ELSEVIER
Marine Geology 131 (1996) 89–102
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Monitoring Termination II at high latitude: anomalies in the planktic foraminiferal record

Henning A. Bauch

GEOMAR, Research Center for Marine Geosciences, Wischhofstraße 1–3, 24148 Kiel, Germany

Received 22 February 1994; revision accepted 28 April 1995

Abstract

Microfaunal studies of planktic foraminifera carried out on 21 sediment cores from the Norwegian–Greenland Sea (NGS) reveal the spatial and lateral distribution as well as meltwater implication of today's non-polar/subpolar species *Beella megastoma* (Earland). Previous findings are verified in that this foraminifera is characteristic only of the deglaciation phases of Termination II, III, and VI and not the ensuing interglacial optima, thus, rendering this species a 'meltwater' indicator. Its distribution is restricted to cores from the central, i.e., more 'pelagic', part of the NGS covering an area as far north as 77° latitude. A detailed investigation of Termination II indicates that *B. megastoma* first appeared in the southwest of the NGS at ~131 ka and then about 6 kyr later in the eastern and northern parts of the NGS. For the entire duration *B. megastoma* always coincided with the deposition of distinct ice-rafted detritus (IRD) suggesting the presence of drifting icebergs during this period. Two different oceanographic models, each with a two-stepped evolution of the post-Saalian surface water circulation, are proposed to account for this time transgressive character. The mechanism of brine formation as possible oceanic phenomenon forcing Atlantic water northwards is suggested for being responsible for the occurrence of *B. megastoma* in the NGS during early Termination II. The presence of *B. megastoma* always ceased with the culmination of the interglacial optimum, oxygen isotopic Substage 5.51 (Eemian), when the subpolar foraminiferal fauna reached highest abundances and a general lack of IRD is observed.

1. Introduction

Extensive studies have been carried out on deep-sea sediments during the past few years to decipher the link between paleoceanographic changes and short-term climatic instabilities recorded in northern hemisphere sediments since the Weichselian maximum (Broecker et al., 1988; Jones and Keigwin, 1988; Lehman and Keigwin, 1992; Veum et al., 1992). The drastic climatic changes within the last post-glacial transition (Termination I) are highly resolved in ice cores, sometimes on a yearly resolution (e.g. Dansgaard et al, 1989; Taylor et al., 1993). Variability in ocean circulation, i.e., of the so-called 'conveyor belt', has been proposed for being partly responsible for these rapid climatic shifts (Broecker and Denton, 1989).

The modern NGS is a region with strong hydrographic contrasts (Fig. 1). These are primarily governed by an inflow of relatively warm, high-saline North Atlantic water from the southeast and an in- and outflow of comparatively cooler and fresher Arctic water through the Fram Strait and Denmark Strait respectively. Both of these

SSDI 0025-3227(95)00147-6

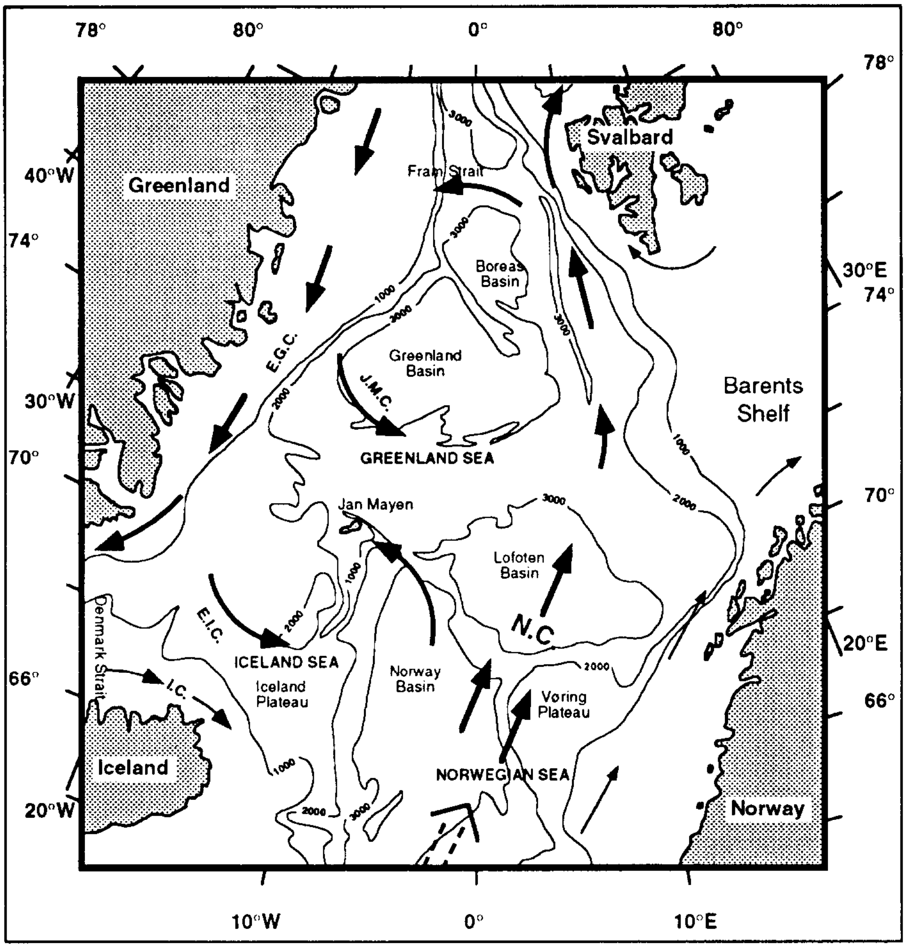


Fig. 1. Overview of the major surface water circulation pattern within the Norwegian–Greenland seas (*E.G.C.* = East Greenland Current; *E.I.C.* = East Iceland Current; *I.C.* = Irminger Current; *J.M.C.* = Jan Mayen Current; *N.C.* = Norwegian Current).

different surface water masses are responsible for the development of certain smaller scale circulation patterns (Swift, 1986).

Various planktic faunal and floral investigations are instrumental in monitoring the variability of oceanic processes during geological time (e.g. Kellogg, 1980; Jansen and Bjørklund, 1985; Baumann and Mathiessen, 1992; Bauch, 1993). A particular marine microfossil assemblage can either serve as direct indicator of the past surface water or can be utilized to estimate specific physical properties, e.g. temperature (Koç-Karpuz and Jansen, 1992).

