Marine ice-rafted debris records constrain maximum extent of Saalian and Weichselian ice-sheets along the northern Eurasian margin

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Received 12 December 1999; accepted 23 May 2001

Abstract

Ice-rafted debris (IRD) (> 2 mm), input in eight sediment cores along the Eurasian continental margin (Arctic Ocean), have been studied over the last two glacial/interglacial cycles. Together with the revised chronologies and new micropaleontological data of two cores from the northern Barents Sea (PS2138) and northeastern Kara Sea (PS2741) spanning Marine Isotope Stages (MIS) 6 to 1, the IRD data give new insights into the glacial history of northern Eurasian ice-sheets over the last 150 ka. The chronologies of the cores are based on stable isotope records, AMS 14C datings, paleomagnetic and biostratigraphic data.

Extensive episodes of northern Barents Sea ice-sheet growth, probably to the shelf edge, occurred during the late Weichselian (MIS 2) and the Saalian (MIS 6). Major IRD discharge at the MIS 4/3-transition hints to another severe glaciation, probably onto the outer shelf, during MIS 4. IRD-based instabilities of the marine-based ice margin along the northern Barents Sea between MIS 4 and 2 are similar in timing with North Atlantic Heinrich events and Nordic Seas IRD events, suggesting similar atmospheric cooling over a broad region or linkage of ice-sheet fluctuations through small sea-level events.

In the relatively low-precipitation areas of eastern Eurasia, IRD peak values during Termination II and MIS 4/3-transition suggest a Kara Sea ice-sheet advance onto the outer shelf, probably to the shelf edge, during glacial MIS 6 and 4. This suggests that during the initial cooling following the interglacials MIS 5, and possibly MIS 7, the combined effect of sustained inflow of Atlantic water into the Arctic Ocean and penetration of moisture-bearing cyclones into easterly direction supported major ice build-up during Saalian (MIS 6) and Mid-Weichselian (MIS 4) glaciation. IRD peak values in MIS 5 indicate at least two advances of the Severnaya Semya ice-sheet to the coast line during the Early Weichselian. In contrast, a distinct Kara Sea ice advance during the Late Weichselian (MIS 2) is not documented by the IRD records along the northeastern Kara Sea margin. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Arctic Ocean; Barents Sea; Kara Sea; Quaternary; ice-rafted debris; ice-sheets
1. Introduction

Coarse terrigenous material (> 500 μm) in deep-sea sediments from the Nordic Seas and the Arctic Ocean is usually assumed to be iceberg-rafted (cf. Nørgaard-Pedersen et al., 1998; Dowdeswell et al., 1998 for a recent discussion). As long as gravity flows and sea-ice transport can be ruled out, peak values of ice-rafted debris (IRD) (> 500 μm) in sediment records possibly monitor glacial maxima and/or deglaciation phases of surrounding ice-sheets during the late Quaternary (e.g. Baumann et al., 1995; Mangerud et al., 1998). Particularly, large volumes of icebergs were released periodically when continental glaciers/ice-sheets reached the coastline, eventually protruded to the shelf edge and disintegrated (e.g. Elverhøi et al., 1995). Consequently, temporal variations in amount and composition of IRD provide important information on the changes in the loci of major continental glaciations, e.g. the Svalbard/Barents Sea ice-sheet (Mangerud et al., 1998).

Our approach to decipher waxing and waning of the northern Eurasian ice-sheets during the Saalian and Weichselian by marine records is based on the excellent temporal coincidence of IRD records from the western Svalbard margin with the glaciation history interpreted from the onshore sections on Sval-

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hard (Mangerud et al., 1998). They concluded that, during the Weichselian, IRD peak values (> 500 μm) occurred mainly during major deglaciation phases of the Svalbard/Barents Sea ice-sheet. However, along the northern Eurasian continental margin, detailed correlation of IRD records and onshore sections during the Weichselian or even the Saalian are hampered by relatively sparse terrestrial data sets. Nevertheless, the recent summaries by Velitchko et al. (1997a,b) and Svendsen et al. (1999) provide a glacial geologic framework which can be tested with IRD records along the Eurasian continental margin (cf. Knies et al., 2000; Kleiber et al., 2000). Svendsen et al. (1999) concluded that the maximum ice-sheet extent occurred prior to 50 ka, probably during MIS 4, whereas much of the Russian Arctic remained ice-free during the late Weichselian (MIS 2).

Here, we revise the current knowledge of the maximum extent of Saalian and Weichselian ice-sheets along the northern Eurasian margin recently published by Polyak et al. (1997), Landvik et al. (1998), Svendsen et al. (1999), Knies et al. (2000), and Kleiber et al. (2000). The IRD input into eight marine records recovered during several expeditions with the ice-breaking research vessel "Polarstern" (Fig. 1; Table 1), and, in particular, the revised chronologies and new micropaleontological data of the cores PS2138 and PS2741 (Matthiessen et al., 2001) may give new insights into the glacial history of Northern Eurasia.

IRD of > 2 mm were studied in 1-cm intervals downcore expressed as No. > 2 mm/10 cm² to ascertain that, during major climatic changes, IRD attributed to sediment delivery from waxing and waning ice-sheets along the Eurasian continental margin is really considered. We exclude sea-ice as transport media for particles > 2 mm in the study area because over 80% of debris in sea-ice is in the silt and clay fraction (Pfirman et al., 1989; Nürnberg et al., 1994). IRD peak values related to gravity flow transport in some of the investigated cores (PS2445-4, PS2446-4, P2447-5) were identified by high resolution seismic profiles (Parasound, 4 kHz) (Kleiber et al., 2000).

Finally, the revised reconstruction of waxing and waning ice-sheets along the northern Eurasian continental margin during the last 145 ka is correlated with Atlantic water inflow variations based on dinoflagellate cysts fluctuations in two sediment records from the northern Barents and Kara Sea margins (Matthiessen et al., 2001). The results provide possible evidence for a direct coupling of Atlantic water inflow variations along the Eurasian continental margin and the resultant penetration of moisture-bearing cyclones into an easterly direction with the asymmetric build-up of the Barents and Kara Sea ice-sheets during the middle (MIS 4) and late Weichselian (MIS 2) glaciations (Svendsen et al., 1999).

