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Development of glacial and interglacial conditions in the Nordic seas between 1.5 and 0.35 Ma

Jan P. Helmke[a,]*, Henning A. Bauch[b], Helmut Erlenkeuser[c]

[a] *GEOMAR Research Center for Marine Geosciences, University of Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany*
[b] *Academy of Sciences, Humanity and Literature, Geschwister-Scholl-Str. 2, D-55131 Mainz, Germany*
[c] *Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, Max-Eyth-Str. 11, D-24118 Kiel, Germany*

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Abstract

Sedimentological and geochemical proxy records of a deep-sea sediment core from the southern central Nordic seas were used to reconstruct the development of glacial and interglacial conditions during the Early and Middle Pleistocene, i.e., late Matuyama to middle Brunhes Chron (1.5–0.35 Ma). An enhancement of both glacial and interglacial characteristics is observed during early Brunhes oxygen isotope stages (OIS) 16 and 15, respectively. Any intensification of the climatic conditions prior to this, as was previously described for the eastern part of the Nordic seas, is not recognized at our study site. It is further shown that the glacial–interglacial environmental contrasts increased from the early to the middle Bruhnes Chron. Of all glacial periods investigated OIS 12 is characterized by the most severe conditions, showing both maximum input of iceberg-rafted debris (IRD) as well as planktic foraminiferal δ^{18}O values comparable to those of the Last Glacial Maximum. Among the interglaciations, OIS 11 is by far the longest interval and the first to show fully developed interglacial conditions, i.e., Holocene-like δ^{18}O values and a minimum of IRD deposition. Hence, our comparison supports bottom water δ^{18}O studies that have indicated the existence of a gradual intensification of glacial–interglacial climate contrasts during the Middle Pleistocene.

1. Introduction

In the high-northern latitudes, the entire Pleistocene period is characterized by alternating intervals of glacial and interglacial climates and subsequent buildup and decay of large continental ice sheets (e.g., Jansen et al., 1988, 1990; Henrich et al., 1989; Ruddiman et al., 1989; Baumann et al., 1995; Fronval and Jansen, 1996). Paleoclimatic and paleoceanographic records from different parts of the world ocean indicate that the characteristics of glacial as well as interglacial intervals intensified after the mid-Pleistocene (Shackleton et al., 1988; Berger et al., 1993; Park and Maasch, 1993; Berger and Jansen, 1994). Strong indication for this general paleoclimatic shift comes from several sedimentological and geochemical analyses using deep-sea sediments from the polar North Atlantic, i.e., the Nordic seas (Henrich, 1989, 1998; Jansen and Sjøholm, 1991; Baumann and Huber, 1999; Helmke and Bauch, 2002).

Further, more detailed investigations on the specific climate characteristics during glacial and interglacial intervals in the Nordic seas region revealed that next to the observed general mid-Pleistocene climate intensification a distinct variability of both warm and cold conditions prevailed. By using records of carbonate content, stable isotopes, and ice-rafted debris (IRD) it was shown that the three most recent pronounced interglaciations marine oxygen isotope stages (OIS) 11, 5e, and 1 were characterized by significant differences, e.g., in global ice volume and sea surface temperatures (Fronval and Jansen, 1997; Bauch et al., 2000a; Bauch and Erlenkeuser, in press). Bauch et al. (2000a) proposed that the interglacial conditions of OIS 1, the Holocene, are rather atypical in the Nordic seas and without any analogue among the older Pleistocene interglaciations, and, furthermore the character of glacial climates seems to vary. Among all cold intervals of the past five climate cycles, OIS 12 was recognized as a

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*Corresponding author. Tel.: +49-431-600-2853; fax: +49-431-600-2941.

E-mail address: jhelmke@geomar.de (J.P. Helmke).

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particularly severe glaciation (Bauch and Erlenkeuser, in press).

However, such studies on similarities and differences among specific warm and cold intervals were limited to the period after the mid-Pleistocene climate shift, i.e., after 0.45 million years (Ma). Our study focuses on deciphering glacial and interglacial conditions during the later Early and early Middle Pleistocene times, from about 1.5–0.35 Ma. This time period covers the development of glacial and interglacial climate conditions before and after the so-called mid-Pleistocene climate shift. To achieve this goal we will analyze some geochemical and sedimentological parameters, i.e., planktic δ^{18}O, carbonate content, and IRD using a long, continuous sediment record from the western Norwegian Sea that was sampled at higher resolution than previous studies.

2. Core location and methods

Sediment core MD992277 from the western Norwegian Sea (69°15′N, 6°19′W; Fig. 1) is a piston core about 32.5 m long that was obtained by R/V *Marion Dufresne* in 1999 from a water depth of about 2800 m at the eastern slope of the Iceland Plateau. At present, the site is located close to the Arctic Front, i.e., the boundary between Atlantic and Arctic water masses, at the western edge of the Norwegian Current (Swift, 1986). Site PS1243 (69°22′N, 6°32′W; 2715 m water depth,

