Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., and Ruddiman, W.F. (Eds.), 1996
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 151

27. LATE NEOGENE PALEOCLIMATES AND PALEOCEANOGRAPHY IN THE ICELAND-NORWEGIAN SEA: EVIDENCE FROM THE ICELAND AND VØRING PLATEAUS[1]

Torben Fronval[2,3] and Eystein Jansen[2]

ABSTRACT

Continuous late Neogene sediment sections from Site 907 on the Iceland Plateau and Sites 642, 643, and 644 on the Vøring Plateau were studied using stable isotope stratigraphy and sedimentological methods. Paleoclimatic and paleoceanographic changes have been placed in a time framework by using paleomagnetic reversals, biostratigraphic events, and isotope stratigraphic events as chronostratigraphic tools. The results show a general cooling of the Iceland-Norwegian Sea deep waters during the last 12 m.y., with major cooling events ~11.0 Ma and 6.4 Ma. At the Vøring Plateau, the oldest pulses of glacial ice-rafted debris (IRD) date to ~12.6 Ma, indicating that glaciers reached sea level as early as the middle Miocene. The records of ice-borne deposits document a gradual intensification of glaciation from 7.2 to 6.0 Ma, which reflects the onset of small-scale glaciation in the Northern Hemisphere. The onset of large-scale Northern Hemisphere glaciation is dated at 2.75 Ma at the Vøring Plateau and 2.90 Ma at the Iceland Plateau, possibly reflecting different timing of growth of large-scale ice sheets in Greenland and Scandinavia. The middle Pleistocene climate shift (~0.9 Ma) is documented in both stable isotope stratigraphy and IRD deposition. The changes indicate a shift toward more extensive glacials of longer duration and the initiation of warmer interglacials with enhanced influx of Atlantic waters and ventilated deep waters. Within the Brunhes, deep-water formation apparently peaks during times of general climate deterioration and is not a linear response to global ice volume and sea-surface temperature. A general increase in planktonic $\delta^{13}C$ ~400 ka may reflect decreased global deep-sea carbonate preservation associated with the middle Brunhes climate transition.

INTRODUCTION

Ocean Drilling Program Legs 151 and 104 provided for the first time continuous sections extending beyond 400 k.y. in the Iceland and Norwegian Seas. The sites on the Vøring Plateau are located close to the Scandinavian mainland, whereas Site 907 is located relatively close to both Greenland and Iceland. The Vøring Plateau is situated within an area influenced by the warm Norwegian current, thereby monitoring the "Nordic Heat Pump," whereas the cold East Greenland current is the major contributor of surface waters to the Iceland Plateau, which today is characterized by cold, Arctic surface water, a mixture of Polar and Atlantic water masses. Variations in heat flux to the Iceland Plateau region has been recorded, and a branch of the warm Norwegian current and the Irminger current transported warmer surface waters to the Iceland Plateau during parts of the last interglacial (isotope Stage 5e) (Eide, 1994; Fronval and Jansen, unpubl. data). An increased heat flux during the early Holocene climate optimum has also been documented (Koç et al., 1993). The location of the sites is therefore ideal for the study of changes in heat flux to the high latitudes and waxing and waning of the surrounding ice sheets.

The Cenozoic is characterized by a significant cooling of the high latitudes which ultimately led to the late Quaternary situation with cold polar regions, cold deep waters and extensive glaciations in both hemispheres. Available evidence suggests that glaciation in east Antarctica dates back to the Eocene (Leg 119 Shipboard Scientific Party, 1988) while limited data indicate that Northern Hemisphere glaciation began between 16 and 10 Ma with the onset of large-scale glaciation ~2.75 Ma (according to the time scale of Shackleton et al., 1990). The glaciation history of Scandinavia and Greenland in particular is poorly known for the time prior to 1 Ma because of the lack of terrestrial evidence from these areas. In this paper, we present paleoclimatic records that document the presence of glaciations back to 12.6 Ma on the continents surrounding the Iceland-Norwegian Sea. In addition, the data record changes in water temperature, circulation patterns, and deep-water formation in the Iceland-Norwegian Sea during the last 12 m.y.

MATERIALS AND METHODS

The samples were collected from Site 907 located on the central Iceland Plateau, Sites 642 and 643 on the outer Vøring Plateau, and Site 644 on the inner Vøring Plateau. The location of sites used in this study is shown in Figure 1 as is their position with respect to surface ocean currents and oceanic fronts of the present ocean. Grain size analyses were performed on one sample every 10 cm for Section 151-907A-1H to 12H. Ice-rafted debris (IRD) was counted in every other sample from Sections 151-907A-6H-4 to 12H-2. Major parts of the sections were barren of foraminifers, resulting in lower stratigraphic resolution or extensive intervals lacking isotope records. Some of the data from the Vøring Plateau are published (e.g., Jansen et al., 1990), and some are unpublished. The stratigraphic resolution/sampling density varies between sites and different stratigraphic intervals. In most cases, the resolution is comparable with that of Site 907; in the case of the last 140 k.y. it is much better. In general, the Vøring Plateau sections offer somewhat more carbonate for foraminiferal and isotope work than does Site 907, but the same general tendency of less carbonate in the sections older than ~1 Ma is also found here.

All stable isotope measurements on samples from Holes 907A, 644A, 642B, and 642C, in addition to some samples from Hole 643A were made at the University of Bergen on a Finnigan MAT 251 mass spectrometer as described by Jansen et al. (1988). The remaining isotope data are from Henrich and Baumann (1994). The planktonic records were produced by analyses of the planktonic foraminifer

[1]Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., and Ruddiman, W.F. (Eds.), 1996. *Proc. ODP, Sci. Results,* 151: College Station, TX (Ocean Drilling Program).

[2]Department of Geology, University of Bergen, Allégaten 41, N-5007 Bergen, Norway. Fronval: torben.fronval@geol.uib.no

[3]Present address: Department of Geology, University of Copenhagen, Ostervoldgade 10, DK-1350 Copenhagen K, Denmark.

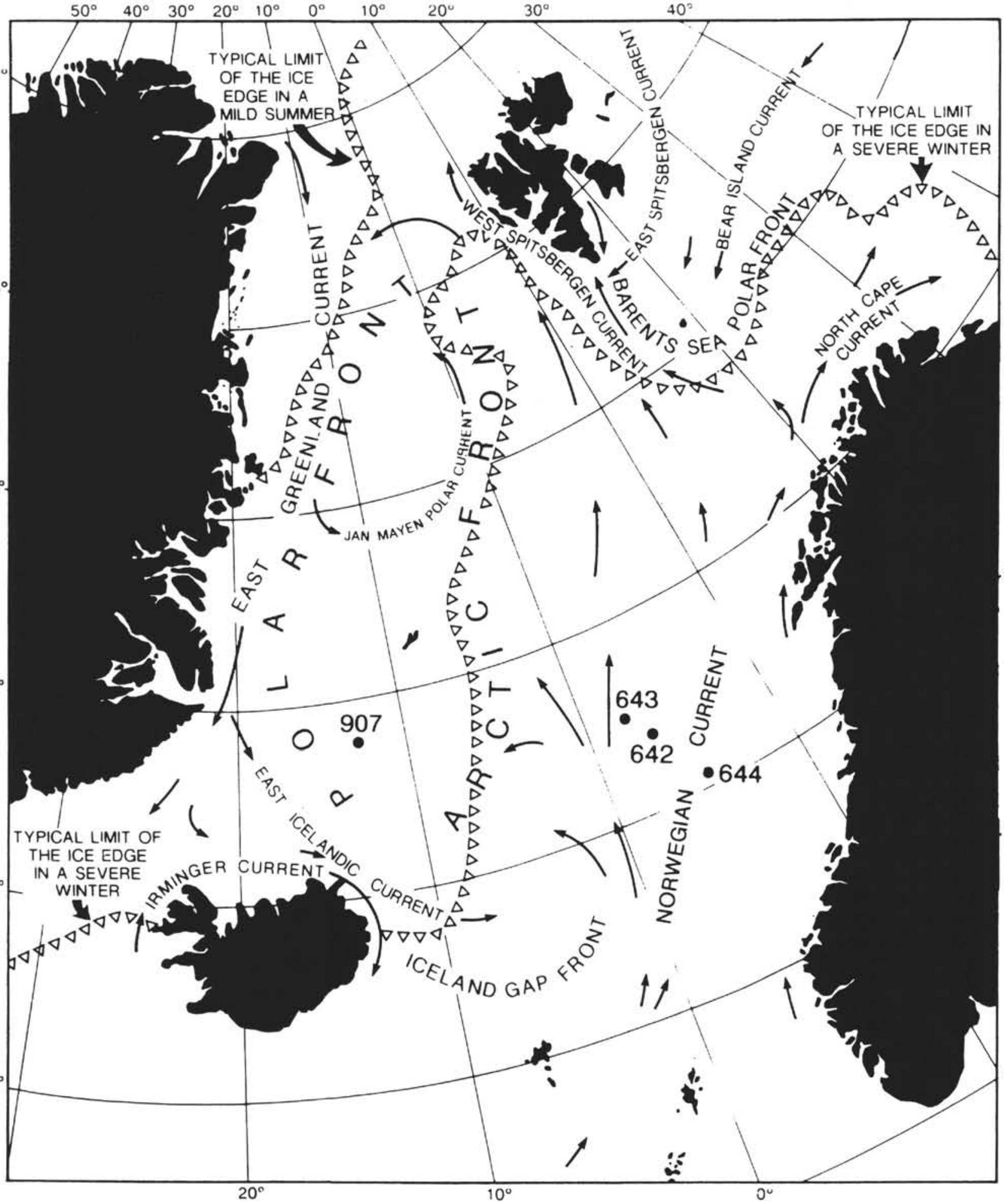

Figure 1. Map showing the surface ocean currents and oceanic fronts of the present ocean and the location of ODP sites used in this study.

Neogloboquadrina pachyderma (s). The benthic record for Site 907 was produced from analyses of the benthic foraminifers *Cibicides* spp., *Cassidulina teretis,* and *Oridosalis umbonatus.* For Sites 642 and 644 measurements were made on *Cibicides* spp. and *C. teretis.* Jansen et al. (1988, 1989) concluded that *C. teretis* secretes its carbonate close to oxygen isotopic equilibrium with the ambient seawater. A number of studies have shown that carbonate shells from species of the genus *Cibicides* are precipitated in oxygen isotopic disequilibrium with the ambient seawater (Duplessy et al., 1980; Graham et al., 1981). The oxygen isotopic offset appears constant and has a mean value of −0.64‰. A similar offset of −0.4‰ has been demonstrated for *O. umbonatus* (Graham et al., 1981). On the basis of this evidence, we adjusted the measured $\delta^{18}O$-values of *Cibicides* and *O. umbonatus* by adding 0.64‰ and 0.4‰, respectively, when producing the benthic oxygen isotope records. However, the validity of the 0.64‰ correlation factor used for *Cibicides* should be viewed with caution below ~6 Ma (Jansen et al., 1990).

To evaluate the influx of ice-rafted material in the sediments, we counted the total number of minerogenic grains (excluding all types of volcanic grains) per gram of dry sediment (IRD/g sed). Using this parameter, small pulses of IRD influx can be detected, which might be overlooked if relative counts (percentages) of the coarse fraction are used. By using the >125 µm fraction, we obtained enough grains to make statistically significant counts and avoided problems associated with possible current deposition of the finer sand-fraction. We emphasize that the IRD record from the Vøring Plateau is constructed from two sites, and Site 644 is situated in a more hemipelagic situation than Site 642. However, as the sites are located on bathymetric highs and no evidence for sedimentary structures indicative of grain flows, contourites, or current deposition exists in the sediments from Site 644 or any of the intervals we use from the other sites, the IRD index is applicable at all sites. The different distance to land and the different sedimentation rates will, however, make a direct comparison of absolute IRD/g sed values between sites impossible.