### 2. Chronology

The age control points for the studied cores along the northern Eurasian margin are mainly provided by — with decreasing priority — AMS ¹³C datings, sta-

<table>
<thead>
<tr>
<th>Core</th>
<th>Recovery Position</th>
<th>Water depth (m)</th>
<th>Age control References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS2138-1SL</td>
<td>631 81°32.1N; 30°34.0E</td>
<td>995</td>
<td>(Knies et al., 2000; Matthiessen et al., 2001)</td>
</tr>
<tr>
<td>PS2445-4KAL</td>
<td>725 82°46.0N; 40°13.6E</td>
<td>2999</td>
<td>(Kleiber et al., 2000)</td>
</tr>
<tr>
<td>PS2446-4KAL</td>
<td>650 82°23.8N; 40°54.5E</td>
<td>2022</td>
<td>(Kleiber et al., 2000)</td>
</tr>
<tr>
<td>PS2447-5SL</td>
<td>417 82°09.7N; 42°02.7E</td>
<td>1025</td>
<td>(Kleiber et al., 2000)</td>
</tr>
<tr>
<td>PS2741-1KAL</td>
<td>637 81°06.3N; 105°23.6E</td>
<td>2530</td>
<td>(Matthiessen et al., 2001)</td>
</tr>
<tr>
<td>PS2742-5SL</td>
<td>381 80°47.3N; 103°48.9E</td>
<td>1890</td>
<td>(Stein et al., 2001)</td>
</tr>
<tr>
<td>PS2782-1SL</td>
<td>520 79°36.6N; 103°21.3E</td>
<td>340</td>
<td>(Knies et al., 2000)</td>
</tr>
<tr>
<td>PS2778-2SL</td>
<td>588 77°58.7N; 113°03.9E</td>
<td>341</td>
<td>(Weiel, 1997)</td>
</tr>
<tr>
<td>PS2719-1SL</td>
<td>655 77°36.0N; 97°32.0E</td>
<td>135</td>
<td>(Stein et al., 2001)</td>
</tr>
</tbody>
</table>
ble oxygen and carbon isotope stratigraphy, magnetostratigraphy, biostratigraphic events, radionuclide records ($^{10}$Be, $^{230}$Th), and lithostratigraphic as well as seismostratigraphic units (cf. references in Table 1 for details). Briefly, age control for the cores along the northern Barents Sea continental margin are based on continuous stable oxygen and carbon isotope data measured on the planktic foraminifer *Neogloboquadrina pachyderma* sinistral, and several AMS $^{14}$C datings (Fig. 2a, Table 2) that allow correlation to the standard oxygen isotope curve (i.e. Martinson et al., 1987). In contrast, AMS $^{14}$C ages provide the major control points for the middle and upper Weichselian (40 ka) for the cores from the northeastern

### NORTHERN BARENTS SEA MARGIN

![Fig. 2](image.png)

Fig. 2. Compilation of IRD records along the Eurasian continental margin versus depth (m bsf). (a) Northern Barents Sea margin, (b) northern Kara Sea margin. Specific locations of the records and each water depth (m bsf) are indicated. The chronostratigraphy of cores is according to references in Table 1. Available AMS $^{14}$C datings (reservoir corrected by subtracting 440 years) are shown. Marine Isotope Stages (MIS) are noted. IRD particles $> 2$ mm were counted downcore on X-radiographs of each centimeter, applying the method of Grobe (1987). The coarse fraction $> 63$ and 250 μm was determined by sieving 5-cm$^3$ sediment over a 63- and 250-μm mesh. Percentages were calculated on a carbonate-free basis.
Ž. Kara Sea margin (Fig. 2b). The Saalian to early Weichselian section of core PS2741 were tentatively dated by correlation of paleomagnetic and susceptibility records as well as biostratigraphic and lithostratigraphic events with cores PS2212 and PS2138 (cf. Nowaczyk et al., 1994; Nowaczyk and Knies, 2000; Knies et al., 2000; Matthiessen et al., 2001 for further details to the revised age model of MIS 5 and 6). The chronostratigraphy of the cores has been obtained by linear interpolation between all available age control points (cf. references in Table 1).

3. IRD patterns along the northern Barents Sea margin

The strongest release of icebergs from the northeastern Svalbard margin as indicated by IRD peak
Table 2
Available AMS $^{14}$C dates for sediment core PS2138-1