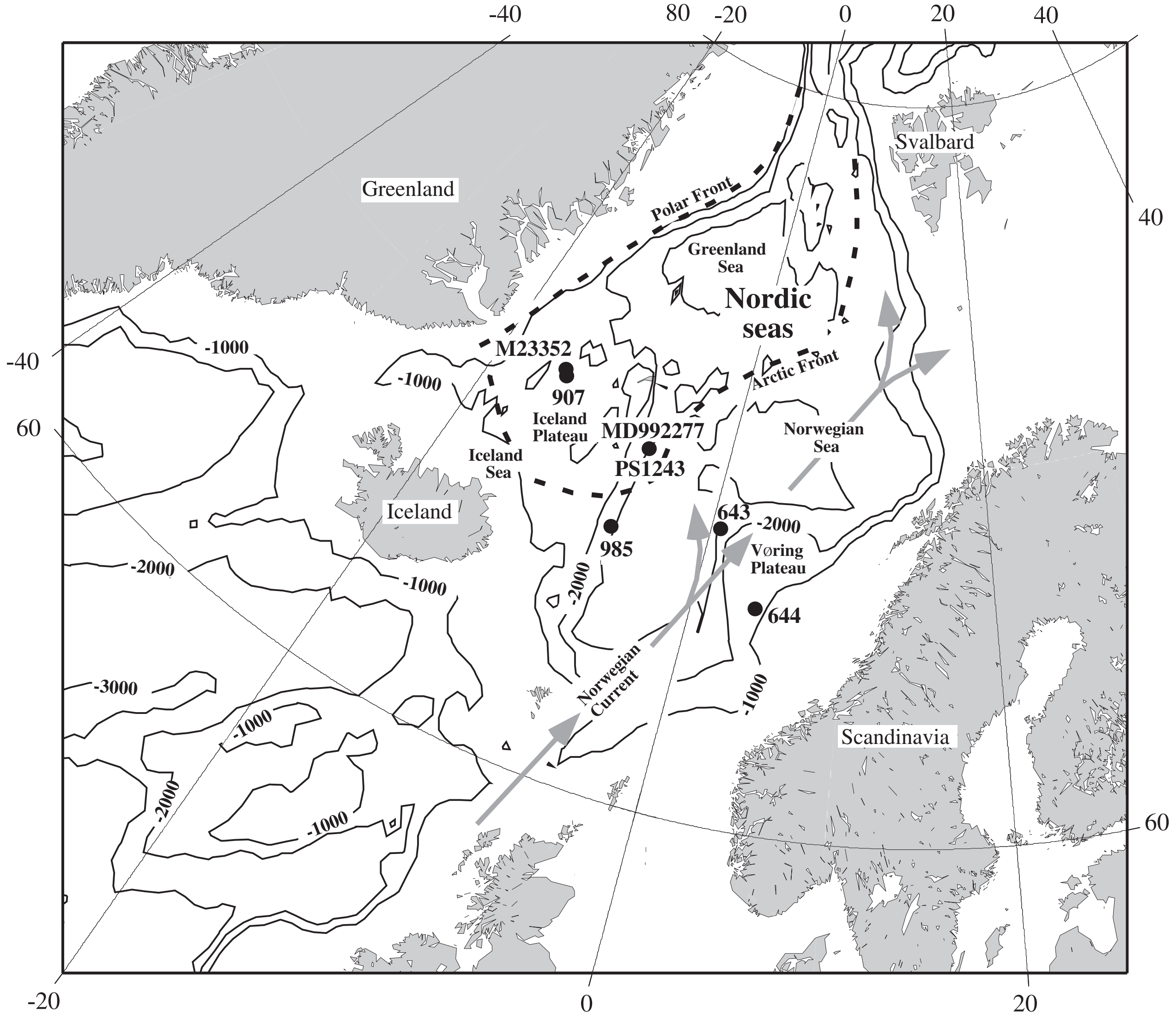

Fig. 1. Geographical position of site MD992277 (69°15′N, 6°19′W, 2800 m water depth) and site PS1243 (69°22′N, 6°32′W, 2715 m water depth) as well as position of several ODP-sites referred to in the discussion part of the text (Site 907, western Iceland Plateau: Fronval and Jansen, 1996; Baumann and Huber, 1999; Jansen et al., 2000; Site 985, southwestern Norwegian Sea: Baumann and Huber, 1999; Sites 643 and 644, Vøring Plateau: Jansen et al., 1988, 1989; Henrich and Baumann, 1994; Fronval and Jansen, 1996). Black dotted lines denote recent position of the Polar and Arctic fronts. The gray arrows indicate modern surface water inflow from the North Atlantic into the Nordic seas via the Norwegian Current.

obtained in 1984 by R/V *Polarstern*; Fig. 1), located in the immediate vicinity of MD992277, has previously been studied in great detail using a wide range of paleoceanographic methods (e.g., Bauch, 1997; Bauch et al., 1999; Helmke and Bauch, 2002). The records of site PS1243, which has an established age model that dates back to OIS 12 (see Bauch et al., 2000a; Bauch and Erlenkeuser, in press), are a splice of a kasten core and an about 8 m long gravity core.

Planktic oxygen isotope measurements were carried out at the Leibniz Laboratory, University of Kiel, with the automated Kiel Carbonate Preparation Device and a Finnigan MAT 252 mass spectrometer system. Analytical accuracy of the system is ±0.08‰ for δ^{18}O. All analyses are given as per mil deviations relative to the Pee Dee Belemnite (PDB) carbonate standard. Measurements were made at a sample resolution of 2.5 cm (between 10 and 24 m core depth) and 5 cm (between 24 m and the core basis) taking for each sample, on average, 20 specimens of the polar planktic foraminifer *Neogloboquadrina pachyderma* (sinistral) from the size fraction 125–250 μm. The average sedimentation rates of the core are between 2 and 3 cm/1000 years. IRD was counted from the size fractions >250 μm with a sample resolution of 2.5 cm. The results are expressed as lithic grains per gram. The bulk carbonate content (wt%) of the sediment was measured every 5 cm using a LECO C-200 carbon determinator. Magnetic remanence and low field bulk (volume) were measured every 2 cm from u-channel samples (see Tauxe et al., 1993) at the Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette. The demagnetization of magnetic remanence was performed at 5 mT steps from 10 to 60 mT by using the high-resolution small access 2 G passthrough magnetometer with online alternating field (AF) device (Weeks et al., 1993).

3. Results

3.1. Stratigraphy and age model

The upper sediment sections of MD992277 can be correlated to PS1243 by aligning the high-resolution sediment color records (Helmke et al., 2003). At the study site, PS1243 covers the past five glacial–interglacial cycles, i.e., the last about 0.45 Ma. Accordingly, all parameters were investigated between 10 m core depth (representing boundary OIS 11/10) and the core base (Fig. 2). Isotope, carbonate content, and IRD measurements from MD992277 were compared directly to the corresponding results from PS1243.

Between OIS 11 and the Brunhes/Matuyama boundary the stratigraphic framework of MD992277 is based on the planktic oxygen isotope values and, additionally, on the carbonate and IRD data (Fig. 2). Ages were assigned by correlation of the oxygen isotope results to the standard SPECMAP chronology for the upper sediment sections up to OIS 15 (Imbrie et al., 1984; Martinson et al., 1987) and by correlation to the "low latitude stack" between OIS 16 and the Brunhes/Matuyama boundary (Bassinot et al., 1994). For the Matuyama Chron, the magnetic reversals Santa Rosa, Jaramillo, Cobb Mountain, and Gardar are the tie points for the age model (Figs. 2 and 3). In order to improve the age model between these polarity tie points several maxima of the isotope record from MD992277 were correlated to corresponding maximum glacial values of the astronomically calibrated benthic oxygen isotope record from ODP Site 659 (Tiedemann et al., 1994). The lowermost part of the sediment reveals unusually large fluctuations between very light and very heavy oxygen isotope values (Figs. 2 and 3). As noted previously, late Matuyama sediments from the Nordic seas are strongly influenced by severe carbonate dissolution (Jansen et al., 1988). Accordingly, the foraminiferal content in the oldest sediment sections of MD992277 is rather low, which made it difficult at times to always obtain sufficient material for stable isotope analyses. To align our isotope record of MD992277 to the standard age models in spite of the high-frequency fluctuations in the lower parts of it, the δ^{18}O data were smoothed with a 7-point least-square running mean (Fig. 2).

