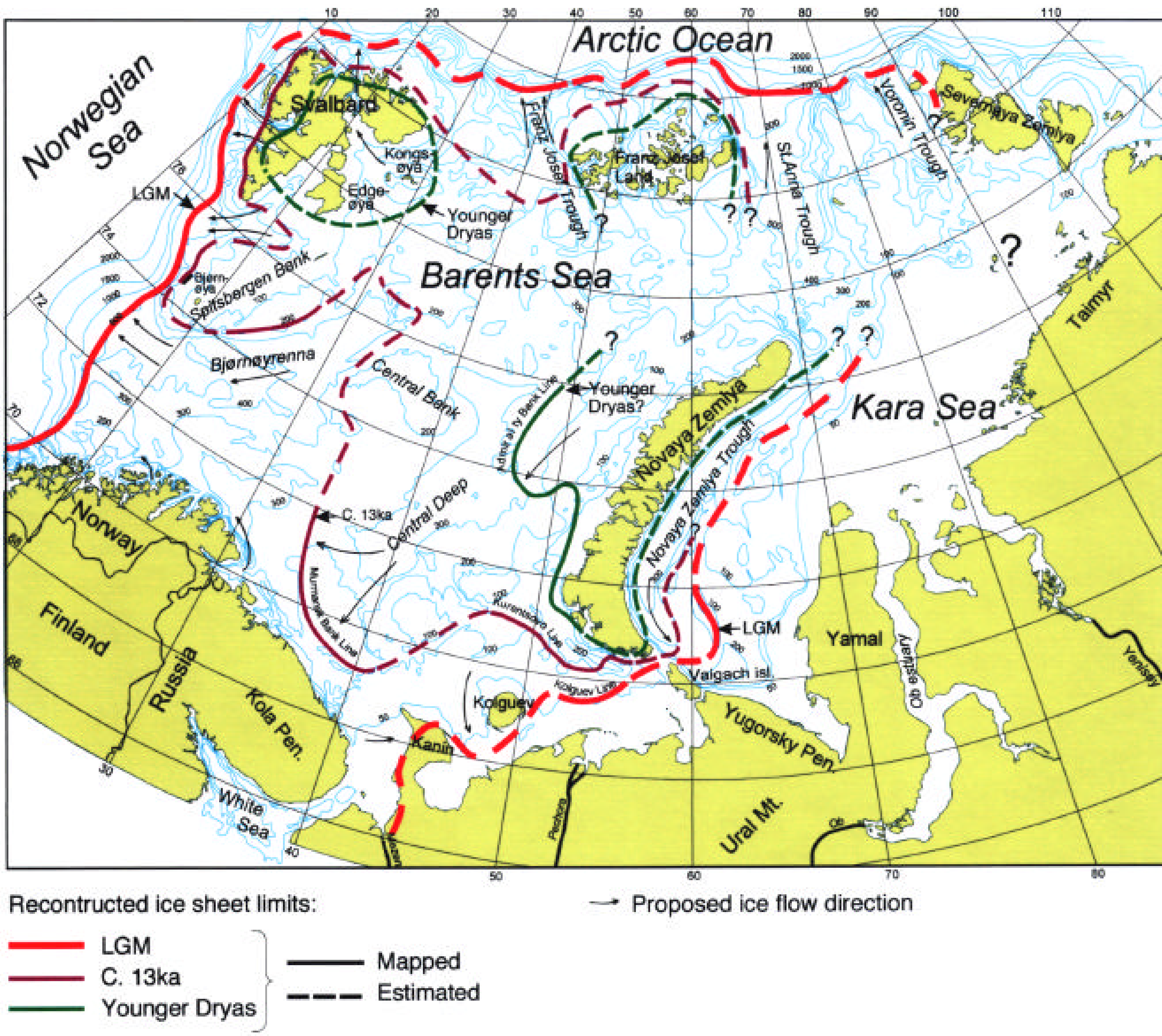

Fig. 2. Map of the Barents and Kara Sea Region showing the interpreted ice sheet limit during the Last Glacial Maximum (21-18 ka). Judging from the distribution of radiocarbon dates and mapped morainic ridges on the shelf (Fig 1) tentative ice-recessional limits have also been drawn at around 13 ka and during the Younger Dryas Chron.