<table>
<thead>
<tr>
<th>Core number</th>
<th>Depth (cm)</th>
<th>$^{14}$C age (BP)</th>
<th>Reservoir corrected age (years BP)</th>
<th>Carbon source</th>
<th>Laboratory</th>
<th>Age used (ka BP)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS2138-1</td>
<td>50</td>
<td>13,460 ± 110</td>
<td>13,020</td>
<td>bivalve shells</td>
<td>KIA-1282</td>
<td>not used</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>13,430 ± 70</td>
<td>12,990</td>
<td>N. pachyderma sin.</td>
<td>KIA-9872</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>80</td>
<td>13,040 + 140 / − 130</td>
<td>12,600</td>
<td>bivalve shells</td>
<td>KIA-363</td>
<td>not used</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>110</td>
<td>14,030 ± 80</td>
<td>13,590</td>
<td>mixed forams</td>
<td>KIA-4765</td>
<td>13.6</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>130</td>
<td>15,850 ± 130</td>
<td>15,410</td>
<td>N. pachyderma sin.</td>
<td>KIA-9873</td>
<td>16.2</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>160</td>
<td>16,670 ± 210</td>
<td>16,880</td>
<td>N. pachyderma sin.</td>
<td>KIA-2745</td>
<td>16.9</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>180</td>
<td>19,230 ± 140</td>
<td>18,790</td>
<td>N. pachyderma sin.</td>
<td>KIA-9873</td>
<td>18.8</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>210</td>
<td>19,710 ± 130</td>
<td>19,270</td>
<td>N. pachyderma sin.</td>
<td>KIA-9874</td>
<td>19.3</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>244</td>
<td>20,420 ± 130</td>
<td>19,980</td>
<td>N. pachyderma sin.</td>
<td>KIA-9875</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>275</td>
<td>20,700 ± 130</td>
<td>20,260</td>
<td>N. pachyderma sin.</td>
<td>KIA-9876</td>
<td>20.3</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>300</td>
<td>20,480 + 330 / − 320</td>
<td>20,040</td>
<td>N. pachyderma sin.</td>
<td>KIA-365</td>
<td>not used</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>316</td>
<td>22,470 ± 160</td>
<td>22,030</td>
<td>N. pachyderma sin.</td>
<td>KIA-9877</td>
<td>22</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>331</td>
<td>25,540 ± 240</td>
<td>23,100</td>
<td>N. pachyderma sin.</td>
<td>KIA-2744</td>
<td>23.1</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>345</td>
<td>24,910 ± 200 / − 190</td>
<td>24,470</td>
<td>N. pachyderma sin.</td>
<td>KIA10372</td>
<td>24.5</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>360</td>
<td>26,240 + 280 / − 270</td>
<td>25,800</td>
<td>N. pachyderma sin.</td>
<td>KIA-4766</td>
<td>25.8</td>
<td>1</td>
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<tr>
<td>PS2138-1</td>
<td>366</td>
<td>26,260 + 230</td>
<td>25,820</td>
<td>N. pachyderma sin.</td>
<td>KIA10373</td>
<td>25.8</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>372</td>
<td>30,290 + 360 / − 350</td>
<td>29,850</td>
<td>N. pachyderma sin.</td>
<td>KIA10374</td>
<td>29.9</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>375</td>
<td>&gt; 45,190</td>
<td></td>
<td>N. pachyderma sin.</td>
<td>KIA10375</td>
<td>not used</td>
<td>2</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>380</td>
<td>35,340 + 1570 / − 1310</td>
<td>34,900</td>
<td>mixed forams</td>
<td>KIA-1284</td>
<td>34.9</td>
<td>1</td>
</tr>
<tr>
<td>PS2138-1</td>
<td>385</td>
<td>30,240 + 380 / − 370</td>
<td></td>
<td>N. pachyderma sin.</td>
<td>KIA10376</td>
<td>not used*</td>
<td>2</td>
</tr>
</tbody>
</table>

1: Knies et al. (2000) and Nowaczyk and Knies (2000); 2: Nowaczyk et al. (in preparation).
A reservoir correction of 440 years have been used.
*Unreliable ages because carbon content of sample was too low.

values in PS2138 occurred during the terminations of the Saalian (MIS 6), Mid- (MIS 4) and Late Weichselian (MIS 2) glaciations in the Svalbard/Barents Sea area (Fig. 2a). However, prominent single IRD peaks in between phases of reduced input are observed both during glacialis and interglacials and indicate periodic melting events of calved glacial ice from the northeastern Svalbard margin during the last 145 ka (Fig. 2a). The transitions to interglacials are marked by a decrease in the content of IRD.

In contrast to the northeastern Svalbard area with low to moderate IRD input during early MIS 2, the base of the cores north of the Franz Victoria Trough (FVT) contain exclusively massive diamictons, which are poorly sorted and include a high content of gravel and scattered mud clasts (Fig. 2a, cf. Kleiber et al., 2000). Based on Parasound seismic profiles (4 kHz), these basal diamictons can be correlated to stacked, acoustically transparent lenses and layers interpreted as debris flows which form large subma-

riner fans at the mouth of the FVT (Kleiber et al., 2000). The prominent IRD layers in PS2446 during middle MIS 2 and Termination I are similar in timing to melting events in PS2138 and can be associated with significant iceberg discharge from the northern Svalbard/Barents Sea ice-sheet (Figs. 2a and 4).

4. IRD pattern along the northeastern Kara Sea margin

A diamicton in PS2782 recovered in 340-m water depth is older than 44 ka and indicates a severe glaciation on Severnaya Semlya (Fig. 2b). The transition to glacial marine sediments is indicated by prominent IRD peaks intercalated in laminated sequences (Fig 2b; Weiel, 1997). Gravel is rare from the laminated sequence to the core top, although a
distinct higher input of IRD is observed in the uppermost 50 cm (Fig. 2b).

During the Saalian (MIS 6) IRD is absent from the continental slope core PS2741, whereas the transition from MIS 6 to 5 (Termination II) is marked by a distinct IRD spike and peak values of coarse fraction (> 63 μm) input (5 wt.%) at 460 cm bsf (Fig. 2b) (Müller, 1999). Prominent single IRD peaks are detected during middle and late MIS 5, respectively. Similar to PS2782, the transition of MIS 4 to 3 is marked by IRD peak values and highest input of terrigenous coarse fraction (up to 25 wt.%). A smaller but distinct IRD and coarse fraction peak is recorded during MIS 3. IRD is almost absent during the middle Weichselian to Holocene (MIS 3 to 1).

High-resolution late glacial and Holocene sediments were recovered SW and NE of the Vilkitsky Strait (Fig. 1). These shallow cores contain only minor amounts of IRD. A thin diamicton is observed in PS2742 and is older than 12.5 14C ka. Two prominent peaks in PS2719, which do not occur in PS2778 are observed at 508 and 100 cm bsf, respectively (Fig. 2b).

