

## Changes in Arctic Ocean paleoproductivity and hydrography during the last 145 kyr: The benthic foraminiferal record

Jutta E. Wollenburg

Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany

Wolfgang Kuhnt

Department of Geosciences, Kiel, Germany

Andreas Mackensen

Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany

**Abstract.** The benthic foraminiferal record of two sediment cores at 900 and 2500 m water depth in the marginal Arctic Ocean reflects fluctuations in paleoproductivity, ice sheet extent, and Atlantic water inflow. Highest paleoproductivity is observed in interglacial periods, and at the termination of interstadials to stadials within oxygen isotope substages (OIS) 6.3, 5.3, 5.1, 3.1, and Termination Ia. Stable and high paleoproductivity at the ice-edge during terminations is indicated by the *Melonis zaandami* benthic foraminiferal association. Periods of glacial ice sheet advance or retreat from the core site are dominated by benthic foraminiferal associations related to seasonal organic carbon flux. Temperate saline Atlantic water entered the Arctic Ocean within OIS 6.3, 5.5 and the Holocene. Coincident paleoproductivity maxima are related to extended seasonal ice retreat. During glacial periods of stagnating Atlantic water advection unusual low paleoproductivity values are observed in the Arctic Ocean, indicating increasing ice coverage. Deep water was poorly ventilated during these periods and the deeper site became exposed to corrosive bottom waters.

### 1. Introduction

Modulated on the astronomic cycles, the paleoceanography of the Arctic Ocean is controlled by the advection of heat from the Atlantic Ocean [Broecker and Denton, 1989; Broecker *et al.*, 1990; Broecker, 1992; Dokken and Jansen, 1999]. Warm, saline Atlantic water flows through Fram Strait and the Barents Sea into the Arctic Ocean and thus maintains poleward heat transport and water exchange with the Atlantic Ocean [e.g., Rudels, 1996]. The inflowing warm Atlantic water significantly influences the temporal and spatial seasonal ice retreat and thus primary production [Wassman and Slagstad, 1993; Gosselin *et al.*, 1998]. A thirty-fold enhanced primary production in seasonally ice-free areas off Spitsbergen, compared to areas under permanent ice cover, is reflected by the modern benthic foraminiferal fauna [Wollenburg and Mackensen, 1998a]. Short-term advectations of temperate Atlantic water through Fram Strait into the Arctic Ocean led to seasonally ice-free waters and enhanced primary production also during the late Weichselian ("Nordway events") [Hebbeln *et al.*, 1994; Dokken and Hald, 1996; Knies and Stein, 1998].

In this study, we analyze the benthic foraminiferal record of two sediment cores of the marginal Arctic Ocean, close to the Fram Strait gateway and close to the mean modern summer ice edge. We compare these data to a data set on Recent living and dead benthic foraminifera derived from 91 sites in the Arctic Ocean [Wollenburg and Mackensen, 1998a; Wollenburg and

Kuhnt, The response of benthic foraminifers to carbon flux and primary production in the Arctic Ocean, submitted to *Marine Micropaleontology*, 2000] [hereinafter referred to as Wollenburg and Kuhnt, submitted manuscript, 2000]. This enables us to discuss faunal results in comparison to the modern Arctic Ocean environment. On the basis of the modern data set a simple transfer function based on the relation between the modern benthic foraminiferal fauna and local primary production was established using correspondence analysis [Wollenburg and Kuhnt, submitted manuscript, 2000]. Here we apply this transfer function to the long term sediment record and make quantitative estimates of paleoproductivity in the marginal Arctic Ocean.<sup>1</sup> Stable isotope data of infaunal and epifaunal benthic foraminifera are compared to previously published planktic foraminiferal isotope curves, and are used to constrain the assemblage-based paleoproductivity estimates.

### 2. Material and Methods

Gravity core PS2138-1 (81°32'N, 30°36'E, 995 m water depth) and kasten core PS2212-3 (82°04'N, 15°43'E, 2550 m water depth) were recovered from the continental slope of the Barents Sea and the Yermak Plateau during R/V *Polarstern* cruises ARK VIII/2 and 3 [Rachor, 1992; Fütterer, 1992] (Figure 1). Both cores were sampled in 5-10 cm intervals. Samples were 1 cm thick, mean sample volume was 48 cm<sup>3</sup>, and mean dry weight was 61 g. Samples were wet sieved after freeze-drying using a 63 µm sieve and dry sieved using a 125 µm sieve. We counted at

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<sup>1</sup>Supporting Tables 2-5 are available electronically via <http://www.pangaea.de/home/jwollenburg>.