Sedimentological data from the ODP site 986 drilled off western Svalbard reveal low IRD values during the interval 2.3-1.6 Ma, suggesting that glaciers in Barents Sea region did not reach the sea (Butt *et al*., 2000). Butt *et al.* (2000) conclude that further glacial expansions took place during 1.5-1.3 Ma and that ice sheets expanded to the shelf break several times after 1.3 Ma. From the seismic stratigraphy it has previously been concluded that the ice sheet in the southwestern Barents Sea expanded to the outer shelf at least eight times (Laberg & Vorren, 1996). The last period of glacial deposition appears to be dominated by aggradation of glacial sediments on the shelf margin rather then progradation. This may reflect a different style of glaciation as the shelf was glacially eroded and eventually became submerged. Accordingly, Solheim *et al*.(1998) suggest that thick eroding ice sheets existed during the oldest glaciations whereas the younger ice sheets were characterised by thinner and more fast-flowing ice streams at the margins.

The maximum extent of Quaternary glaciation

Tills and other glacial features show that the shelf-centered ice sheets expanded far onto the Russian mainland several times (Yakovlev,1956; Arkhipov *et al*.,1995; Astakhov *et al*.,1999; 2001 reference missing!). In West Siberia the Quaternary glaciation limit is located as much as *c*.1400 km to the south of the Arctic coastline, testifying to the existence of at least one enormous ice sheet (Krasnov, 1971; Astakhov, this volume). Some observations suggest

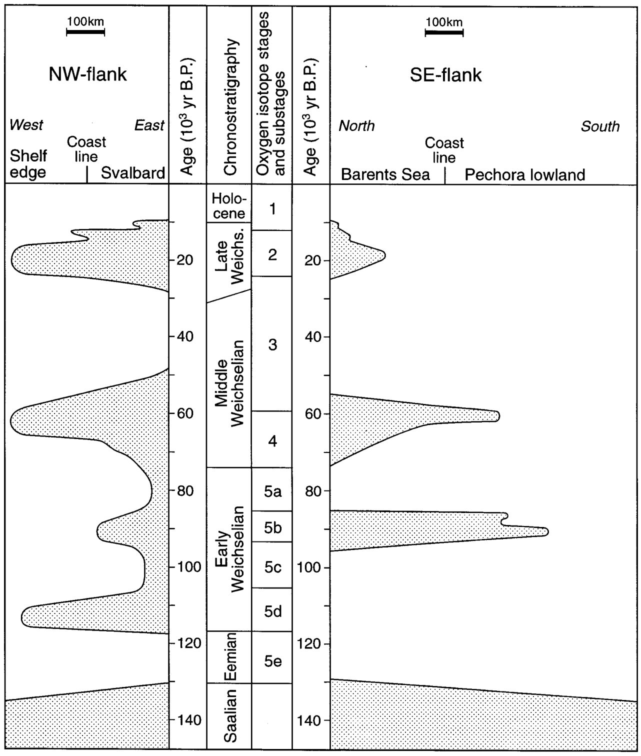

Fig. 3. Time-distance diagrams showing recorded advances of the northwestern (Svalbard) and southeastern (northern Russia) flank of the Barents-Kara Ice Sheet during the last 150 ka (modified from Mangerud et al., 1998; 2001).

that the ice sheet at some point was fringed by a thick marine ice shelf that grew into the Arctic Basin. Ploughmarks on the Yermak Plateau reflect grounded ice down to more than 850 m below present sea level (Vogt *et al*., 1994); an interpretation that is supported by coring results (Myhre *et al*., 1995). More surprisingly, seismic profiles and side-scan records from the Lomonosov Ridge crest in the Arctic Basin shows not only ploughmarks of several kilometres in length, but also a pronounced regional erosional truncation to 1000 m below present sea level, interpreted to have been eroded by a grounded ice shelf (Jakobsson, 1999; Polyak *et al.*, 2001).