5. Northern Barents Sea

5.1. Saalian–Middle Weichselian glaciations in the northern Barents Sea

The IRD pattern NE of Svalbard (PS2138) seems not to be confined to ice volume maxima at MIS 6, 5d and 5b, 4, and 2 (Fig. 3). However, when comparing the glaciation on Svalbard with the IRD pattern in PS2138, the general coincidence of major IRD peaks with deglacial phases on western Svalbard at the MIS 2/1, 4/3, and—with a slightly lower intensity—6/5 transitions, is striking (Fig. 3). The Saalian glaciation probably reached the northern Barents Sea shelf edge because enhanced bulk accumulation rates (up to 10 g/cm²/ka) coupled with increased input of reworked material from the central Barents Sea indicate that large quantities of glacially derived sediments were deposited by the ice-sheet directly onto the upper continental slope (cf. Knies et al., 2000). Three IRD peaks mark significant deglacial events along the northern Svalbard margin during upper MIS 6 (Fig 3). The first prominent IRD pulse reflects the MIS event 6.3 and may indicate a destabilisation of the ice margin induced by a short-term warming period (Matthiessen et al., 2001 for details to the stable isotope stratigraphy of PS2138). The onset of disintegration of the ice-sheet is recognised at ~ 134 ka by a single IRD peak. After a short delay, a second IRD spike between ~ 129 and ~ 127 ka marks the final retreat from the outer shelf (Termination II) (Fig. 3). A similar scenario of waxing and waning ice-sheets during late MIS 6 is described from the western Scandinavian margin (Wagner, 1993; Baumann et al., 1995; Fronval and Jansen, 1997) suggesting a link in the behaviour of both ice-sheets.

During early Weichselian, moderate IRD input suggests minor glacial activity onshore in contrast to
MIS 6. After the Eemian (MIS 5e), five smaller IRD pulses were recorded between ~112 and ~70 ka. The first IRD event at ~112 ka possibly marks the first widespread, substantial cooling and the initial glaciation on Svalbard during MIS 5d (Mangerud et al., 1998). Moderate IRD input during the transitions 5d/5c and 5b/5a may reflect smaller glacier advances to the outer coastline during MIS 5d and 5b (Fig. 3).

Build-up of the major middle Weichselian glaciation on Svalbard is possibly documented by distinct IRD episodes at the beginning of MIS 4 (cf. Fig. 3). As the ice masses extended again beyond the fjord systems and onto the continental shelves, sediment delivery from calving icebergs mainly affected the core sites. A steep increase in IRD input is interpreted to reflect the ice front reaching the outer coastline at ~65 ka (Fig. 3). The major retreat of the ice-sheets following MIS 4 is a pronounced event along the western Svalbard margin and the central Arctic Ocean (Lloyd et al., 1996; Darby et al., 1997; Nørgaard-Pedersen et al., 1998; Poore et al., 1999). IRD pulses from 62 to 52 ka in PS2138 may reflect this major deglaciation event and probably indicate huge iceberg discharge from a retreating ice-margin from the outer shelf areas (Fig. 3) (cf. Mangerud et al., 1998).

5.2. Late Weichselian Glacial Maximum and Termination I in the Northern Barents Sea

Elverhøi et al. (1995) concluded that there was no grounded ice prior to 23 $^{14}$C ka on the western Svalbard margin, and that glaciers on Svalbard were restricted to the inner fjords. The first significant advance to the shelf edge occurred after 19.6 $^{14}$C ka (Andersen et al., 1996). In contrast, Dokken (1995) proposed in accordance with Vorren and Laberg (1996) that a major deglacial phase along the western Svalbard margin occurred in between two major ice-sheet advances (29–23 and 19–15 $^{14}$C ka). For the Barents Sea, only the latter ice advance after 22 $^{14}$C ka has been proven so far (Landvik et al., 1998).

Along the northern Svalbard margin and the Franz Victoria Trough, moisture supplied by intruding Atlantic water in combination with lower summer insolation that may have prohibited iceberg calving, as indicated by diminished IRD input in PS2138 (Fig. 4), possibly enforced the rapid build-up of the Svalbard/Barents Sea ice-sheet during the early stage of the Late Weichselian (after 30 $^{14}$C ka) (Knies et al., 2000). The first initial instability of the extended ice-sheet during build-up is recorded by a distinct IRD peak centered at ~27 $^{14}$C ka (SB3) (Fig. 4). When the ice-sheet was at the shelf break during full glacial conditions (23 $^{14}$C ka), the fast flowing ice streams in the Franz Victoria Trough delivered large quantities of sediment to the upper slope (PS2447). Parasound profiles (4 kHz) and the cores from the FVT continental slope show a series of large debris flows that form a major fan (cf. Kleiber et al., 2000, in accordance with e.g. Laberg and Vorren, 1995). A comparable scenario is not recorded in PS2138, probably because sedimentation is not directly influenced by a fast-flowing ice stream, but by a more stable ice margin. Dowdeswell et al. (1998) noted that sediment delivery at stable margins is greatly reduced compared to an ice stream regime, even though the ice-sheet protruded to the outer shelf or to the shelf edge. The absence of debris flow deposits along the continental margin of Nordaustlandet (Solheim et al., 1996) may indicate that the LGM ice-sheet extent did not reach the shelf edge (Leirdal, 1997; Forman and Ingólfsson, 2000). Although Østerholm (1990) argued, based on the marine limit on Prins Oscars Land, Nordaustlandet, at about 50 m asl, that the Svalbard/Barents Sea ice-sheet extended only to the coast line during the Late Weichselian, a proximal position of an ice-sheet after 23 $^{14}$C ka is indicated by a steep increase in bulk accumulation rates in PS2138 (up to 50 g/cm$^2$/ka) and highest input of kaolinite-rich sediments likely related to glacially eroded bedrocks from the northern and central Barents Sea (cf. Knies et al., 2000). In contact with the sea, the marine-based ice-sheet broke up at ~21 $^{14}$C ka (SB 2), as indicated by major IRD pulses in PS2138 and PS2446 (Fig. 4). Based on these results, we strongly favour the scenario of an ice-sheet extended to the shelf edge earlier than 19 $^{14}$C ka and propose a maximum position reached at ~23 $^{14}$C ka along the northern Barents Sea margin.