3.2. Downcore records

In general, the three proxies used in this study have for a long time been taken as direct indicators for past climate conditions. Planktic oxygen isotopes are used to estimate past sea surface temperatures, but vital effects as well as changes in salinity have to be considered for such temperature reconstructions. IRD in deep-sea sediments mainly records rates of terrigenous input by melting ice and, hence, gives information about ice sheet expansion on the continents. However, additional parameters like the sediment transport within the ice sheet or the drift vectors of the released icebergs may change the IRD distribution. The carbonate content of the sediment is mainly a measure for plankton bioproductivity, but dilution and dissolution of the carbonate component may alter the signal.

The entire sediment section covers the past about 1.5 Ma (Fig. 3) and, thus, contains information about the climate characteristics during the late Matuyama and the Brunhes Chron. Several studies on Pleistocene cores (e.g., Kellogg, 1977, 1980; Bauch, 1997; Henrich, 1998) have clearly shown that glacial sediments from the high-northern latitudes are characterized by maxima in the planktic oxygen isotope record (maximum isotope values of PS1243 during the Last Glacial Maximum (LGM) vary around 4.8‰, see also Fig. 4 and Bauch

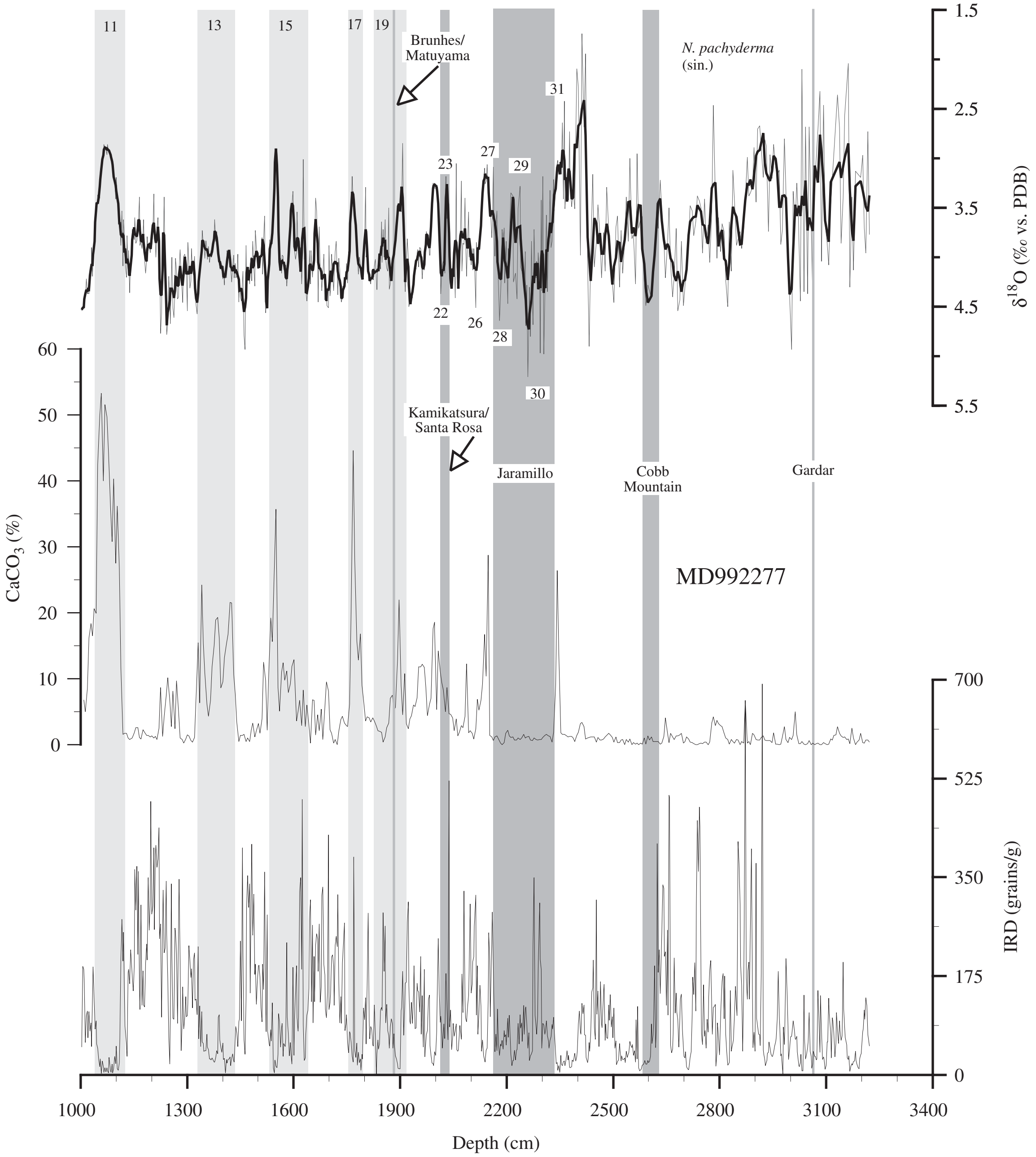

Fig. 2. Downcore records (between 10 m and the core base) of planktic $\delta^{18}O$ (‰ vs. PDB of *N. pachyderma* sinistral; thick black line is a 7-point smooth record of the isotope data), carbonate content (% of weight), and IRD (grains/gram) from site MD992277. Areas shaded in light gray denote interglacial OIS between OIS 11 and 19 and are labeled for reference (details about the stratigraphy of the Brunhes chron are given in the text). Also, some glacial and interglacial intervals between OIS 22 and 31 are indicated for reference (see text for details). Areas shaded in dark gray denote the position of the Brunhes/Matuyama boundary and of some magnetic reversals from the Matuyama chron inclination record (magnetic reversals are labeled for reference).