The time control is primarily provided by the paleomagnetic records of Bleil (1989) and D. Williamson, pers. comm., 1995). Ages to paleomagnetic events are assigned from Cande and Kent (1992), hence ages published for the Leg 104 Sites have been changed to match the Cande and Kent (1992) time scale (Table 1). In the interval 120–179 meters below seafloor (mbsf) in Hole 642C, we used the biostratigraphic ages from Müller and Spiegler (1993) (Table 1). Outside of the dated levels (magnetic reversal boundaries and biostratigraphic boundaries), we constructed time scales by linear interpolation, assuming constant sedimentation rates, except in the Brunhes chron where oxygen isotope Stages 1 to 21 were recognized in Holes 644A, 643A, and 907A. The time scale of Shackleton et al. (1990) was employed for these. Age-depth diagrams and sedimentation rate curves for Site 907 and the Vøring Plateau Sites 644 and 642 are shown in Figure 2. Relatively constant sedimentation rates (10–20 m/m.y.) are obtained at Site 907, whereas the sedimentation rates at the Vøring plateau sites, according to the age model used, vary significantly within the studied sections.

RESULTS

Planktonic Oxygen Isotopes

Figures 3 and 4 show the isotope results from Hole 907A plotted against depth. In Figure 4, we have proposed, on the basis of the planktonic record, an interpretation of isotope stages in the upper 20 m. Our interpretation agrees with the carbonate data (Baumann et al., this volume) as the light isotope peaks interpreted as interglacials correspond to high carbonate content. Isotope data from Holes 643A, 644A, and 907A and the benthic record from Site 677 (Shackleton et al., 1990) plotted against age are presented in Figure 5. The Site 677 record is used as a reference standard global record documenting the global ice volume changes. Comparing Sites 907 and 677 shows that the planktonic record from Site 907 to a large degree follows the ice volume changes, lending credibility to the isotope stage assignments. The records from the Vøring Plateau, however, particularly in the younger part, are more influenced by local anomalies (e.g., meltwater spikes). The stratigraphy in Sites 907 and 643 seems to be complete, but no Stage 11 can be identified in the Site 644 record and Stage 9 is significantly reduced. The warm period within Stage 18 seems to be well developed in the Iceland-Norwegian Sea with $\delta^{18}O$-values lighter than some interglacials.

The planktonic oxygen isotope values are generally lighter on the Vøring Plateau than they are at Site 907, with the lightest values at

Table 1. Dates for Holes 907A, 644A, 642B, and 642C.

Hole	Depth (mbsf)	Age (Ma)	Hole	Depth (mbsf)	Age (Ma)
907A	0	0	644A	0	0
907A	16.15	0.780	644A	83.50	0.780
907A	17.05	0.984	644A	103.90	0.984
907A	19.15	1.049	644A	111.10	1.049
907A	33.85	1.757	644A	166.80	1.757
907A	38.15	1.983	644A	180.85	1.983
907A	41.55	2.197	644A	225.25	2.600
907A	41.95	2.229	642B	66.96	3.221
907A	49.05	2.600	642B	68.16	3.325
907A	57.95	3.054	642B	69.99	3.553
907A	59.35	3.127	642B	75.97	4.033
907A	61.25	3.221	642B	76.75	4.134
907A	63.25	3.325	642B	77.35	4.265
907A	66.85	3.553	642B	77.66	4.432
907A	69.95	4.033	642B	79.75	4.611
907A	71.15	4.134	642B	81.88	4.694
907A	71.65	4.265	642B	83.35	4.812
907A	72.75	4.432	642B	84.25	5.046
907A	74.25	4.611	642B	97.26	5.705
907A	75.35	4.694	642B	105.15	5.946
907A	76.05	4.812	642C	104.51	5.946
907A	78.75	5.046	642C	106.76	6.078
907A	89.55	5.705	642C	114.75	6.376
907A	92.25	5.946	642C	118.46	6.744
907A	93.35	6.078	642C	120.01	6.901
907A	96.45	6.376	642C	126.04	8.000*
907A	101.35	7.464	642C	132.57	9.600*
907A	105.25	7.892	642C	138.33	11.000*
907A	111.85	8.529	642C	152.22	11.400*
907A	114.55	8.861	642C	179.01	13.476

Note: *Biostratigraphic dates.

the easternmost Site 644. During interglacial times, the difference between Site 644 and 907 is as much as 1.5‰, whereas the values are almost identical in the glacials. In comparison, Johannessen et al. (1994) detected a difference of ~1.5‰ in Holocene foraminifers between the Iceland and Norwegian Seas. The $\delta^{18}O$ values from the Vøring Plateau were as light as in the Holocene only during Stages 5 and 17. On the Iceland Plateau, $\delta^{18}O$ values were lighter than Holocene values only in Stages 5 and 15. Stages 9 and 13 were characterized by relatively heavy values at both the Iceland and the Vøring Plateau.

Extensive barren intervals dominate the planktonic record below the Brunhes at Site 907 and the data points are too few to give any reliable indications about long-term changes in oxygen isotopic distribution. However, the available data support the pattern recognized at the Vøring Plateau: heavy values in the Brunhes (3‰–5‰); intermediate values within the Matuyama, Gauss, and Gilbert (2‰–4‰); and light values of ~1‰ prior to 6–7 m.y. (Jansen et al., 1989; E. Jansen, unpubl. data).

Benthic Oxygen Isotopes

Benthic oxygen isotope values from Site 907 are plotted against depth in Figure 3 and 4. Intervals barren in benthic foraminifers dominate the record below the Brunhes, as was also the case for planktonic foraminifers. The benthic isotope records from the Vøring Plateau sites are also hampered by barren intervals below the Brunhes (Fig. 6), but these intervals are of shorter duration than they are at Site 907.

Oxygen isotopic equilibrium in deep waters is +4.65‰ at −2°C and present day salinities using the Shackleton (1974) paleotemperature equation and the Craig and Gordon (1965) values for the $\delta^{18}O$/salinity relationship of seawater. As the deep waters of the Iceland-Norwegian Sea cannot become colder than −2°C, $\delta^{18}O$ values greater than +4.65‰ reflect global ice volumes in excess of the present ice volume. The benthic $\delta^{18}O$-records from Site 907 and Sites 642 and

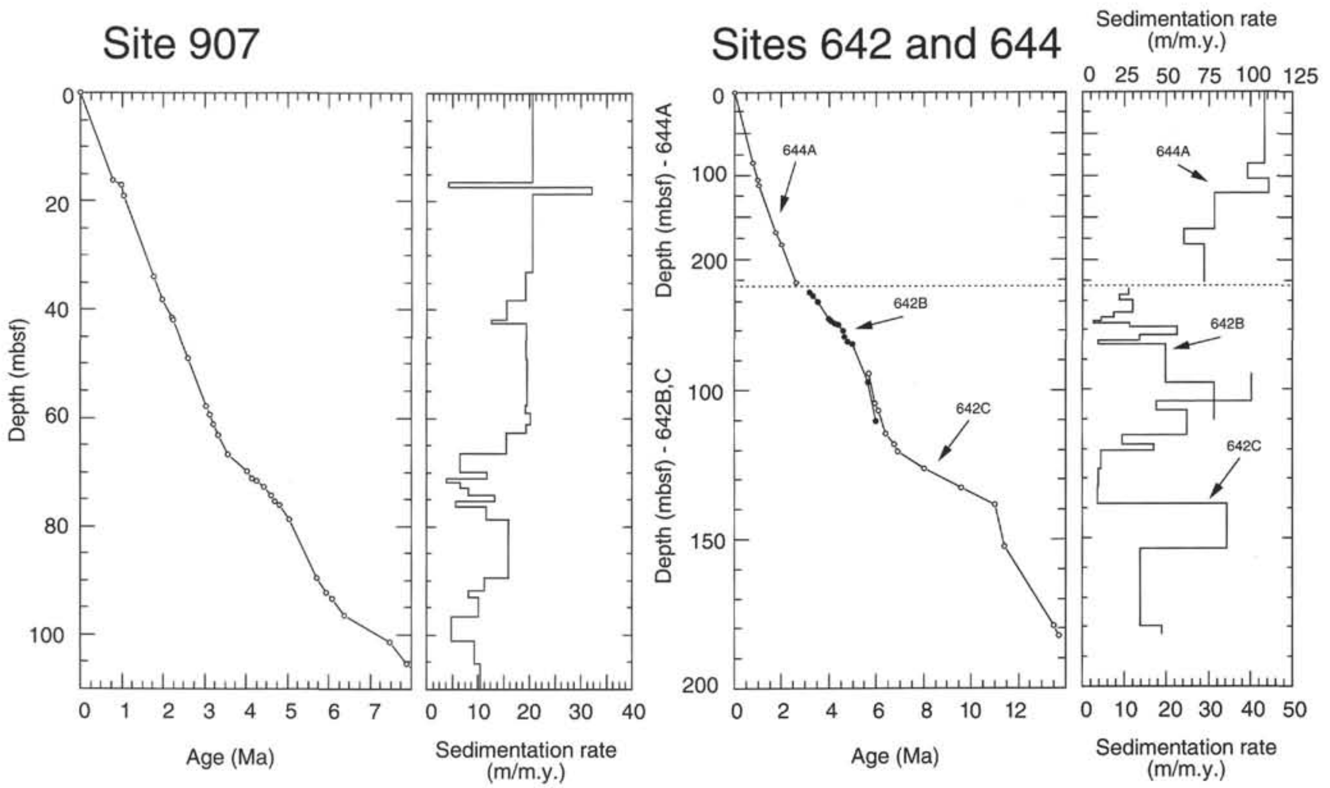

Figure 2. Age-depth diagrams and sedimentation rate curves for Site 907 and Holes 644A, 642B, and 642C. Note the different scales of depth and sedimentation rate for Site 644 and Site 642.

644 indicate relatively high $\delta^{18}O$ values in the Brunhes and a depletion in ^{18}O from the Matuyama and back to ~12 Ma. A benthic $\delta^{18}O$ enrichment of ~1‰ at ~11 Ma is recorded in the Vøring Plateau section, suggesting significantly increased ice volume and decreasing temperature of Norwegian Sea bottom water at this time. Distinct glacial excursions (heavy isotope values) are recognized back to ~6.5 Ma, whereas the records show interglacial (light isotope) values and indicate lower amplitude, climatic variability between 12 and 6.5 Ma. Between 6.5 and 2.5 Ma, the records document large (1‰–1.5‰) fluctuations indicating long-lasting changes in either global ice volume or Norwegian Sea bottom water temperature or both. Superimposed on these are lower amplitude (0.5–1.0‰), higher frequency fluctuations, possibly reflecting shorter lived variations in bottom water temperature.