In the modern NGS, planktic foraminifera are a major component to hemipelagic and pelagic sediments, resulting in high amounts of carbonate in the surface sediments (Kellogg, 1975; Baumann et al., 1993). Because of its nearly continuous presence in both glacial and interglacial high-latitude sediments, the polar species *Neogloboquadrina pachyderma* is most commonly used for stable isotopic analyses providing the downcore stratigraphical framework. Subpolar foraminifera do occur in the NGS during interglacial times and are indicative of the presence of Atlantic water. Kellogg (1976, 1977, 1980) first documented the strong climatic and oceanographic resemblance of the last interglacial optimum, isotopic Substage 5.51, with that of the Holocene. A comparative faunal study of Termination I (isotope stage boundary 1/2) and the Saalian deglaciation, i.e. isotope stage boundary 6/5 (Termination II), by Haake and Pflaumann (1989) also revealed a similarity between these two glacial–interglacial transitions. During Termination II, III, and VI (isotope stage boundaries 6/5, 8/7, 16/15) the planktic foraminifera *Beella megastoma*, of which the genus, as it appears, reveals a subtropical–temperate latitudinal distribution today (Kennett and Srinivasan, 1983; Holmes, 1984), was the only observed species in NGS sediments from such a southerly provenance (Bauch, 1992, 1994). This points to the specific character of terminations which has already been described by Sarnthein and Tiedemann (1990) in sediments off western Africa. Moreover, each of these three *Beella* occurrences in the NGS, named Events B_2, B_3, and B_6 (Bauch, 1994), coincide with the deposition of a distinct terrigenous matrix which always ceased just prior to the subsequent interglacial maximum. These events are likely the result of yet unknown circulation and water mass changes in the NGS and certainly call for a plausible oceanographic explanation. The purposes of this study are to briefly describe the lateral and spatial distribution of *B. megastoma* and eventually to focus on the paleoceanographic evolution of Termination II in more detail.

2. Material and methods

Foraminiferal content and sedimentological aspects of 21 sediment cores from the NGS were used to investigate glacial–interglacial transitions. These cores cover a wide area of the NGS and were collected during cruises of the last decade (Table 1). Most cores have been used for investigations in coarse-size fraction analyses and stable isotope analyses. The samples of the previous workers were used for the micropaleontological investigations of this study. The stratigraphical framework of the cores is mainly based on oxygen isotopes of *N. pachyderma* (sin.) and the SPECMAP time scale with its assignment of oxygen isotope stages and substages according to various authors (Imbrie et al., 1984; Martinson et al., 1987; Vogelsang, 1990). Only two cores extended as far back as Stage 16, i.e. including Termination VI, however the majority of the cores covered at least the past three glacial–interglacial transitions (Table 1).

Table 1
Investigated core material (besides ODP Hole 643A all core numbers according to *Geologisch–Paläontologisches Institut* Kiel, Germany)

Core	Geogr. position		Water depth	Core length	Stratigr. length
	Lat. (°N)	Long.	(m)	(m)	O-Stage
17728-2	76°31.1′	03°57.3′E	2485	6.23	12
17730-4	72°06.7′	07°23.3′E	2749	7.31	7?
17732-1	71°36.8′	04°12.8′E	3103	5.93	7?
21852-2	70°15.7′	15°49.5′W	1117	5.73	8
21906-2	76°50.1′	02°09,1′W	2939	6.53	12
21910-2	75°37.0′	01°20.0′E	2454	6.60	10
23059-3	70°18.3′	03°07.4′W	2281	6.22	10
23062-1	68°43.7′	00°10.1′E	2244	7.00	10
23063-3	68°45.0′	00°00.0′W	2299	9.18	12
23068-3	67°50.0′	01°30.3′E	2230	6.96	7
23243-1	69°22.3′	06°32,1′W	2710	7.67	13
23244-2	69°22.0′	08°40.0′W	2162	6.68	13
23245-1	69°23.0′	10°47.0′W	1750	6.17	15
23246-4	69°23.6′	12°52.1′W	1902	7.09	15
23259-2	72°01.8′	09°15.9′E	2518	7.51	6
23269-1	71°26.3′	00°40.1′E	2867	5.62	6
23351-1	70°21.5′	18°13.2′W	1672	6.19	7?
23352-3	70°00.4′	12°25.8′W	1819	8.26	12
23342-6	71°38.2′	08°38.2′W	1974	5.98	7
23353-5	70°34.2′	12°43.3′W	1394	10.68	11
23359-4	65°31.7′	04°09.6′W	2820	5.99	11
643A	67°42.9′	01°02.0′E	2753	565	

During the past 130 ka, sedimentation rates averaged less than 2 cm/kyr for those cores from the central part of the NGS (e.g. Core 23246), but increased to about 3.5 cm/kyr at sites closer to the shelf (e.g. Core 17732). These linear rates are of course averages and by no means reflect the actual depositional complexity of Terminations. The sedimentation rates vary significantly with much higher values occurring during the glacial–interglacial transitions. This is caused a.o. by the melting of large numbers of icebergs that accompanied the onset of global warming after a glacial period and thus, these time intervals are marked by the delivery of varying amounts of terrigenous ice rafted detritus (IRD) into the marine environment (Henrich, 1992; Bischof, 1994).

Samples used in this investigation were taken as 1 cm thick slices at usually 5–10 cm intervals. For studying the foraminiferal assemblage the size-fractions 125–250 μm and >250 μm were considered separately. All faunal results are expressed as specimens per gram dry bulk sediment. *Beella megastoma* rarely occurred in sizes smaller than 250 μm (Bauch, 1993) and because this species is only present in low concentrations, the entire >250 μm size-fraction was left unsplit during the process of quantification, to take into account every available specimen. Due to the relatively wide sample intervals and hence the possibility that the peak event was not always sampled properly in each core, total numbers of counted *Beella* specimens show strong variations between the cores. The numbers per sample may be as high as 150 to 200 counted specimens (e.g., Cores 21906, and 23352) or considerably lower summing up to a total of only 3 specimens (e.g., Cores 23243, and 23359). But as will be shown even these low numbers are valuable evidence for the presence of a *Beella*-event at these particular core sites.

3. Foraminiferal record

The lateral and stratigraphical distribution of *B. megastoma* for all cores is given in Fig. 2. It is apparent that this species occurrence concentrates on the central part of the NGS ranging from the Aegir Ridge in the south to the Greenland Fracture Zone in the north (Site 21906). This distribution is bounded on either side by cores which did not yield any specimens of *B. megastoma*. Its stratigraphic appearance is restricted to Termination II, III, and VI. It should be noted that it was not possible to identify all of these *Beella*-events in each core, due to the relative wide sampling intervals and the fact that only two out of the entire set of sediment cores actually penetrate isotope stage boundary 15/16 while others even lack stage boundary 7/8 (Table 1). Based on Core 23246 only, Bauch (1994) indicated that the abundances of *B. megastoma* appears to be generally lower in Termination III than in Termination II and VI. With respect to an evaluation of Termination II with Termination III, the original result is confirmed by this study, in which only very few and relatively small-sized specimens were found in Termination III. Nevertheless Event B_2 has a similar distinct lateral distribution as Event B_3. Since the record of *B. megastoma* is strongest in Termination II the following results concentrate on the B_2-event.