et al., 2000a), low or zero carbonate content, and high input of IRD (e.g., Kellogg et al., 1978; Baumann et al., 1995; Henrich et al., 1995). In general, full interglacial conditions in the Nordic seas are characterized by light $\delta^{18}O$ values (average peak values from PS1243 are 3‰, for OIS 1, see also Fig. 5 and Bauch et al., 2000a), high carbonate content (the maximum OIS 1 value from PS1243 is about 50%, see also Bauch et al., 2000a), and zero or very low input of IRD. According to these characteristics of Pleistocene glaciations and interglaciations all proxy records of MD992277 clearly reveal alternating periods of glacial and interglacial climates for the entire time interval between 1.5 and 0.35 Ma (Figs. 2 and 3). Between the core base and about 1 Ma the carbonate content is very low or zero despite of glacial or interglacial conditions (Fig. 3). This does not

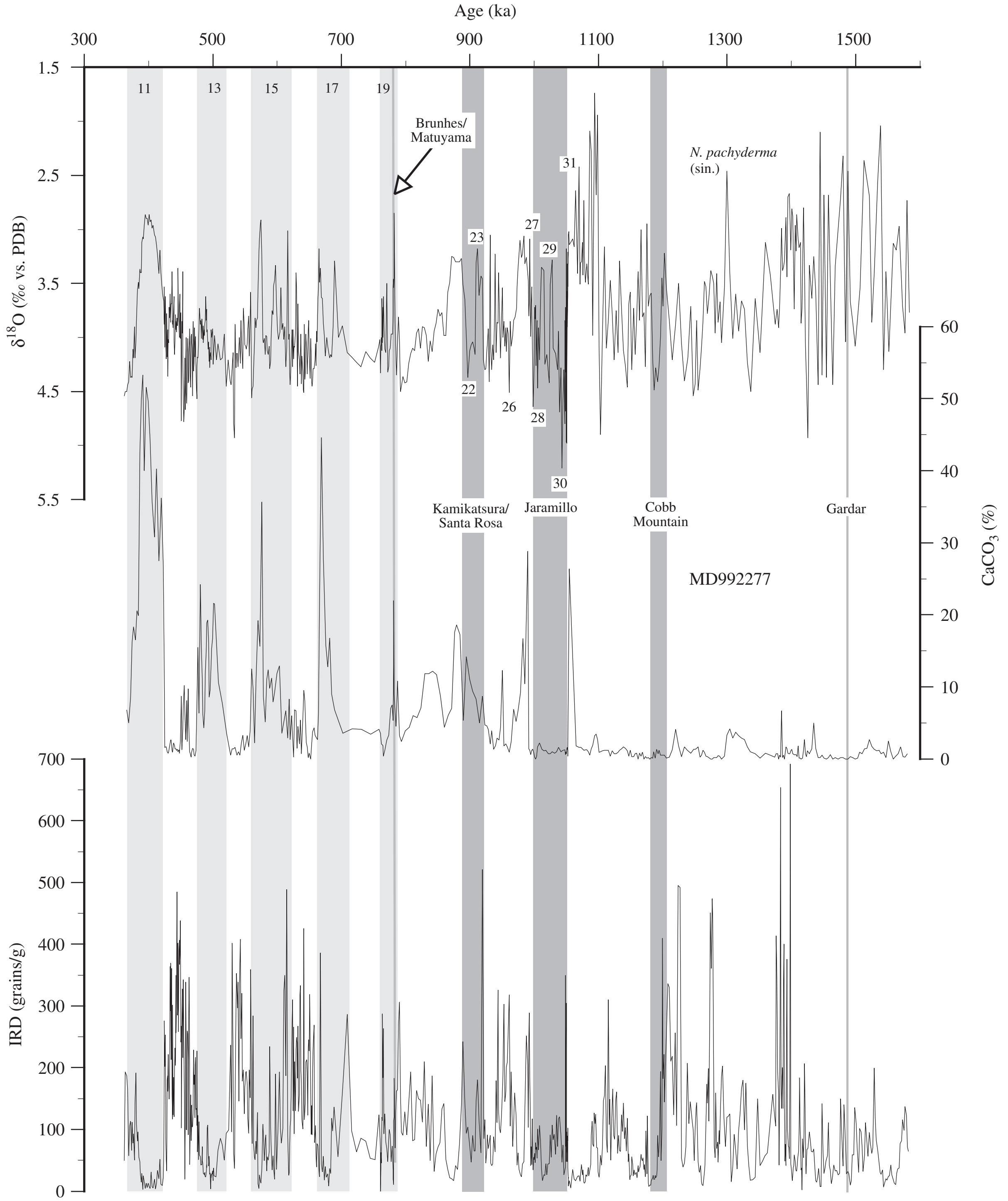

Fig. 3. Same records than in Fig. 2 vs. age (see text for details about the age model). Areas shaded in light gray denote interglacial OIS between OIS 11 and 19 and are labeled for reference. Also, some glacial and interglacial intervals between OIS 22 and 31 are indicated for reference (see text for details). Areas shaded in dark gray denote the position of the Brunhes/Matuyama boundary and of some magnetic reversals from the Matuyama chron (labeled for reference).

reflect a general change in carbonate surface water bioproductivity, but can be related to the strong carbonate dissolution typically observed during the late Matuyama Chron in the Nordic seas (Jansen et al., 1988; Henrich and Baumann, 1994).

3.3. Glacial characteristics

In general, all glacial OIS that were studied in greater detail at site MD992277 reveal a continuous and substantial input of IRD with peak values between 300

