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Comparison of glacial and interglacial conditions between the polar and subpolar North Atlantic region over the last five climatic cycles

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[1] A multiparameter-based interpretation of sediment records from the northeast Atlantic and the western Nordic seas suggests that during the last 500,000 years only in marine isotopes stage (MIS) 11, 5e, and 1 were there somewhat comparable interglacial boundary conditions in both regions, i.e., strongly reduced occurrence of iceberg-rafted debris (IRD) and high carbonate bioproductivity. Although the northeast Atlantic experienced such conditions during all peak interglaciations, with the exception of MIS 7, planktic foraminiferal $\delta^{18}O$ from this region would still indicate that significantly colder sea surface temperatures (SST) prevailed during MIS 11 than during MIS 9, 5e, and 1. This assumption is corroborated by a continuous input of IRD into the western Nordic seas during MIS 11, implying a much steeper SST gradient between the polar and subpolar region and an overall reduced thermohaline activity in the polar latitudes. The iceberg proxy also reveals that maximum IRD discharge always happened during the final phase of glaciation and into early deglaciation (terminations). As these IRD records from the two regions are characterized by a high time coherency, it is concluded that short-term variability is a persistent feature of the glacial climate system. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 9325 Information Related to Geographic Region: Atlantic Ocean; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* North Atlantic, polar and subpolar region, Late Pleistocene, glacial-interglacial climates

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1. Introduction

[2] A large portion of recent paleoceanographic research using high-northern latitude sediment cores has investigated the climatic and environmental conditions of specific glacial and interglacial periods, focusing, in particular, on the last glacial period [e.g., *Labeyrie et al.*, 1992; *Sarnthein et al.*, 1995; *Fronval and Jansen*, 1996; *Bauch*, 1996; *McManus et al.*, 1998]. Comparative analyses of North Atlantic marine sediment records and Greenland ice cores have demonstrated that this last glaciation was not of a stable climatic nature but was punctuated by two different modes of abrupt millennial-scale climate change, the so-called "Heinrich events" and the "Dansgaard-Oeschger cycles" [*Broecker et al.*, 1992; *Bond et al.*, 1992; *Dansgaard et al.*, 1993]. Some of the cold stadial events of these cycles seem time-coeval between the subpolar North Atlantic and the Nordic seas, i.e., the polar North Atlantic, even for longer time intervals such as the last interglacial-glacial cycle [*McManus et al.*, 1994; *Fronval and Jansen*, 1997]. However, so far, a detailed comparison of climatic conditions during glacial and interglacial periods older than the last climate cycle has for these two regions only been done for the last peak interglaciation, marine isotope stage (MIS) 5e [*Cortijo et al.*, 1994; *Fronval and Jansen*, 1997; *Bauch et al.*, 2000a].

[3] Nearly 25 years ago, a first paleoclimatic reconstruction of the Nordic seas suggested that during the last 450,000 years only MIS 5e and 1 were characterized by a similar strength of warm Atlantic surface water inflow into the Norwegian and Greenland seas, resulting in full interglacial conditions in this region [*Kellogg*, 1976, 1977]. More recently, comparisons of peak interglaciations in the Nordic seas have revealed significant differences in the overall water mass pattern, for instance colder conditions during MIS 11 when compared to MIS 5e and 1, suggesting that the boundary conditions of peak interglacial climates in the Nordic seas were dissimilar throughout the upper Quaternary [*Bauch et al.*, 1999, 2000b]. In contrast, sea surface temperature (SST) estimates near 55°N indicate that interglaciations with peak warm conditions prevailed more frequently in the subpolar North Atlantic over the last five climatic cycles [*Ruddiman et al.*, 1986; *McManus et al.*, 1999].

[4] Taking all the published evidence together implies that major differences in the surface ocean conditions of peak interglacial periods must have existed between the polar and subpolar North Atlantic regions. The purpose of this study therefore is to determine the climatic conditions

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of glacial and interglacial periods over the last five climate cycles in order to investigate possible coherent or non-coherent behavior of the glacial-interglacial climate system at high-northern latitudes. Using a multiparameter approach, sediment cores were selected that are located in oceanographically sensitive areas of the northeast Atlantic and the Nordic seas.

2. Core Material and Methods

[5] Site M23352 from the northwestern Iceland Plateau in the Nordic seas and site M23414 from the southern edge of the Rockall Plateau in the northeast Atlantic were investigated for this study (Figure 1). Site M23352 is a spliced record of trigger box core M23352-2 and kasten core M23352-3, M23414 is a spliced record of trigger box core M23414-6, kasten core M23414-9 and piston core M23414-8. The splice of all three cores from site M23414 was produced on the basis of the excellent correlation between the carbonate curve and the cm-sampled lightness curve from both cores. From the core top into MIS 8 the data of the kasten core were used for the splice record, in the lower part back to MIS 13 all data of the splice records are from piston core M23414-8 (see *Helmke and Bauch* [2001] for further details). For M23352 and M23414, the trigger box core was used because of its undisturbed surface section and the core splicing at both study sites was based on several sediment proxy data as well as by considering AMS datings. Site M23352 was selected because it is located close to the recent Polar Front, which is expected to have shifted repeatedly across the Iceland Plateau and further south during colder climatic intervals than at present. Accordingly, the Iceland Plateau sediment record from this core should reveal the contrasts of glacial-interglacial climatic conditions in the polar North Atlantic. Site M23414 is situated directly below the North Atlantic Drift. This region has demonstrated its suitability for recording both the warm water advection that is most pronounced during the warmer climate periods and the major expansions of iceberg drift that characterize extreme conditions during glacial times [e.g., *Ruddiman and McIntyre*, 1976].

[6] The stratigraphic frameworks (Figure 2) are based on stable oxygen isotope records measured on the planktic foraminifers *Neogloboquadrina pachyderma* sinistral (sin.) in core M23352 (sampling interval 1–3 cm) and on *Globigerina bulloides* in core M23414 (2.5 cm sampling interval). Additionally, the right-coiling planktic foraminifer *Neogloboquadrina pachyderma* dextral was measured in 1–3 cm steps across selected core sections at site M23414. All stable isotope analyses on these two cores were done using specimens from the size fraction 125–250 μm and were conducted at the Leibniz Laboratory (Kiel University) using multiple-specimen samples and standard laboratory techniques [*Bauch et al.*, 2000a].

[7] Sedimentologic investigations were carried out by various means and at different depth intervals (Figure 2). The sediment color was measured at discrete 1 cm steps using a Minolta CM-2002 spectrophotometer and the results are given as lightness L* of the L*a*b* color space. Ice-rafted debris (IRD) was counted in the mesh size >250 μm with an average sample interval of 2.5 cm, and is expressed as lithic grains per gram. The bulk carbonate content (% weight) was measured every 5 cm.