The principle results of the faunal analyses for Termination II are shown in Fig. 3. The good correlation of *Turborotalita quinqueloba* peak abundances with the oxygen Substage 5.51 (Eemian) can be exploited to identify the Eemian in either of those cores without isotope record, e.g. Cores 23245 and 23244, or where depth samples of both data sets do not exactly correspond (Core 23059). The light spike in the isotope curve of Core 17732 that predates the *T. quinqueloba* peak is most probably not the Eemian optimum and will be discussed elsewhere (Bauch and Weinelt, in prep.).

All cores document a major occurrence of *B. megastoma* and, with the exception of Cores 21906 and 23359, coincide with the increasing slope towards lighter oxygen values after the Saalian last glacial maximum, isotope Substage 6.2. These low $\delta^{18}O$ values are characteristic for the deglacial process of Termination II prior to Substage 5.51. Besides the investigated biogenic components, it has been noted that *Beella*-event samples are always composed of a certain type of ice-rafted terrigenous material. This consists of angular crystalline rock fragments, e.g. quartz, feldspar, mica, metamorphics, whereas the peak of the *T. quinqueloba* abundances is devoid of any IRD material larger than 63 μm. Due to very small samples available at the time of this investigation (1/4 of the original sample), the weak record of *B. megastoma* in Core 23359 stands out from the others in showing one minor peak above Substage 5.51. This spike is based on a single found specimen and could therefore likely be caused by bioturbation.

The fluctuations in test concentrations of *B. megastoma* reveal that the highest abundances occur in the northern (Core 21906) and western

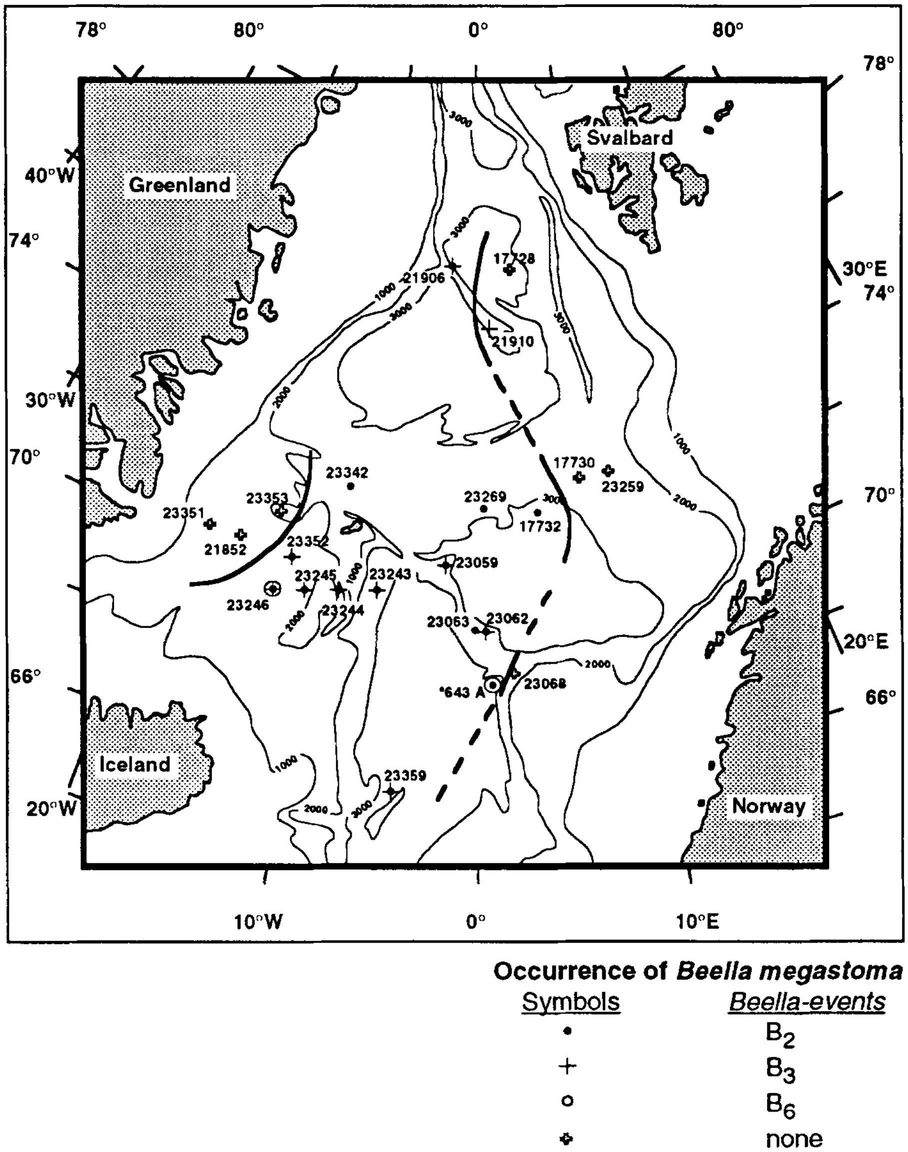
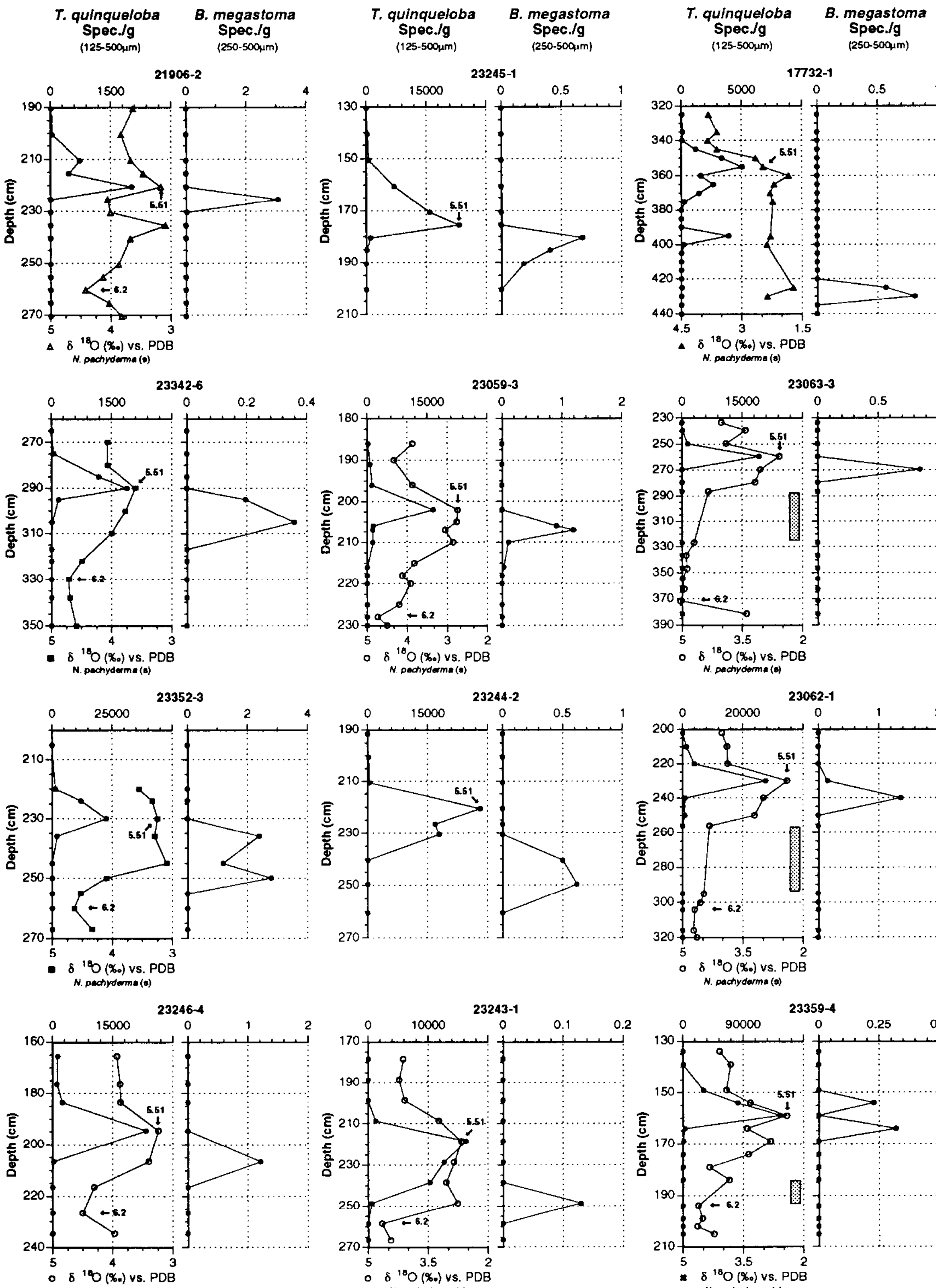