A comparison of the benthic records from Site 677 with the Iceland-Norwegian Sea records (Fig. 7) shows that major global ice volume changes are detectable in the Iceland-Norwegian bottom-water records during the last million years. A number of high-amplitude/high-frequency fluctuations occur within the glacials, often overshooting Holocene values, indicating significant changes in either bottom-water temperature or, more likely, bottom-water $\delta^{18}O$ during the glacials. As many of these fluctuations are not recognizable in the planktonic records, the fluctuations may be restricted to or at least be more pronounced in the bottom water as compared with the surface water. The general benthic glacial-interglacial amplitude is less than it is in the Pacific (Site 677), documenting, as has been shown for the last glacial cycle (Labeyrie et al., 1987), that Norwegian Sea benthic records have the lowest amplitude of benthic records in the different ocean basins. This may indicate that they are less influenced by deep water temperature changes than is the remainder of the world ocean. However, within the Iceland-Norwegian Sea, brine formation and circulation-driven changes in $\delta^{18}O$ can lead to a reduction of the glacial-interglacial ^{18}O amplitude, thereby masking the temperature signal. As expected, no gradient in benthic ^{18}O existed between the Iceland and Vøring Plateaus during the last million years (Fig. 7). This suggests similar bottom-water temperatures over the entire basin.

Carbon Isotopes

Carbon isotope data from below 1 Ma at Site 907 are too sparse to detect any general decrease or increase in the planktonic or benthic $\delta^{13}C$ values between 8 Ma and the present (Fig. 3). However, a major movement towards lighter planktonic values occurred ~3.2 Ma, and a shift in benthic $\delta^{13}C$ is observed in the *Cibicides* values at ~3.1 Ma, which may indicate variable deep-water ventilation.

Around 0.4–0.5 Ma, a major shift towards heavier $\delta^{13}C$ values in both glacials and interglacials occur all over the basin (Fig. 8). Values equal to or heavier than Holocene values occur only in interglacials later than 0.5 Ma; a pattern also found at Sites 910 (Yermack Plateau) and 919 (south of the Denmark Strait) (Flower, this volume; B. Flower, pers. comm., 1995). Maximum planktonic carbon isotope values occur either within the peak glacials or at the interglacial/glacial transitions, in good agreement with published isotope records for the time period back to Stage 12 in the Nordic Seas (Vogelsang, 1990; Eide, 1994). The planktonic carbon isotope values are generally highest in the easternmost Site 644 and heaviest at the Iceland Plateau, Site 907. A similar trend towards lighter $\delta^{13}C$ values in the east is found in Holocene foraminifers in the region (Johannessen at al., 1994) and in sediment cores for the time period back to 0.4 Ma (Vogelsang, 1990).

Within the Brunhes, fluctuations in benthic $\delta^{13}C$ are generally in phase with changes in planktonic $\delta^{13}C$. Most of the benthic $\delta^{13}C$ maxima occur at the interglacial/glacial transitions or during colder parts of the interglacials (Fig. 4). Thus, the $\delta^{13}C$ maxima do not correspond to the peak interglacials.

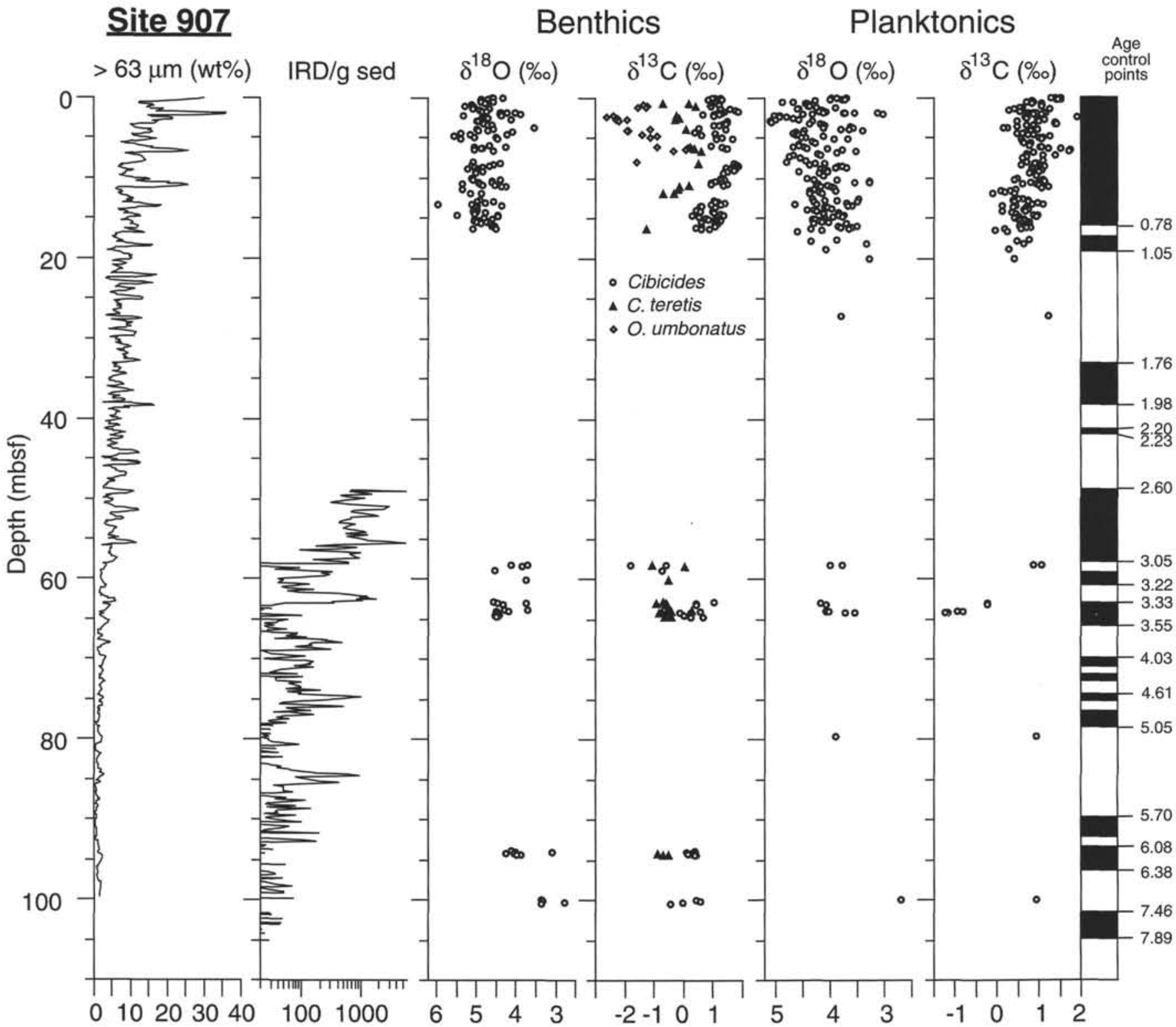

Figure 3. Summary of stable isotope, grain size, IRD, and paleomagnetic records from Hole 907A.

Ice-Rafted Debris

In the coarse fraction record (>63 µm) from Site 907 shown in Figures 3, 9, and 10, data from volcanic ash layers have been omitted to produce a curve chiefly reflecting changes in ice-rafted input to the area. A good correlation between IRD fluxes and coarse fraction data is primarily expected for the time period of 3–1 Ma where the sediments are dominated by ice-rafted material. The close correspondence between the two parameters within this interval is illustrated in Figure 9. We therefore conclude that the coarse fraction record from Site 907 can be used as an IRD proxy for the time period 3–1 Ma. IRD/g sed records exist for the time period ~8–2.6 Ma at Site 907 and ~13–0.6 Ma at Sites 642 and 644. The location of Site 907 relatively close to Greenland implies that the IRD fluctuations may reflect waxing and waning of the Greenland ice sheet. IRD fluctuations recorded on the Vøring Plateau most likely reflect fluctuations of the Scandinavian ice sheet. However, the small IRD peaks in the older part of the Site 642 record could reflect drift of icebergs from Greenland or somewhere around the Arctic Ocean.

Because some of the IRD peaks are very small, it is important to verify the nature of the grains. Scanning electron microscopy (SEM) analyses (Jansen et al., 1990) of supposed IRD grains in older peaks from Site 642 demonstrate that these grains show diagnostic features of glacially abraded grains reported from studies of recent glacial sediments. Based on this investigation, and the visual appearance of the grains when analyzed under binocular microscopy showing the same sub-angular and fragmented appearance, we conclude that the majority of the minerogenic grains are produced by glacial activity and deposited by ice rafting.

At the Vøring Plateau IRD is detected in the sediments back to ~12.6 Ma (Fig. 6). During the period from 12.6 to 7 Ma, the IRD influx was relatively small and two intervals without IRD deposition occur ~9.5–9.0 Ma and from 8.0 to 7.0 Ma. The IRD record from Site 907 documents ice rafting back to ~8 Ma, when our investigation ends. A small increase in IRD deposition at ~7.2 Ma is recorded in the Iceland Plateau sequence. One large pulse of IRD is recorded ~6.9 Ma at the Vøring Plateau, also suggesting increased IRD input from ~7 Ma. However, a possible hiatus below this level makes the

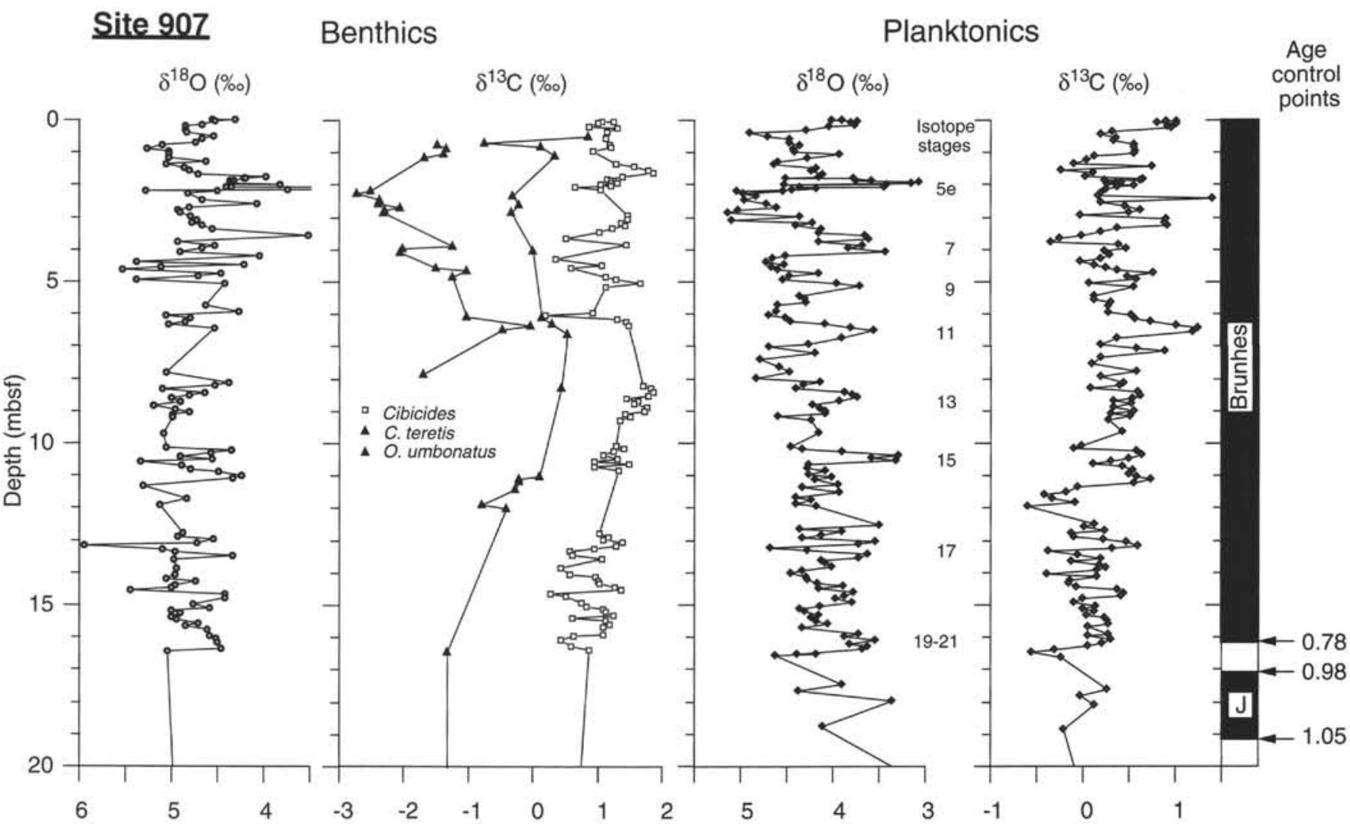

Figure 4. Stable isotope records and paleomagnetics from the upper 20 m of Hole 907A. The stratigraphic positions of oxygen isotope Stages 5 to 21 are indicated by numbers.

exact timing of the IRD increase on the Vøring Plateau uncertain. The next million years is characterized by decreasing IRD fluxes followed by a new significant increase in IRD deposition ~6 Ma (6.3 Ma at Site 642, 6.0 Ma at Site 907; i.e., during the Messinian interval). During the next 3 million years, significant IRD pulses are also observed at ~5.4 Ma, between 4.9 and 4.6 Ma, between 4.0 and 3.6 Ma, and ~3.3 and 3.0 Ma. Two intervals, 5.3–5.0 Ma and 4.4–4.2 Ma, that have very low input of IRD, are recorded at both sites.