3. Chronology

[8] At site M23352, the extremely light $\delta^{18}O$ spike in early MIS 5e (at ~240 cm core depth) is associated with low carbonate and an IRD peak (Figure 2). This spike has thus been identified as meltwater event that preceded the peak interglacial interval [*Bauch et al.*, 2000b]. However, meltwater overprints in planktic $\delta^{18}O$ records are a common feature in the Nordic seas. Due to these meltwater events, and because of the high-frequency oscillations of the isotope signal below 500 cm at site M23352, establishing a chronology on the basis of $\delta^{18}O$ alone is difficult. This is especially true below MIS 7 if no other means, such as $\delta^{13}C$ records, sedimentologic and faunal evidence, were taken into account [*Bauch*, 1997]. Accordingly, for these intervals we used the IRD, carbonate and lightness data to more precisely define the glacial and interglacial stages. For example, the carbonate and lightness peak at ~660 cm core depth in M23352 has previously been identified as peak interglacial MIS 11 [*Bauch and Helmke*, 1999].

[9] Age models were constructed by synchronizing the planktic oxygen isotope record of M23352 and M23414 together with the sediment lightness record of M23414 to the standard SPECMAP chronology. Figure 3 shows some of the major tie points between the isotope records of the study sites and the SPECMAP stack [*Imbrie et al.*, 1984; *Martinson et al.*, 1987]. The reasons for additionally taking the lightness data at site M23414 into account are twofold: (a) The record has a very dense sampling interval and (b) it also partly gives stratigraphic information that is less pronounced in the isotope record. For example, stadial and interstadial intervals in late MIS 5 are easily defined when using lightness and isotope data rather than using the *G. bulloides* isotope record alone (Figure 3).

[10] To align the isotope record from site M23352 to the SPECMAP chronology in spite of the high-frequency fluctuations in parts of it, the data were smoothed with a 14-point least squares running average (Figure 3). In addition, the age models for the younger sections of each core (i.e.,<40,000 years) were refined with AMS ^{14}C ages [*Didié et al.*, 2002] measured on *N. pachyderma* (sin.) and by using Heinrich events 1–6 (Figure 3). AMS dates younger than 25 ka were converted into calendar years with the CALIB 4.1.2. software, which generates a reservoir age of about 400 years [*Stuiver and Reimer*, 1993]. Ages above 25 ka were converted following the method by *Voelker et al.* [1998]. Identification of Heinrich layer deposition was based on the concentration of lithic grains [see *Didié and Bauch*, 2000] and by direct comparison with many other published records from the North Atlantic region. Ages of the Heinrich events were defined following the results compiled by *Sarnthein et al.* [2001].

[11] The positions of the tie points between M23352 and SPECMAP in the lower part of both records (Figure 3) indicate that the rather atypical large-scale fluctuations of the isotope values, especially during MIS 10 and 12, were most likely caused by an increase in sedimentation rates due to massive IRD input resulting in a rather low content of

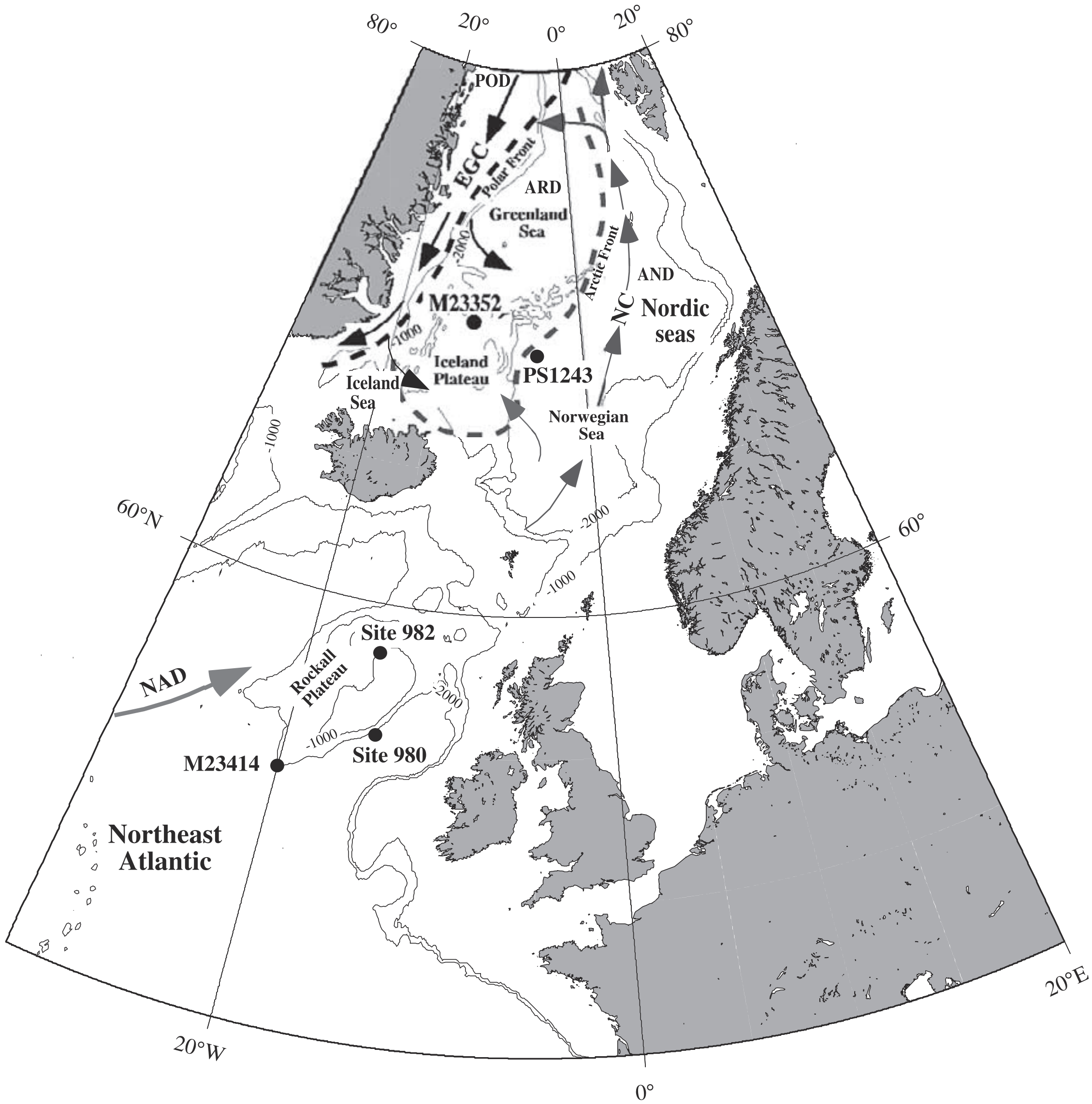

Figure 1. Geographical position of study sites on the Iceland Plateau (M23352, 70°00′N, 12°25′W, water depth 1820 m) and the Rockall Plateau (M23414, 53°32′N, 20°17′W, water depth 2200 m). Also shown are the modern surface water circulation as well as major oceanographic regimes [*Swift*, 1986]. Gray and black arrows denote warmer and cooler surface currents, respectively. NAD, North Atlantic Drift; NC, Norwegian Current; EGC, East Greenland Current. Dashed black and gray lines indicate the recent position of the Polar and the Arctic fronts in the Nordic Seas. POD, Polar Domain; ARD, Arctic Domain; AND, Atlantic Domain. Also depicted are the geographical positions of sediment sites referred to in the text.