Fig. 2. Investigated cores showing the stratigraphical (symbols) and lateral distribution (inside the lines) of *Beella megastoma*.

part of the NGS (Core 23352) and not below the modern track of the Norwegian Current. Especially Core 23352 can be distinguished from the others because (1) it contains by far the thickest section with specimens of *B. megastoma* and (2) the tests reach the largest observable sizes ranging from 200 to over 700 μm, possibly indicating the presence of pre-adult and adult specimens. Sizes in the remaining cores stay notably below 500 μm.

Those cores from the Norwegian side which did not even yield a B_2-event are characterized by a very broad interval of light stable isotope values (Vogelsang, 1990; Schacht, 1991; Weinelt, 1993).


T. quinqueloba Spec./g (125-500µm)
B. megastoma Spec./g (250-500µm)
21906-2
23245-1
17732-1
23342-6
23059-3
23063-3
23352-3
23244-2
23062-1
23246-4
23243-1
23359-4
Depth (cm)
δ 18O (‰) vs. PDB
N. pachyderma (s)
5.51
6.2

4. The timing of event B_2

4.1. Sedimentological evidence

Besides using the stable isotopes and biostratigraphy as the principle framework, detailed sedimentological observations on the IRD content can be used to gain information about the actual onset of Event B_2 in relation to the entire deglacial process, which more or less progressed continuously since the end of oxygen Substage 6.2. The synchronous appearance of typical crystalline IRD and *B. megastoma* is one important feature. The other one, also noted by Bauch (1994), is the occurrence of grey clastic sediments (mainly siltstones) just prior to Event B_2. The sediments probably derive from the early decay of shelf-based glaciers such as the Barents Sea ice sheet (Spielhagen, 1991; Bischof, 1994). These grey sediments are constituents of a typical dark-colored facies, rarely contain any biogenic carbonates and if any, then these are strongly corroded. This facies reappears at various deglacial phases almost exclusively within cores from the Norwegian side of the NGS and has been recognized as diamictons (Henrich et al. 1989; Vogelsang, 1990; Kuhlemann et al., 1993). These diamictons are present at all eastern sites shown in Fig. 3, cores 23063, 23062, and 23359.

The simultaneous deposition of *B. megastoma* and immature crystalline rock fragments and the absence of diamictons points to a major change in paleoceanographic conditions as well as ice-sheet dynamics. It appears as if during this time glaciers did not incorporate their load from the shelves any longer, but directly from the subaerial continent. Crystalline rocks, e.g. granites, gneisses, and other metamorphics are potential sources and are present in sufficient mass within the Caledonides on either side of the NGS.

4.2. Age framework

Age control of Event B_2 is principally based on oxygen isotopes. Considering the sedimentation processes that have been described from Termination II, the exact assignment of defined substages such as 5.51, 5.52, 5.53, 6.0, and 6.2 from the SPECMAP time scale to the isotope data appears in places to be rather difficult. This especially applies to Substages 5.52–6.0, which are in particular masked by the IRD-meltwater effect (Vogelsang, 1990). Furthermore, previous studies on Termination I based on AMS ^{14}C-ages show that even prominent meltwater spikes may vary considerably in age (Jones and Keigwin, 1989; Vogelsang, 1990; Sarnthein et al., 1992). Therefore, to define the relative age of Event B_2 only Substages 5.51 and 6.2, which are relatively easy to identify, were used for interpolation.

For those cores with stable isotopes, the calculated average age of each B_2-event maximum is listed in Table 2. It is evident that the precision of these ages is strongly dependent upon the sedimentation rate and the density of the sampling intervals. This fact has been taken into account by calculating the average deviation of each B_2-maximum to its closest sample above and below. The isotope record (Fig. 3) and the sediment descriptions (e.g., Dettmer, 1988; Henrich, 1992) reveal that each of the more eastern cores, e.g. 23063 and 23062, contain a thick diamicton during early Termination II. This unusual increase in thickness is caused by high sedimentation rates and document an increase in the number of drifting icebergs and the associated meltwater plumes in this region during Termination II. The diamictons are most likely depositional events of very short duration and represent episodes of increased melting processes. Thus, the apparent scarcity and corrosive nature of occasionally contained biogenic carbonates may result from dilution and possibly reworking of older material rather than from dissolution. These sudden events of increased terrigenous input tend to distort the age framework making the actual *Beella*-event slightly younger. Due to this unexpected strong increase of an otherwise supposedly linear sedimentation rate between Substage

Fig. 3. Test concentrations of subpolar foraminifera *Turborotalia quinqueloba* and *Beella megastoma* in comparison to the $\delta^{18}O$ record (note differences in scale). Grey bars mark the position of diamictons. Isotope data are from × = Gehring, 1989; ○ = Vogelsang, 1990; △ = Hamich, 1991; ▲ = Weinelt, 1993; ■ = this study.