The age of the Quaternary glacial maximum when the Lomonosov Ridge was eroded is uncertain. One of the most extensive glaciations occurred during the Late Saalian (Marine Isotope Stage 6) when the entire shelf in the Barents and Kara seas was ice covered (Mangerud *et al.*,1998; Knies *et al*., 2001). According to Jakobsson *et al.* (2001) the possible ice grounding on the crest of the Lomonosov Ridge took place at this time. However, it should be noted that this chronology is at variance with the age model suggested by Spielhagen *et al.* (1997) who date the correlative horizon with MIS 16 (625-690 ka). This latter chronology is also supported by Flower (1997) who concludes that the last ice grounding on the Yermak Plateau occurred over 660 ka ago.

The ice sheet history during the Early/Middle Weichselian Substages

A synthesis of the Late Pleistocene glacial fluctuations in the northwestern Barents Sea have been given by Mangerud *et al.* (1998), who correlate the onshore record of Svalbard with IRD in cores from the ocean to the west (Fig. 3). They identified three major glacial advances during the Weichselian which, according to their chronology terminated on the shelf west of Svalbard during the Marine Isotope Substage 5 d (110 ka), MIS 4 (60 ka) and 2 (20 ka). The large glaciations were probably separated by long-lasting periods when glaciers were not significantly larger than today. During the Middle Weichselian (50-30 ka), Mangerud *et al.* (1998) consider that the shelf area east of Svalbard was ice free. However, it remains unclear if the shelf between Svalbard and mainland Norway was also affected by three separate glaciations during the Weichselian. Thus far only one till unit has been identified overlying the last interglacial (Eemian) in the outer part of the Bjørnøya Trough (Sættem *et al.*, 1992; Laberg & Vorren, 1995). This may imply that this part of the shelf remained ice free during the Early and Middle Weichselian glaciations. However, more investigations are necessary to resolve the Weichselian glacial history of this area.

During the Early and Middle Weichselian the Barents-Kara Ice Sheet expanded much further southeastwards, inundating the northern rim of the Russian mainland (Astakhov *et al*., 1999; Forman *et al*., 1999; Alexandersson *et al.*, 2001; Hjort *et al.*, this volume). Large ice dammed lakes formed and flooded the Russian lowland in front of the advancing Early Weichselian ice sheet. A series of optically stimulated luminescence (OSL) dates indicate that the maximum ice sheet extent was attained at around 90 ka (Marine Isotope Substage 5 b) (Mangerud *et al.*, 2001; Alexandersson *et al.*, 2001). A regrowth of the ice sheet probably occurred during MIS 4 leading to another advance that culminated at around 60 ka (Henriksen *et al.*, 2001; Houmark-Nielsen *et al.*, 2001) (Fig. 3). Along the Pechora River, in the European Russian Arctic, the ice front reached as far south as the preceding ice advance, but the ice extent was more restricted further to the east than during the glacial maximum at 90 ka. Sediment cores from the Pechora Sea indicate that the deglaciation after the last advance occurred before 35 ka (Polyak *et al.*, 2000a). Moreover, radiocarbon dates from raised shorelines on Severnaya Zemlya have yielded ages ranging from 21 ka to more than 50 ka (Bolshiyanov & Makeyev, 1995). These shorelines are thought to reflect a significant rebound of the crust following comprehensive Middle Weichselian deglaciation. Investigations of sediment cores from the continental slope to the northeast of Severnaya Zemlya show a pronounced peak in IRD content around 60 ka, with a smaller peak around 90 ka (Knies *et al.*, 2000). Knies *et al*. (2000) maintain that the youngest till on the shelf margin to the east of Severnaya Zemlya is of Middle Weichselian age, reflecting an ice sheet with a grounding line at least 340 m below the present sea level.

As will be apparent from the above review, the LGM was clearly preceded by at least two major Weichselian glaciations. However, the proposed age for the Early Weichselian glacial maximum is not quite the same in the different sectors. The Svalbard record suggest that the first ice advance occurred during Marine Isotope Substage 5d (110 ka) whereas in northern Russia the maximum ice sheet position has been ascribed to MI Substage 5b (90 ka). This age difference may be real, but it is possibly also an artifact of dating uncertainties.

