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Changes in sedimentation patterns of the Nordic seas region across the mid-Pleistocene

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Abstract

Sediment core data from a site in the central Nordic seas suggest that during the mid-Pleistocene revolution (MPR) this region has experienced a systematic change in its overall oceanographic and climatic conditions. First distinct changes occur around 1 Ma and reveal the beginning of a shift in climate periodicity from stronger 41-ka cycles towards a dominant 100-ka cyclicity. Most pronounced are the changes at the study region between about 700 and 420 ka, when parallel to the evolution of large 100-ka cycles a distinct decrease in the input of magnetic particles is observed. Also, for this interval an intensification of glacial conditions is indicated by a marked increase in the accumulation rates of ice-rafted debris (IRD) during marine isotope stages 16 and 12.

The observed mid-Pleistocene changes were likely due to a gradual shift from a more zonal behavior of the coupled ocean–atmosphere system at high northern latitudes prior to the MPR to more meridionality thereafter, a shift that affected both the patterns of ocean circulation and ice drift in the Nordic seas region. Accordingly, the subsequent MPR-related changes of these two climate parameters should be responsible for the decrease in the concentration of magnetic particles at the study site after 700 ka. With the mid-Pleistocene strengthening of the Nordic heat pump the mode of deep-water production and the flow of bottom currents changed at high northern latitudes, which led to an increased export of magnetic particles from basaltic source regions around Greenland and Iceland into the subpolar North Atlantic. Consequently, less magnetic material was deposited in the Nordic seas than before the MPR when water mass exchange between the Nordic seas and the North Atlantic was more restricted. In addition, the large Late-Pleistocene expansions of glacial ice caps on the eastern margin of the Nordic seas led to a major change in the composition of IRD material in the study area, with more material originating from the Scandinavian and Barents Sea shelf regions, which ultimately caused a dilution of the magnetic signal.

Keywords: mid-Pleistocene revolution; Nordic seas; sedimentation patterns

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1. Introduction

It is well known that the strong glacial–interglacial climate cyclicity of the Northern Hemisphere as it is recognized for the past about 500 kyr is not representative for the behavior of the entire Pleistocene climate system (Shackleton et al., 1988; Berger and Jansen, 1994; Baumann and Huber, 1999). During Early to early Middle Pleistocene times, the climatic conditions in the northern North Atlantic (Nordic seas) showed long periods of moderate glacial conditions and only episodic interglacial intervals, i.e., northward-directed intrusions of temperate water masses into the Nordic seas (e.g., Henrich, 1989; Fronval and Jansen, 1996). It was only after the so-called mid-Pleistocene revolution (MPR) that the characteristics of glacial and interglacial climates intensified, leading to the more pronounced contrasts of the high northern climate system so typical for the Late Pleistocene (Jansen et al., 1989; Henrich and Baumann, 1994; Baumann et al., 1996).

Along with the mid-Pleistocene climate intensification goes the mid-Pleistocene shift from a dominant climate periodicity around 41 ka (Earth's orbital obliquity) to a dominant periodicity around 100 ka (Earth's orbital eccentricity) (e.g., Ruddiman et al., 1989; Berger et al., 1994; Bolton et al., 1995). It is still under debate why we observe this pronounced increase in glacial–interglacial climate contrasts and the systematic shift into the late-Pleistocene 100 ka world (Boyle, 1988; Maasch and Saltzman, 1990; Clark and Pollard, 1998; Berger et al., 1999), as the orbital forcing parameters did not change across the mid-Pleistocene (Saltzman and Verbitsky, 1994; Raymo et al., 1997).

To improve our current knowledge as well as our concepts about forcing factors and environmental consequences of the mid-Pleistocene climate shift, we need further high quality proxy records. However, the current proxy information about character and timing of the mid-Pleistocene paleoceanographic and paleoclimatic changes are rather limited, especially from the region where the climatic consequences of the MPR are expected to be rather pronounced, i.e., the Nordic seas. Here, most of the evidence about Early and Middle Pleistocene conditions comes from some sediment records obtained by the Ocean Drilling Program (e.g., (Henrich, 1989; Jansen et al., 1989; Fronval and Jansen, 1996), which are, in general, characterized by relatively low sample resolution. To gain more detailed insights into the specific climatic response of the high northern latitudes, we present a number of high-resolution sediment records from an IMAGES core site in the deep Norwegian Sea (eastern Nordic seas), which cover the past about 1.6 Ma.

2. Core material, methods and chronology

The about 34-m-long piston core MD992277 (Fig. 1) was recovered from the eastern slope of the Iceland Plateau in the western Norwegian Sea during the IMAGES V campaign in 1999. Magnetic remanence and low field bulk susceptibility (volume) were measured at the Laboratoire des Sciences du Climat et de ĺEnvironnement, Gif-sur-Yvette, France (Fig. 2; for details see Helmke et al., 2003a). Magnetic susceptibility (MS) of the core was recorded onboard at 2 cm steps (Fig. 3). Planktic $\delta^{18}O$ (given as per mil deviations relative to the Pee Dee Belemnite (PDB) carbonate standard) was sampled at a resolution of 2.5 cm across the studied mid-Pleistocene interval (resolution for Early Pleistocene sections is 5 cm) and measured at the Leibniz Laboratory (University of Kiel) with the automated Kiel Carbonate Preparation Device and a Finnigan MAT 251 mass spectrometer system. On average, 20 specimens of the polar planktic foraminifer *Neogloboquadrina pachyderma* (sinistral) from the size fraction 125–250 μm were taken for each analysis. From 10 m core depth down, IRD was counted in the mesh size >250 μm with an average sample interval of 2.5 cm. The results are expressed as lithic grains per gram (Fig. 2). The bulk carbonate content (% weight) was measured every 5 cm in the same core sections as IRD (Fig. 2). Calcium (Ca), iron (Fe) and titanium (Ti) concentrations in the sediment were measured in 2 cm steps using the X-ray fluorescence (XRF) corescanner (Röhl and Abrams, 2000; Haug et al., 2001) at the University of Bremen, Germany (Figs. 2 and 3).