Table 2
Dating and sample resolution of the Event B_2 (maximum concentrations of tests of *B. megastoma*) for those 2 sets of studied cores for which stable isotope record (Substage 6.2–5.51) and subpolar faunal record (*T. quinqueloba*) are available

Core	Depth (cm)	Age (ka)	Sed. rate (cm)	Resolution (kyr[a])	O-Stages
23059[b]	202	122.56	2.07		5.51
	206	124.49			
	207	124.97		0.96	
	210	126.42			
	228	135.10			6.2
23063	260	122.56	8.77		5.51
	270	123.70		1.14	
	280	124.84			
	370	135.10			6.2
21906	220.5	122.56	3.19		5.51
	225.5	124.13		1.57	
	230.5	125.70			
	260.5	135.10			6.2
23062	230	122.56	5.90		5.51
	240	124.25		1.69	
	250	125.95			
	304	135.10			6.2
23359	159	122.56	2.79		5.51
	164	124.35		1.79	
	169	126.14			
	194	135.10			6.2
23352[b]	230	122.56	2.39		5.51
	245	128.83			
	250	130.92		2.09	
	255	133.01			
	260	135.10			6.2
23342	290	122.56	3.19		5.51
	295	124.13			
	305	121.26		3.14	
	310	128.83			
	330	135.10			6.2
23243	218.5	122.56	3.19		5.51
	238.5	128.83			
	248.5	131.97		3.13	
	258.5	135.10			6.2
23246	194.5	122.56	2.55		5.51
	206.5	127.26		4.31	
	216.5	131.18			
	226.5	135.10			6.2

[a]Average resolution of Event B_2. [b]Standard cores with highest sample resolution and no diamicton.

6.2 and 5.51, cores with diamictons therefore also show an artificially good resolution and low ages. If the diamicton in Core 23063 is corrected ($\leqslant$40 cm), the resolution will increase to 1.8 kyr and the age of the B_2-event will rise to 124.4 ka. Considering this fact, the top 5 cores in Table 2 reveal the best resolution, whereas Core 23246 has a deviation of 4.31 kyr due to a low linear sedimentation rate and wide sampling intervals between Substage 5.51 and 6.2. Furthermore, by comparing the ages of each B_2-maximum it becomes apparent that a set of cores from the Iceland Sea and around Jan Mayen (Cores 23243, 23246, 23342, 23352) generally show higher ages than the remaining cores from the north and east. The ages of the Event B_2 differ according to those two cores of both sets with highest resolution and low terrigenous dilution, Core 23352 and Core 23059, as much as 6 kyr.

5. Paleoceanographic interpretation

The large time discrepancy of about 6 kyr between the east/north set of cores and the western cores as well as the presence of *B. megastoma* itself calls for a plausible paleoceanographic explanation.

Based on the presented data, two principle oceanographic scenarios, 'A' and 'B', are suggested which may also be applicable to either Event B_3 and/or B_6. Both scenarios commence at a time during deglaciation when the melting of shelf-based ice masses was complete and glaciers retreated onto the surrounding subaerial landmasses. The continuous calving of glaciers and hence, the presence of melting icebergs resulted in a strongly developed meltwater lid, particularly on the Norwegian side of the NGS (Vogelsang, 1990).

(A) During an early phase of scenario 'A' (Fig. 4), at a time when the East Greenland Current (EGC) was still only marginally developed (see also Fig. 1), a so-called 'Proto-Irminger Current' (grey arrows) carrying Atlantic water was able to penetrate onto the northern Iceland Plateau via Denmark Strait. Due to the continuing deglaciation especially on the Scandinavian continent, and hence, a gradually diminishing meltwater lid

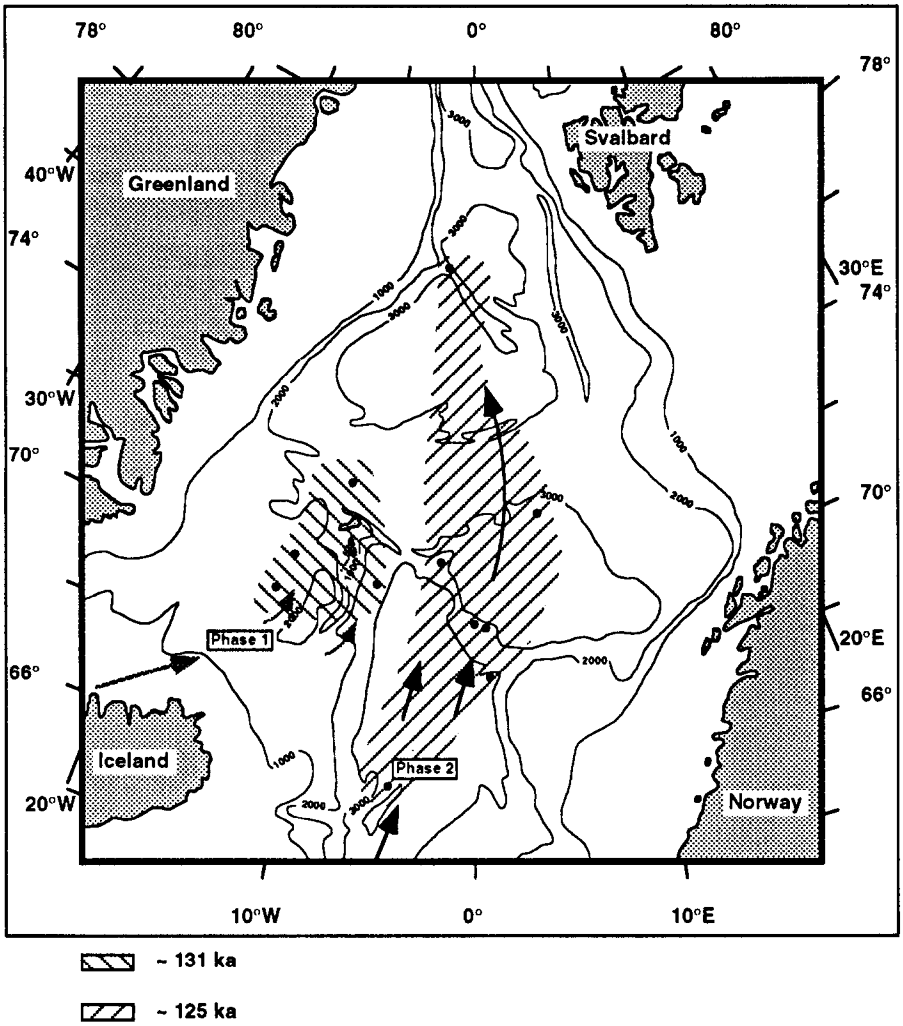


Fig. 4. Proposed two-stepped surface circulation model 'Scenario A' during Event B_2. Grey arrows indicate the proposed 'Proto-Irminger Current', black arrows the Norwegian Current.

in the Norwegian Sea, the 'modern-type' surface water circulation pattern of the NGS started to develop with an inflow of Atlantic water across the Iceland–Scotland Ridge (black arrows). This also promoted a simultaneous strengthening of the EGC and East Iceland Current pushing the former 'Proto-Irminger Current' towards Iceland.