A major increase in IRD input occurs at ~2.75 Ma at the Vøring Plateau and at ~2.9 Ma at the Iceland Plateau (Fig. 10). The divergent ages on this event could reflect that different ice sheets with different histories are the primary source of IRD for the two sites or it could be a result of dating problems at Site 644 where a possible hiatus in the Gauss chron makes the age estimate below the Matuyama/Gauss boundary unsure. The dating is as a first approach based on extrapolation below the Matuyama/Gauss boundary, assuming the same sedimentation rates as above. At Site 907, high IRD fluxes continued until ~2.35 Ma, whereas a marked decrease in IRD deposition happened at the Vøring Plateau at ~2.5 Ma. Inputs were low at both sites from 2.35 Ma to ~1.55 Ma, with the exception of one large IRD peak that occurred at ~2.0 Ma at the Iceland Plateau site. A new intensification in ice rafting toward modern glacial values took place at ~1.5 Ma.

DISCUSSION

Iceland-Norwegian Sea Paleoceanography (12.5–1 Ma)

Carbonate barren intervals are common particularly in the older parts of our records. On the Iceland Plateau, the number of carbonate-free intervals are higher and the duration of these events much longer compared with the Vøring Plateau (see also Baumann et al., this volume). According to Bohrmann et al. (1990), and by analogy to the modern situation, periods of carbonate accumulation may represent times of increased water mass exchange with the North Atlantic with carbonate production and accumulation reflecting influx of warm Atlantic water. One possibility is that during most of these periods a strong temperature gradient existed in the Iceland-Norwegian Sea with warm currents on the eastern side and cold currents on the western side. Only a few times (~7.4 and 6.2 Ma and between 3.5 and 3.0 Ma) did warmer North Atlantic waters reach the Iceland Plateau and the western part of the basin. The generally low carbonate content in the late Neogene may in part be a reflection of dissolution (Henrich, 1989) with more poorly ventilated waters possibly also a consequence of less influx of Atlantic waters and more sluggish deep-water renewal, or higher freshwater fluxes to the region, which also would reduce deep-water ventilation. The Iceland Plateau is deeper than the Vøring Plateau and would be more susceptible to dissolution in a situation with a shallow lysocline situated close to the depth of the Vøring Plateau.

Comparisons with the global sea-level curve by Haq et al. (1987) and isotope records supposed to reflect global ice volume changes (Kennett, 1986; Miller et al., 1987; Jansen et al., 1993) suggest that the benthic oxygen isotope records from Site 907 and Sites 642 and 644 (Fig. 7) only partly reflect ice volume changes. The increase in $\delta^{18}O$ from ~11 Ma to ~6 Ma does not correlate easily to global ice volume and may chiefly document the cooling of Nordic Seas deep waters. An interval ~4.5 Ma dominated by light isotope values corresponds to a period of enhanced ice volume (at Hole 806B, Jansen et al., 1993), thus indicating high deep-water temperatures in the Norwegian Sea at this time. The overall increase in benthic $\delta^{18}O$ values from 12 to 1 Ma may therefore be interpreted as documenting a gradual cooling of Iceland-Norwegian Sea deep waters. If so, major events on the cooling trend occurred ~11 Ma and ~6.4 Ma, almost si-

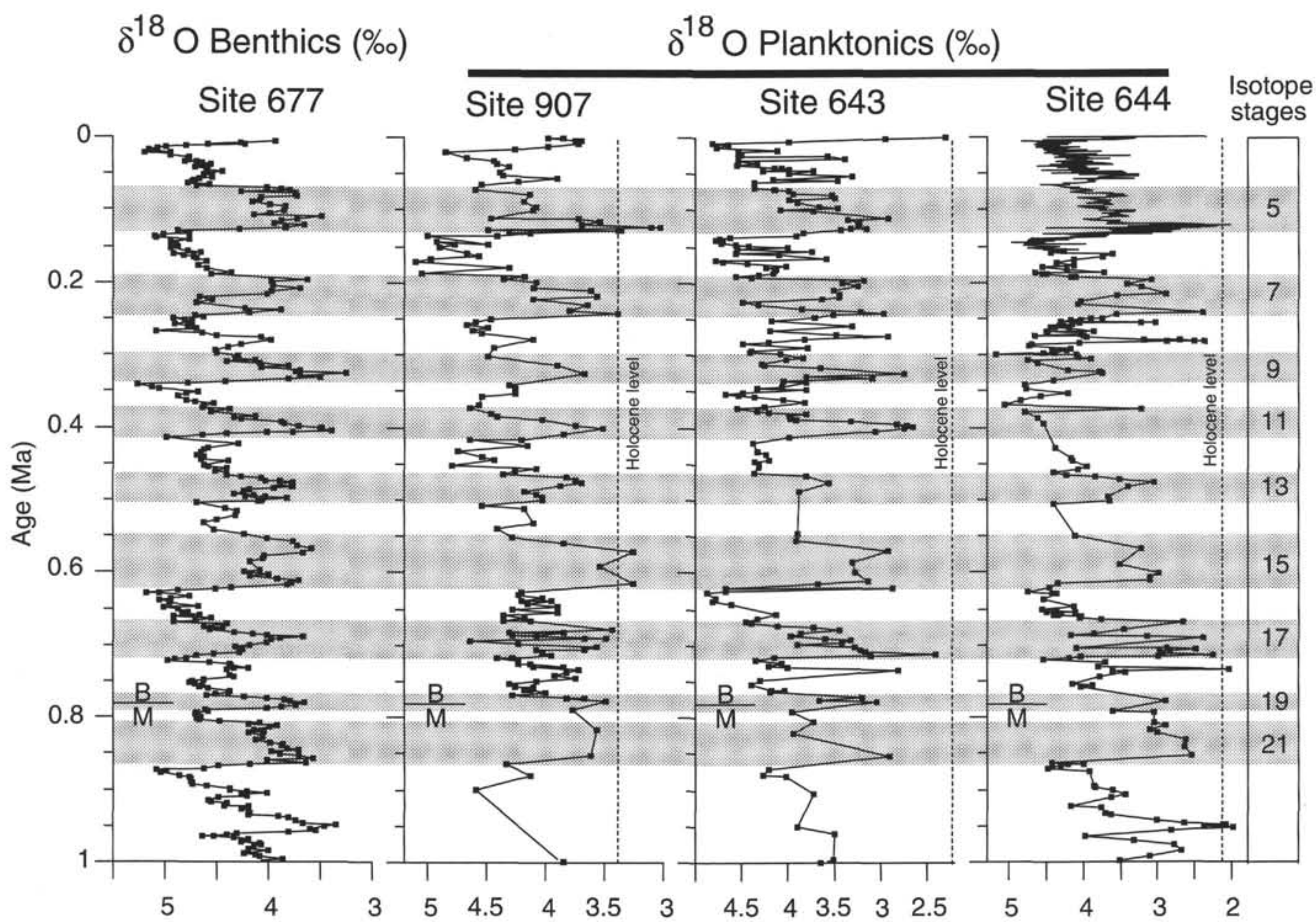

Figure 5. Planktonic oxygen isotope records of Sites 907, 643, and 644 covering the last million years plotted against age and the correlation to the benthic oxygen isotope curve from Site 677 in the Pacific. The stratigraphic positions of oxygen isotope Stages 5 to 21 are indicated by numbers and shaded bars. Holocene $\delta^{18}O$ levels at the respective sites are indicated by vertical dotted lines. The stratigraphic position of the Brunhes/Matuyama boundary is shown for all sites.

multaneously with increases in IRD input to the Iceland-Norwegian Sea.

A comparison of planktonic $\delta^{18}O$ records from the Iceland and Vøring Plateaus indicates a decrease in surface water temperatures at ~7 to 6 Ma and just prior to 1 Ma (Fig. 3; E. Jansen, unpubl. data), because the detected shifts are far too large to reflect ice volume changes only. The shifts occur at times characterized by increasing ice rafting, and the temperature changes may thus be in phase with intensifications of Northern Hemisphere glaciation.

Assuming that parts of the carbon isotope signal reflects deep-water ventilation rates, our data indicate some large changes in ventilation rate between 3.5 and 3.0 Ma. Within this time interval, marked deglaciations may have occurred in Alaska (Kaufman and Brigham-Grette, 1993), Arctic Canada (Matthews and Ovenden, 1990), and Eastern Antarctica (Barrett et al., 1992; Hambrey and Barrett, 1993). According to Haq et al. (1987), global sea level changed dramatically in this period, which may have affected the deep-water ventilation in the Iceland Sea.

Neogene Northern Hemisphere Glacial History (12.5–1 Ma)

Based on the close correlation of IRD flux and the onshore glaciation record that has been documented for the last glacial-interglacial cycle (Baumann et al., 1995; Fronval et al., 1995; Dokken, 1995), we use the IRD record from the ODP sites in the following discussion as a first-order monitor of the scale of glaciation on the continents surrounding the Nordic Seas, noting that, in general, the basic determining factor for IRD deposition is the availability of calving icebergs that can release their sediment contents upon melting in the ocean. Availability is closely coupled with the supply rate (i.e., local ice volume), although sea-surface temperature and current and wind directions also determine the supply of icebergs and melting rates. These, however, act to a lesser degree than the size of the ice sheets.