foraminifers. Thus any isotopic signal of a foraminiferal test from these sections most likely also represents a shorter time duration when compared to intervals with enhanced pelagic sedimentation, e.g., during the peak of MIS 11.

4. Results

4.1. The Rockall Plateau Record

[12] At site M23414, all peak interglacial warm periods are characterized by minima in planktic oxygen isotope values, no IRD deposition, and maxima in bulk carbonate content ranging between 50 and 90%. These high carbonate values correlate with maxima in sediment lightness, except in MIS 1. Despite the different sample resolution applied, there is a strikingly good correlation between carbonate content and the much higher-resolved sediment lightness record (Figure 2). MIS 13 reveals both the highest carbonate content and corresponding sediment lightness of the entire record. Peak interglacial carbonate contents seem to show a decreasing trend between MIS 13 and MIS 7 but increase again in MIS 5 and 1 (Figure 2). Although this trend is similarly reflected in the sediment lightness, there is a

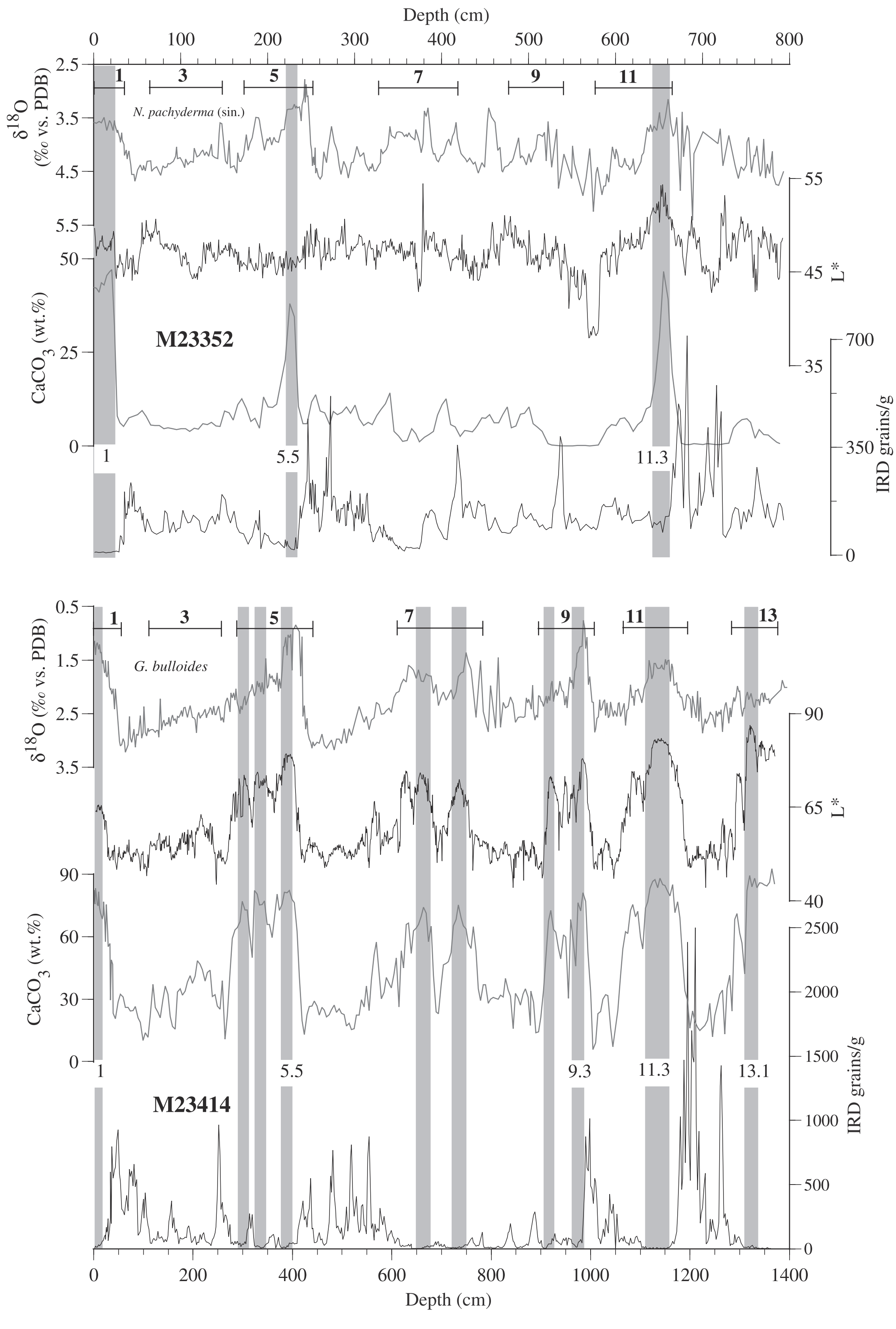

Figure 2. Downcore records of planktic $\delta^{18}O$, sediment lightness (L*), $CaCO_3$ content, and IRD content from the Iceland Plateau (upper panel) and the Rockall Plateau (lower panel. Data taken partly from *Jung* [1996] and *Didié and Bauch* [2000]), with odd numbered interglacial MIS indicated for reference. Shaded areas denote interglacial intervals with high $CaCO_3$ content but low IRD input.