- Location of surface samples (multiple or box cores) analyzed for living and dead foraminifers
- ⊛ Location of sediment cores PS2138-1 and PS2212-3
- Mean summer sea ice edge after Sanderson [1988]
- Atlantic water inflow; WSC: Westspitsbergen Current
- East Greenland Current : passage of outflowing Arctic water masses and sea ice

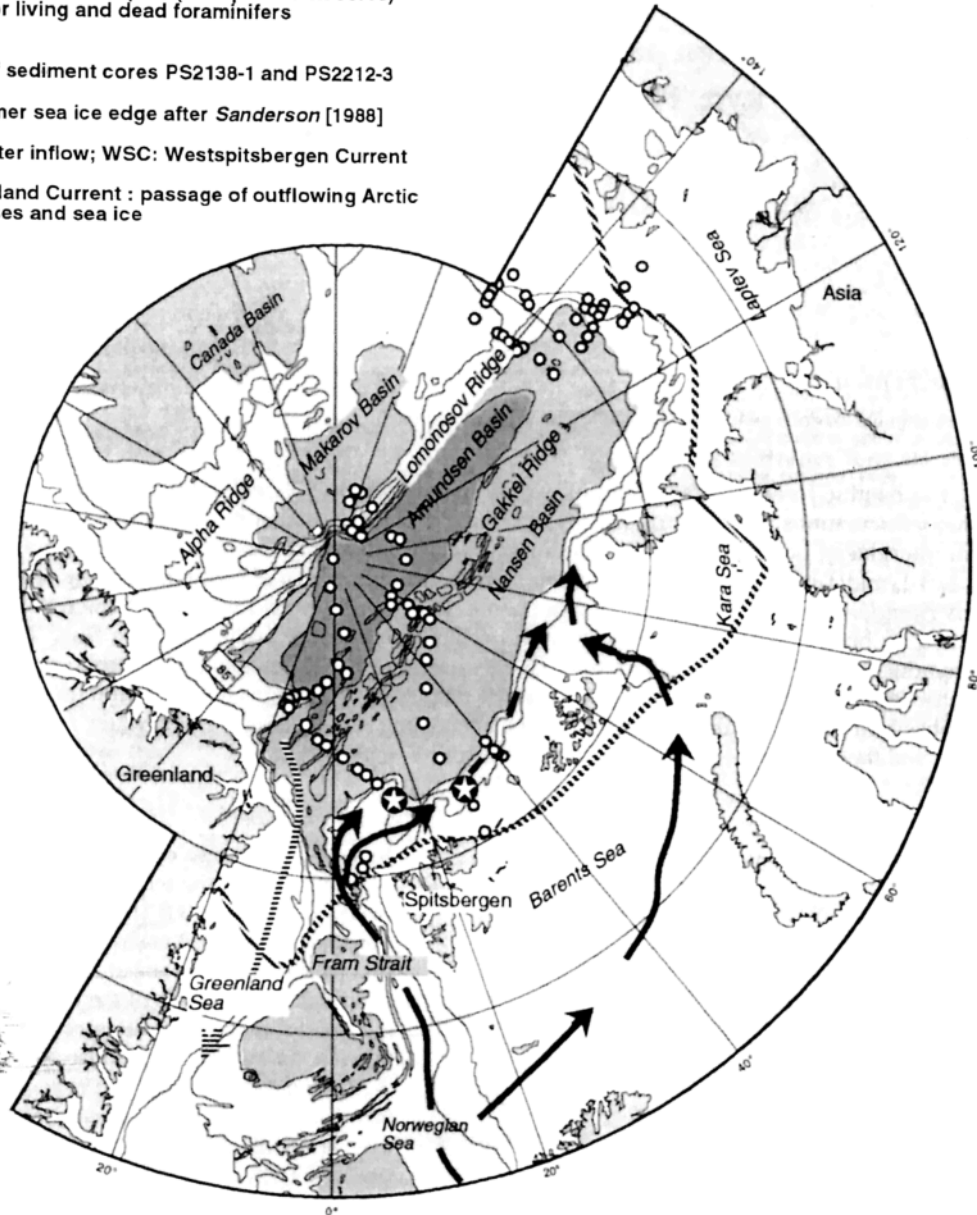


Figure 1. Study area with sample locations.

least 300 foraminifera from each size fraction (>125, and 63-125  $\mu\text{m}$ ). Data of the >125, and 63-125  $\mu\text{m}$  size fractions were combined for the statistical faunal analyses.