Our data document a cooling of Norwegian-Iceland Sea deep waters and a stepwise intensification of Northern Hemisphere glaciations from the middle Miocene to Pleistocene (Fig. 6). A middle Miocene initiation of Northern Hemisphere glaciation agrees well with records of global ice volume, deep water temperature and sea level, which indicate pronounced global cooling following the middle Miocene thermal maximum at ~16 Ma (Prentice and Matthews, 1988; Wright and Miller, 1992; Wright et al., 1992). However, only limited evidence exists for Northern Hemisphere glaciations of pre-Pliocene age, and the actual timing of the initiation of glaciation is still unknown. At the Vøring Plateau, the oldest pulses of glacial IRD are dated to ~12.6 Ma (using the chronology of Müller and Spiegler, 1993), suggesting that glaciers first reach sea level at this time. The initiation of ice rafting coincides with a shift from extensive biogenic opal deposition to carbonate accumulation in the sediments, which may indicate the establishment of Atlantic inflow, deep convection which deepens the lysocline, and the intensification of North Atlantic Deep Water (NADW) production at 12.5 Ma (Wright and Miller,

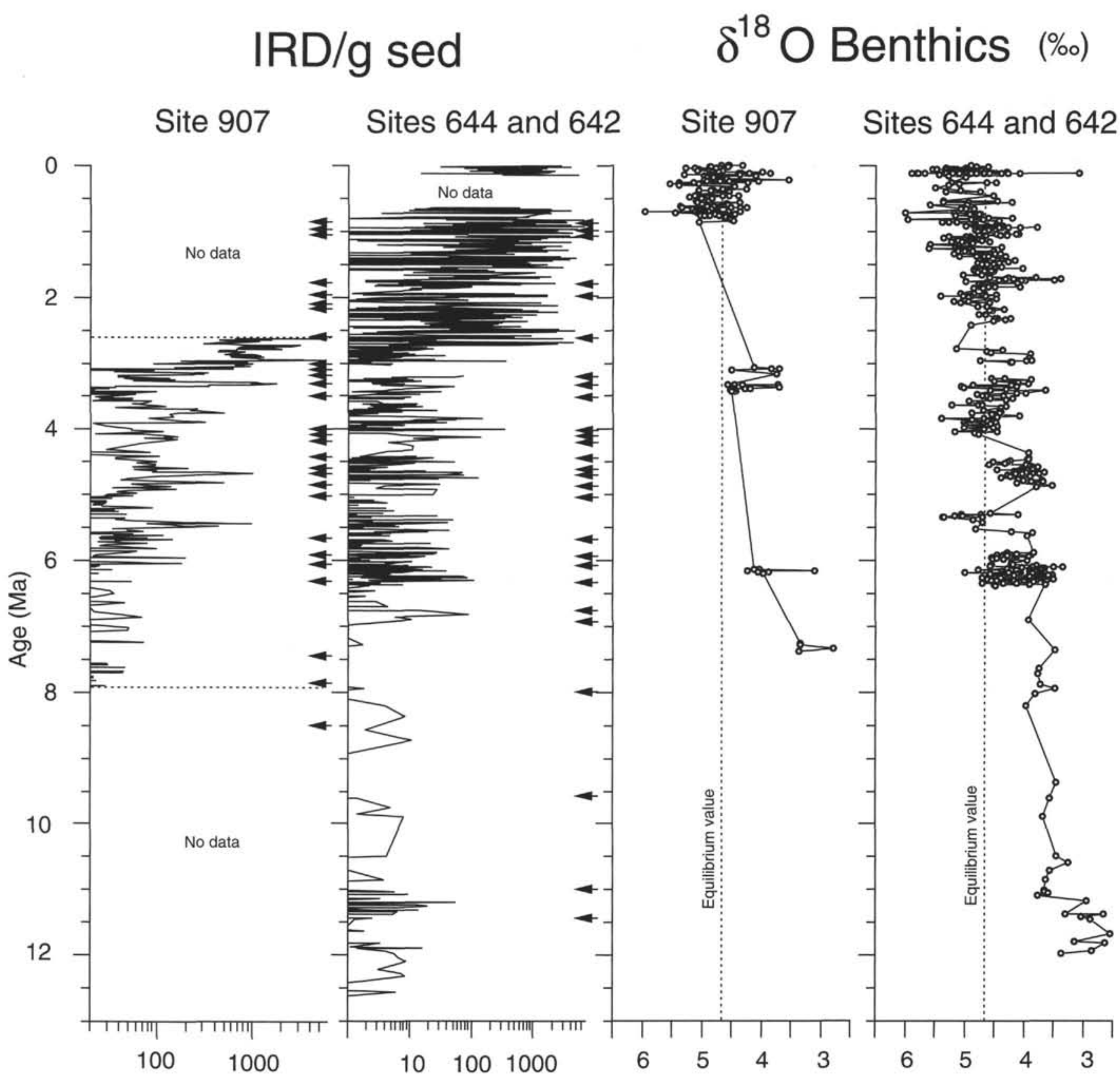

Figure 6. IRD and benthic oxygen isotope records from Site 907 and Sites 644 and 642 plotted vs. age. The vertical dotted lines refer to the present-day $\delta^{18}O$ equilibrium value at −2°C. Age control points are shown by arrows.

1993). Climatic records from middle latitude North America (Wolfe, 1994a) and Beringia (Wolfe, 1994b) indicate a decrease in mean annual temperature of ~6°C between 14 and 12 Ma, suggesting a close coupling between the initiation of Northern Hemisphere glaciation and pronounced middle Miocene cooling. Our data from Site 907 only record IRD fluctuations back to 8 Ma (105 mbsf), where our detailed investigation ends, but the occurrence of dropstones and relatively quartz-rich sediments down to 118 mbsf (~10 Ma) indicate significant ice rafting also prior to 8 Ma (Myhre, Thiede, Firth, et al., 1995). The occurrence of traces of Northern Hemisphere glaciations in the middle Miocene section from Site 642 is in line with evidence of early glaciation from the Yakataga Formation in Alaska (Marincovich, 1990). The exact date of these glaciomarine deposits is strongly debated, however, and age estimates vary from 16 to <10 Ma. Terrigenous particle counts from Site 646 in the Labrador Sea (Wolf and Thiede, 1991) also indicate that glaciation dates back to at least 10 Ma. Pollen data from Eastern Iceland indicate a cooling of approximately 10°C ~9.6 Ma (Mudie and Helgason, 1983). Our data do not record increased glaciation after 9.6 Ma. Thus, a possible cooling of regional significance at ~9.6 Ma did not result in an immediate intensification of glaciation around the Norwegian Sea of a magnitude that led to traceable records in the deep-sea sediments (Fig. 6).

Our data indicate significant intensifications of glaciation at ~7.0 and ~6.0 Ma, which suggests a late late Miocene onset of small-scale glaciation in the Northern Hemisphere. During this phase, benthic $\delta^{18}O$ for the first time exceeds Holocene values, documenting both a

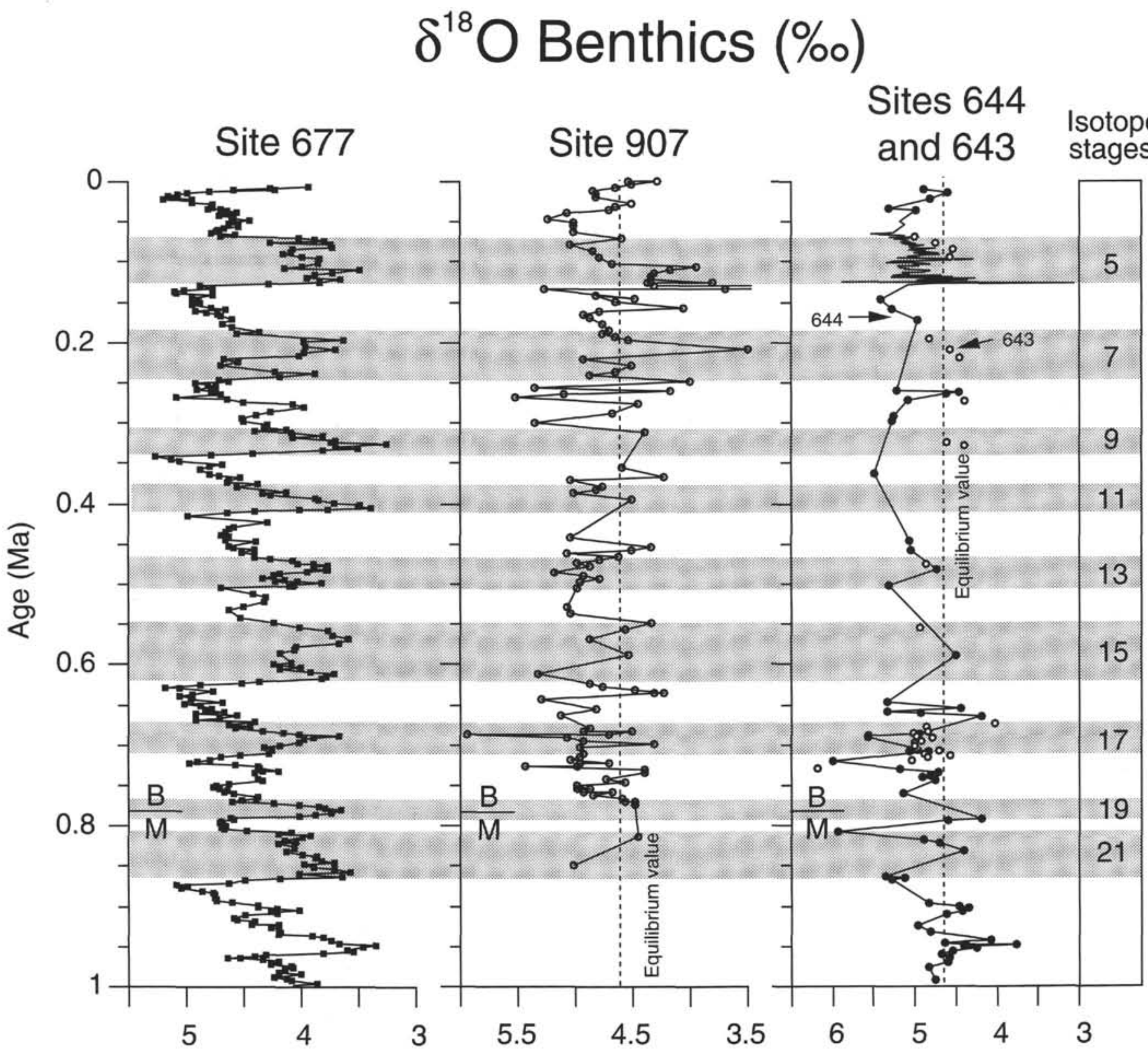

Figure 7. Benthic oxygen isotope records of Sites 907 and 643/644 covering the last million years plotted against age and the correlation to the benthic oxygen isotope curve from Site 677 in the Pacific. The stratigraphic positions of oxygen isotope Stages 5 to 21 are indicated by numbers and shaded bars. The present-day $\delta^{18}O$ equilibrium value at −2°C is indicated by vertical dotted lines. The stratigraphic position of the Brunhes/Matuyama boundary are shown for all sites.

cooling of deep waters to below 0°C and periods with global ice volumes in excess of the present (Fig. 6). In agreement with our data, age estimates of glacial deposits from northeast Alaska (Hamilton, 1994) and Iceland (Einarsson and Albertsson, 1988) indicate the occurrence of local glaciations back to late upper Miocene (7–5 Ma). Evidence from Site 918 off southeast Greenland demonstrate diamictites and dropstones in sediments back to ~7 Ma (Larsen et al., 1994), and in Baffin Bay (Site 645) the first dropstones are recorded in sediments dated to ~7.5 Ma (Korstgärd and Nielsen, 1989). On Western Iceland, a change from warm temperate forest to boreal forest and steppe vegetation demonstrates a marked cooling between 8 and 5 Ma (Simonarson, 1979). According to Bohrmann et al. (1990), the onset of Denmark Strait overflow also dates to ~7 Ma and records of global ice volume and sea level indicate global cooling and growth of ice sheets during the Messinian period, ~7–6 Ma (Kennett, 1986; Prentice and Matthews, 1988). Another important aspect of this is the apparent conjunction of the 7 Ma glacial intensification and the onset of the modern Atlantic-Pacific deep-water gradients of $\delta^{13}C$ (Wright and Miller, 1993), indicating a possible link between glacial developments and the type of deep sea circulation, as was also shown above at 12.5 Ma.