Rapid ice-sheet disintegration started at ~15.4 $^{14}$C ka. This is obvious from major IRD pulses in PS2138 and PS2446 (Fig. 4). A short delay after the
Fig. 4. The left panel shows extension of the ice-sheet on the northern Barents Sea margin during the last glacial/interglacial cycle (in $^{14}$C ages) with respect to Atlantic water inflow (Knies et al., 1999), debris flow occurrences (Kleiber et al., 2000), and IRD peak values. The right panel shows the data corresponding to the model. The reconstruction is based on IRD-records of the cores PS2138-1 and PS2446-4. Available AMS $^{14}$C datings are indicated. SB2 and SB3 (SB: Svalbard/Barents Sea) mark pronounced IRD deposition events contemporary to the North Atlantic Heinrich Events H2 and H3 (cf. Bond et al., 1993; Grousset et al., 2000).
first prominent IRD pulse at 15.4 $^{14}$C ka indicates that armadas of icebergs and extensive meltwater released during the initial phase may have prohibited further decay of the ice-sheet. A significant cooling of the ocean, possibly triggered by positive ice-albedo feedback mechanisms and sea-ice formation, may have caused the delay and subsequently prevented a rapid decay of the ice-sheet (cf. Ruddiman and McIntyre, 1981). After this delay a second major IRD pulse at ~13.6 $^{14}$C ka in PS2138 and PS2446 reflects increased iceberg calving due to further ice-sheet decay by still rising summer insolation and sea level (Fig. 4). The transition from the stratified diamicton to the massive pebbly silty clay at ~13.4 $^{14}$C ka in PS2447 (Fig. 2) indicates grounding-line retreat from the shelf edge in the FVT (cf. Kleiber et al., 2000). AMS $^{14}$C dates from the ice proximal laminated clay overlying the diamicton in the central FVT yield a ~13 $^{14}$C ka age that reflects stepwise retreat to the inner shelf (Polyak and Solheim, 1994; Lubinski et al., 1996).

5.3. Correlation of Arctic Ocean IRD pulses to the north Atlantic Heinrich events?

There is still an ongoing debate about synchronicity of iceberg discharge from Northern Hemisphere

![Fig. 5. Prominent IRD deposition events (SB1–SB4) along the northern Barents Sea margin between 40 and 12 $^{14}$C ka from core PS2138-1. T1a (Termination) marks the initial decay of the northern Barents Sea ice-sheet during the late Weichselian. SB2–SB4 have average ages of 21.3, 26.8, and 34 $^{14}$C ka, respectively. Arrows indicate the AMS $^{14}$C dates used to derive the age of each event.]
ice-sheets during the so-called Heinrich events in the North Atlantic and the Nordic seas (e.g. Elliot et al., 1998; Dowdeswell et al., 1999; Grousset et al., 2000; Van Kreveld et al., 2000). It is assumed that if some of the IRD events in the Nordic Seas occurred simultaneously with the Heinrich events in the North Atlantic, then a rapid interaction between the Northern Hemisphere ice-sheets in response to a common environmental cause probably has to be taken into account (Broecker, 1994; Bond and Lotti, 1995; Elliot et al., 1998). Grousset et al. (2000) and Van Kreveld et al. (2000) stated that for most of the Heinrich events, the icebergs were calved first from the European ice-sheets, i.e. Greenland, Iceland, Scandinavia, and possibly Svalbard, predating the Laurentide surges. They suggested that the cyclic release of European icebergs every ~1500 years acted as triggering precursors for the massive Laurentide surges ( Elliot et al., 1998). However, Dowdeswell et al. (1999) pointed out, based on more or less asynchronous IRD layers in the North Atlantic and the Nordic seas sediment records over the past 60 ka, that the Nordic seas ice-sheets did not exhibit unstable behaviour coincident with iceberg discharge from the drainage basin of the Laurentide ice-sheet. In a recent review, Andrews (1998) stated that, before demonstrating syn- or asynchrony between Heinrich events and IRD layers elsewhere, radiocarbon dating needs to be carried out with considerable rigour. In fact, and in contrast to Dowdeswell et al. (1999), Völler et al. (1998), Völker (1999), and Van Kreveld et al. (2000) demonstrated that high resolution sediment cores with numerous AMS 14C ages from the Irminger, Iceland and Norwegian seas show IRD layers approximately coeval with the Heinrich events in the North Atlantic (Bond et al., 1993; Bond and Lotti, 1995).

In Fig. 5 we examine each significant IRD pulse in PS2138 over the last 40 ka (SB1–SB4) with respect to their synchrony to the Heinrich events (H1–H4). Although a relatively low temporal resolution of PS2138 hampers a precise correlation of its IRD pulses to the Heinrich events, the interpolated ages of three of the distinct IRD pulses (SB2–SB4) correspond approximately to Heinrich events 2, 3, and 4 (Table 3, Fig. 5). An exception is the IRD layer associated with the initial decay of the northern Barents Sea ice margin during Termination Ia (15.4 14C ka); it clearly predates Heinrich Event H1 (Fig. 5a) and is, thus, not synchronous to the collapse of the Laurentide or other ice-sheets in the northern Hemisphere (Dowdeswell et al., 1999; Kleiber et al., 2000 for details). The IRD layers analogous to H2 and H3 (Fig. 5b,c) have an average age of 21.3 and 26.8 14C ka, respectively. Even the prominent IRD layer SB4 with an average age of 34 14C ka (Fig. 5d) matches the Heinrich event H4 (Table 3; Elliot et al., 1998). The high kaolinite content and δ13Corg values <−25‰ during each IRD event point to the Barents Sea ice-sheet as the most probable source (cf. Knies et al., 2000). Thus, in contrast to Dowdeswell et al. (1999), we propose that frequent iceberg discharges from the northern Barents Sea ice-sheet are similar in timing with the Heinrich events H2–H4, suggesting similar atmospheric cooling over a broad region or linkage of ice-sheet fluctuations through small sea-level events (Bond and Lotti, 1995; Elliot et al., 1998).