A number of parameters were used to obtain an age model for the study site. Core PS1243 is located in

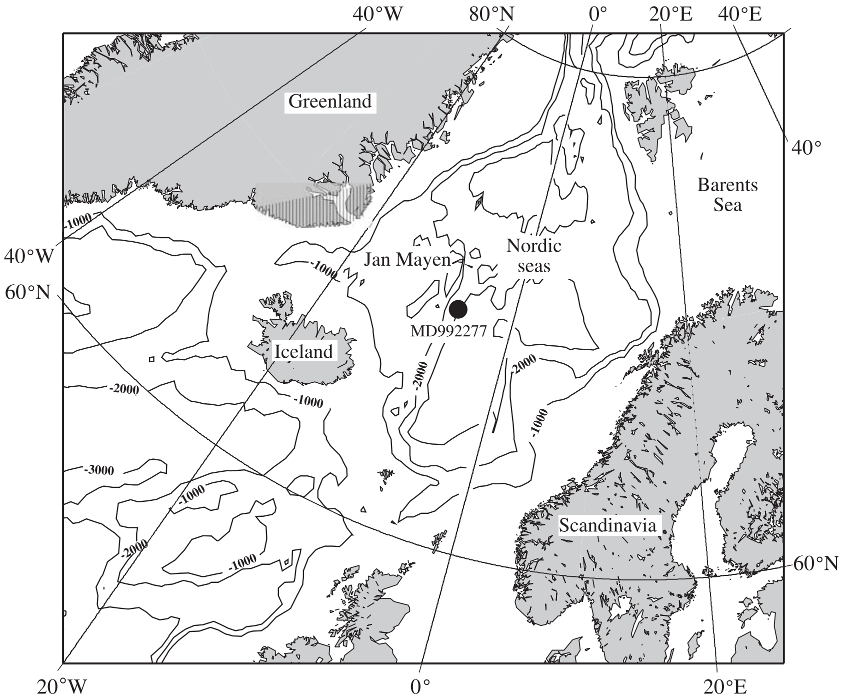
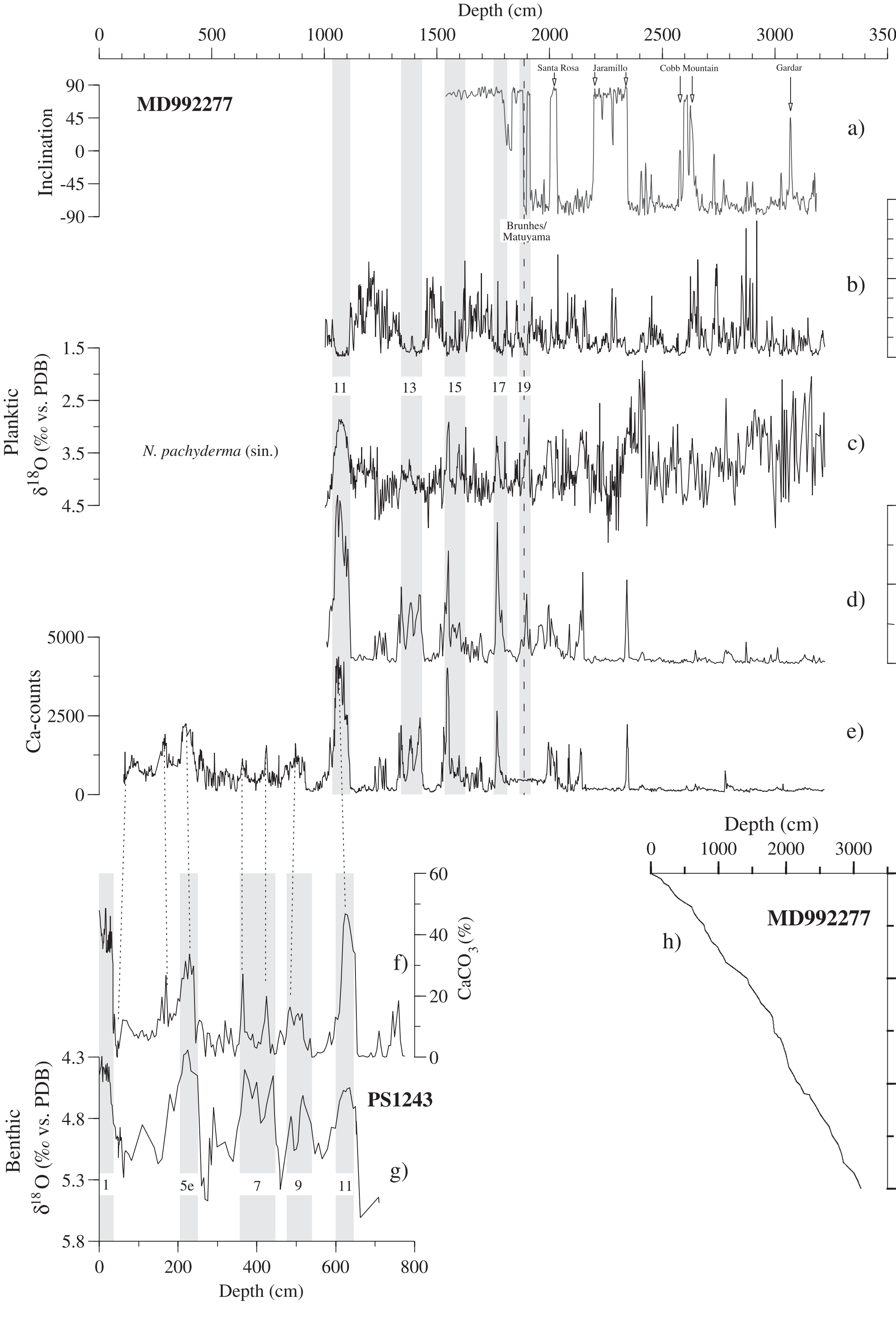


Fig. 1. Overview of working area and position of study site in the Nordic seas (MD992277: western Norwegian Sea, 69°15′ N, 6°19′ W, 2800 m water depth). Stippled area indicates potential source region of basaltic material around Scoresby Sund in Greenland.

very close vicinity to core MD992277 and has an established age model for the past about 450 kyr based on various sedimentological proxies (Fig. 2; see Bauch, 1997; Bauch et al., 2000). In the upper about 10 m of core MD992277, the Ca-counts, which are highly correlative to the carbonate data of the same core (Fig. 2), give a perfect match to the carbonate record of PS1243 (Fig. 2). Disregarding this younger part, glacial and interglacial marine isotope stages (MIS) older than MIS 10 were identified in core MD992277 using the planktic $\delta^{18}O$, the Ca-counts, as well as the carbonate and the IRD records. In general, interglacial periods are characterized by low $\delta^{18}O$, high Ca-counts and high values of carbonate content as well as low IRD (Fig. 2). Ages were assigned by correlation to the chronologies of SPECMAP (Imbrie et al., 1984) and the "low latitude stack" (Bassinot et al., 1994). In the lower part of the record, polarity chron boundaries were used as age tie points (Fig. 2). Between these tie points the age model was improved by correlating the $\delta^{18}O$ of MD992277 to the astronomically calibrated benthic oxygen isotope record from ODP Site 659 (Tiedemann et al., 1994). Linear interpolation was applied between all age model tie points.