(B) Scenario 'B' shown in Fig. 5 is principally based on the modern circulation pattern with an early inflow of Atlantic water east of Site 23359 (grey arrows). But due to an at that time seasonally existing meltwater lid and ice cover to the north and along the Scandinavian continental margin, this water was hindered on its northbound path. Instead it was deflected to the west along the southern flank of the Vøring Plateau and the Jan Mayen Fracture Zone, similar to the modern branch-off (Fig. 1). During the later phase the proper Norwegian Current started to develop swerving north- and eastwards with *B. megastoma* appearing later in this area.

In both scenarios the final stage (Substage 5.51) is a water circulation pattern similar to today's. Neither meltwater nor ice-rafted material was

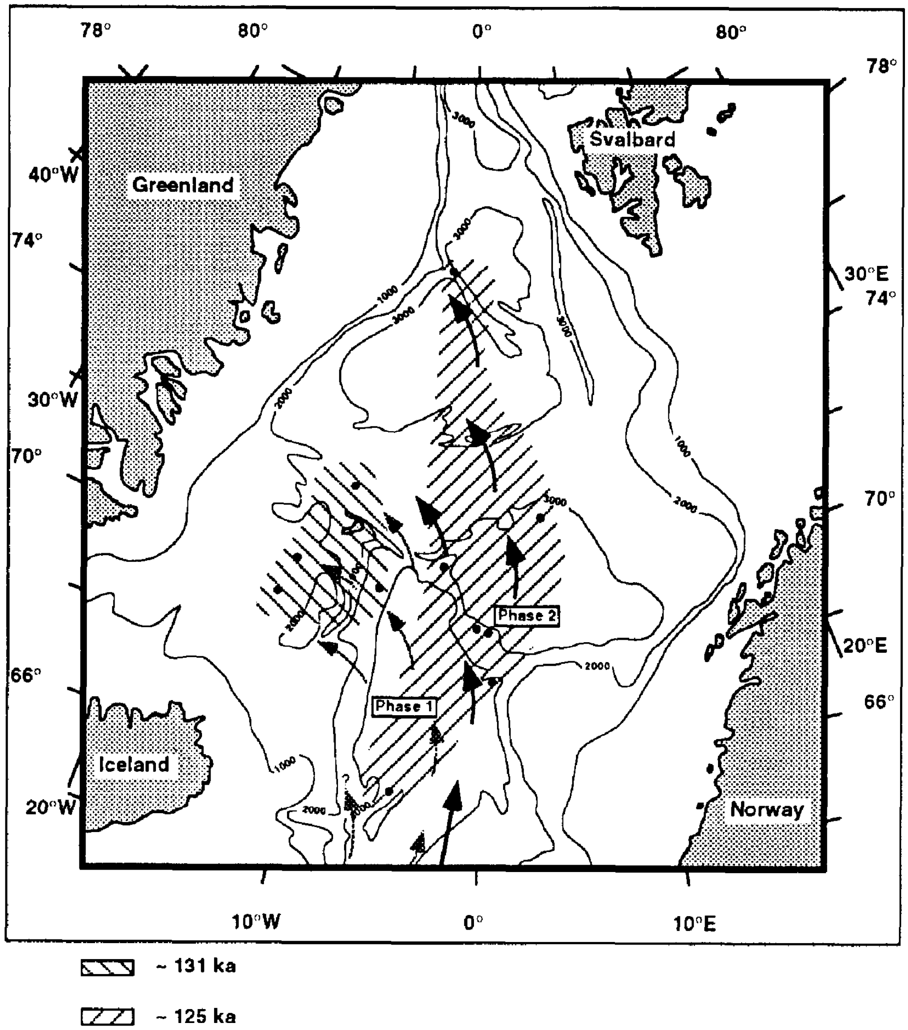


Fig. 5. Proposed two-stepped surface circulation model 'Scenario B' during Event B_2. Grey arrows indicate the early, and black arrows the late Atlantic water inflow during Termination II.

delivered to the NGS, and a subpolar fauna which was much better adapted to this new type of oceanic environment took over from the transient *B. megastoma*.

Both proposed scenarios do not explain why there is such an obvious faunal signal only during Termination II, III, and VI but not during Termination I, IV, and V. All three *Beella*-events coincide with those Terminations proposed to be periods of rapid melting and sea-level rise (Sarnthein and Tiedemann, 1990). Was it possible that these processes resulted in incursions of warm Atlantic water into the NGS during early deglaciation? What we know is that this period lasted ~6 kyr, which is the maximum duration of *B. megastoma*.

Due to the total lack of information concerning the life-habitat of *B. megastoma* it is not known yet if this species can serve as an indicator for a specific Atlantic water mass. For NGS paleoceanographic interpretations Vogelsang (1990), Weinelt et al. (1991), and Sarnthein et al. (1992) have put forward several hypotheses in which a reversal from the present anti-estuarine circulation in the NGS to an estuarine circulation, i.e. a southwardly directed outflow of surface water from the NGS, occurred during times of strong meltwater input, e.g. early Termination I (I_a). Accordingly, this surficial outflow was compensated by an inflow of North Atlantic Intermediate Water (NAIW). Is *B. megastoma* therefore a species that has been transported into the NGS by an inflow of NAIW? Several arguments contradict such a simple solution: (1) It appears unlikely that North Atlantic water is capable of transporting possibly empty planktic foraminiferal tests as far north as 77° latitude during times of generally reduced circulation; (2) if this was the case, then we would expect to find other planktic foraminifera of similar latitudinal provenance as *B. megastoma*. As this study has indicated, subtropical to temperate species occur in very low abundances in the Norwegian Sea, mainly in its southern part below the present track of the Norwegian Current, with peak test concentrations always within Substage 5.51 (Bauch, 1993; Bauch and Weinelt in prep.). This pattern is also reflected in surface sediments (Kellogg, 1976); (3) The presence of *B. megastoma* in various sizes, especially in Core 23352, may indicate the presence of reproductive cycles. Today, planktic foraminifera bloom in the northern NGS during early summer (Carstens and Wefer, 1992). Considering a possible lunar cycle for a foraminifer's life-span (Hemleben et al., 1989), it again appears impossible that living specimens of *B. megastoma* were able to cover the enormous distance from the Rockall area west of Ireland (~50°N), where it can be found today (Holmes, 1984), to 77°N in the NGS, within a very short period during the summer. Consequently, this species was indigenous to the NGS at the time of its occurrence; (4) The unusual large test sizes of sometimes more than 700 μm (Bauch, 1992) support the idea that *B. megastoma* is a fast growing surface dweller, similar to *G. bulloides* (Kroon, 1988) and therefore not indicative of a supposed inflow of NAIW.