Our IRD data document the presence of small-scale ice sheets around the Iceland-Norwegian Sea between 6 and 3 Ma. However, the records also demonstrate periods of up to three hundred thousand years, with only minor ice rafting indicative of reduced local ice volumes. A very pronounced increase in terrigenous particle input ~4 Ma at Site 646 in the Labrador Sea (Wolf and Thiede, 1991) cannot be detected in the IRD records from the Nordic Seas. Cooling is indicated by the benthic $\delta^{18}O$ record, however. Other important climatic events such as the apparent establishment of the East Greenland cur-

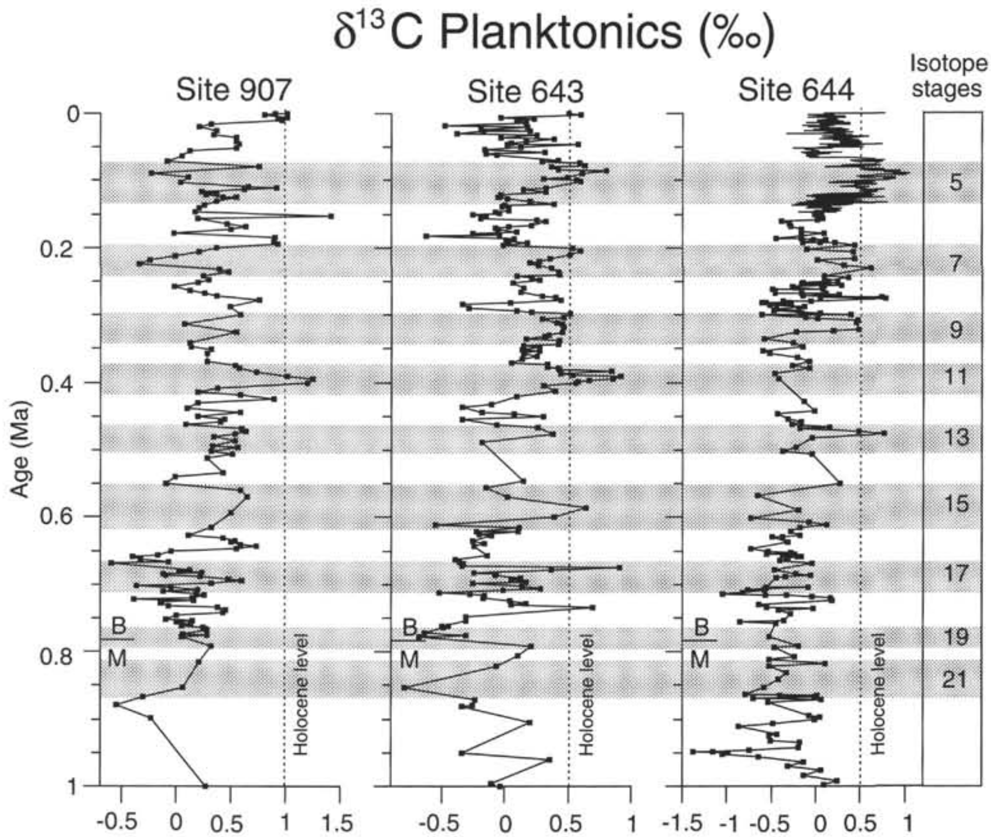

Figure 8. Planktonic carbon isotope records of Sites 907, 643, and 644 covering the last million years plotted against age. The stratigraphic positions of oxygen isotope Stages 5 to 21 are indicated by numbers and shaded bars. Holocene $\delta^{13}C$ levels at the respective sites are indicated by vertical dotted lines. The stratigraphic position of the Brunhes/Matuyama boundary is shown for all sites.

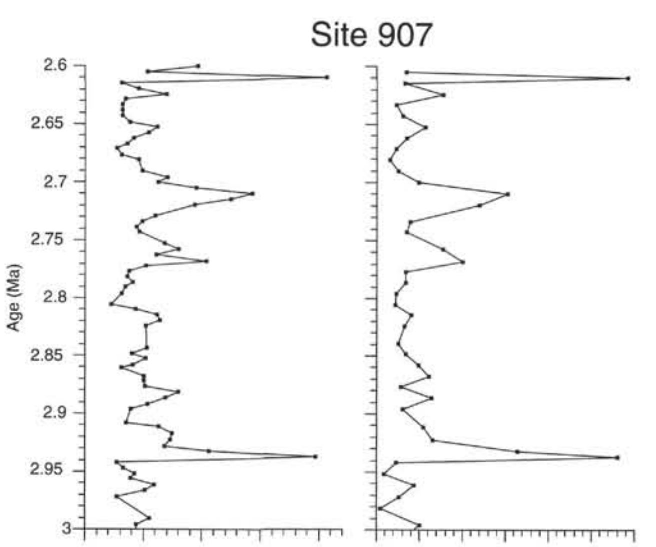

Figure 9. Comparison of the grain size (>63 µm) and IRD/g sed records in Hole 907A for the period 3.0–2.6 Ma.

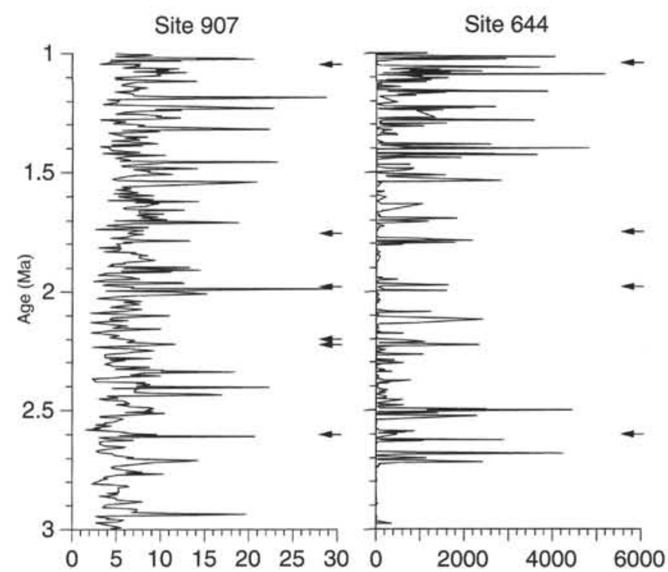

Figure 10. Comparison of the grain size (% >63 µm) record (an IRD proxy) from Site 907 and the IRD/g sed record from Site 644 for the period 3.0–1.0 Ma. Age control points are shown by arrows.

rent (~4 Ma) and the closure of the Panama Seaway (4–3 Ma) also occurred within this period (Bohrmann et al., 1990; Keigwin, 1982), but these events did not have a clear impact on IRD fluxes to the Iceland-Norwegian Sea. On Iceland, local glaciations have been dated to ~3.8 Ma and ~3.4 Ma (Geirsdottir and Eiriksson, 1994). Whether or not these glaciations were simultaneous with two large IRD pulses at the Iceland Plateau dated to 3.7 and 3.3 Ma is not possible to determine.

The onset of large-scale Northern Hemisphere glaciation as evidenced by a marked increase in IRD flux is dated to ~2.9 Ma at the Iceland Plateau. Using the timescale of Cande and Kent (1992), the benthic $\delta^{18}O$ records from Sites 607, 610, and 704 indicate a major intensification of glaciation at this stage (Raymo et al., 1992; Kleiven, 1995), and from studies of gradients in benthic $\delta^{13}C$ comes evidence of a weakening in the NADW production at ~2.9 Ma (Raymo et al., 1992; Kleiven, 1995), also supporting an intensification of glaciation at this time. Our records give an younger age of 2.75 Ma for the onset of large-scale Northern Hemisphere glaciation at the Vøring Plateau. Evidence for increasing ice build-up at this point also comes from carbonate and benthic $\delta^{18}O$ records at Site 610 (Kleiven, 1995) and a coherent decrease in NADW production is indicated by an enhanced gradient in benthic $\delta^{13}C$ between the West and East Atlantic (Raymo et al., 1992). IRD and dropstone data from the North Atlantic Sites 607, 609, 610, and 647, document ice rafting back to ~2.69 Ma, but date the major intensification of Northern Hemisphere glaciation to some time later, between 2.55 and 2.6 Ma (Raymo et al., 1987; Ruddiman et al., 1987; Korstgärd and Nielsen, 1989; Kleiven, 1995). The different timing of the IRD increase at Sites 907 and 642 could reflect that the growth of large-scale ice sheets did not occur coherently in Greenland and Scandinavia or that the IRD sedimentation was more restricted to the western Nordic Seas during the first phase of increased glaciation. The younger date on intensified IRD sedimentation in the North Atlantic may further indicate that large-scale glaciation in North America, in the form of ice sheets capable of large-scale IRD delivery to the North Atlantic, was delayed compared to glacial intensification in both Greenland and Scandinavia.

A series of pronounced deglaciations and periods with air temperatures as much as 10°C higher than present are recorded in 3- to 2.5-Ma-old sediments from Alaska and Arctic Canada (Matthews and Ovenden, 1990; Brigham-Grette and Carter, 1992). No obvious evidence for periods of warmer climate can be detected in our records. One would expect such marked events also to affect climate around the Iceland-Norwegian Sea and to be reflected by increased carbonate accumulation and warm faunal and floral elements. If the warm intervals were of relatively short duration, the resolution of our record could be too low to detect this kind of event, or the warm-interval microfossil elements might have been dissolved away. The lack of carbonate testifies, however, to a rather restricted water-mass exchange with the North Atlantic.

After 2.75 Ma, significant fluctuations in IRD fluxes can also be detected. In the Iceland Plateau and Vøring Plateau data, reduced glacial IRD fluxes is recorded in the time intervals 2.3 to ~1.55 Ma and 2.5 to ~1.55 Ma, respectively. This suggests that the first period with extensive ice sheets in Greenland and Scandinavia were followed by an interval characterized by less severe glaciations that lasted until ~1.55 Ma. From 1.55 Ma, a new intensification of glaciation is evident from the IRD records. This course of events is supported by shelf and land evidence. Seismic data from the east Greenland shelf indicate maximum extension of the Greenland ice sheet as early as 2.5 Ma (Funder, 1989), and paleotemperature reconstructions from the Netherlands show that the most pronounced cooling within the Matuyama occurred just after the Gauss/Matuyama boundary (Zaigwijn, 1992). Glacial deposits from Denmark and the northern North Sea along with occurrences of Fennoscandian erratic rocks in the Netherlands document that the Scandinavian ice sheet reached beyond the Norwegian coastline for the first time between 1.8 and 1.1 Ma (Mangerud et al., in press). In Northern Greenland (Kap København) evidence from uplifted marine sediments that are dated to between 2.5 and 1.8 Ma indicate ice-free conditions and forest vegetation (Funder et al., 1985; S. Funder, pers. comm., 1995). The marked IRD pulse ~2.0 Ma at Site 907 may reflect a major deglaciation. At the Vøring Plateau the very low IRD fluxes between 2.0 and 1.8 Ma and the light $\delta^{18}O$ values (the lightest values in Matuyama) ~1.8 Ma may be evidence for a relatively warm climate ~2.0 Ma.This is, however, not clearly documented in the microfossil record (Eldholm, Thiede, Taylor, et al., 1987).

Paleoceanography and Paleoclimate (1–0 Ma)

A significant climate shift ~0.9 Ma towards larger climatic amplitudes and lower frequency oscillations has formerly been documented in the North Atlantic and the Pacific (e.g., Berger and Jansen, 1994). Pre-shift and post-shift times differ in that precession-driven variations became more important and the 100-k.y. cycle became dominant in the late Quaternary. In our data the middle Pleistocene climate shift is manifested by enhanced foraminifer content, increasing planktonic $\delta^{18}O$ values (in glacials), decreasing $\delta^{18}O$ gradient between deep and surface water, and increasing $\delta^{13}C$ values. In addition, enhanced IRD fluxes are documented at Site 644 and also further north at Site 912 (Myhre, Thiede, Firth, et al., 1995). These changes indicate a shift towards more extensive glacials of longer duration and the initiation of warmer interglacials with influx of warm surface waters and ventilated deep waters similar to the Holocene.