3. Pleistocene development of sedimentological records at site MD992277

The Ti and Fe records are generally in good agreement and both records show during the last 1.6 Ma many changes that are also recognized in the MS record (Fig. 3). In more detail there are several obvious differences between the XRF and MS data. For instance, the marked minimum in Fe and Ti during full interglacial MIS 11 at about 400 ka is not accompanied by a large MS minimum, or the MS maximum in early MIS 15 at about 600 ka is represented neither in the Ti nor the Fe values (Fig. 3). The input of magnetic particles to site MD992277 is not strictly limited to the glacial and stadial periods, e.g., a high Fe and Ti input is noted during peak interglacial substage 21.1 at about 820 ka (Fig. 3). Most prominent in the XRF and MS records is a clear mid-Pleistocene shift in mean values. The onset of


Depth (cm)
0
500
1000
1500
2000
2500
3000
3500
MD992277
Inclination
90
45
0
-45
-90
Santa Rosa
Jaramillo
Cobb Mountain
Gardar
Brunhes/
Matuyama
a)
b)
IRD (grains/g)
800
400
0
Planktic
δ18O (‰ vs. PDB)
1.5
2.5
3.5
4.5
N. pachyderma (sin.)
11
13
15
17
19
c)
d)
CaCO3(%)
50
25
0
Ca-counts
5000
2500
0
e)
60
40
20
0
CaCO3 (%)
f)
PS1243
Benthic
δ18O (‰ vs. PDB)
4.3
4.8
5.3
5.8
g)
1
5e
7
9
11
0
200
400
600
800
Depth (cm)
Depth (cm)
0
1000
2000
3000
MD992277
h)
Age (ka)
0
500
1000
1500

this systematic shift varies between the three records and occurs between about 700 and 550 ka. Prior to the shift, during Early and Middle Pleistocene times, the mean values of the magnetic components and the mean MS values were significantly higher than during Late Pleistocene times. Besides the prominent minimum in the XRF records during MIS 11, these constantly lowered Late Pleistocene mean values are most obvious between about 550 and 150 ka. Then, during the past about 150 ka, another less pronounced decrease of mean values can be observed for both the records of XRF and MS (Fig. 3).

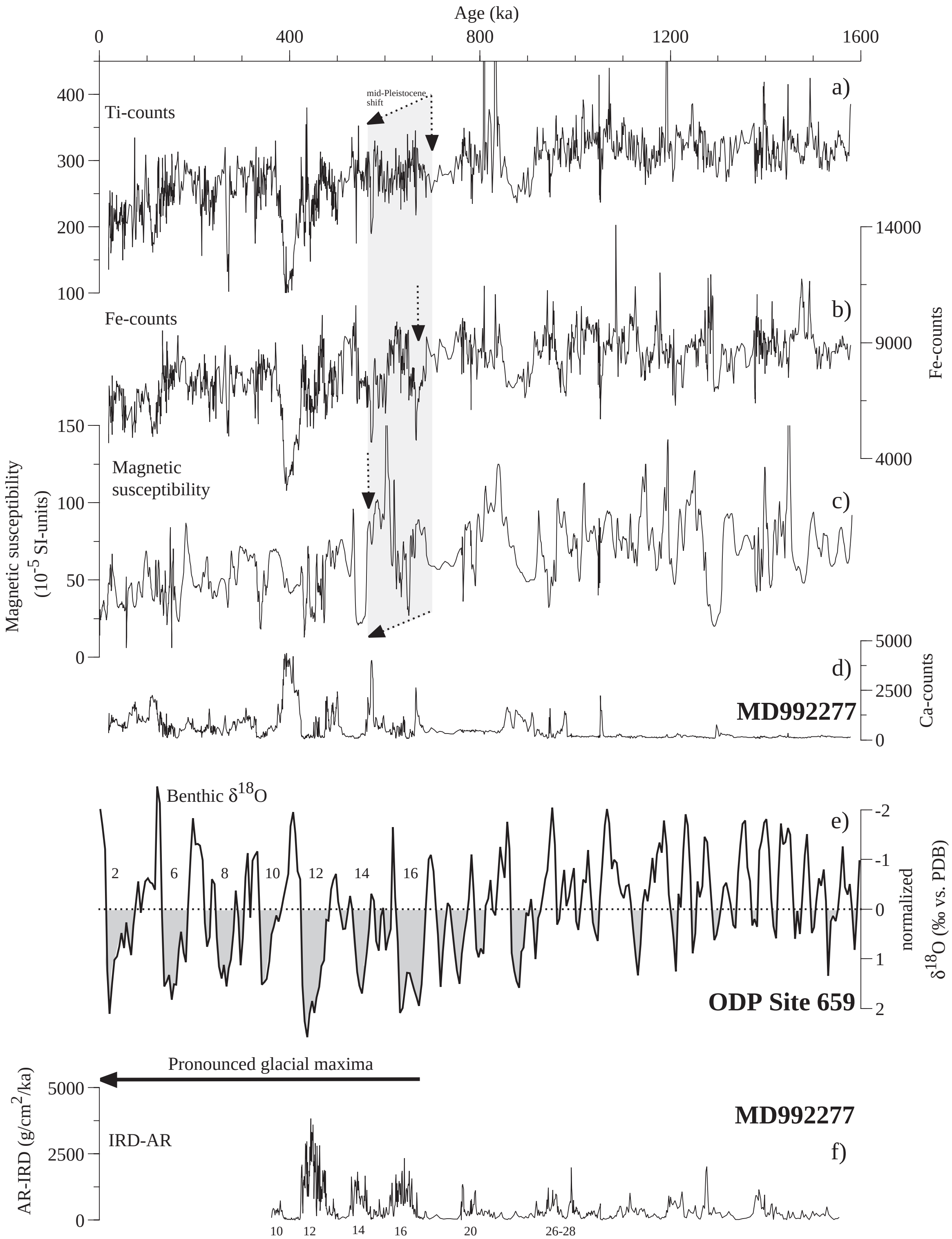
The IRD record, which covers the time between 1.6 Ma and 350 ka, shows alternating periods of massive terrigenous input that can be related to glacial and stadial intervals (Figs. 2 and 3). Besides this almost continuous high terrigenous input, strongly reduced IRD is always observed during the few peak interglacial time intervals (Figs. 2 and 3). This glacial–interglacial relation of relative IRD input at our study site remained unchanged during the Pleistocene, giving no clear indication of a systematic mid-Pleistocene shift as observed in our other sedimentological records (Fig. 2). Within this dominant glacial–interglacial pattern, a notable increase in the glacial input of ice-rafted material occurred at site MD992277 between about 700 and 420 ka. The glacial IRD accumulation rates of the entire record show highest values during MIS 16 and MIS 12. The input of ice-rafted terrigenous material in these two glaciations was about two to four times higher when compared to the previous glacial and stadial intervals with notably increased IRD accumulation rates, e.g., MIS 20 and MIS 26–28 (Fig. 3).