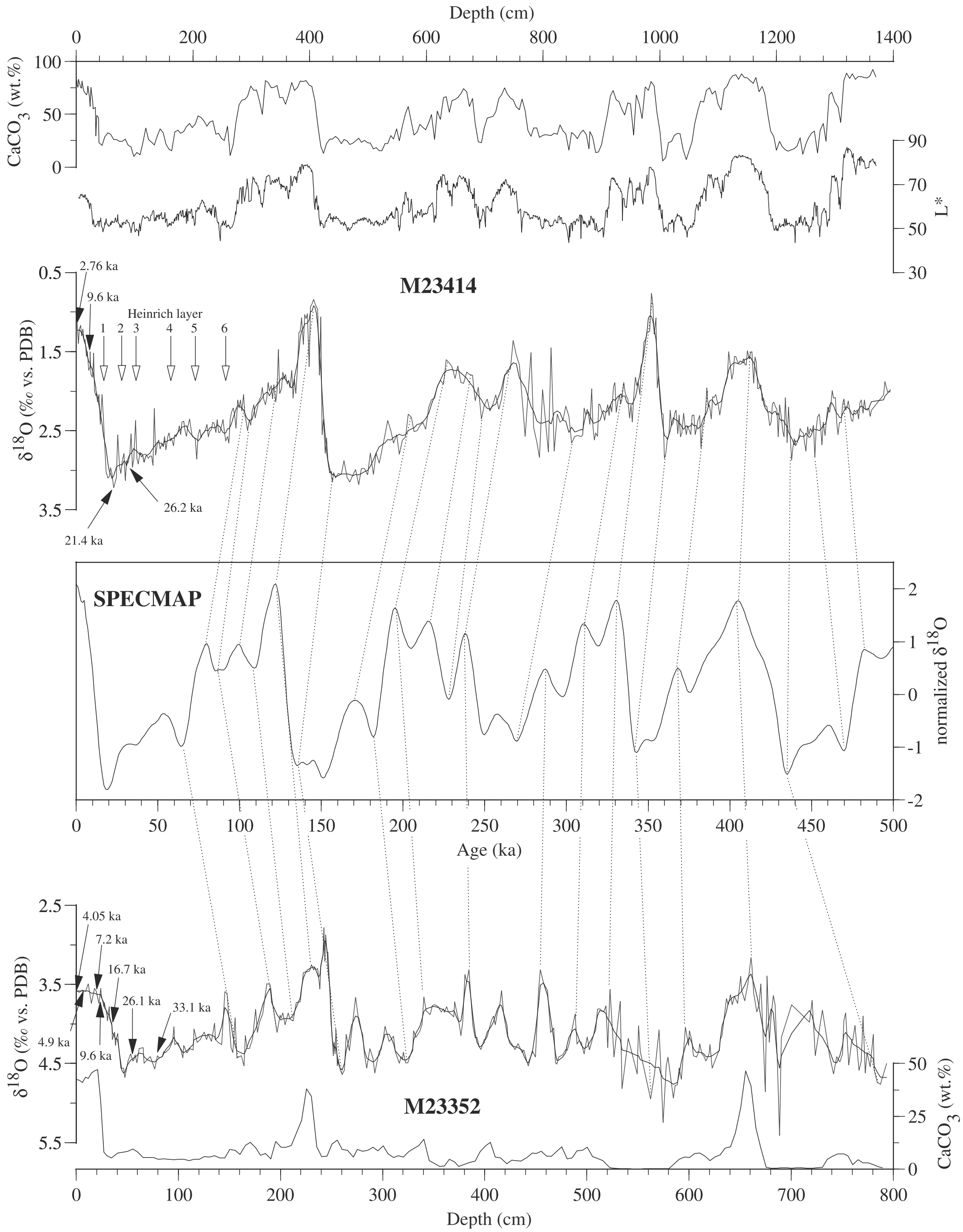

Figure 3. Major tie points (stippled black lines) between the SPECMAP age stack (middle panel) and the planktic oxygen isotope records (versus depth) of sites M23414 (upper panels) and M23352 (lower panels) The thin gray line underlying both isotope records (black lines) represents 14-point least squares running average of raw isotopic data. Also shown are the carbonate content records from both study sites and the lightness record from site M23414. Black arrows indicate the position of AMS datings in both cores (see text for details of calibration), white arrows show the position of the Heinrich layers 1–6 at the Rockall Plateau site.