Eventually, we need to consider that during Termination II, which coincidentally was also the time of the insolation maximum at high latitudes (Imbrie et al., 1993), the enormous release of meltwater led to a strong salinity decrease, in particular, during the early summer months. This in turn must have caused plenty of sea-ice formation during winter and thus, strong surface water cooling. A further consequence would have been vertical convection (deep water formation) due to brine formation as suggested by Veum et al. (1992) for Termination Ia. The strong seasonal thermal gradient enhanced the vertical overturn due to sea-ice and brine formation and could be a possible trigger mechanism for all recognized *Beella*-events, because deep water formation in the NGS needed to be compensated by a North Atlantic inflow.

6. Conclusions

The data presented in this study confirm the initial results that *B. megastoma* is indicative of Termination II, III, and VI. A detailed investigation from the Saalian isotopic Substage 6.2 to the Eemian interglacial optimum, Substage 5.51 shows that the occurrence of this species (Event B_2) is a hitherto unknown oceanic phenomenon. This oceanic process that accompanied the ensuing deglaciation phase is characterized by the following evidence:

The early onset of the deglaciation witnessed an increased input of greyish siltstones that was derived from the decay of shelf-based glaciers. Once the ice masses had retreated onto the adjacent landmasses of Norway and Greenland, only fresh detrital rock fragments that were not reworked were incorporated and then released via drifting icebergs into the NGS.

The occurrence of *B. megastoma* is first noted in cores from the northern Iceland Plateau at ~131 ka, simultaneously with the deposition of the continental-derived IRD. In the eastern and northern core sites this species appears about 6 kyr later at ~125 ka near the end of the entire Event B_2.

Two scenarios each based on a two-stepped evolution of the Eemian surface water circulation are proposed to account for the presence of *B. megastoma* and the W–E time lag:

During the beginning of scenario 'A' a 'Proto-

Irminger Current' caused an inflow of Atlantic water through the Denmark Strait onto the northern Iceland Plateau. Later, due to a steady strengthening of the NGS circulation pattern, Atlantic water penetrated into the NGS across the Iceland–Scotland Ridge.

Scenario 'B' commences with an early inflow of Atlantic water via the Iceland–Scotland Ridge which circulated westward onto the Iceland Plateau, due to existing meltwater plumes along the Norwegian continental margin and north of the Vøring Plateau. The increasing build-up towards a modern-type circulation pattern and the vanishing meltwater lid in the east, forced the main axis of Atlantic water inflow to shift then north- and eastwards.

The W–E diachronous nature of Event B_2 may also be explained by the permanent presence of meltwater plumes in the Norwegian Sea and thus varying spatial environmental conditions. This meltwater lid led then to a habitat unfavorable for *B. megastoma*.

The wide range of test sizes of *B. megastoma* and its lateral distribution indicate that environmental conditions in the west of the NGS were suitable for this subtropical–temperate species to thrive. Furthermore, the large sizes support the idea that this species is rapidly growing and thus a possible tracer for Atlantic surface water.

A strong seasonal thermal gradient, which promoted winter sea-ice formation and vertical overturn via brine formation, may be the oceanic mechanism that was responsible for the presence of Atlantic water in the NGS already during the early Termination II.

The occurrence of *B. megastoma* stops just prior to the interglacial optimum, Substage 5.51, when the subpolar species *T. quinqueloba* has its highest test concentrations suggesting a modern-type circulation pattern with no deposition of IRD and hence, no meltwater.

There still remains the unsolved question, were these oceanic phenomena which appear to be so dominant during Termination II, III, and VI, but do not occur during Termination I, IV, and V, (1) a simple consequence of the global climatic change at a specific time or, (2) were they actually instrumental in triggering the climatic instability inherent to glacial–interglacial transitions? This undoubtedly poses more questions on the complexities of the oceanographic circumstances which accompanied the major deglaciation phases.

Acknowledgements

This research was supported by grants of the *Deutsche Forschungsgemeinschaft*. I am indebted to D. Bauch, R. Keir, M. Maslin, C. Wold, and R. Zahn for their critical readings and suggestions. Many thanks also to those numerous persons who helped collecting the cores during the various cruises and to those who provided their washed samples as well as isotope data. This paper is contribution No. 221 of the *Sonderforschungsbereich* 313 at Kiel University, Germany.

References

Bauch, H.A., 1992. First record of the genus *Beella* Banner and Blow, 1960, in Upper Pleistocene sediments (past 600 ka) from the Norwegian–Greenland Sea. J. Micropalaeontol., 11(1): 58.

Bauch, H.A., 1993. Planktische Foraminiferen im Europäischen Nordmeer—ihre Bedeutung für die paläo-ozeanographische Interpretation während der letzten 600.000 Jahre. Ber. Sonderforschungsbereich 313, Univ. Kiel, Germany, 40: 1–108.

Bauch, H.A., 1994. *Beella megastoma* (Earland) in late Pleistocene Norwegian–Greenland Sea sediments: Stratigraphy and meltwater implication. J. Foraminiferal Res., 24(3): 171–177.

Baumann, K.-H. and Matthiessen, J., 1992. Variations in surface water mass conditions in the Norwegian Sea, evidence from Holocene coccolith and dinoflagellate cyst assemblages. Mar. Micropaleontol., 20: 129–146.

Baumann, K.-H., Lackschewitz, K.S., Erlenkeuser, H., Henrich, R. and Jünger, B., 1993. Late Quaternary calcium carbonate sedimentation and terrigenous input along the east Greenland continental margin. Mar. Geol., 114: 13–36.

Bischof, J., 1994. The decay of the Barents ice sheet as documented in Nordic seas ice-rafted debris. Mar. Geol., 117: 35–55.

Broecker, W.S. and Denton, G.H., 1989. The role of ocean–atmosphere reorganisations in glacial cycles. Geochim. Cosmochim. Acta, 53(10): 2465–2501.

Broecker, W.S., Andree, M., Wolfli, W., Oeschger, H., Bonani, G., Kennett, J. and Peteet, D., 1988. The chronology of the last deglaciation: Implications to the cause of the Younger Dryas event. Paleoceanography, 3(1): 1–19.

Carstens, J. and Wefer, G., 1992. Recent Distribution of planktonic foraminifera in the Nansen Basin, Arctic Ocean. Deep-Sea Res., 39(Suppl. 2): S507–S524.

Dansgaard, W., White, J.W.C. and Johnson, S.J., 1989. The abrupt termination of the Younger Dryas climate event. Nature, 339: 532–533.

Dettmer, A., 1988. Ein Beitrag zur Rekonstruktion der spätquatären Entwicklung der zentralen Norwegisch-Grönländischen See des Meteor-Kernes GIK 23063-3. M.Sc. Thesis, Univ. Kiel, Germany.

Gehring, H., 1989. Beitrag zur paläo-ozeanographischen Entwicklung der südwestlichen Norwegischen See während der letzten 405.000 Jahre. M.Sc. Thesis, part 2, Univ. Kiel, Germany, pp. 1–65.