The geological evidence for the reconstructed ice-sheet advances compare fairly well with a recent model simulation for the repeated growth and decay of the Eurasian ice sheets during the Weichselian (Siegert *et al.*, 2001). It is also worth noting that the model, which is forced by global sea level and solar insulation changes, creates three major glaciations in the Barents and Kara Sea region that culminated at around 90 ka, 60 ka and the LGM. Moreover, in accordance with the empirical reconstructions, the Siegert *et al.* (2001) model predicts that each ice-sheet advance was followed by an almost total deglaciation of the shelf.

The Late Weichselian glacial maximum (LGM)

A major ice sheet formed over the Barents Sea shelf during the Late Weichselian Substage (e.g. Landvik *et al*.,1998). Till overlain by glaciomarine sediments that date from the Late Weichselian has been mapped on the sea floor throughout most of the Barents Sea and is also found on many islands (Fig. 1). One of the most convincing lines of evidence for a grounded ice sheet in the Barents Sea is the occurrence of subglacially-formed flute bedforms. Such features have been discovered in the Bjørnøy Trough, near the central part of the Barents Sea (Solheim *et al*., 1990) and in the St.Anna Trough to the east of Franz Josef Land (Polyak *et al*., 1997). The pattern of raised shorelines provide further evidence in supporting the existence of a major Late Weichselian ice sheet (e.g. Salvigsen *et al.*, 1981 reference missing!) (Fig. 1). The reconstructed shoreline isobases define a centre of Holocene glacio-isostatic uplift in the north-central Barents Sea, resulting from a former ice dome in this area (Forman *et al.*, 1995).

According to Landvik *et al.*'s (1998) reconstruction, the ice sheet overrode all islands on Franz Josef Land and Svalbard during the LGM, when the ice front reached the outer shelf margins with a grounding line at 500-600 m below present sea level. Based on radiocarbon dates of shells and foraminifers from sediment cores, the last major ice sheet advance terminated at the western shelf break in the Barents Sea, between 19 and 15 ka (Landvik *et al.*, 1998). In the northern Barents Sea, the Late Weichselian till sheet has been traced to the shelf break at the mouth of the Franz Victoria Trough (Lubinski *et al.* 1996; Kleiber *et al.* 2000). Here the occurrence of debris-flow sediments and glaciomarine diamictons on the continental slope led Kleiber *et al*. (2000) to conclude that the ice sheet reached the shelf break as early as 23 ka (Kleiber *et al*. 2000). It has also been demonstrated that the ice sheet centred on the Barents Sea shelf filled the St. Anna Trough to the east of Franz Josef Land (Polyak *et al.*,1997). Here the grounding line probably occurred close to shelf break along the entire shelf margin from Svalbard and eastwards to the St.Anna Trough (Fig. 2). However, more investigations are necessary to define the eastern ice-sheet limit on the northern Kara Sea shelf.

Until recently, it was a common view that the southeastern margin of the Barents-Kara Ice Sheet expanded well onto the Russian mainland during the LGM (e.g. Landvik *et al.*, 1998). However, new land-based evidence from Russia contradicted this view (Astakhov *et al.*, 1999; Forman *et al*., 1999; Mangerud *et al*., 1999). On the basis of marine geological and geophysical data this ice limit has now been identified on the sea floor off the mainland (Figs 1 and 2) (Svendsen *et al*., 1999; Polyak *et al*., 2000a; Gataullin *et al*., 2001). This boundary in the Pechora Sea, termed the Kolguev Line, marks the southern limit of the uppermost till sheet (SSU III) in the Barents Sea. It is assumed that the southern flank of the ice sheet coalesced with the Scandinavian Ice Sheet near the northern tip of the Kanin Peninsula, but the exact boundary remains to be defined in this confluence area. To the south of the proposed ice-sheet limit, and distal to the mouth of the Pechora River, there is a one hundred metre thick wedge of Middle Weichselian prodeltaic marine sediments that is not overlain by till (Polyak *et al*., 2000a; Gataullin *et al*., 2001). The relative sea level in the southern Pechora Sea was apparently 15-20 m below the present during the LGM, reflecting a glacioisostatic depression of *c*. 100 m near the ice limit (Gataullin *et al*., 2001). The glacioisostatic uplift caused the relative sea level to fall after the ice front receded from its maximal position and a minimum level of 50-60 m b.s.l. was established at the very end of the Late Weichselian (10-12 ka).