The bandpass-filtered IRD record from site MD992277 reveals a clear change from a dominant variance around 41 ka during Early and early Middle Pleistocene times to a dominant 100 ka cyclicity during the late Middle Pleistocene, a pattern also recognizable in the MS signal (Fig. 4b). The amplitude minimum of the 100 ka-filter from both IRD and MS as well as the amplitude maximum of the 41 ka filter from IRD are observed at 1 Ma. The maximum in the amplitude of the 41 ka-filtered MS signal is noted at 1.2 Ma (Fig. 4b). In general, changes in both filter signals are most pronounced between 1 Ma and 500 ka (Fig. 4b). Parallel with the first marked shift in the MS and XRF values, the amplitude of the 100-ka cycle begins to increase at about 700 ka.

4. Timing of mid-Pleistocene change

The timing of the main changes in the XRF and MS records of MD992277 suggests a close relation to the overall MPR-shift in paleoclimatic and paleoceanographic conditions of the Northern Hemisphere. Previous studies from the Nordic seas region have indicated that a first significant change in the character of the Pleistocene climate conditions occurred around 1 Ma (Jansen et al., 1988; Henrich, 1989; Fronval and Jansen, 1996), with a second marked intensification of both glacial and interglacial conditions after about 650 ka (e.g., Krissek, 1989; Henrich and Baumann, 1994; Baumann et al., 1996; Baumann and Huber, 1999; Helmke et al., 2003b). The systematic shift in our XRF and MS values is also observed when the climate contrasts intensified at around 650 ka. This timing of changes in climatic conditions is also clearly seen in the IRD accumulation rates at MD992277 with the first major maximum during MIS 16 (Fig. 3). This increase in IRD corresponds well with the development of benthic oxygen isotopes in the Northeast Atlantic (Tiedemann et al., 1994), where the first prominent glacial maximum in MIS 16 (Fig. 3) reflects the major onset of the eccentricity cycle (Mudelsee and Stattegger, 1997). A further significant increase of IRD accumulation rates occurs at site MD992277 during MIS 12 when the rates are more than four times higher than before the MPR and

Fig. 2. Top five records are results of a) inclination (for age of Cobb Mountain, see also Channell et al., 2002), b) IRD (grains/g), c) planktic $\delta^{18}O$ (‰ vs. PDB), d) carbonate content (% of weight), and e) Ca-counts vs. depth from core MD992277; note that the results from the upper four panels do not cover the entire core sections. Next two panels show records of f) carbonate content (% of weight) and g) benthic $\delta^{18}O$ (‰ vs. PDB) vs. depth from reference site PS1243 (69°22′ N, 6°32′ W, Bauch, 1997; Bauch and Erlenkeuser, 2003). Areas shaded in light gray denote interglacial MIS in both cores. Interglacial MIS are labeled for reference. Magnetic polarity events of the inclination record are indicated by arrows and also labeled for reference. Vertical, stippled line in the MD992277 records shows position of the Brunhes/Matuyama chron boundary. Dashed, vertical lines between the carbonate record of PS1243 and the Ca counts from MD992277 represent some of the tie points for the chronology of the lower sediment sections from MD992277. Panel h) is age–depth plot of site MD992277.


Age (ka)
0
400
800
1200
1600
Ti-counts
mid-Pleistocene shift
a)
400
300
200
100
14000
Fe-counts
b)
9000
Fe-counts
4000
150
Magnetic susceptibility
c)
100
50
0
Magnetic susceptibility (10-5 SI-units)
5000
d)
2500
Ca-counts
MD992277
Benthic δ18O
e)
-2
-1
0
1
2
2
6
8
10
12
14
16
normalized δ18O (‰ vs. PDB)
ODP Site 659
Pronounced glacial maxima
AR-IRD (g/cm2/ka)
5000
2500
0
MD992277
IRD-AR
f)
10
12
14
16
20
26-28