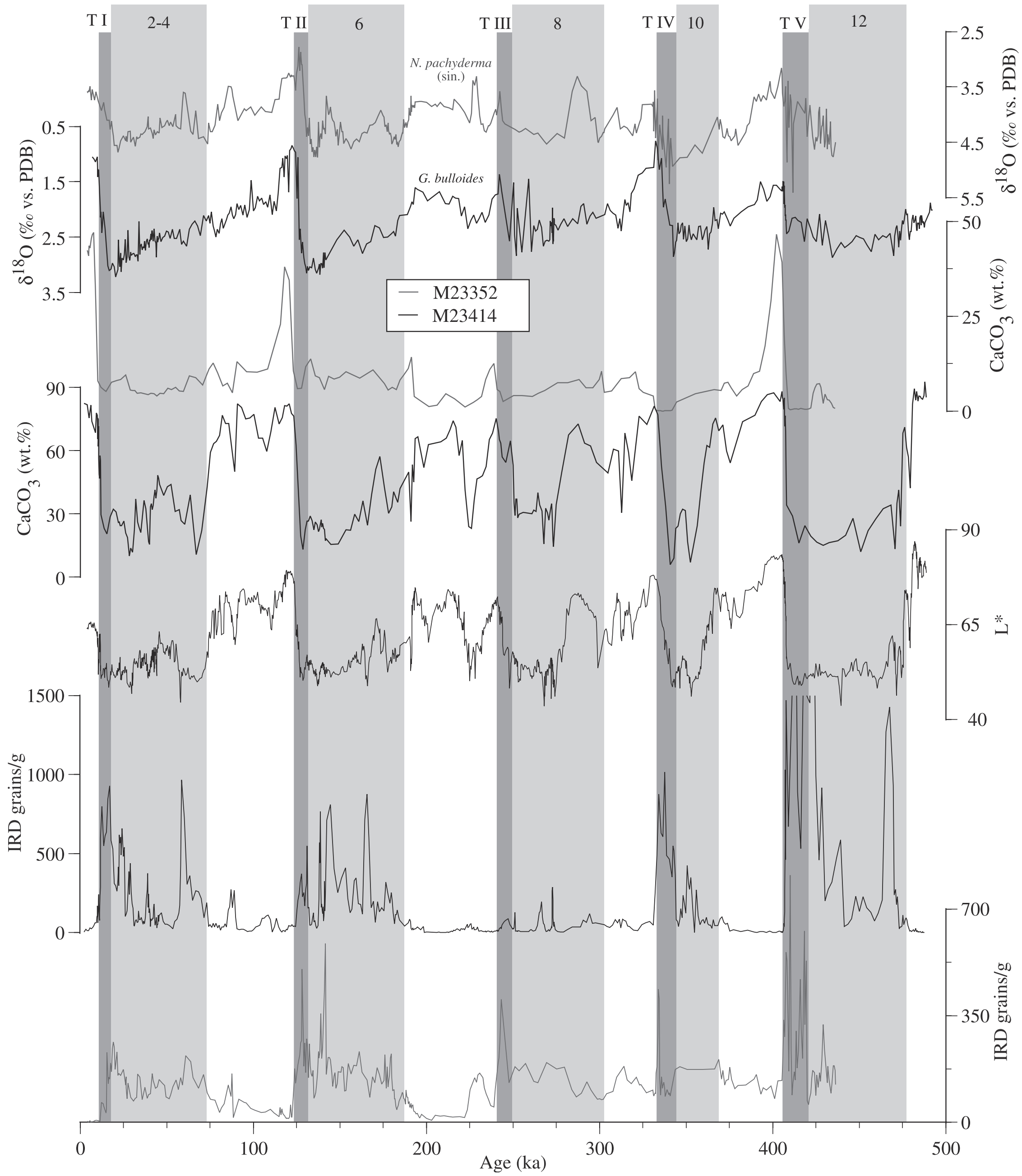

Figure 4. Records of planktic $\delta^{18}O$, $CaCO_3$ content, and IRD content of cores M23352 (gray lines) and M23414 (black lines; lightness is also shown) from the Iceland and Rockall plateaus, respectively. Age models are based on the standard SPECMAP chronology [*Imbrie et al.*, 1984; *Martinson et al.*, 1987] (see text for details). Glacial MIS and Terminations I-V (T I-V) are shaded in gray and labeled for reference. Note that IRD at site M23414 is cut of at 1500 grains/g.

notable mismatch between carbonate content and sediment lightness for MIS 1, the Holocene.

[13] A pronounced glacial-interglacial difference is observed in the IRD record of site M23414, with little or no IRD input during the peak interglacial warm phases of MIS 13, 11, 9, 7, 5, and 1. However, this site received measurable amounts of IRD during cooler interglacial substages, such as within MIS 7 and 5 (Figure 2). IRD was deposited continuously at the Rockall Plateau during glacial periods (i.e., MIS 12, 10, 6, and 4–2), with millennial-scale recurrence periods of maxima in glacial IRD input (Figure 4). Distinct IRD peaks in the last two glacial periods have been identified as Heinrich events and Heinrich-like IRD events, respectively [*Didié and Bauch*, 2000]. All glacial IRD maxima at the Rockall Plateau, including those of low-amplitude such as in MIS 8, correspond with minima in sediment lightness and carbonate (Figure 4). By far the highest input of IRD during the last 500,000 years occurred

in late MIS 12, with two distinct series of peaks that reach into the ensuing deglacial transition (Termination V). Nearly all later glacial intervals and terminations are characterized by IRD input of rather similar amplitudes. Only MIS 8 stands out by showing extremely low glacial IRD depositional rates (Figure 4).

[14] Planktic isotope values of *G. bulloides* at the Rockall Plateau show significant differences between the peak interglacial periods MIS 11, 9, 5e, and 1 (Figure 2). MIS 9 and 5e have values of ~0.9‰, whereas values in MIS 1 and 11 are heavier by 0.3 and 0.7‰, respectively. In fact, planktic isotope values of MIS 11 are heavier than those of all later peak interglaciations but lighter than the preceding interglaciation MIS 13, which reveals values of ~2.1‰.

4.2. The Iceland Plateau Record

[15] When compared to the Rockall Plateau, the sediment sequence on the Iceland Plateau contains generally less carbonate (<10%), with higher values (30–50%) occurring only in MIS 11, 5e, and 1 (Figure 2). The two younger peak interglacial intervals reveal minimum isotope values associated with strongly reduced or no IRD, as at the Rockall Plateau. However, MIS 11 is characterized by significant IRD (Figure 4). In contrast to the Rockall study site, the Iceland Plateau record does not show any strong correlation between carbonate content and sediment lightness in general. This is due to the overall low carbonate content of the sediment [*Bauch and Helmke*, 1999].

[16] The Iceland Plateau received an almost continuous input of IRD, regardless of glacial or interglacial climate modes (Figures 2 and 4). Besides MIS 5e and 1, strongly reduced IRD input and IRD-free intervals occurred episodically only in late MIS 7. In contrast to MIS 5e and 1, the reduced IRD deposition during late MIS 7 is associated with a relatively low carbonate content (up to 15%). Based on faunal evidence, i.e., the high ratio of polar to subpolar planktic foraminifers, MIS 7 does not seem representative of a significant warm phase [*Bauch*, 1997]. In general, the glacial IRD record from the Iceland Plateau shows a pattern of millennial-scale variability during MIS 12, 10, 6, and 4–2 (Figure 4). Like at the Rockall Plateau, the end of MIS 12 and the ensuing Termination V are both marked by highest IRD deposition made up of two distinct peaks. After Termination V, IRD maxima are of comparable amplitude during the remaining glacial intervals, with steep and short-term increases occurring during Terminations IV-II. In contrast to the Rockall Plateau, the IRD input on the Iceland Plateau during MIS 8 shows values comparable to the later glaciations (Figure 4).

[17] Planktic oxygen isotope values of *N. pachyderma* (sin.) show only minor differences between MIS 11, 5.5, and 1, except for the meltwater event during early MIS 5 as already described. Mean minimum values of the warm substages during these three interglaciations range between 3.5‰ for MIS 5.5 and 11 and 3.2‰ for MIS 1 (Figure 2).

5. Discussion

[18] In accordance with previous results [e.g., *Kellogg*, 1980; *Bauch*, 1997; *Henrich*, 1998], our stable isotope, carbonate, and IRD records from the Iceland Plateau demonstrate that during the last 500,000 years full interglacial conditions with significant northward advection of warm Atlantic surface water into the Nordic seas prevailed only in MIS 11, 5e, and 1. In contrast to other interglacial sections from our Iceland Plateau record these intervals are characterized by light oxygen isotope values, high carbonate content and little or no IRD.

[19] Site M23352 indicates that IRD occurs on the central Iceland Plateau continuously during MIS 11 in contrast to the results from the later interglacial periods MIS 5e and MIS 1 (Figures 2 and 5). These observations also differ from the situation in the Norwegian Sea, where deep sea site PS1243 (Figure 1) experienced an about 10,000 years long IRD-free interval during MIS 11, but notably only during its later full phase (Figure 5) [*Bauch et al.*, 2000b]. The foraminiferal assemblage data from site PS1243, i.e., the ratio of polar to subpolar planktic foraminfers, indicate that SSTs in the Nordic seas were in general significantly lower in MIS 11 than in MIS 1 [*Bauch et al.*, 2000b].