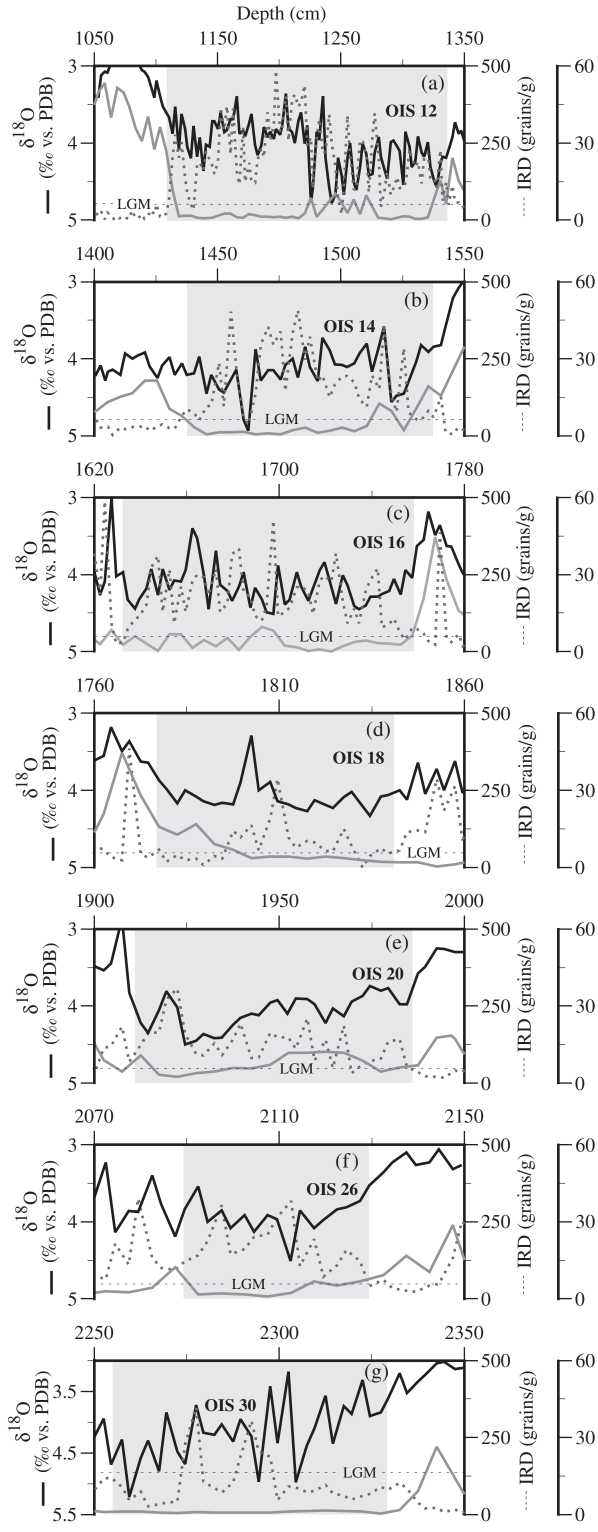

Fig. 4. Direct comparison of the planktic $\delta^{18}O$ (black line), carbonate content (thick, gray line), and IRD (dotted, gray line) records from 7 glacial intervals (a–f; glaciations are labeled for reference). Shaded, gray areas denote position of glacial OIS. Horizontal, dashed line indicates the average Last Glacial Maximum (LGM) planktic oxygen isotope level from the PS1243 record for reference.

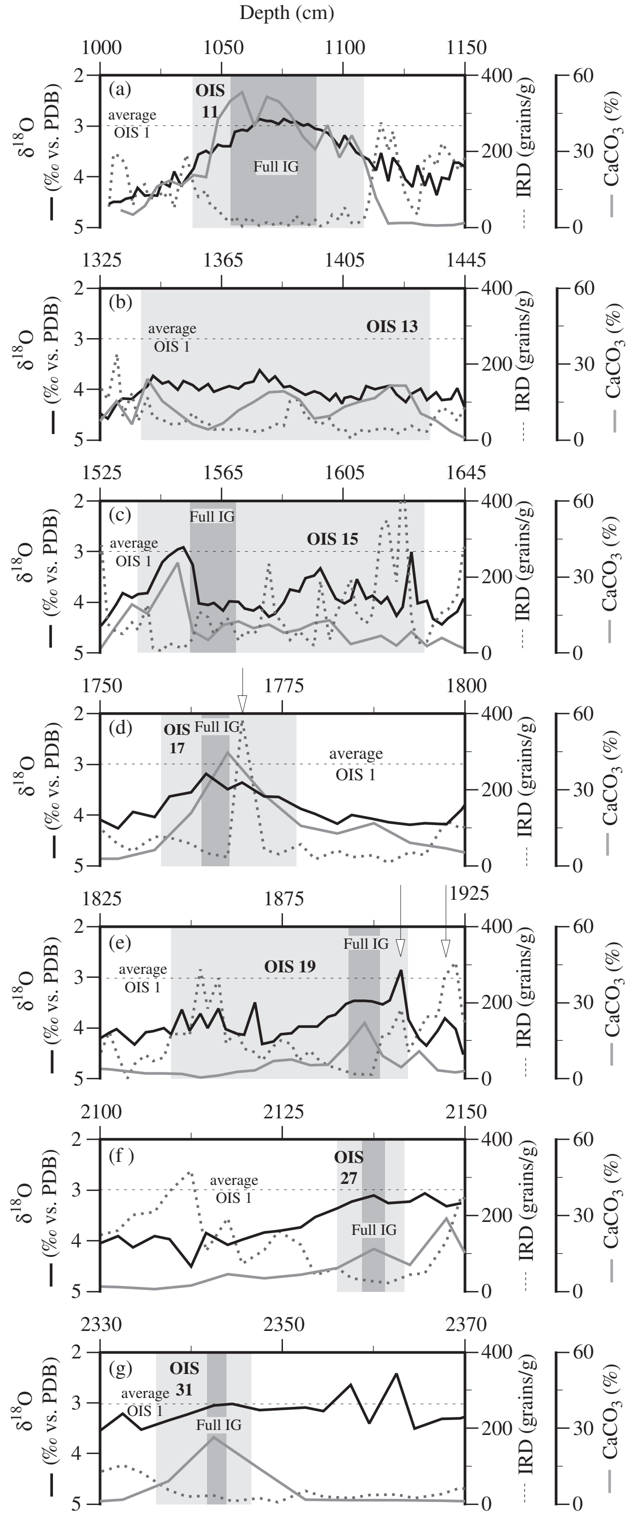

Fig. 5. Direct comparison of the planktic $\delta^{18}O$ (black line), carbonate content (thick, gray line), and IRD (dotted, gray line) records from 7 interglacial intervals (a–f; interglaciations are labeled for reference). Areas shaded in light gray denote position of interglacial OIS. Areas shaded in dark gray denote full interglacial conditions within the interglacial OIS (full interglacial intervals are labeled for reference; see text for details about definition of full interglacial conditions). Horizontal, dashed line indicates the average Holocene (OIS 1) planktic $\delta^{18}O$ level from the PS1243 record for reference. Black arrows in 5d and 5e denote light $\delta^{18}O$ and associated IRD maxima during terminations OIS 18/17 and OIS 20/19.