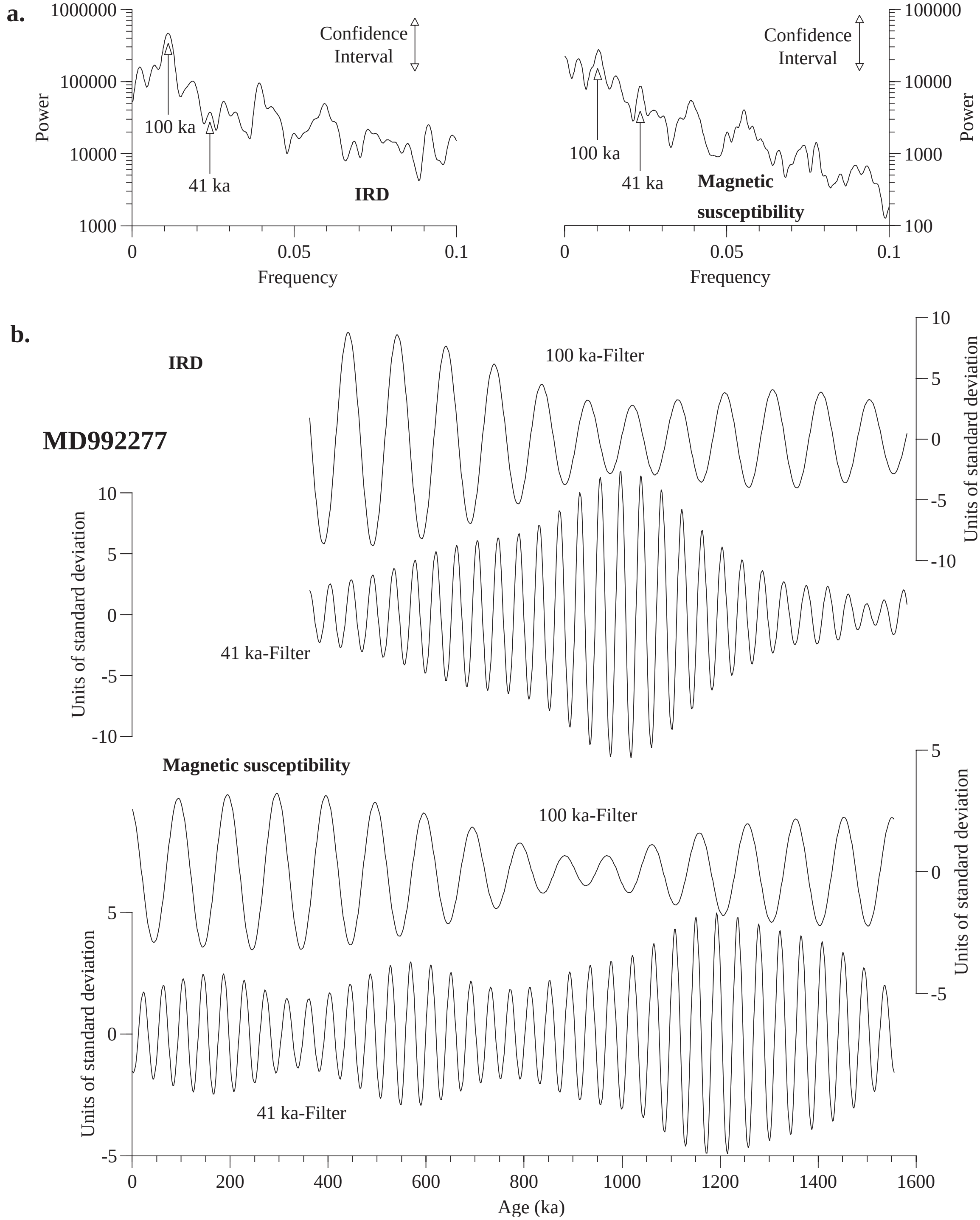
corresponds to a time when global ice volume appears to have been highest during the Pleistocene (Fig. 3). Hence, from our sedimentological data, it is indicated that after the global initiation of the MPR (Prell, 1982; Berger and Jansen, 1994) we observe strong MPR-related changes at the study area between about 700 ka and the so-called mid-Brunhes event, i.e., during the transition between glacial MIS 12 and interglacial MIS 11.

However, some indication for changes as early as about 1 Ma are also evident at the study site from the frequency analysis data showing a clear increase of the eccentricity signal (Fig. 4b). In this respect, our data support observations from other regions about the Pleistocene evolution of the orbital signals (Shackleton et al., 1990; Park and Maasch, 1993; Chen et al., 1995) and corroborate the limited evidence so far available from the Nordic seas that also indicated a change in frequency dominance during the mid-Pleistocene (e.g., Jansen et al., 2000). A strong increase of the eccentricity signal occurs gradually after 700 ka, i.e., time-coeval with the major changes of the sedimentological records. Such a notable lag in the onset of large 100 ka cycles after the Northern Hemisphere ice mass built up at about 900 ka has previously been described (Mudelsee and Stattegger, 1997; Mudelsee and Schulz, 1997).

5. Depositional processes

The shift in our proxy records should be due to certain changes in the input of terrigenous material into the sediment. Terrigenous material from the surrounding continents must be regarded as the main component of deep-sea sediments in the Nordic seas and at the study site. In addition, there are some other intervals, i.e., with enhanced calcium carbonate concentration (e.g., Kellogg, 1977) and sporadic tephra layers (Wallrabe-Adams and Lackschewitz, 2003), when terrigenous input from land is significantly reduced. The rather synchronous general shift in the values of MS, Fe and Ti in MD992277 suggests that the concentration of the ferromagnetic particles strongly influences magnetic susceptibility (Fig. 3). Besides this overall good agreement between MS and the XRF records, there are nevertheless some notable differences. For example, the pronounced minima in the XRF records during MIS 11 around 400 ka are not accompanied by a corresponding strong minimum in MS (Fig. 3). In fact, MS of marine sediments is not solely controlled by ferromagnetic components but may also be influenced by the carbonate concentration of the sediment, i.e., increased carbonate content can reduce the MS values (Opdyke and Chanell, 1996; Andrews and Tedesco, 1992). Our records do not reveal a clear negative correlation between carbonate content and MS that would point to a dilution of the MS signal by carbonate components. For example, the marked interglacial carbonate maxima between MIS 17 and 11 do not correspond to minima in the MS record (Fig. 2). Moreover, some of the discrepancies between MS and the XRF records are found in the older relative carbonate-free sediment sections. The records between 1.3 and 1.1 Ma (Fig. 3) suggest that those differences cannot be explained by the variability of the carbonate record but might be related to an influence of other non-magnetic material. Despite the observed discrepancies, the overall mid-Pleistocene shift in the amount of ferromagnetic particles as well as in the MS signal suggests a major change in the composition of the terrigenous material delivered to our core site. This suggests that after the shift we should expect a somewhat modified main transport direction for the magnetic particles to the study region and/or a dilution of the MS signal due to increased input of terrigenous material from non-magnetic source regions. The main source region for Fe and Ti in the Nordic seas is likely the Tertiary basaltic province, which stretches from southeast Greenland

Fig. 3. Records of a) Ti, b) Fe, c) MS and d) calcium counts (upper four panels) and f) IRD accumulation rates (lowest panel, calculation following van Andel et al., 1975) vs. age from MD992277; note that Ti counts and MS values are cut off at 450 (maximum value is 800) and at 150 10^{-5} SI-units (maximum is value is 220) to better illustrate the general trends. The 5th panel from top e) shows normalized benthic δ^{18}O from ODP Site 659 vs. age (Tiedemann et al., 1994). Shaded rectangular with vertical black arrows indicates time interval between about 750 and 550 ka where the shift in mean values of XFR and MS occurs. Horizontal black arrows denote the respective starting points of systematic mid-Pleistocene changes in these three records. The intensification of glacial conditions is characterized by an increase in IRD accumulation rates at MD992277 and by raised glacial–interglacial amplitudes of benthic δ^{18}O at Site 659 (dashed black arrow and shading of glacial intervals in benthic δ^{18}O indicate this intensification of glacial climates). In the lowermost two records some glacial MIS are labeled for reference.


a.
1000000
100000
10000
1000
Power
Confidence Interval
100 ka
41 ka
IRD
0
0.05
0.1
Frequency
100000
10000
1000
100
Power
Confidence Interval
100 ka
41 ka
Magnetic susceptibility
Frequency
b.
IRD
MD992277
100 ka-Filter
41 ka-Filter
Units of standard deviation
10
5
0
-5
-10
Magnetic susceptibility
100 ka-Filter
41 ka-Filter
0
200
400
600
800
1000
1200
1400
1600
Age (ka)

across Iceland to the northwestern part of the British Isles (Parra et al., 1987; Kissel et al., 1999). Another potential source area for basaltic material at the core site is Jan Mayen northeast of Iceland (Fig. 1).