[20] These findings together with the results from previous paleoceanographic studies on deep sea sediments from the Nordic seas [*Bauch*, 1997; *Bauch et al.*, 1999] would suggest a different pattern of surface water circulation and a shift in the position of the major water mass boundaries in the Nordic seas during MIS 11 when compared with MIS 5e and 1. At present, the cold surface waters of the East Greenland Current (EGC) stretch in the Nordic seas closely along the eastern continental margin of Greenland. These waters are influenced by iceberg drift and show extended seasonal sea ice cover. It seems that during MIS 11 the polar front, i.e., the boundary between the cold water masses of the EGC and the more temperate surface waters of the Arctic and Atlantic domains (Figure 1), was positioned further east, similar to what is known from the Little Ice Age [*Lamb*, 1979]. Hence, during MIS 11, the areas of the Nordic seas region influenced by the EGC and, consequently, characterized by rather cold surface water temperatures were more extensive. It was previously shown that the deglaciation from the strong glacial conditions of MIS 12 into interglacial MIS 11 lasted about three times longer than the last deglacial period and extended far into the full interglacial period of MIS 11 [*Bauch et al.*, 2000b]. This suggests more melt during most of MIS 11, which in turn would have expanded the influence of the cold, polar water masses on the Nordic seas regions at that time. The occurrence of massive melt would imply diminished surface salinities, and hence a pronounced pycnocline. The situation of a more eastern occurrence of such water masses with low-salinity surface waters could have led to subdued advection of warm Atlantic water into the Nordic seas and a weakening of the thermohaline circulation system in general [*Manabe and Stouffer*, 1995; *Ganopolski and Rahmstorf*, 2001; *Renssen et al.*, 2002]. As a consequence of such a reduced heat transfer to the high latitudes, the meridional temperature gradient between the polar and subpolar North Atlantic would have been strongly increased.

[21] The peak interglacial episodes of MIS 13, 11, 9, 7, 5, and 1, all of which are marked by low or no IRD input but high contents of carbonate, are clearly recognized by us as

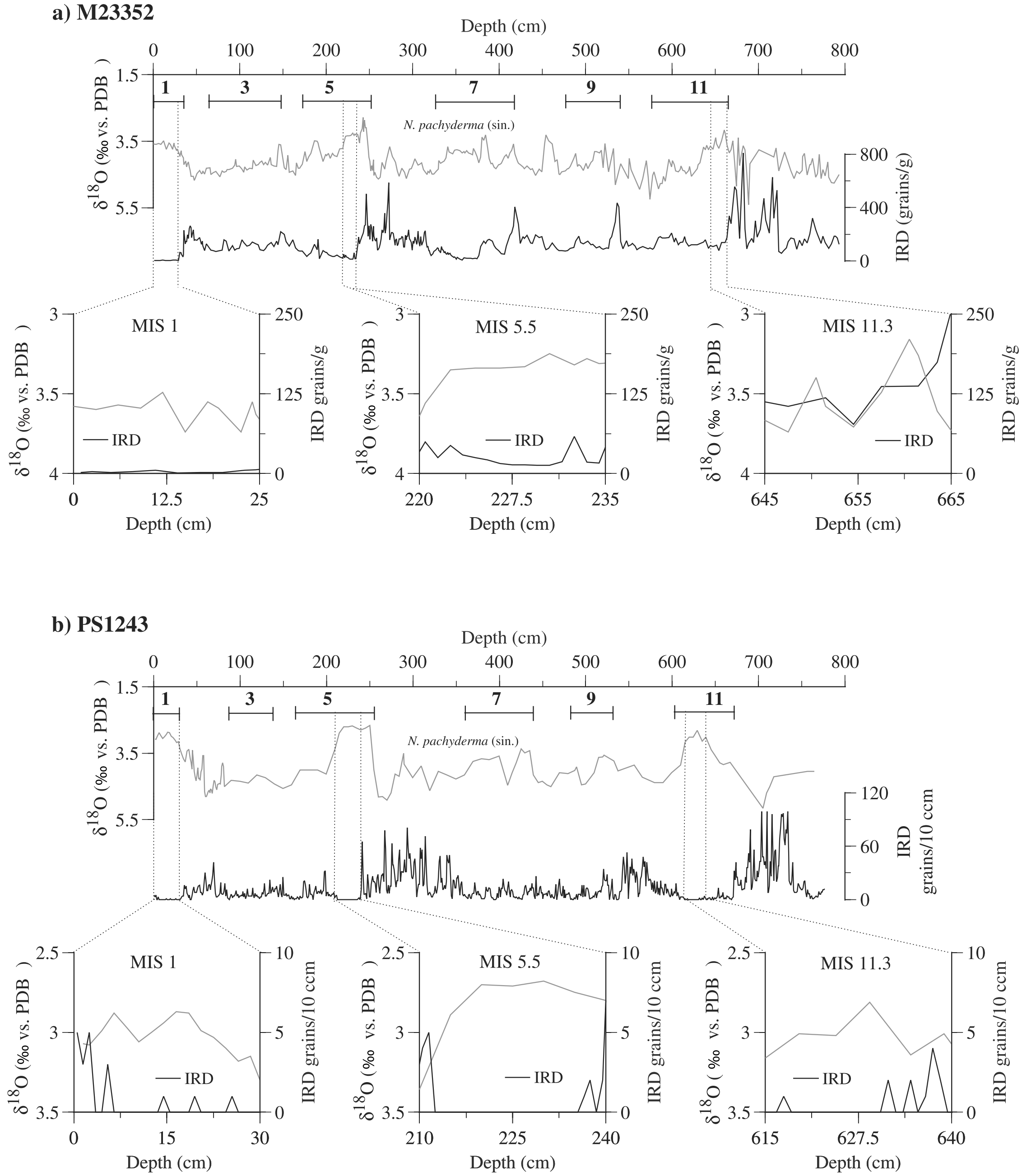

Figure 5. Downcore records of planktic oxygen isotopes and IRD from M23352 and PS1243 with a detailed comparison of these parameters for the full interglacial intervals of MIS 1, 5.5 and 11 (position of these intervals indicated by stippled black lines). Interglacial MIS are labeled for reference. Note that IRD in M23352 is given as grains/g and in PS1243 as grains/10 ccm.

periods of low global ice volume and relatively warm SST, in accordance with other investigations from this region [*Ruddiman et al.*, 1986; *McManus et al.*, 1999]. In agreement with our planktic isotope record, benthic $\delta^{18}O$ data from nearby ODP Site 980 (Figures 1 and 6) show the heaviest full interglacial values in MIS 13 [*McManus et al.*, 1999], indicating a larger ice volume than during the later interglaciations. During peak MIS 11, average benthic $\delta^{18}O$ values at Site 980 are about 0.7‰ lower than during MIS 13 but comparable to MIS 9, 5e, and 1, thus suggesting ice volumes of similar magnitude in these warm periods.