Table 3
Different core locations in the North Atlantic, Nordic Seas, and the northern Barents Sea (this study) and their AMS 14C dated IRD events corresponding to and/or are similar in timing (this study) with the Heinrich Events (HE) 1–4 in the North Atlantic

<table>
<thead>
<tr>
<th>Core</th>
<th>Latitude; longitude</th>
<th>Depth (m)</th>
<th>HE1 14C-age</th>
<th>HE2 14C-age</th>
<th>HE3 14C-age</th>
<th>HE4 14C-age</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS2138-1</td>
<td>81°32'N; 30°34'E</td>
<td>995</td>
<td>~15.4–13.3</td>
<td>~21.6–21.3</td>
<td>~27.2–26.3</td>
<td>~35.4–31.8</td>
<td>this study</td>
</tr>
<tr>
<td>PS2644-4</td>
<td>67°52'N; 21°46'W</td>
<td>777</td>
<td>14.8–&gt;12.8</td>
<td>21.0–20.4</td>
<td>26.4–25.6</td>
<td>34.2–32.4</td>
<td>1</td>
</tr>
<tr>
<td>SU90-24</td>
<td>62°40'N; 40°54'W</td>
<td>2100</td>
<td>14.6–13.0</td>
<td>22.6–20.3</td>
<td>26.5–25.8</td>
<td>35.1–33.9</td>
<td>2</td>
</tr>
<tr>
<td>V23-81</td>
<td>54°15'N; 16°50'W</td>
<td>2400</td>
<td>15.0–13.5</td>
<td>21.9–20.6</td>
<td>27.9–26.2</td>
<td>35.2–34.1</td>
<td>3</td>
</tr>
<tr>
<td>ODP 609</td>
<td>49°52'N; 24°14'W</td>
<td>3900</td>
<td>15.4–13.2</td>
<td>22.6–20.4</td>
<td>28.0–25.6</td>
<td>35.3–34.6</td>
<td>3</td>
</tr>
<tr>
<td>SU90-08</td>
<td>43°31'N; 30°24'W</td>
<td>3100</td>
<td>15.1–13.4</td>
<td>21.5–20.4</td>
<td>26.7–26.0</td>
<td>35.3–34.5</td>
<td>4, 5</td>
</tr>
</tbody>
</table>

1: Völker (1999); 2: Elliot et al. (1998); 3: Bond et al. (1993); 4: Vidal et al. (1997); 5: Cortijo et al. (1997).
6. Northeastern Kara Sea

6.1. Saalian–Middle Weichselian glaciations in the northeastern Kara Sea

The relatively low content of IRD in core PS2741 during the last 150 ka compared to the records from the Svalbard/Barents margin may reflect either the presence of relatively stable ice-sheets with small fluctuations of the ice margin or stable glacimarine conditions when ice-sheets had a small extent or were even absent (Fig. 6). A distinct IRD spike and peak values of coarse fraction input indicate a broad ice front in an advanced position on the outer shelf, possibly along the shelf edge, at the MIS 6/5-transition (Termination II) (Figs. 2b and 6). We postulate that this IRD event monitors the Saalian deglaciation phase of the SSIS when large amounts of icebergs were released. Fine laminated sequences with high contents of fossil/reworked organic matter, smectite and kaolinite indicating glacially derived sediment input from the Kara Sea precede the IRD pulse in PS2741 (Vogt, 1997; Knies et al., 2000). These sediment characteristics on the lower continental slope may indicate severe climatic conditions during MIS 6 with a closed sea-ice cover and huge sediment

Fig. 6. IRD records of PS2782-1 (versus depth, cm bsf) and PS2741-1 (versus $^{14}$C ages). Dark shaded area indicates an Early Weichselian diamicton in PS2782-1. Light shaded area indicates the MIS transition 4/3. Prominent IRD peak values in PS2741-1 are outlined.
supply from the far extended Kara Sea ice-sheet (Müller, 1999; Knies et al., 2000). Support for this interpretation from onshore sections is sparse. However, Mangerud et al. (1999) mentioned an uplift of Eemian shore lines of \( \sim 50 \) m above the present in the Pechora Basin between the White Sea and the Ural mountains, which can only be explained by isostatic depression produced by a large Saalian ice-sheet in the Barents and Kara seas. In addition, Astakhov et al. (1999) pointed out that the old eroded morainic plateaus south of the Markhida Line (Pechora Basin)—which are assumed to represent the southern extent of an Early/Middle Weichselian glaciation (Mangerud et al., 1999)—presumably predate the Eemian deposits and may be caused by the maximum Saalian ice advance.

During MIS 5, two distinct IRD peaks dated—based on linear interpolation—at the MIS transitions 5d/5c and 5b/5a might reflect the deglaciation patterns from two readvances of the SSIS to the outer shelf (cf. Fig. 6). Onshore investigations in the Russian Arctic revealed only one Early Weichselian glaciation in the Kara Sea, but did not exclude multiple glaciations (Svendsen et al., 1999, and references therein). Indeed, Houmark-Nielsen et al. (2001) have evidences for more than one ice advance or local glaciations during the Early Weichselian in the Arkhangelsk region, which actually support our findings from the northern Severnaya Semlya margin.

An ice-sheet advance onto the outer shelf off Severnaya Semlya during MIS 4 is indicated by a distinct IRD peak overlain by laminated sediments during MIS 4/3 transition of PS2741 (cf. Fig. 6). This pronounced event may reflect disintegration of the SSIS during the Middle Weichselian (MIS 4). Possible evidence for a grounded ice-sheet along the northern margin of Severnaya Semlya during MIS 4 is a coarse-grained diamicton at the base of PS2782 resembling that observed in the Franz Victoria and St. Anna troughs (Lubinski et al., 1996; Polyak et al., 1997; Kleiber et al., 2000) and interpreted as till or ice-marginal debris flow. The PS2782 diamicton, however, differs by being older than the Late Weichselian (Fig. 6). This is indicated by an infinite \(^{14}C\) age (\( > 44 \) ka) at 321-cm core depth. In addition, the occurrence of well-defined moraine ridges at 385 m water depth close to core location PS2782 (cf. Niessen et al., 1997; Weiel, 1997) could be of similar age than the diamicton because there is no terrestrial evidence of a Late Weichselian ice-sheet that may have produced such ridges (see next chapter). An Early/Mid Weichselian diamicton interpreted as till was also recorded in the Changeable Lake on Severnaya Semlya (Raab et al., 1999), supporting the assumption of a severe glaciation on Severnaya Semlya during MIS 4. The diamicton in PS2782 is overlain by laminated sediments and several IRD pulses, which point to a distinct deglaciation phase (cf. Fig. 6). Although an Early Weichselian age for the diamicton and the moraines cannot be ruled out, we hypothesize that the laminated and IRD-enriched sedimentary sequence above the diamicton corresponds to the distinct deglacial 4/3 transition in PS2741. Therefore, we propose a grounded ice-sheet along the outer shelf of northern Severnaya Semlya in at least 340-m water depth during the Mid Weichselian (MIS 4) glaciation.