6. Climate-induced changes in sedimentation patterns

In general, the input of terrigenous particles into the sediments of the Nordic seas may take place via ocean currents, by aeolian transport, and via ice rafting. Increased transport of terrigenous material by "dust blow" from the glacial ice shields is a well-known phenomenon recorded in several Arctic and Antarctic ice cores (Petit et al., 1990, 1999; Jouzel et al., 1996). Thus, strong catabatic winds from continental ice sheets may, episodically, also influence the signal of terrigenous material in the Nordic seas area by transporting particles from the exposed shelf regions into the deep ocean. However, any long-term systematic changes in the regional wind system of the Northern Hemisphere during the Pleistocene should be related to the alternating rhythm of glacial–interglacial climates and wind transport as a main controlling factor for the MPR change in our sedimentological records seems rather unlikely.

6.1. Role of the ocean current system

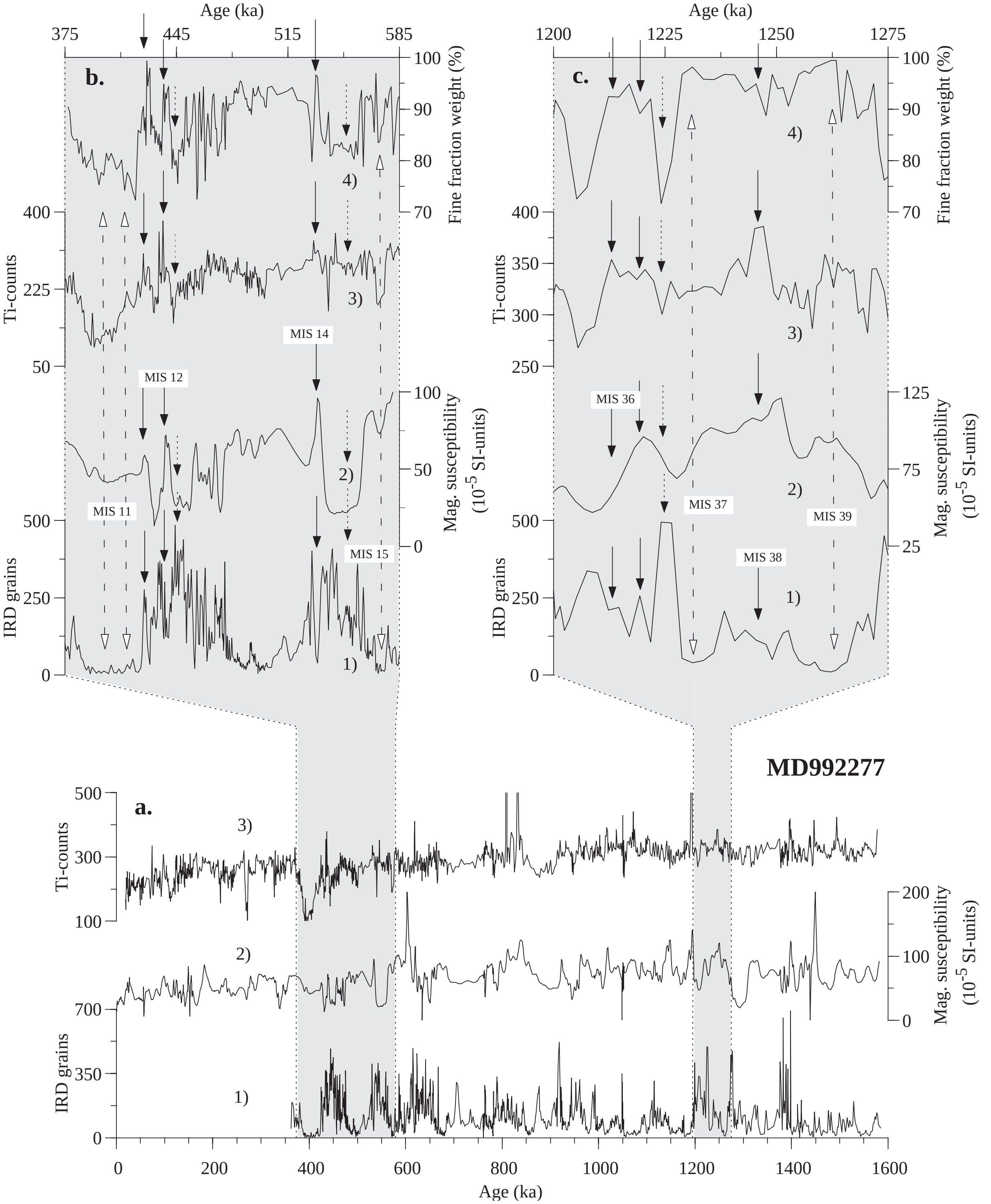
As the patterns of global thermohaline circulation are known to have been non-constant over the entire Pleistocene period (Kuijpers, 1989; Henrich et al., 2002; Gröger et al., 2003), variable material transport by ocean currents has to be considered as possible mechanism to explain the terrigenous signal of MD992277. Moreover, a coupling between variability of deep currents and the sedimentation pattern of magnetic particles has been described for a number of North Atlantic core sites (Moros et al., 1997; Kissel et al., 1999). Proxy data from the Nordic seas, e.g., carbonate preservation records, indicate that prior to the MPR the ocean circulation at high northern latitudes had a more zonal character, which resulted in a persistent but reduced surface and deep water exchange between the Nordic seas and the North Atlantic (Jansen et al., 1988; Henrich, 1989; Baumann et al., 1996; Austin and Evans, 2000). Our records from site MD992277 support a scenario of reduced northward heat transfer and of a carbonate undersaturated water column in the Nordic seas by showing strong carbonate dissolution and constant input of ice-rafted material prior to about 1 Ma (Fig. 3). However, the details of the regional surface and deep-water circulation system of the Early and early Middle Pleistocene remain speculative, although there are some speculations on the modes of deep water formation at that time (Henrich and Baumann, 1994; Henrich et al., 2002). If there was indeed a somewhat restricted vertical overturning of surface waters in the Nordic seas and if current transport mainly drove the overall terrigenous input to site MD992277 before the mid-Pleistocene, then the high content of ferromagnetic particles in the western Norwegian Sea should be related to an eastward directed bottom water flow from the basaltic regions offshore Greenland and Iceland. For Late-Pleistocene times, an increased meridionality of the Nordic seas circulation system as well as a strengthening of the so-called Nordic heat pump with generally stronger outflow of bottom water masses from the western part of the Nordic seas into the North Atlantic have been proposed (Berger and Jansen, 1994; Baumann and Huber, 1999). If this is correct, a transport by deep currents of magnetic particles from the basaltic regions around Greenland and Iceland is rather directed to the south out of the Nordic seas and into the North Atlantic region rather than into the Norwegian Sea. Consequently, less magnetic particles are delivered to the core site and