[22] Our planktic foraminifers *G. bulloides* and *N. pachyderma* (dex.) yield much heavier $\delta^{18}O$ values in MIS 11 than later in MIS 9, 5e, and 1 (Figure 6). At face value, this indicates that during the last 450,000 years the coldest full interglacial SSTs at the southern Rockall Plateau occurred in MIS 11. This is supported by data from the northwestern Rockall Plateau where similar trends in $\delta^{18}O$ of *G. bulloides* are found (Figure 6). However, the benthic isotope record of Site 980 indicates that the ice volume and deep water temperature signals across Termination V are larger than the total $\delta^{18}O$ change in *G. bulloides* (Figure 6). This would

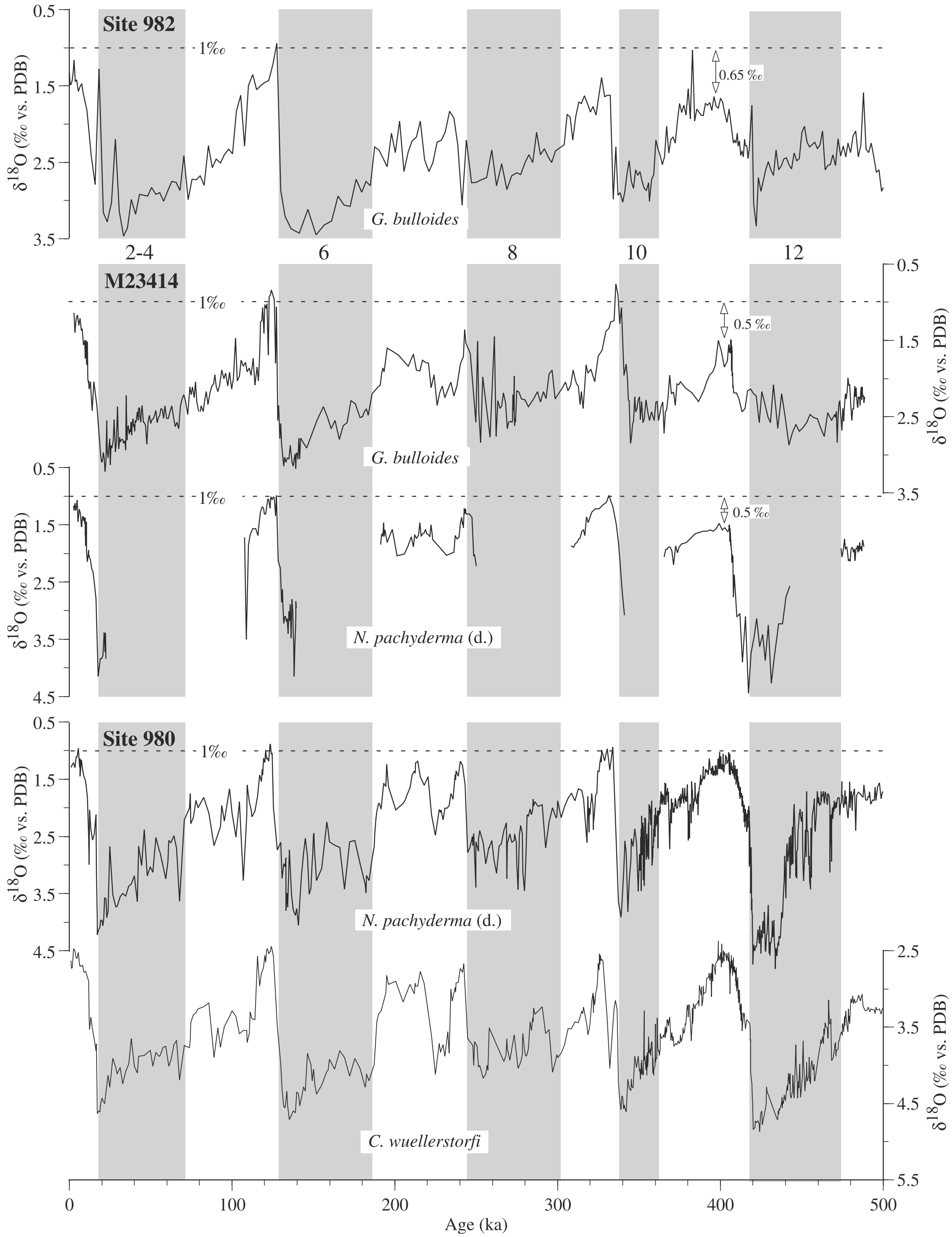

Figure 6. Upper panel is planktic $\delta^{18}O$ (*G. bulloides*) from ODP Site 982 [*Venz et al.*, 1999] compared with planktic $\delta^{18}O$ (*G. bulloides* and *N. pachyderma* dextral) from M23414 (middle panel) and planktic (*N. pachyderma* dextral) and benthic $\delta^{18}O$ (*C. wuellerstorfi*) data from ODP Site 980 [*McManus et al.*, 1999]. Glacial MIS are labeled for reference. Dashed black lines denote the 1‰ level of the planktic oxygen isotope records. Arrows denote the difference between the 1‰ level and the average minimum values during full interglacial MIS 11. Note that the records of the ODP sites are based on independent chronologies.

suggest that SSTs during MIS 11 were lower when compared to MIS 12. However, the total abundance of *G. bulloides* in samples of MIS 12 is quite low. Hence the unusually light glacial $\delta^{18}O$ values of *G. bulloides*, e.g., when compared to glacial MIS 6 and 2, are probably due to the fact that tests of this species from MIS 12 reflect short intervals of rather warm conditions during this period.

[23] Our results are contradictory to isotopic SST results from Site 980 on the basis of *N. pachyderma* (dex.), which reveals comparable maximum SSTs for all full interglacial intervals since MIS 12 [*McManus et al.*, 1999]. Although the $\delta^{18}O$ signals in M23414 during MIS 11 show a comparable trend between foraminiferal species, their ecology in the North Atlantic is a quite different one: whereas *N. pachyderma* (dex.) is frequently found during spring and summer, living mainly beneath the mixed layer [*Hemleben et al.*, 1989; *Duplessy et al.*, 1991], *G. bulloides* prefers to live in and above the thermocline, and its abundance in the subpolar North Atlantic seems to coincide with the spring plankton bloom [*Ottens*, 1992; *Schiebel et al.*, 1997; *Schiebel and Hemleben*, 2000]. Hence any SST estimates based on these two species should likely reflect some differences in temporal and spatial distribution.