The maximum ice sheet limit during the LGM in the southern Kara Sea probably occurred at a well-defined morainic ridge SE of the southern end of the Novaya Zemlya Trough (Svendsen et al., 1999; Polyak et al., 2000b). On the floor of this trough there is only a 4 - 5 m thick veneer of marine sediments upon the till, whereas a much thicker accumulation (up to 100 m) has been recorded closer to the morainic ridge. Further north, we assume that the LGM limit is thought to have occurred along the eastern margin of the Novaya Zemlya Trough (Fig. 2), although a more extensive ice cover in this part of the Kara Sea cannot be excluded (Polyak *et al*., 2000b).

The ice-sheet configuration in the northern Kara Sea is more uncertain and we have therefore no ice limits have been drawn in this area. Land-based investigations show that the central part of the Taymyr Peninsula was ice free during the LGM (Möller *et al.*, 1999). Two AMS dates of molluscs that were incorporated in glacier ice on the Taymyr Peninsula have yielded ages of around 20 ka suggesting that a younger glacier advance affected the NW coast during the LGM (Alexandersson *et al*., 2001; Hjort *et *al*., this volume). An alternative interpretation is that this was a lobe of the Barents-Kara Ice Sheet that reached Taymyr. However, no observations confirm that there was an ice-dammed lake along the northern rim of the Russian Lowland at this time, implying that the northbound drainage on the continent was not blocked by a coherent ice sheet. Accordingly, it is concluded that the glacier advance that reached the NW coast on Taymyr was unconnected with the Barents-Kara Ice Sheet, i.e. there was an ice-free corridor on the shelf.

Marine geological investigations it is concluded that the continental shelf to the east of Severnaya Zemlya was ice free during the LGM (Knies *et al.,* 2000). Furthermore, the lack of IRD in the marine sediments from this period suggests that that there was no calving ice front on this side of the archipelago. This assumption is supported by radiocarbon dates from mammoth remains on Severnaya Zemlya (Makeyev *et al*., 1979; Bolshiyanov & Makeyev, 1995) suggesting that the local glaciers on these islands were not significantly larger than today.

The early deglaciation of the shelf

A step-like deglaciation during the period 15-10 ka is thought to have occurred (e.g. Polyak *et al.*, 1995; Kleiber *et al.* 2000). At the mouth of the Franz Victoria Trough in the northern Barents Sea the initial disintegration of the ice sheet is indicated by a pronounced increase in the flux of IRD to the slope around 15.4 ka and a subsequent isotopically-depleted meltwater signal (Kleiber *et al.* 2000). Radiocarbon dates obtained from glaciomarine sediments above the upper till bed led Kleiber *et al.* (2000) conclude that the grounding line retreated from its maximum position shortly before 13.4 ka. Moreover, on the continental slope to the west of Svalbard a distinct meltwater event is reflected in the oxygen isotope record at 15 ka (Elverhøi *et al*., 1995). Sediment cores retrieved from the outer shelf in this region indicate that the ice sheet began receding before 14.8 ka (Svendsen *et al*., 1996), or perhaps as early as 16.4 ka (Cadman,1996). A very similar age for the onset of deglaciation was proposed by Vorren *et al*. (1988) reference missing! for the confluence area between the Scandinavian and Barents-Kara ice sheets. The fact that the postglacial uplift in northern Norway and the Kola Peninsula in Russia is little influenced by the former Barents-Kara Ice Sheet has been explained by a significant reduction of the ice load prior to 15 ka (Elverhøi *et al*.,1993). However, there is no positive evidence to suggest that the ice front retreated far inside the shelf margin at this time, and it is possible that this early stage of deglaciation mainly occurred as a thinning of the ice sheet.