Fig. 4. a. Power spectra of IRD per gram and magnetic susceptibility (MS) from MD992277. We used the software package AnalySeries 1.1 (Paillard et al., 1996) to perform the classical Blackman–Tukey (Blackman and Tukey, 1958) spectral method (with a confidence level of 95%). In this method, the algorithm first computes the autocovariance of the record, applies a window and Fourier transforms it to compute the spectrum. The confidence intervals of the spectra are indicated for reference. Bandwidth is 0.004 for IRD and 0.003 for MS. Position of the 100 ka and 41 ka spectral peaks are indicated. Additional peaks at frequency of about 0.04 and 0.55 are related to the precessional signal (19 and 23 ka). Note that ordinates are on logarithmic scales. b. Gaussian band pass filters (also calculated using AnalySeries) of IRD grains (upper two panels) and MS (lower two panels). The filters centered at 100 ka have a bandwidth of 0.0005 (periods are between 95 and 105 ka). The filters centered at 41 ka have a bandwidth of 0.002 (periods are between 38.5 and 43.5 ka).

the XRF values of MD992277 show generally reduced values after the mid-Pleistocene (Fig. 3). With respect to this scenario, it is interesting to note that in a comparative study on sediment records from MIS 3 (Kissel et al., 1999), a single investigated site from the central Nordic seas showed much lower concentration of magnetic particles than the more southern North Atlantic sites and, for the magnetic material found at all these sites, the authors suggest the Tertiary basaltic province to be the main source region.

If magnetic particles at site MD992277 were mainly delivered by deep ocean currents, then a higher concentration of these components should be expected during intervals with comparatively vigorous deep-water flow. It has previously been shown that fine fraction analyses, ideally results of analyses with respect to the sorting processes of the fraction 10–63 μm, are a useful indicator to reconstruct current speed intensity in the North Atlantic on glacial–interglacial time scales (Manighetti and McCave, 1995; McCave et al., 1995). More recent studies by Prins et al. (2000, 2002) have indicated that this method may produce inadequate results, as admixtures of silt-sized IRD to the sediment might incorrectly be attributed to changes in bottom current intensity. The authors therefore suggest the use of end-member modeling of the grain-size distributions to unmix the signals of bottom water flow and iceberg drift. However, in order to define periods of enhanced bottom-water flow in the study region, we measured the portion of the size-fraction <63 μm in some selected sections of MD992277, as we should expect some sort of response also of the silt and clay fraction to variations in bottom-water flow (Fig. 5). During the Pleistocene, highest intensity of deep currents in the Nordic seas is expected during the pronounced interglacial intervals (e.g. Henrich, 1998). As these intervals are generally characterized by very low iceberg activity, any larger influence of silt-sized IRD on the grain-size data from these intervals seems rather unlikely. The good agreement between the <63 μm fraction and the Ti-concentration (Fig. 5b and c) suggests that much of the Ti signal in core MD992277 is carried by the silt and clay fraction. During interglaciations prior to the mid-Pleistocene shift, i.e., MIS 37 and 39, there are some notable differences (Fig. 5c). During MIS 39, the fine fraction component and Ti both have a maximum time-coeval with low IRD implying that an increased bottom-water flow caused enhanced accumulation of fine-grained magnetic particles at site MD992277. However, MIS 37 is characterized by comparatively low Ti values and, thus, would not support the idea of an increased input of magnetic particles by increased strength of interglacial bottom currents. It has previously been shown that in the Nordic seas MIS 15 and 11 are the two most pronounced warm intervals within the entire Middle Pleistocene period (Helmke et al., 2003b). Consequently, these interglaciations should be characterized by a vigorous deep-water flow. The full-interglacial IRD-free intervals of MIS 15 and 11 show clear minima in Ti as well as in the portion of the <63 μm fraction (Fig. 5b). These observations would support the above discussed scenario of a southward export of magnetic particles from the basaltic regions of the Nordic seas into the North Atlantic after the onset of the mid-Pleistocene climate transition during intervals of enhanced deep-water flow. Although the Ti concentration shows certain minima during glacial times with massive IRD, e.g., during MIS 12 (Fig. 5b), enhanced Ti values occur before as well as after the MPR, usually during times of notable IRD deposition (Fig. 5b and c). Hence, it seems as if the proposed mid-Pleistocene shift in the pattern of deep-water circulation of the Nordic seas has some influence on the sedimentological records of site MD992277, but ice-rafted transport of terrigenous material certainly has to be considered essential to explain the changes observed in our records.

Fig. 5. Records of 1) IRD grains, 2) magnetic susceptibility, 3) titanium counts, and 4) weight (%) of fine size fraction (<63 mm vs. age) from MD992277. Shaded intervals denote those sections of the complete downcore record a. that were magnified in the uppermost four panels (the interval between MIS 11 and 15 is shown in b.; c. shows the interval between MIS 36 and 39). Stippled white arrows in b. and c. indicate intervals of reduced IRD within interglacial isotopic stages (these interglacial MIS are labeled for reference) that are referred to in the discussion about the role of ocean currents on the input of magnetic particles. Short black arrows in b. and c. denote some marked glacial maxima and minima in the Ti record and relation of these events to IRD input and amount of the fine fraction (the glacial MIS are labeled for reference). See discussion about input of magnetic particles by currents and IRD.