Haake, F.W. and Pflaumann, U., 1989. Late Pleistocene foraminiferal stratigraphy on the Vøring Plateau, Norwegian Sea. Boreas, 18(4): 343–356.

Hamich, A., 1991. Sedimentologische Untersuchungen eines Kernes (GIK 21906-2) der Grönlandsee. M.Sc. Thesis, part 2, Univ. Kiel, Germany, pp. 1–78.

Hemleben, C., Spindler, M. and Anderson, O.R., 1989. Modern Planktonic Foraminifera. Springer, New York, 363 pp.

Henrich, R., 1992. Beckenanalyse des Europäischen Nordmeeres: Pelagische und glaziomarine Sedimenteinflüsse im Zeitraum 2.6 Ma bis rezent. Habilitation, Univ. Kiel, Germany.

Henrich, R., Kassens, H., Vogelsang, E. and Thiede, J., 1989, Sedimentary facies of glacial/interglacial cycles in the Norwegian Sea during the last 350 ka. Mar. Geol., 86: 283–319.

Holmes, N.A., 1984. An emendation of the genera *Beella* Banner and Blow, 1960, and *Turborotalita* Blow and Banner 1962, with notes on *Orcardia* Boltovskoy and Watanabe, 1982. J. Foraminiferal Res., 14(2): 101–110.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L. and Shackleton, N.J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: A.L. Berger et al. (Editors), Milankovitch and Climate, I. Kluwer, Dordrecht, pp. 269–305.

Imbrie, J., Berger, A., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J., Martinson, D.G., McIntyre, A., Mix, A.C., Molfino, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shackleton, N.J. and Toggweiler, J.R., 1993. On the structure and origin of major glaciation cycles 2. The 100,000-year cycle. Paleoceanography, 8(6): 699–735.

Jansen, E. and Bjørklund, K.R., 1985. Surface ocean circulation in the Norwegian Sea, 15,000 B.P. to Present. Boreas, 14: 243–257.

Jones, G.A. and Keigwin, L.D., 1989. Evidence from Fram Strait (78°) for early deglaciations. Nature, 336: 56–59.

Kellogg, T.B., 1975. Late Quaternary climatic changes in the Norwegian–Greenland Sea. In: G. Weller and S.A. Bowling (Editors), Climate of the Arctic. Proc. 24th Alaska Sci. Conf. Geophys. Inst., Univ. Alaska, Fairbanks, AK, pp. 3–36.

Kellogg, T.B., 1976. Late Quaternary Climatic Changes: Evidence from the Deep-Sea cores of Norwegian and Greenland Seas. Geol. Soc. Am. Mem., 145: 77–110.

Kellogg, T.B., 1977. Paleoclimatology and paleo-oceanography of the Norwegian and Greenland Seas: The last 450.000 years. Mar. Micropaleontol., 2: 235–249.

Kellogg, T.B., 1980. Paleoclimatology and paleoceanography of the Norwegian and Greenland Seas: Glacial–interglacial contrasts. Boreas, 9: 115–137.

Kennett, J.P. and Srinivasan, M.S., 1983. Neogene Planktonic Foraminifera. Hutchinson Ross, Stroudsburg, PA, 265 pp.

Koç-Karpuz, N. and Jansen, E., 1992. A high-resolution diatom record of the last deglaciation from the SE Norwegian Sea: Documentation of rapid climatic changes. Paleoceanography, 7(4): 499–520.

Kroon, D., 1988. The planktic $\delta^{13}C$ record, upwelling and climate. In: D.A. Brummer and D. Kroon (Editors), Planktonic Foraminifers as Tracers of Ocean-Climate History. Amsterdam, pp. 335–346.

Kuhlemann, J., Lange, H. and Paetsch, H., 1993. Implication of a connection between clay mineral variations and coarse grained debris and lithology in the central Norwegian–Greenland Sea. Mar. Geol., 114: 1–11.

Lehman, S.J. and Keigwin, L.D., 1992. High resolution record of the North Atlantic drift 14–8 kyr BP: Implications for climate, circulation, and ice sheet melting. Nature, 356: 757–762.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C. and Shackleton, N.J., 1987. Age dating and the orbital theory of the Ice Ages: Development of a high-resolution 0 to 300.000 years chronostratigraphy. Quat. Res., 27: 1–29.

Sarnthein, M. and Tiedemann, R., 1990. Younger Dryas-style cooling events at glacial Terminations I–VI at ODP-Site 658: Associated benthic $\delta^{13}C$ anomalies constrain meltwater hypothesis: Paleoceanography, 5(6): 1041–1055.

Sarnthein, M., Jansen, E., Arnold, M., Duplessy, J.C., Erlenkeuser, H., Flatoy, A., Weinelt, M., Veum, T. and Vogelsang, E., 1992. $\delta^{18}O$ time-slice reconstructions of meltwater anomalies at Termination I in the North Atlantic between 50 and 80°N. In: E. Bard and W.S. Broecker (Editors), The Last Deglaciation: Absolute and Radiocarbon Chronologies. Springer, Berlin, pp. 183–200.

Schacht, R., 1991. Paläo-ozeanographische Entwicklung des Gebietes der zentralen Greenland-Fracture-Zone während der vergangenen 350.000 Jahre. M.Sc. Thesis, Univ. Kiel, Germany.

Spielhagen, R., 1991. Die Eisdrift in der Framstaße während der letzten 200.000 Jahre. Geomar Rep., Univ. Kiel, Germany, 4: 1–133.

Swift, J.H., 1986. The Arctic Waters. In: B.G. Hurdle (Editor), The Nordic Seas. Springer, New York, pp. 129–151.

Taylor, K.C., Lamorey, G.W., Doyle, G.A., Alley, R.B., Grootes, P.M., Mayewski, P.A., White, J.W.C. and Barlow, L.K., 1993. The 'flickering switch' of late Pleistocene climate change. Nature, 361: 432–436.

Veum, T., Jansen, E., Arnold, M., Beyer, I. and Duplessy, J.-C., 1992. Water mass exchange between the North Atlantic

and the Norwegian Sea during the past 28,000 years. Nature, 356: 783–785.
Vogelsang, E., 1990. Paläo-Ozeanographie des Europäischen Nordmeeres anhand stabiler Kohlenstoff- und Sauerstoffisotope. Ber. Sonderforschungsbereich 313, Univ. Kiel., Germany, 23: 1–137.
Weinelt, M., 1993. Veränderungen der Oberflächenzirkulation im Europäischen Nordmeer während der letzten 60.000 Jahre—Hinweise aus stabilen Isotopen. Ber. Sonderforschungsbereich 313, Univ. Kiel, Germany, 41: 1–106.
Weinelt, M.S., Sarnthein, M., Vogelsang, E. and Erlenkeuser, H., 1991. Early decay of the Barents shelf ice sheet—Spread of stable isotope signals across the eastern Norwegian Sea. Nor. Geol. Tidsskr., 71: 137–140.