There are a number of end moraines on the floor of the Barents Sea which, according to the authors'correlations may represent a contemporaneous glacial event (Fig.1). In the southeastern Barents Sea this event is marked by the Kurentsovo Line, a series of long ice-pushed ridges that are located 50-100 km north of the apparent LGM limit (Gataullin *et al*., 2001). Accumulations of glaciomarine sediments up to 100 m thick are found on the southern side of these ridges, whereas less than 10-20 m occur on the northern side. The Kurentsovo Line can be traced to the southern end of Novaya Zemlya, preliminary results suggesting that the ice front terminated along the eastern margin of the Novaya Zemlya Trough at this time. The western continuation of this line is presumably marked by the Murmansk Bank Moraines, a chain of morainic ridges, *c*. 400 km long, north of the Kola Peninsula. It is also possible that a series of 20-50 m high ridges at 300 m water depth along the western and southern margins of the Spitsbergen Bank are of the same age (Elverhøi & Solheim, 1983). These ridges are correlated with thick accumulations of ice-proximal marine sediments on the inner part of Bjørnøyrenna and at the mouth of Storfjordrenna (Elverhøi *et al*., 1990; 1993).

Investigations of exposed marine sediments indicate that the ice limit at around 13 ka was located near the extreme western coastline of Svalbard (Fig. 2) (Landvik *et al*., 1998). At this time the Franz Josef Trough and St. Anna Trough were largely ice free, but a major ice dome still covered the central part of the Barents Sea shelf. It is likely that the end moraines in the southern and western Barents Sea mentioned above are of a similar or slightly older age. The sediment sequences in cores from the Central Deep suggest that the ice front receded from this line shortly after13 ka and later much of the shelf was ice free a few hundred years (Polyak *et al.*,1995). Along the western margin of Svalbard, the deglaciation was interrupted by a short-lived glacier readvance that culminated on the inner part of the shelf shortly after 12.4 ka (Svendsen *et al*., 1996). In spite of a rapid global transgression, the relative sea level was falling beyond the receding ice front, reflecting strong glacio-isostatic uplift.

The Younger Dryas and the final deglaciation

The large Admiralty Bank moraines are located west of Novaya Zemlya (Fig. 1) (Gataullin & Polyak, 1997). Judging from radiocarbon dates from the Central Deep (Polyak *et al*., 1995), this ice margin is younger than ~12.5-13 ka. This led Gataullin *et al.* (2001) to hypothesise that the moraines were formed during the Younger Dryas Chron. However, more dates are necessary to confirm this assumption. A thickening of the glaciomarine sediments on the distal side of this line may suggest that the ice front halted at this position for some time. The configuration of the ice sheet that deposited the Admiralty Bank Moraines is not clear, but the orientation of the ridge system points towards an ice dispersal centre that was positioned over the northernmost part of the Novaya Zemlya area or even further to the N-NW. A coherent ice cover may have occurred between Novaya Zemlya and Franz Josef Land (Fig. 2). The few radiocarbon-dated sediment sequences on Franz Josef Land suggest that this area was deglaciated at the end of the Younger Dryas and/or very early in the Holocene (Forman *et al.*, 1997).

During the Younger Dryas, local glaciers on the west coast of Svalbard were of the same size as those today or even smaller (Mangerud & Svendsen, 1990). In contrast, a major ice sheet was centred on eastern Svalbard, with long outlet glaciers in the fjords. An almost stable position of the relative sea level along the west coast of Svalbard during the Younger Dryas implies the occurrence of a stable or growing ice load in the east (Landvik *et al.*, 1998). Even though the Younger Dryas limits around Svalbard have not been mapped, the available radiocarbon dates from uplifted marine sediments suggest that eastern Svalbard and the adjacent shelf was still covered by a sizeable ice cap at this time, and that it may have been larger than shown in this reconstruction.

It seems that the last remains of the Barents-Kara Ice sheet occurred over the northern part of the Barents Sea and that the ice caps remained stable or expanded as a response to the Younger Dryas cooling. This pattern of deglaciation is consistent with the 10 ka shoreline isobase that reflects an uplift dome over the northern Barents Sea. The ice caps melted rapidly at around 10 ka as a result of the abrupt Holocene climatic warming and as much as ~ 90 % of glacio-isostatic rebound was completed by *c*. 6 ka (Forman *et al.*, 1997). During the early and middle Holocene the glaciers on Svalbard and Franz Josef Land were smaller than today (Svendsen & Mangerud, 1997; Lubinski *et al.*, 1999).

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