These conclusions regarding ice-marginal positions are consistent with land studies by Svendsen et al. (1999, and references therein). They conclude that the Barents and Kara Sea ice-sheets attained their maximum Weichselian positions in northern Russia prior to 50,000 years. We extend this conclusion by proposing that the maximum Weichselian glaciation corresponds to MIS 4.

6.2. Late Weichselian glacial maximum and Holocene in the northeastern Kara Sea

We concur with Svendsen et al. (1999, and further references therein), in rejecting the so-called “Pan-Arctic Glaciation of the Northern Hemisphere” model as proposed by Grosswald (1993) and Denton and Hughes (1981) for the late Weichselian glaciation. Very low bulk accumulation rates during MIS 2 (Knies et al., 2000) and absence of any IRD-input during the last deglaciation in PS2741 (Fig. 6) probably indicate a perennial sea-ice cover and absence of a larger ice-sheet. Even in the shallow water core PS2719, very low IRD values do not suggest an ice advance to the outer coastline (Fig. 6).

However, there is evidence for local ice-sheets and/or ice caps on Severnaya Semlya during the last deglaciation and Holocene. The upper slope core PS2742 northeast of Severnaya Semlya is the only
record in the study area containing a thin diamicton of late glacial age (Fig. 7) (Weiel, 1997; Müller, 1999; Stein et al., 2001). The diamicton reveals large-sized dropstones of up to 5 cm in diameter and could be tentatively dated to the late Termination Ia, based on a single age control point at 321 cm bsf (12.5 $^{14}$C ka). It probably documents the retreat of smaller ice caps on Severnaya Semlya, presumably from the coast line to the inner fjords. A second possibility to explain the thin diamicton in PS2742 could be iceberg discharge from the retreating marine based Barents/Kara Sea ice-sheet in the St. Anna Trough and subsequent transport along the Eurasian Continental Margin with the increasing Atlantic water inflow from the west after 13 $^{14}$C ka (cf. Polyak et al., 1997; Hald et al., 1999).

Hjort et al. (1999) proposed an ice-sheet originating on the northeastern Kara Sea shelf that terminated along the “Isayeva Line” on the western Taymyr Peninsula during the late Weichselian maximum. Based on several AMS $^{14}$C datings Hjort et al. (1999) assume a minimum age of the ice-sheet buildup and decay between ~ 19.5 and ~ 9.5 $^{14}$C ka. The lithology of the sediment core (PS2719-1) SW of the Vilkitzky Strait (130 m water depth) (Fig. 1), which is located in a proximal position to the proposed ice-sheet does not reflect a severe glaciation or deglaciation in the area. An IRD spike at 508 cm bsf could mark a deglacial period of local origin comparable to the thin diamicton in PS2742 dated before 12.5 $^{14}$C ka. A thin laminated sequence that is possibly caused by melting sea-ice underlies this

Fig. 7. Magnetic susceptibility (10e $^{-5}$ SI), lithological features, and IRD records of PS2742-5, PS2719-1, and PS2778-2 versus depth (cm bsf). AMS $^{14}$C dates are indicated (cf. Weiel, 1997; Stein et al., 2001, for details of the magnetic susceptibility data). Tentative correlation of the 12.5 $^{14}$C ka level is based on similarity of the magnetic susceptibility records. Locations and water depth (m bsf) are denoted.
prominent IRD spike (Fig. 7). Diamictons that could indicate the existence of potential ice-sheets are absent in the core. In contrast, bioturbation tracks below and above the laminated sequences point to seasonal open-water conditions in the late Weichselian (Fig. 7). In fact, the high susceptibility values in PS2719 and PS2778 between ~ 10 and ~ 13 \(^{14}\)C ka (Fig. 7) indicate distinct meltwater supply from the Putoran mountains via Khatanga and Yenissei rivers during late deglaciation (cf. Niessen et al., 1997; Weiel, 1997; Stein et al., 2001). Thus, indications of an extended ice-sheet in the southern Vilkitsky Strait are not obvious and, thus, potential ice-sheets may have existed earlier than ~ 16 \(^{14}\)C ka based on linear interpolation to the core base.

A second distinct pulse of coarse fraction (> 250 \(\mu\)m and > 2 mm) in the Holocene record PS2719 occurred at ~ 7.4 \(^{14}\)C ka (Fig. 7). Although poorly constrained by our \(^{14}\)C dates, this calving event appears to be related to the brief cooling event (4–8 \(^{\circ}\)C)—probably induced by a massive outflow of fresh water from the Hudson Strait (Barber et al., 1999)—that was recorded in the Greenland ice cores (GISP2) between 8.4 and 8.0 cal. ka (7.65–7.2 \(^{14}\)C ka) (Fig. 8; Alley et al., 1997). In the northern Kara Sea, however, evidence for remnant ice-sheets into the early Holocene that could have delivered icebergs during waxing and waning does not exist (e.g. Weiel, 1997; Lubinski et al., 1999; Kleiber and Niessen, 1999). Only calve-off ice margins roughly similar to those of the present, e.g. from the Oktober Revolution Island on Severnaya Semlya (Rachor, 1997), are potential sources for icebergs that could have reached PS2719 at ~ 7.4 \(^{14}\)C ka. However, as long as other processes for the IRD pulse in the shallow core such as winnowing, fast ice erosion and bottom currents cannot be ruled out, a connection of the cooling event on Greenland and short-term ice build-up in the northeastern Kara Sea remains speculative.