and 500 grains per gram as well as low carbonate content between zero and 10% (Fig. 4). Highest IRD input can be observed during OIS 12 (Fig. 4a). During the early and middle Brunhes Chron the average IRD input at glacial times increases from OIS 16 to 12 (Fig. 4a–c). A generally lower input of terrigenous components is observed during the investigated glaciations from the Matuyama (Fig. 4e–g). However, when considering also the lower part of the Matuyama section some short IRD events show maxima that are comparable to the Brunhes Chron record (Fig. 3). The planktic isotope values during OIS 12, 14, and 30 correspond to the characteristics of OIS 2 showing maximum glacial values that are comparable to the LGM value of 4.8‰ or even heavier (Fig. 4a, b and g). In contrast, the maximum $\delta^{18}O$ values of OIS 16, 20, and 26 are lighter and vary around 4.5‰ (Fig. 4c,e and f). OIS 18 differs noticeably from the other investigated glacial intervals and is characterized by glacial isotope values of only 4.3‰. Moreover, the terrigenous input during this glacial interval is rather low (Fig. 4d) and comparable to the average material input during interglacial times (Figs. 3 and 5). Maximum values of glacial IRD do not solely correspond to glacial maxima in the isotope record (e.g., during OIS 16 and 26) but can also coincide with peak light values within glacial intervals (e.g., during OIS 12, 14 and 20). With the exception of OIS 20 (Fig. 4e) all glacial intervals show light isotopic peaks with glacial planktic oxygen isotope minimum values around 3.5‰.

3.4. Interglacial characteristics

By comparison, the two interglaciations OIS 11 and 15 reveal rather similar full interglacial conditions (Fig. 5). However, OIS 11 (Fig. 5a) shows much higher carbonate contents than OIS 15 (Fig. 5c). For the entire OIS 13 the oxygen isotope values of MD992277 vary around 4‰ (Fig. 5b). Full interglacial conditions can also be observed during OIS 17 and 19 (Fig. 5d–e). Here, the average minimum values of the planktic oxygen isotopes vary around 3.2‰ and 3.5‰. The light peak in the oxygen isotope values within OIS 19 at 1907.5 cm is associated with increased IRD and a minimum in carbonate content (Fig. 5e). Hence, this minimum seems to indicate a meltwater event during the deglaciation and does not represent the interval when full interglacial conditions occurred in OIS 19. During the full warm intervals of OIS 27 (Fig. 5f) and 31 (Fig. 5g) the peak planktic oxygen isotope values are on the level of OIS 11 and 15, but both intervals show significantly lower maximum carbonate contents and noticeably higher IRD input. During all investigated interglacial periods the input of terrigenous, iceberg-rafted material does not cease entirely, although during several full interglacial periods IRD shows values close to zero (Fig. 5).

4. Discussion

4.1. Development of glacial conditions

The glacial intervals from the Matuyama Chron, i.e., OIS 20, 26, and 30 (Fig. 4e–g), all show continuous terrigenous input and several distinct glacial IRD peaks both of intermediate height. Several studies on Late Pleistocene Nordic seas sediments have indicated a tight coupling between the flux of IRD and the extent of onshore glaciations (e.g., Baumann et al., 1995; Fronval et al., 1995; Fronval and Jansen, 1997). Hence, it seems that during the late Matuyama the continents around the Nordic seas were affected by several large ice sheet expansions and subsequent substantial iceberg calving onto the adjacent shelves and deep basins. IRD records from the Vøring Plateau (Sites 643 and 644; Fig. 1) as well as from the western Norwegian Sea (Site 985; Fig. 1) indicate intermediate glacial conditions during the late Matuyama, but also point to a mid-Pleistocene intensification of glacial conditions at about 1.2 Ma (Jansen et al., 1988; Krissek, 1989; Jansen and Sjøholm, 1991; Henrich and Baumann, 1994; Baumann and Huber, 1999).

However, site MD992277 does not show any significant difference in average and peak glacial terrigenous input between 1.5 and about 0.65 Ma (Fig. 3). This striking difference to other, more easterly core sites may be due to the relative proximity of our study site to the Greenland ice sheet, which is believed to be the main source of Plio-Pleistocene IRD input onto the Iceland Plateau (Jansen et al., 2000). IRD as well as glacial tills and glaciomarine diamicts from marine sediments suggest that during the Late Miocene glaciers on Greenland expanded for the first time onto the eastern Greenland shelf with further repeated advances of the ice sheet during Plio-Pleistocene times (Larsen et al., 1994). However, during the Pleistocene Greenland ice sheet fluctuations on glacial–interglacial timescales are thought to have been less frequent when compared to other European ice sheets (Solheim et al., 1998). Accordingly, the glacial iceberg calving and release of ice-rafted terrigenous material into the Greenland and Iceland seas did probably not change significantly at that time. It seems therefore likely that prior to 0.65 Ma IRD input at site MD992277 was under stronger influence of the Greenland ice sheet than cores located further east where the values of glacial IRD remained almost constant. A rather uniform glacial iceberg drift on the Iceland Plateau in the late Matuyama and early Brunhes was previously observed on the western part of the Plateau (Site 907, Fig. 1; Jansen et al., 2000).

Planktic $\delta^{18}O$ from a marine sediment record can generally be used to compare the relative changes in sea surface temperatures at a certain study site. However, at high latitudes one has to keep in mind that excursions of light planktic δ^{18}O are often due to meltwater events (e.g., Jones and Keigwin, 1988; Sarnthein et al., 1995; Bauch et al., 2000b), which typically show light δ^{18}O and increased IRD. Hence, to avoid any misinterpretations, we will restrict our estimates about changes in sea surface temperatures at site MD992277 to the intervals without meltwater influence, i.e., full interglaciations and glacial maxima. Sediment cores from the western Iceland Plateau and the Vøring Plateau both reveal a stepwise depletion of glacial isotope values during the late Matuyama that has been interpreted as an intensification of glacial conditions (Jansen et al., 1988; Fronval and Jansen, 1996; Jansen et al., 2000). In contrast, at site MD992277 maximum glacial planktic δ^{18}O values from the Matuyama Chron suggest that sea surface temperatures during some cold events of this interval were at least as low as during the LGM (Fig. 3). In general, our high-resolution planktic δ^{18}O record from the Matuyama gives—like IRD—no indication for any general trend or an enhancement of glacial conditions after about 1.2 Ma, but it repeatedly shows glacial maxima around 4.5‰. This suggests a persistent influence of comparable glacial surface water masses on the western Norwegian Sea during the late Matuyama and the early Brunhes.