[24] Recently it was suggested that the $\delta^{18}O$ isotopes of *N. pachyderma* (dex.) records mean annual SST in the northeast Atlantic more accurately than other planktic foraminifera [*Oppo et al.*, 1998]. The fact that MIS 11 is consistent in both of our $\delta^{18}O$ records and at Site 982 underlines the validity of these data as water mass signal. The obvious discrepancy to ODP Site 980 should therefore be related to a regional water mass difference between the eastern and the western Rockall Plateau. In this respect, our data agree with ice core data from Antarctica, which also indicate a comparatively cool interglacial MIS 11 [*Petit et al.*, 1999]. However, the data from the Vostok ice core may not cover the peak of MIS 11. Thus any further speculations in this matter need to be supported by more complete ice core records.

[25] The maximum input of IRD toward the end of MIS 12 at both our study sites may reflect unusually large discharges of icebergs from the Laurentide and European ice sheets into the polar and subpolar North Atlantic alike. The fact that these periods of high IRD input toward the end of MIS 12 reflect the terminal stage of a very pronounced glaciation with the largest global ice volume of the past 500,000 years is further supported by high benthic oxygen isotope values from ODP sites 980 (Figure 6) and 982 [*McManus et al.*, 1999; *Venz et al.*, 1999], as well as by Pleistocene sea level lowstand calculations [*Rohling et al.*, 1998]. The IRD maxima indicate large amplitude climate variations, although insolation forcing during Termination V was less strong than during later terminations [*Berger*, 1978]. A maximum input of IRD during Termination V is also reported from late Pleistocene sediments of ODP Site 982 [*Venz et al.*, 1999]. These authors linked their IRD record to glacial deep water production and characterized MIS 12 as an interval of perennial sea ice cover in the Nordic seas.

[26] Based on the low IRD input to the Rockall Plateau during MIS 8, the iceberg discharge from northern ice sheets is expected to have been less when compared to previous and later glaciations. This finding is in good agreement with benthic isotopes from the Rockall area [*McManus et al.*, 1999; *Venz et al.*, 1999] and with sea level lowstand estimates that characterize MIS 8 as the glacial period with the smallest ice volume of the past 500,000 years [*Rohling et al.*, 1998]. The obvious discrepancy in IRD input between the Iceland and Rockall Plateaus during this time can be explained by the geographical position of the study sites with respect to potentially glaciated areas. Because the Laurentide ice sheet is believed to be the major source of massive IRD input into the North Atlantic during the last glacial period [e.g., *Broecker*, 1994; *McManus et al.*, 1998], the low IRD deposition at the southern Rockall Plateau during MIS 8 probably indicates reduced glacier activity and less iceberg drift along the northwest Atlantic margin. Since the Iceland Plateau record gives evidence of a continuous supply of icebergs for this time, most likely because of the proximity to glaciated landmasses, there may have been a different behavior of North American and European ice sheets in general, similar to the last climate cycle [*Snoeckx et al.*, 1999; *Grousset et al.*, 2000].

[27] During Termination III, sites 980 and 982 both record an IRD input comparable to other terminations [*McManus et al.*, 1999; *Venz et al.*, 1999]. This difference as compared to our southern Rockall Plateau record may be due to the latter sites more southerly position with respect to the ODP sites. It would imply that during MIS 8 the main area affected by iceberg drift was located to the north of our study site. Such a scenario would, for instance, explain the absence of a major IRD peak noted at Site 980 during MIS 8 [*McManus et al.*, 1999]. Despite some discrepancies, there is a good overall agreement with Site 980 with regard to the IRD input during other glacial times, e.g., MIS 6 and 12.

[28] The "cold" climate IRD proxy shows a geographically remarkably coherent pattern of variability between the Iceland and Rockall plateaus during the past 500,000 years, despite the differences in the total amount of IRD deposited at each core site (Figures 2 and 4). At the Rockall Plateau, distinct IRD maxima of the last climate cycle have been identified as Heinrich events [*Didié and Bauch*, 2000]. The time-coeval Iceland Plateau IRD record also reveals millennial-scale variability but without pronounced distinct events [*Didié et al.*, 2002]. Prior to the last glaciation, both records show variations in IRD on millennial timescales, suggesting that comparable short-term climate fluctuations with iceberg calving from the Northern Hemisphere ice sheets and large discharges of IRD on the Iceland and Rockall plateaus also occurred during earlier glaciations.

[29] Noncoherent intervals of increased IRD input between the subpolar and polar North Atlantic, e.g., during MIS 8 and further into Termination III, indicate differences in ice sheet dynamics between the Laurentide Ice Sheet, the major source of North Atlantic IRD events [*Bond and Lotti*, 1995], and ice sheet outlet glaciers draining into the Nordic seas, and iceberg drift on the Iceland Plateau [*Dowdeswell et al.*, 1999; *Grousset et al.*, 2000]. Because ice sheet basins of varying size respond asynchronously to any single external forcing [*Johannessen et al.*, 1989], there is a local

variability in the drift tracks and sediment-release histories of groups of icebergs [*Dowdeswell and Murray*, 1990]. Thus the geographical position of our study sites with respect to the Northern Hemisphere ice sheets during the upper Quaternary caused some differences in the periods of IRD input into the polar and subpolar North Atlantic. Additionally, the Iceland Plateau site is located near the recent Polar Front (Figure 1). As can be expected, the polar front with its cold and low-salinity waters, as well as icebergs, shifted repeatedly toward the southeast across the study site during glacial periods. Therefore the Iceland Plateau received, in contrast to the Rockall Plateau, almost continuous IRD sedimentation during the last five climate cycles. However, the IRD patterns in the two cores demonstrate that unstable climatic modes with rapid, short-term fluctuations prevailed during glacial intervals, reflecting the overall dynamic nature of the upper Quaternary climate system at high-northern latitudes.

6. Summary and Conclusions

[30] We conclude that the Nordic seas experienced full interglacial conditions only three times during the last 500,000 years (i.e., MIS 11, 5e, and 1), whereas full interglacial periods were more frequent in the northeast Atlantic. By comparison, planktic $\delta^{18}O$ from the northeast Atlantic indicate strong discrepancies among interglacial SSTs, most notably that relatively cold SSTs are indicated for MIS 11 compared with other peak warm periods (MIS 9, 5e, and 1). The IRD record from the Nordic seas reveals a major meridional temperature gradient in the North Atlantic with reduced advection of warm surface water into the Nordic seas during interglacial MIS 11. This reduced heat transfer into the Nordic seas should have had a major impact on deep water processes, which affected both the vigor of high-latitude thermohaline circulation and climatic conditions on the adjacent continents. At both studied sites IRD input was highest during the final phases of glaciations (including early terminations), revealing an almost coherent pattern of IRD deposition between the two study areas with certain differences in the timing of major iceberg discharges between the Laurentide Ice Sheet and European ice sheets. Despite these regional differences, the IRD records point to persistent mechanisms that operated on millennial timescales synchronously affecting the glacial climate system of both the Nordic seas and the North Atlantic.

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