7. Correlation of IRD-based glacial history since MIS 6 with Atlantic water advection deduced from dinoflagellate cyst data

Fig. 9 summarizes the current knowledge of the glacial history since MIS 6 deduced from IRD studies on eight marine records along the northern Eurasian continental margin. Three main glacial phases are recorded along the northern Barents Sea margin; that is during MIS 6, 4 and 2. The most extensive ice-sheet in the Kara Sea existed during MIS 6 and 4 (Figs. 9 and 10). A major discrepancy between marine and terrestrial records exists for MIS 5 and is probably caused by the lower temporal resolution of the land sections. The marine record reveals two prominent ice advances north of Severnaya Semlya during MIS substages 5d and 5b similar to the glacial history on Svalbard. No record of a large, extended ice-sheet during the Last Glacial Maximum was found near Severnaya Semlya (Fig. 10). A very thin diamicton in a single record during Termination I, however, may indicate the retreat of

![Fig. 8. Correlation of \(\delta^{18}\)O Greenland ice core record (GISP2) and the IRD > 2 mm and coarse fraction (> 250 \(\mu\)m) records from the eastern Kara Sea (PS2719-1) between 7.5 and 10 ka (cal. years). The thicker-shaded area marks the prominent cooling on Greenland and enhanced IRD input in the eastern Kara Sea at ± 8.2 cal. ka.](image-url)
Fig. 9. The left panel shows the reconstructed ice-sheet advances along the northern Eurasian margin over the last two glacial/interglacial cycles. In addition, abundances of the warm adapted dinoflagellate cysts in PS2138-1 (northern Barents Sea) and PS2741-1 (northern Kara Sea) indicating influence of warm Atlantic-derived water masses are displayed (cf. Matthiessen et al., 2001 for details). The right panels explain the environmental conditions along the Eurasian continental margin during MIS 5 \( \frac{47}{6?} \) a and \( \frac{3}{2} \) transitions b, respectively. No data are available for MIS 7 \( \frac{6?}{6} \) so far. Based on evidences for an extended ice-sheets during the Saalian, we hypothesize that comparable environmental conditions than during MIS 5 \( \frac{47}{6?} \) prevailed. a Significant ice-free conditions in the Nordic Seas during the end of MIS 5 MIS 7? —indicated by enhanced abundances of warm adapted dinoflagellate cysts in PS2138-1—could have provided enough moisture to build up ice-sheets in the Barents and Kara Sea during MIS 4 MIS 6. b In contrast, restricted and time limited areas of open water conditions along the western and northern Eurasian continental margin—e.g. indicated by generally low dinoflagellate cysts abundances in PS2138-1 and PS2741-1—and growth of severe anticyclones over Siberia could have caused build-up of only local ice caps in the Kara Sea during the late Weichselian (modified after Velitchko et al., 1997a,b).
Ž. Ž. Fig. 10. Distribution of maximum ice-sheets in the Barents and Kara Sea during the Middle Weichselian and Late Weichselian glaciation based on this study and various authors (Polyak et al., 1997; Mangerud et al., 1998; Landvik et al., 1998; Svendsen et al., 1999; Knies et al., 2000; Kleiber et al., 2000). Dashed lines mark the hypothetical easternmost extension of the Late Weichselian ice-sheets deduced from onshore data according to Svendsen et al. (1999).

By comparing the IRD results with the dinoflagellate cyst distribution along the northern Eurasian continental margin, we hypothesize that the extension of ice-sheets in the Barents and Kara seas are directly coupled to the influence of Atlantic water and therefore to moisture supply from western to eastern Eurasia. The interglacial/glacial transitions MIS 5/4 were apparently marked by continuous Atlantic water inflow at least to the Franz Victoria Trough—as indicated by higher abundances of warm-adapted dinoflagellate cysts during the Eemian and MIS 5a (Fig. 9)—and eastward penetration of moisture-bearing cyclones. These inflows and penetrations may have supported major ice-sheet build-up in the Kara Sea during the Mid-Weichselian (MIS 4).

A similar scenario which led to the Saalian ice-sheet build-up is assumed for the transition between MIS 7...
and 6 (Fig. 9). The asymmetry of the cryosphere in northern Eurasia during the late Weichselian (MIS 2) can possibly be explained by rather limited and seasonal inflow of Atlantic water to the Arctic Ocean as indicated by low concentrations of warm adapted dinoflagellate cysts (Fig. 9). The reduced moisture supply and the formation of severe anticyclone systems over Siberia could have prohibited major ice-sheet build-up in the Kara Sea during the Late Weichselian (cf. Velitchko et al., 1997a,b; Knies et al., 2000).

8. Conclusions

The maximum extent of the Barents and Kara Sea ice-sheets along the northern Eurasian Continental Margin has been examined based on IRD content (> 2 mm) of eight dated sedimentary records. Evidence was found for a far extended ice-sheet along the northern Barents and Kara Sea margin during MIS 6 and 4 (Fig. 10). Furthermore, a far extended ice-sheet to the shelf edge along the northern Barents Sea margin including the St. Anna Trough (cf. Polyak et al., 1997) has been proven during the Last Glacial Maximum (Fig. 10). Indications for an ice-sheet advancing from Severnaya Semlya to the shelf edge during the Late Weichselian could not be found. Along the “Isayeva Line” west of Taymir Peninsula, indications for an ice-sheet were not recorded during Termination I, but possibly existed earlier than 16 14C ka.

Acknowledgements

We sincerely acknowledge the masters and crews of RV “Polarstern” for cooperation during the Arctic expeditions in 1991, 1993, and 1995. For discussion and comments on earlier drafts of the manuscript we thank C. Hass, C. Vogt, and N. Nørgaard-Pedersen. We acknowledge the fruitful discussions with many colleagues at the 3rd QUEEN workshop in Øystese, Norway, which were all very helpful and informative. In particular, we thank C. Hjort, E. Larsen, and J. Mangerud for information about first results of recent field studies in Russia. We thank Iain Henderson who improved the English language and the reviewers A. Elverhøi and D. Lubinski for their critical comments.

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