Our isotope and, especially, IRD results point at an intensification of the glaciations during the early to middle Brunhes. The peak and also the mean glacial IRD values from OIS 12, 14, and 16 (Fig. 4a–c) are higher when compared to the investigated glaciations of the late Matuyama (Fig. 4e–g). The glacial δ^{18}O values during OIS 12 and 14 (Fig. 4a and b) are—with the exception of OIS 30—heavier than during earlier glaciations and in the range of the LGM value. In general, after about 0.65 Ma our records indicate lower glacial surface water temperatures and larger ice sheets than within the previous glacial intervals (Fig. 4c–f). It is very likely that this intensification of glacial conditions in the Northern Hemisphere after 0.65 Ma was associated with several major glacial advances of the northern European ice sheets and substantial iceberg drift from these ice sheets into the western Norwegian Sea (Henrich and Baumann, 1994; Baumann and Huber, 1999). Accordingly, at the study site the relative influence of icebergs and IRD from the Greenland ice sheet decreased. A scenario of a change in the share of certain source regions on the total iceberg drift during the early and middle Brunhes is supported by further sedimentological evidence. Some parameters from site MD992277, i.e., magnetic susceptibility and sediment color, also reveal a systematic shift during the early Brunhes that can be related to a change in the relative contribution of specific ice sheets on the total terrigenous input into the western Norwegian Sea (Helmke et al., 2003). Interestingly, on the western Iceland Plateau the amount of glacial IRD input persists to be rather uniform during the entire Brunhes interval pointing to a continuous influence of the Greenland ice sheet (Jansen et al., 2000). In contrast to the observed general difference between Brunhes and Matuyama are our results from OIS 18, where IRD and also the oxygen isotopes indicate rather weak glacial conditions (Fig. 4d). Such unusually light isotope values in the range of interglacial periods are in good agreement with the contemporaneous data from the Vøring Plateau (Fronval and Jansen, 1996).

According to our planktic oxygen isotopes surface-water temperatures during OIS 12 and 14 were lower when compared to OIS 16. This is in contrast to the records from the Vøring Plateau but identical to the observations from the western Iceland Plateau (Fig. 1; Jansen et al., 1989; Fronval and Jansen, 1996). The observations may point at a distinct temperature gradient for this interval between the western and the eastern part of the Nordic seas with particularly low temperatures in the eastern basin during OIS 16. An east-west gradient in surface water temperatures can also be seen during OIS 12 and 14. For these glacial periods the colder conditions prevailed in the western Nordic seas (Fronval and Jansen, 1996).

A second trend in the IRD record is obvious within the Brunhes Chron (Fig. 4a–d), where the successive glacial intervals reveal a stepwise increase in the average IRD input with OIS 12 being characterized by the highest mean IRD values. This seems to reflect an intensification of cold conditions during these glaciations with the most severe glacial conditions occurring during OIS 12. Records of the last five glacial–interglacial cycles from PS1243 and from the Iceland Plateau (M23352; Fig. 1) have evoked a corresponding line of interpretation (Bauch and Erlenkeuser, in press). At these sites, IRD and both planktic and benthic isotopes show maximum glacial values of the past 0.45 Ma during OIS 12 indicating largest global ice volume or, conversely, lowest sea level relative to all subsequent younger glacial maxima.

It is well known that during the late Middle and Late Pleistocene the glacial–interglacial transitions are especially marked by severe climatic perturbations (e.g., Sarnthein and Tiedemann, 1990; McManus et al., 1994). In the Nordic seas region, the three pronounced glacial–interglacial transitions of the past 0.45 Ma, i.e., Terminations I, II and V, have previously been studied in greater detail and with high temporal resolution (e.g., Sejrup et al., 1995; Bauch et al., 1996; Fronval and Jansen, 1997). It was shown that these Late Pleistocene terminations are typically marked by several rapid decreases in planktic δ^{18}O that go along with increases in IRD. These excursions are most probably related to the repeated occurrence of meltwater events during the intervals of deglaciation. At the end of each termination, full-interglacial conditions developed (Bauch et al., 2000a, b). Although the sample resolution of our Norwegian Sea data is not sufficient to examine the course of the mid-Pleistocene climate transitions in detail, the general trends of the MD992277 records (Figs. 3 and 5) obviously correspond to the Late Pleistocene Nordic seas records. For example, the transitions OIS 18/17 and OIS 20/19 both clearly reveal light planktic δ^{18}O spikes that are associated with maxima in the IRD record (Fig. 5d and e; in the figure the events are denoted by arrows). After these events, the full-interglacial conditions of OIS 17 and, respectively, OIS 19 develop with minima in both δ^{18}O and IRD. Hence, it can be assumed that the general character of glacial–interglacial transitions during the mid-Pleistocene period was equivalent to the behavior of Late Pleistocene terminations.

4.2. *Development of interglacial conditions*

In general, the records clearly indicate that full-interglacial conditions prevailed during certain intervals of both polarity periods, the Brunhes and the Matuyama chrons (Figs. 3 and 5). A noticable occurrence of interglacial conditions during some periods of the late Matuyama is also known from the Vøring and Iceland plateaus and from the western Norwegian Sea (Fig. 1; Jansen et al., 1988; Henrich and Baumann, 1994; Baumann and Huber, 1999; Jansen et al., 2000). Records from these regions denote that the interglacial conditions between about 1.65 and 1 Ma occurred as rather short episodes. The general climate in the Nordic seas seems to have been dominated by cold conditions. In the course of the mid-Pleistocene climate shift pronounced warm interglaciations of longer duration became more common (Henrich and Baumann, 1994; Baumann et al., 1996). Our data also reveal an intensification of such interglacial characteristics. However, the shift appears later, during the early to middle Brunhes.

The Matuyama Chron interglaciations OIS 27 and 31 (Fig. 5f–g) and also OIS 17 and 19 (Fig. 5d–e), the earliest two Brunhes Chron interglaciations, reveal rather short full-interglacial episodes, which according to our age model lasted only about 1–2 ka (Fig. 3). In contrast, it is indicated that warm conditions during OIS 15 lasted for about 5 ka and during OIS 11 they existed for more than 10 ka (Fig. 3). Our IRD record also points to less pronounced interglaciations in the late Matuyama and enhancing interglacial conditions in the Brunhes. During all interglaciations between 1.5 and 0.35 Ma (Figs. 3 and 5) the IRD input never ceased completely. In some warm interglacial periods, e.g., within OIS 17 and 27, IRD remains a significant feature in the proxy records (Fig. 5d and f). Over a long interval of OIS 11 IRD is very low and shows the minimum values of the entire record (Fig. 5a) indicating more pronounced interglacial conditions at that time.