According to our planktonic oxygen isotope data, surface water temperatures at the Iceland Plateau were higher than Holocene values in two interglacials (Stages 15 and 5e). At the Vøring Plateau, no interglacials appear warmer than the Holocene although Stages 17, 7, and 5e may have experienced almost similar sea-surface temperatures. Other isotope records from the area covering the timespan back to Stage 12 support this view (Sejrup et al., 1989; Vogelsang, 1990). Note that the surface-water temperatures during the marked interstadial within Stage 18 may have been as high as in the warmest interglacials. The planktonic isotope data further document that glacial periods became colder and more pronounced after 0.5 Ma with the exception of Stage 16 (~0.65 Ma), which may have been a period with particularly low surface-water temperatures in the eastern part of the basin. During the entire last one million years an east-west gradient in interglacial surface-water temperature existed, with the highest temperatures on the inner Vøring Plateau and the coldest conditions on the Iceland Plateau. The temperature difference is on the order of up to 6°C (1.5‰) in some interglacials (e.g., Stages 7 and 17) but only about 1°C (0.25‰) in others (e.g., Stage 15). These marked variations in the strength of the temperature gradient indicate that the circulation patterns varied from interglacial to interglacial.

The benthic isotope records document no clear gradient in deep water temperature across the basin. No significant warming of the deep waters at any time, with the possible exception of Stage 5e, are indicated from the data. Instead, the benthic isotope records demonstrate global ice volume larger than the present during major parts of glacials and also in a number of interglacials. It should be noted that some of the lightest benthic oxygen isotope values occur within glacial periods (e.g., Stages 16 and 8). These light values do probably not reflect decreased ice volume or increased bottom water temperature but might document the inflow of waters low in $\delta^{18}O$, probably reflecting the influence of brines.

In both glacial and interglacial times, an east-west gradient in planktonic carbon isotope values existed with the heaviest values in the Iceland Plateau surface waters. The difference between the Iceland and Vøring Plateaus averaged 0.5‰ over the last 0.9 m.y. which is close to the difference detected in surface sediments (Johannessen et al., 1994). In general, the heaviest planktonic $\delta^{13}C$ values fall within the interglacials, but sometimes the $\delta^{13}C$ maximum occurs at the interglacial/glacial transition or in the beginning of the glacials. This is particularly common in the Site 907 record. The fluctuations in planktonic $\delta^{13}C$ may reflect global variations in the partitioning of carbon between different carbon reservoirs or demonstrate changes in biogenic assimilation of carbon and in the exchange of carbon between Iceland-Norwegian Sea surface waters and the atmosphere. A number of paleoclimatic transitions occurred in the middle Brunhes (~400 ka), including a decrease in deep-sea carbonate preservation (Crowley, 1985). Such a deviation in carbonate preservation would lead to $\delta^{13}C$-enrichment of the global marine bicarbonate reservoir, which may explain the marked increase in planktonic $\delta^{13}C$ at ~400 k.y. found in records from all parts of the Nordic Seas.

The maxima in benthic $\delta^{13}C$ are concentrated around the interglacial/glacial transitions. As high benthic $\delta^{13}C$ are interpreted as reflecting enhanced deep-water ventilation and formation, our data suggest that deep water formation is not a linear response to global ice volume or surface-water temperature changes. Instead the deep-water ventilation apparently peaked during times of general climate deterioration.

Evidence of general climate instability during the last interglacial/glacial cycle from proxy temperature data from Greenland ice cores (Dansgaard et al., 1993), North Atlantic sediment cores (Bond et al., 1993), and from Site 644 (Fronval et al., 1995) has raised the question whether or not high frequency climate fluctuations are the rule rather than the exception also in former glacial cycles. Our data reveal some climate variability during most glacials, but the resolution is too low to detect Dansgaard-Oeschger-like cycles in the sediments. General climate instability and significant temperature fluctuations are also indicated for most interglacial periods with the possible exception of Stages 9 and 11. Stage 17, especially, was punctuated by severe cold spells, although the youngest of the light $\delta^{18}O$ excursions might reflect a meltwater event. The degree of climate variability within the last interglacial (the Eemian) is still under debate (e.g., McManus et al., 1994; Johnsen et al., 1995). Planktonic $\delta^{18}O$ data from both Sites 907 and 644 indicate high-amplitude temperature fluctuations within the last interglacial supporting the general idea of an unstable Eemian climate.

SUMMARY AND CONCLUSIONS

At the Iceland Plateau, intervals barren in foraminifers dominate the record below the Brunhes chron. The Vøring Plateau offers generally more carbonate for isotopic work, but the same trend of less carbonate in sections older than ~1 Ma is found. The low carbonate content could reflect restricted inflow of North Atlantic surface water and calcite dissolution with poorly ventilated deep waters possibly also a consequence of restricted influx of Atlantic waters. In that case, the enhanced carbonate content in the eastern part of the basin reflects a strong gradient with warm currents on the eastern side and cold currents at the western site. Only a few times before 1 Ma (~7.4 and 6.2 Ma and between 3.5 and 3.0 Ma) did warmer North Atlantic waters reach the Iceland Plateau and the western parts of the basin.

Comparisons with sea-level curves and isotope records supposed to reflect global ice volume, suggest that the long-term trend in benthic oxygen isotope records from both the Iceland and Vøring plateau mostly reflect changes in deep water temperatures. An overall increase in benthic $\delta^{18}O$ from 12 to 1 Ma are therefore interpreted as documenting a gradual cooling of Iceland-Norwegian Sea deep waters with major cooling events occurring ~11 Ma and 6.4 Ma.

Ice-rafted debris is detected in sediments dating back to ~12.6 Ma, indicating that glaciers reached sea level as early as the middle Miocene. The initiation of ice rafting coincides with a decrease in mean annual temperature at middle and high latitudes, an intensification of North Atlantic deep water production, and a change in circulation patterns within the Iceland-Norwegian Sea, as indicated by a shift from extensive biogenic opal deposition to carbonate accumulation at the Vøring Plateau. IRD records from both the Iceland and Vøring Plateau suggest further intensifications of Northern Hemisphere glaciations at ~7 and 6 Ma. The expansion of ice sheets around the Iceland-Norwegian Sea at 7–6 Ma are interpreted as the onset of small-scale glaciation in the Northern Hemisphere, which is also indicated by glacial records from Alaska, Baffin Bay, Iceland, and off southeast Greenland. Between 6 and 3 Ma, small-scale ice sheets periodically existed around the Iceland-Norwegian Sea, interrupted by intervals with lesser local ice volumes as indicated by reduced ice rafting.

The onset of large-scale Northern Hemisphere glaciation is dated to 2.75 Ma at the Vøring Plateau and 2.9 Ma at the Iceland Plateau. The different timing could reflect that the growth of large-scale ice sheets did not occur simultaneously in Greenland and Scandinavia or that IRD sedimentation was more restricted to the western part of the basin during the first phase of large-scale glaciation. After 2.75 Ma significant fluctuations in IRD fluxes can also be detected. The period from 2.5–2.3 Ma to 1.55 Ma in particular is characterized by less severe glaciations around the Iceland-Norwegian Sea.

The middle Pleistocene climate shift ~0.9 Ma is documented in both oxygen and carbon isotope composition, foraminiferal content, and IRD deposition. The changes document a shift toward more extensive glacials of longer duration and the initiation of warmer interglacials with influx of warm surface waters and ventilated deep waters similar to the Holocene situation.

At the Iceland Plateau, surface-water temperatures were higher than Holocene values in two interglacials, isotope Stages 15 and 5e, whereas no interglacials appear warmer than Holocene at the Vøring Plateau. During the last million years an east-west gradient in interglacial surface water temperature (up to ~6°C) existed with the highest temperatures on the inner Vøring Plateau and the coldest conditions on the Iceland Plateau. No significant warming of deep waters, with the possible exception of Stage 5e, are indicated from the data and no clear gradient in deep water temperature across the basin are detected within the Brunhes chron.

Maxima in benthic $\delta^{13}C$ are concentrated around the interglacial/glacial transitions. This suggests that deep water formation is not a linear response to global ice volume or surface-water temperature changes. Instead the deep-water ventilation apparently peaked during times of general climate deterioration. The middle Brunhes climate shift, which includes an increase in global deep-sea carbonate dissolution, may be reflected in the Nordic Seas by a marked increase in planktonic $\delta^{13}C$ ~400 ka.

ACKNOWLEDGMENTS

We thank the crew and scientific party of Leg 151 for a successful Arctic venture and ODP for providing samples. We also thank R. Sørås and O. Hansen for mass spectrometer operation and several others for laboratory assistance. R. Zahn, G. Bond, and the ODP Editorial Review Board carefully reviewed the paper and helped improve it. This work was supported by the Norwegian Research Council and Bergen University.

REFERENCES

Barrett, P.J., Adams, C.J., McIntosh, W.C., Swisher, C.C., III, and Wilson, G.S., 1992. Geochronological evidence supporting Antarctic deglaciation three million years ago. *Nature,* 359:816–818.

Baumann, K.-H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf-Welling, T.C.W., Henrich, R., and Kassens, H., 1995. Reflection of Scandinavian ice sheet fluctuations in Norwegian Sea sediments during the past 150,000 years. *Quat. Res.,* 43:185–197.

Berger, W.H., and Jansen, E., 1994. Mid-Pleistocene climate shift: the Nansen connection. *In* Johannessen, O.M., Muensch, R.D., and Overland, J.E. (Eds.), *The Role of the Polar Oceans in Shaping the Global Environment.* Geophys. Monogr., Am. Geophys. Union, 84:295–311.

Bleil, U., 1989. Magnetostratigraphy of Neogene and Quaternary sediment series from the Norwegian Sea: Ocean Drilling Program, Leg 104. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program), 829–901.

Bohrmann, G., Henrich, R., and Thiede, J., 1990. Miocene to Quaternary paleoceanography in the northern North Atlantic: variability in changes in carbonate and biogenic opal accumulation. *In* Bleil, U., and Thiede, J. (Eds.), *Geological History of the Polar Oceans: Arctic versus Antarctic.* NATO ASI Series C, 647–675.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G., 1993. Correlations between climate records from the North Atlantic sediments and Greenland ice. *Nature,* 365:143–147.

Brigham-Grette, J., and Carter, L.D., 1992. Pliocene marine transgressions of northern Alaska: circumarctic correlations and paleoclimate interpretations. *Arctic,* 45:74–89.

Cande, S.C., and Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.,* 97:13917–13951.

Craig, H., and Gordon, L.I., 1965. Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. *In* Tongiorgi, E. (Ed.), *Stable Isotopes in Oceanographic Studies and Paleotemperatures:* Pisa (Cons. Naz. delle Ric., Lab. di Geol. Nucleare), 9–130.

Crowley, T.J., 1985. Late Quaternary carbonate changes in the North Atlantic and Atlantic/Pacific comparisons. *In* Sundquist, E.T., and Broecker, W.S. (Eds.), *The Carbon Cycle and Atmospheric CO_2: Natural Variations, Archean to Present.* Geophys. Monogr., Am. Geophys. Union, 32:271–284.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J., and Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature,* 364:218–220.