Age (ka)
375
445
515
585
b.
100
90
80
70
Fine fraction weight (%)
4)
400
225
50
Ti-counts
3)
MIS 14
MIS 12
100
50
0
Mag. susceptibility (10^-5 SI-units)
2)
MIS 11
500
250
0
IRD grains
MIS 15
1)
Age (ka)
1200
1225
1250
1275
c.
4)
400
350
300
250
3)
MIS 36
125
75
25
MIS 37
MIS 39
MIS 38
MD992277
a.
500
300
100
200
700
350
0
Age (ka)
0
200
400
600
800
1000
1200
1400
1600

6.2. Role of sea ice and iceberg drift

A systematic MPR-related shift in the sea ice export from the Arctic Ocean into the Nordic seas may contribute to the terrigenous changes observed in MD992277. Arctic sea ice, for instance, can carry large amounts of terrigenous silt and clay into the Nordic seas and, after its release from the melted ice, this fine-grained material may drift over some distances before it finally settles on the seafloor (Pfirman et al., 1997; Ramseier et al., 2001). It seems very likely that after the climatic intensification of the mid-Pleistocene, the export of terrigenous material from the Arctic Ocean into the Nordic seas sediments via sea ice transport was enhanced. This additional sediment from the Arctic region and its glacier-covered archipelagos could, after the MPR, have led to a dilution of the Fe and Ti content as well as the MS signal and, thus, contributed to the shift towards more reduced values observed during the Late Pleistocene.

Most of the coarse-grained terrigenous material in the Nordic seas is probably derived from icebergs of the surrounding glaciated continents and shelves. It has been stated that some glaciers over Scandinavia reached the western shelf region and released icebergs into the Nordic seas prior to the MPR (Sejrup et al., 1991) although, in general, the glacial ice caps of the Fennoscandian ice sheet were smaller than during later glaciations (Sejrup et al., 1995; Vorren and Laberg, 1997). Since the Greenland ice sheet oscillated considerably less than the ice cap over Scandinavia, it almost constantly released icebergs into the Nordic seas during the Pleistocene (Jansen and Sjøholm, 1991; Jansen et al., 2000). These findings are in line with the evidence from MD992277, where, with the exception of very few IRD-free interglacial intervals (e.g., during MIS 15 and 11), a continuous input of terrigenous material by ice is observed for the past about 1.6 Ma (Fig. 2).

A systematic change in the ice drift over the study region, that was related to the overall change from strong zonality at high northern latitudes prior to the MPR towards enhanced meridionality after the climate transition, may have occurred across the mid-Pleistocene. It has recently been proposed that during Early Pleistocene times, obliquity-driven variations in the insolation gradient between low and high latitudes control the flux of moisture, and also heat, to the high northern latitudes (Raymo and Nisancioglu, 2003). A stronger zonality of the ocean–atmosphere system at high northern latitudes in the Early Pleistocene would lead to a reduced moisture transport into the far north and more moisture could be kept south of the Nordic seas. As the effects of moisture supply for ice cap growth are probably more efficient over Scandinavia than over Greenland, the relative contribution of the Greenland ice sheet to the total iceberg drift in the Nordic seas must have been greater before the climate shift. Another high relative contribution of icebergs prior to the MPR can be expected from the glaciers on Iceland where we find some indications for the repeated occurrence of Late Cenozoic glacial ice sheets (Eiriksson and Geirsdottir, 1991; Geirsdottir and Eiriksson, 1994). On Iceland, the strong zonality of the ocean–atmosphere circulation before the climate shift should ultimately foster the requisites for ice sheet growth during Early and early Middle Plesitocene times. Increased eastward drift of icebergs from the basaltic regions of Greenland (e.g., from Scoresby Sund) and Iceland into the western Nordic seas before the MPR could also have caused increased input of magnetic particles into the sediment at the study site during intervals of notable glacial and stadial IRD (Fig. 5).

With the strengthening of the Nordic heat pump during the mid-Pleistocene (Berger and Jansen, 1994), more moisture is brought to the high northern latitudes. This increased meridional moisture delivery and the cooling of the polar region due to decreasing obliquity (Raymo and Nisancioglu, 2003) then promoted the large Late-Pleistocene expansions of the Fennoscandian and Barents Sea ice sheets. It is therefore suggested that, as a consequence of this mid-Pleistocene climate intensification, Scandinavia and the Barents Sea shelf became the dominant source regions of iceberg drift at the study region. Due to this, the relative influence of icebergs from the other sources around the Nordic seas became less significant. The massive input of terrigenous material from Scandinavia and the Barents Sea shelf at site MD992277 during the Late Pleistocene glaciations eventually caused a dilution in the concentration of Fe and Ti, thereby reducing the absolute values of MS.

7. Summary and conclusions

A 1.6 Ma long sediment record from the western Norwegian Sea suggests that this region has experienced a systematic gradual shift in its environmental conditions during the course of the MPR. First signs of this major shift can be observed in the evolutionary frequency analysis of the IRD and MS signals, which reveal changes beginning at around 1 Ma, when a variance around 100 ka emerges from a 41 ka-cyclicity, which had dominated the frequency spectrum during earlier Pleistocene times. A significant increase in the amplitudes of the 100-ka cycle is obvious after about 700 ka, time-coeval with the main changes of the sedimentological parameters. Between 700 and 500 ka, the XRF and MS records point to a marked decrease in the concentration of magnetic particles at site MD992277. Also, within the mid-Pleistocene interval, the sediments are characterized by a stepwise increase in the IRD accumulation rates at MIS 16 and at MIS12.

It is indicated that an MPR-related shift from stronger zonality towards an increased meridonality of the climate system at high northern latitudes with subsequent changes in deep-water flow and ice-drift pattern in the Nordic seas is responsible for the observed changes at the study site. Based on the sedimentological evidence, a change in the bottom-water flow across the mid-Pleistocene is proposed. It seems that, during Early and early Middle Pleistocene times, a notable deep-water flow existed from the western Nordic seas into the Norwegian Sea carrying magnetic particles to the core site. After the climate shift during the Late Pleistocene, a strong overflow of bottom waters into the North Atlantic is observed at high northern latitudes and the transport of terrigenous material to the core site by deep ocean currents seems to have vanished largely.

The sediment records document that, next to the current system, the ice-drift pattern in the Nordic seas has to be considered as important mechanism in order to explain the mid-Pleistocene climate changes. Prior to the mid-Pleistocene shift, during those cold periods when the ice-sheet cover over the continental margins of the Northern Hemisphere was generally reduced, a significant contribution to the total ice drift in the study area originated from the Greenland and Iceland glaciers. As a consequence, terrigenous input at site MD992277 was also strongly influenced by material from basaltic sources. With the onset of the larger glaciations on the eastern and northeastern margins of the Nordic seas, as they are obvious from the IRD accumulation rates, this pattern changed and ice drift from the glaciated regions of Scandinavia and the Barents Sea increased. We thus observe a decrease in the concentration of magnetic particles in the sediment related to this relocation of the source regions for terrigenous material transported by ice.

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