During the late Matuyama and the early Brunhes the western Iceland Plateau shows moderately high IRD during interglaciations (Jansen et al., 2000), whereas IRD at MD992277 is lower, but a consistent feature (Figs. 3 and 5). This suggests that at these times the interglacial Polar Front was located closer to the Iceland Plateau than today (Fig. 1) or may even have been located over the Plateau. Consequently, during these mid-Pleistocene interglaciations the Iceland Plateau was under strong influence of polar waters and icebergs drifted eastward across the entire Plateau and also into the Norwegian Sea. During the middle Brunhes interglaciations OIS 15 (Fig. 5c) and 11 (Fig. 5a; see also Bauch and Erlenkeuser, in press) interglacial IRD at MD992277 in the western Norwegian Sea almost ceased, whereas on the Iceland Plateau the input was still substantial (Jansen et al., 2000). Hence, when compared with the previous warm intervals a more northwesterly position of the Polar Front may be assumed during these two interglaciations. Accordingly, the influence of colder water masses with occasional icebergs on our study site and the Norwegian Sea in general should have been strongly reduced. It was previously suggested that the input of IRD on the Iceland Plateau during OIS 11 (site M23352) could be linked to a more southeast interglacial position of the Polar Front with respect to the present day situation (Fig. 1), implying a persistent influence of Greenland icebergs (Bauch and Erlenkeuser, in press). Moreover, it was also shown that at our study site, as well as on the Iceland Plateau, the last two interglaciations, OIS 5.5 and 1, were free of iceberg drift (Bauch and Erlenkeuser, in press). All these observations seem to point at a gradual northwest retreat of the interglacial Polar Front between the late Matuyama and today.

During certain intervals, such as within OIS 11, 27, and 31, our study site has experienced almost similar sea-surface temperatures that were equivalent to the recent surface water conditions (Fig. 5). The carbonate data additionally indicate enhanced surface water bioproductivity at these interglaciations. In the Nordic seas such conditions are generally attributed to intervals with high potential heat export from the North Atlantic via strengthening of the Norwegian current (Fig. 1; Henrich, 1989; Baumann et al., 1996).

Our data indicate that the study region shows Holocene-like surface water conditions and high carbonate content during OIS 15. For the western Iceland Plateau it is indicated that the surface water temperatures of OIS 15 were probably higher than during the Holocene (Fronval and Jansen, 1996). In contrast, on the Vøring Plateau this interglaciation was characterized by significantly lower surface temperatures than in the Holocene, although at that time the surface water temperatures were still higher than on the Iceland Plateau. Additionally, carbonate and isotope data suggest higher temperatures and increased plankton productivity on the outer, more westerly part of the Vøring Plateau (Fronval and Jansen, 1996; Baumann and Huber, 1999). Taking these observations as a face value, they seem to reflect a less steep east-west surface water temperature gradient in the southern Nordic seas during OIS 15 when compared with the Holocene. This would also imply that the surface water circulation mode in the Nordic seas during this interglaciation should have been somewhat different from the recent Holocene circulation pattern. In the modern situation the inflow of warm Atlantic water follows the Norwegian shelf margin northward flowing into the eastern Arctic Ocean basin and, subsequently, surface water temperatures in the Nordic seas decrease steeply towards the west (Bauch et al., 1999; Fig. 1). During OIS 15 the main warm water intrusion was seemingly less close to the shelf but shifted more to the west. When comparing the western Iceland Plateau and Vøring Plateau isotope data of OIS 19 (Fronval and Jansen, 1996) with MD992277 (Fig. 5e) an analogue interglacial decrease in the west-east temperature gradient may be implied, however, the trend is less pronounced than during OIS 15.

The absence of full interglacial characteristics in the Nordic seas during OIS 13, as indicated by the records from MD992277, is confirmed by other investigations from the Vøring and the western Iceland Plateau (Henrich and Baumann, 1994; Fronval and Jansen, 1996). Nordic seas sediments from OIS 13 are marked by minimum peak δ^{18}O of the late Matuyama and Brunhes interglacial intervals and by relatively low carbonate content. This points to a strongly reduced influence of warm surface water masses, i.e., a weak heat flux from the North Atlantic and subsequent low carbonate surface water bioproductivity across the Nordic seas during this interglaciation.

5. Summary and conclusions

Piston core MD992277 from the southwestern Norwegian Sea was used to study the development of glacial and interglacial conditions at high-northern latitudes between 1.5 and 0.35 Ma. The interval between 1.5 and 0.65 Ma (OIS 16) is characterized by distinct cold conditions with enhanced input of ice-rafted terrigenous material and low sea-surface temperatures particularly during glaciations. Interglacial conditions with increased surface water temperatures and elevated carbonate plankton productivity are observed in between these cold intervals. However, these warmer periods were of rather short duration, as IRD remained a common feature, although in reduced numbers when compared with the peak glaciations.

During OIS 16 and 15 glacial as well as interglacial conditions in the southwestern Norwegian Sea became more pronounced. The average and the maximum glacial input of IRD increase points to repeated advances of the continental ice-sheets. These advances appear to have been substantially larger than during any previous cold period. During OIS 15, full-interglacial conditions prevailed longer than during any preceding interglaciation, showing almost no terrigenous input but increased surface water productivity. Interglacial conditions in OIS 13 differ significantly from the other Brunhes interglaciations and do not seem to represent a true warm period. Isotope and carbonate data both suggest that the heat transfer from the Atlantic into the Nordic seas during interglacial OIS 15, and probably also during OIS 19, must have differed significantly from the recent surface water circulation pattern.

In contrast to observations from the eastern Nordic seas, a first intensification of Pleistocene climate contrasts during the late Matuyama is not recorded at MD992277. This may reflect a major difference in the influence of the Greenland and European ice sheets on glacial conditions for various parts of the Nordic seas during this Chron. The data point to a further enhancement of glacial and interglacial characteristics in the middle Brunhes. OIS 12 and 11 reveal the most pronounced glacial and interglacial conditions of the entire record. Maximum IRD deposition combined with comparatively heavy oxygen isotopes characterize OIS 12 as a time when rather severe glacial conditions must have prevailed on the surrounding continents. During peak OIS 11, which is marked by δ^{18}O values comparable to the Holocene and by a minimum of IRD input, full-interglacial conditions lasted much longer than during any preceding interglaciation.

The glacial-to-interglacial transitions in core MD992277 are usually marked by several rapid changes in planktic δ^{18}O together with enhanced IRD fluctuations before eventually interglacial conditions were reached. This implies that climate variability, so well-known from younger glacial terminations, is a common feature of the glacial–interglacial climate system in general, and not restricted to the Late Pleistocene when glacial and interglacial contrasts became more pronounced.

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