Dokken, T.M., 1995. Paleoceanographic changes during the last Interglacial-Glacial cycle from the Svalbard-Barents Sea margin [Ph.D. dissert.]. Univ. of Tromsø, Norway.

Duplessy, J.-C., Moyes, J., and Pujol, C., 1980. Deep water formation in the North Atlantic during the last ice age. *Nature,* 286:479–482.

Eide, L.K., 1994. Quaternary interglacials in the Iceland Sea: surface water paleoenvironments, with emphasis on coccolith assemblages [Ph.D. dissert.]. Univ. of Bergen, Norway.

Einarsson, T., and Albertsson, K. J., 1988. The glacial history of Iceland during the past three million years: a discussion. *Philos. Trans. R. Soc. Lond.,* 318:637–644.

Eldholm, O., Thiede, J., Taylor, E., et al., 1987. *Proc. ODP, Init. Repts.,* 104: College Station, TX (Ocean Drilling Program).

Fronval, T., Jansen, E., Bloemendal, J., and Johnsen, S., 1995. Oceanic evidence for coherent fluctuations in Fennoscandian and Laurentide ice sheets on millennium timescales. *Nature,* 374:443–446.

Funder, S., 1989. Quaternary geology of East Greenland. *In* Fulton, R. (Ed.), *Quaternary Geology of Canada and Greenland.* Geol. Soc. Am, Geol. of North Am. Ser., K-1:756–763.

Funder, S., Abrahamsen, N., Bennike, O., and Feyling-Hanssen, R.W., 1985. Forested Arctic: evidence from North Greenland. *Geology,* 13:542–546.

Geirsdottir, A., and Eiriksson, J., 1994. Growth of an intermittent ice sheet in Iceland during the Late Pliocene and Early Pleistocene. *Quat. Res.,* 42:115–130.

Graham, D.W., Corliss, B.H., Bender, M.L., and Keigwin, L.D., Jr., 1981. Carbon and oxygen isotopic disequilibria of Recent deep-sea benthic foraminifera. *Mar. Micropaleontol.,* 6:483–497.

Hambrey, M.J., and Barrett, P.J., 1993. Cenozoic sedimentary and climatic record, Ross Sea region, Antarctica. *Antarct. Paleoenviron.,* 60:91–124.

Hamilton, T.D., 1994. Late Cenozoic glaciation of Alaska. *In* Plafker, G., and Berg, H.C. (Eds.), *The Geology of Alaska.* Geol. Soc. Am., 813–844.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science,* 235:1156–1167.

Henrich, R., 1989. Glacial/interglacial cycles in the Norwegian Sea: sedimentology, paleoceanography, and evolution of late Pliocene to Quaternary Northern Hemisphere climate. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program), 189–232.

Henrich, R., and Baumann, K.H. 1994. Evolution of the Norwegian Current and the Scandinavian Ice Sheets during the past 2.6 m.y.: evidence from ODP Leg 104 biogenic carbonate and terrigenous records. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 108:75–94.

Jansen, E., Bleil, U., Henrich, R., Kringstad, L., and Slettemark, B., 1988. Paleoenvironmental changes in the Norwegian Sea and Northeast Atlantic during the last 2.8 m.y.: Deep Sea Drilling Project/Ocean Drilling Program Sites 610, 642, 643, and 644. *Paleoceanography,* 3:563–581.

Jansen, E., Mayer, L.A., Backman, J., Leckie, R.M., and Takayama, T., 1993. Evolution of Pliocene climate cyclicity at Hole 806B (5–2 Ma): oxygen isotope record. *In* Berger, W.H., Kroenke, L.W., Mayer, L.A., et al., *Proc. ODP, Sci. Results,* 130: College Station, TX (Ocean Drilling Program), 349–362.

Jansen, E., Sjøholm, J., Bleil, U., and Erichsen, J.A., 1990. Neogene and Pleistocene glaciations in the northern hemisphere and late Miocene-Pliocene global ice volume fluctuations: evidence from the Norwegian Sea. *In* Bleil, U., and Thiede, J. (Eds.), *Geological History of the Polar Oceans: Arctic Versus Antarctic:* Dordrecht (Kluwer), 677–705.

Jansen, E., Slettemark, B., Bleil, U., Henrich, R., Kringstad, L., and Rolfsen, S., 1989. Oxygen and carbon isotope stratigraphy and magnetostratigraphy of the last 2.8 Ma: paleoclimatic comparisons between the Norwegian Sea and the North Atlantic. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program), 255–269.

Johannessen, T., Jansen, E., Flatøy, A., and Ravelo, A.C., 1994. The relationship between surface water masses, oceanographic fronts and paleoclimatic proxies in surface sediments of the Greenland, Iceland and Norwegian Seas. *In* Zahn, R., and Kaminski, M. (Eds.), *Carbon Cycling in the Glacial Ocean:* Heidelberg (Springer-Verlag).

Johnsen, S., Clausen, H.B., Dansgaard, W., Gundestrup, N.S., Hammer, C.U., and Tauber, H., 1995. The eem stable isotope record along the GRIP ice core and its interpretation. *Quat. Res.,* 43:117–124.

Kaufman, D., and Brigham-Grette, J., 1993. Aminostratigraphic correlations and paleotemperature implications, Pliocene-Pleistocene high-sea-level deposits, Northwestern Alaska. *Quat. Sci. Rev.,* 12:21–33.

Keigwin, L., 1982. Isotopic paleoceanography of the Caribbean and East Pacific: role of Panama Uplift in late Neogene time. *Science,* 217:350–353.

Kennett, J.P., 1986. Miocene to early Pliocene oxygen and carbon isotope stratigraphy in the southwest Pacific, Deep Sea Drilling Project Leg 90. *In* Kennett, J.P., von der Borch, C.C., et al., *Init. Repts. DSDP,* 90 (Part 2): Washington (U.S. Govt. Printing Office), 1383–1411.

Kleiven, H.F., 1995. Late Neogene Northern Hemisphere climate fluctuations: chronology and correlation based on ODP and DSDP Sites 644 and 610 [M.S. thesis]. Univ. of Bergen, Norway.

Koç, N., Haflidason, H., and Jansen, E., 1993. Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian seas through the last 14 ka, based on diatoms. *Quat. Sci. Rev.,* 12:115–140.

Korstgärd, J.A., and Nielsen, O.B., 1989. Provenance of dropstones in Baffin Bay and Labrador Sea, Leg 105. *In* Srivastava, S.P., Arthur, M.A., Clement, B., et al., *Proc. ODP, Sci. Results,* 105: College Station, TX (Ocean Drilling Program), 65–69.

Labeyrie, L.D., Duplessy, J.C., and Blanc, P.L., 1987. Variations in mode of formation and temperature of oceanic deep waters over the past 125,000 years. *Nature,* 327:477–482.

Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W., Spezzaferri, S., and the ODP Leg 152 Scientific Party, 1994. Seven million years of glaciation in Greenland. *Science,* 264:952–955.

Leg 119 Shipboard Scientific Party, 1988. Early glaciation of Antarctica. *Nature,* 333:303–304.

Mangerud, J., Jansen, E., and Landvik, J.Y., in press. Late Cenozoic history of the Scandinavian and Barents Sea ice sheets. *Global Planet. Change.*

Marincovich, L., 1990. Molluscan evidence for early middle Miocene marine glaciation in Southern Alaska. *Geol. Soc. Am. Bull.,* 102:1591–1599.

Matthews, J.V., and Ovenden, L.E., 1990. Late Tertiary macrofossils from localities in Arctic/Subarctic North America: a review of the data. *Arctic,* 43:364–392.

McManus, J.F., Bond, G.C., Broecker, W.S., Johnsen, S., Labeyrie, L., and Higgins, S., 1994. High-resolution climate records from the North Atlantic during the last interglacial. *Nature,* 371:326–329.

Miller, K.G., Fairbanks, R.G., and Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion. *Paleoceanography,* 2:1–19.

Mudie, P.J., and Helgason, J., 1983. Palynological evidence for Miocene climatic cooling in eastern Iceland about 9.8 Myr ago. *Nature,* 303:689–692.

Müller, C., and Spiegler, D., 1993. Revision of late/middle Miocene boundary on the Voering Plateau (ODP Leg 104). *Newsl. Stratigr.,* 28:171–178.

Myhre, A.M., Thiede, J., Firth, J.V., et al., 1995. *Proc. ODP, Init. Repts.,* 151: College Station, TX (Ocean Drilling Program).

Prentice, M.L., and Matthews, R.K., 1988. Cenozoic ice-volume history: development of a composite oxygen isotope record. *Geology,* 16:963–966.

Raymo, M.E., Hodell, D., and Jansen, E., 1992. Response of deep ocean circulation to initiation of Northern Hemisphere glaciation (3–2 Ma). *Paleoceanography,* 7:645–672.

Raymo, M.E., Ruddiman, W.F., and Clement, B.M., 1987. Pliocene-Pleistocene paleoceanography of the North Atlantic at DSDP Site 609. *In* Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., *Init. Repts. DSDP,* 94 (Pt. 2): Washington (U.S. Govt. Printing Office), 895–901.

Ruddiman, W.F., McIntyre, A., and Raymo, M., 1987. Paleo-environmental results from North Atlantic Sites 607 and 609. *In* Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., *Init. Repts. DSDP,* 94 (Pt. 2): Washington (U.S. Govt. Printing Office), 855–878.

Sejrup, H.-P., Sjøholm, J., Furnes, H., Beyer, I., Eide, L., Jansen, E., and Mangerud, J., 1989. Quaternary tephrachronology on the Iceland Plateau, north of Iceland. *J. Quat. Sci.,* 4:109–114.

Shackleton, N.J., 1974. Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina:* isotopic changes in the ocean during the last glacial. *Les Meth. Quant. d'etude Var. Clim. au Cours du Pleist., Coll. Int. C.N.R.S.,* 219:203–209.

Shackleton, N.J., Berger, A., and Peltier, W.A., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Trans. R. Soc. Edinburgh: Earth Sci.,* 81:251–261.

Simonarson, L.A., 1979. On climatic changes in Iceland. *Joekull,* 29:44–46.

Vogelsang, E., 1990. Palao-Ozeanographie des Europaischen Nordmmeeres an Hand stabiler Kohlenstoff-und Sauerstoffisotope [Ph.D. dissert.]. Christian-Albrechts-Univ. zu Kiel.

Wolf, T.C.W., and Thiede, J., 1991. History of terrigenous sedimentation during the past 10 m.y. in the North Atlantic (ODP Legs 104 and 105 and DSDP Leg 94). *Mar. Geol.,* 101:83–102.

Wolfe, J.A., 1994a. Tertiary climatic changes at middle latitudes of western North America. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 108:195–205.

————, 1994b. An analysis of Neogene climates in Beringia. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 108:207–216.

Wright, J.D., and Miller, K.G., 1992. Miocene stable isotope stratigraphy, Site 747, Kerguelen Plateau. *In* Wise, S.W., Jr., Schlich, R., et al., *Proc. ODP, Sci. Results,* 120: College Station, TX (Ocean Drilling Program), 855–866.

————, 1993. Southern Ocean influences on late Eocene to Miocene deepwater circulation. *Antarct. Res. Ser.,* 60:1–25.

Wright, J.D., Miller, K.G., and Fairbanks, R.G., 1992. Early and middle Miocene stable isotopes: implications for deepwater circulation and climate. *Paleoceanography,* 7:357–389.

Zaigwijn, W.H., 1992. The beginning of the ice age in Europe and its major subdivisions. *Quat. Sci. Rev.,* 11:583–591.

Date of initial receipt: 10 July 1995
Date of acceptance: 7 December 1995
Ms 151SR-134