Benthic foraminiferal accumulation rates (BFAR) were calculated from the number of individuals per gram dry sediment using mass accumulation rates (MAR) of Knies [1999] and Vogt [1997]. These MAR were calculated from wet bulk density and linear interpolated sedimentation rates between stratigraphic tie points using the equation of van Andel [1975]:

$$\text{MAR} = \text{LSR} * [\text{WBD} - 1.026 (\text{PO}/100)];$$

where LSR = linear sedimentation rate ( $\text{cm } 1000 \text{ yr}^{-1}$ ), WBD is wet bulk density ( $\text{g}/\text{cm}^3$ ), and PO is porosity (in percent)

We used a commercially distributed program (SYSTAT 5) for Q mode principal component analysis with subsequent Varimax rotation. The principal components were used for the definition

of foraminiferal associations. Samples which contained <30 specimens and species which did not exceed 1% of the fauna in at least two samples were excluded from the data set [Mackensen *et al.*, 1995]. We used the software package ECOLOGIX written in 1982 by M. Roux (Montpellier University) for correspondence factor analysis (AFC). The core foraminiferal counts were transformed into a 0-9 scale maintaining the same scaling as in the coding of the modern foraminiferal counts (Table 1). We used the modern dead foraminiferal counts [Wollenburg and Kuhnt, submitted manuscript, 2000] as active matrix and treated foraminiferal counts of the core samples as passive elements (see Kuhnt *et al.* [1999] for details). AFC revealed only one meaningful factor (CF1). The modern dead foraminiferal CF1 values showed an obvious correlation to organic carbon flux ( $C_{org}$  flux =  $0.291 \times 10^{11} \text{ g C yr}^{-1}$ , correlation coefficient of  $r = 0.9$ ) [Wollenburg

**Table 1.** Correspondence Analysis: Foraminiferal Counts / Codings

Active Data Set: Dead Foraminifers of Surface Samples		Passive Data Set Fossil Foraminifers	
Code	Counts	Code	Counts
0	<30	0	<4
1	<100	1	<13
2	<250	2	<33
3	<500	3	<66
4	<750	4	<99
5	<1250	5	<165
6	<2500	6	<333
7	<5000	7	<666
8	<10000	8	<1332
9	>10000	9	>1332

Specimen numbers of foraminifers were transformed in a 0-9 matrix according to their absolute abundances per 10 cm<sup>2</sup> sediment surface and per 10 g dry sediment for active and passive data set, respectively.

and Kuhnt, submitted manuscript, 2000]. This correlation function was used as transfer function for the calculation of paleo-C<sub>org</sub> fluxes from the core CF1. Paleoproductivities were calculated using the equation of Suess [1980], after sea level correction according to Vogelsang [1990, Table A-7]. The Shannon-Wiener index ((H(S)) [Hayek and Buzas, 1997] was used for the calculation of diversities.

Stable isotope analyses were carried out in the stable isotope laboratory at the Alfred-Wegener-Institute in Bremerhaven with a Finnigan MAT 251 isotope ratio gas mass spectrometer directly coupled to an automatic carbonate preparation device (Kiel I) and calibrated via NBS-19 to the Peedee belemnite (PDB) scale. All values are given in  $\delta$  notation versus Vienna Peedee belemnite (VPDB). The overall precision of the measurements based on repeated analyses of a laboratory standard (Solnhofen limestone) over a 1 year period was better than 0.06 and 0.08‰ for carbon and oxygen, respectively.

The stratigraphic framework of core PS2138-1 is based on oxygen and carbon isotope records of the planktonic foraminifer *Neoglobobulimina pachyderma* sinistral (s) [Knies and Stein, 1998]. The definition of oxygen isotope stages and their conversion into absolute ages follows the timescale of Martinson et al. [1987]. The stratigraphic control is further supported by several accelerator mass spectrometry (AMS) <sup>14</sup>C dates [Knies and Stein, 1998], pre-Holocene maxima occurrences of benthic foraminifer *Pullenia bulloides* indicating oxygen isotope stages (OIS) 5.1 and 5.5 [Haake and Pflaumann, 1989], and *Siphotextularia rolshauseni* confined to the late OIS 3.2 [Nees and Struck, 1994]. The <sup>14</sup>C dates are  $\delta^{13}$ C-normalized and corrected for a reservoir effect of 440 years [Knies and Stein, 1998]. We applied the age model of Knies and Stein [1998] but recalculated the calendar ages between 34 and 59 <sup>14</sup>C kyr according to Völker et al. [1998]. Given ages if not denoted as <sup>14</sup>C ages will be calendar ages. Because of extended zones barren of calcareous foraminifera core PS2212-3 was not directly dated but correlated to the nearby well-dated core PS1533-3 using paleomagnetic data [Nowaczyk and Baumann, 1992; Nowaczyk et al., 1994; Vogt, 1997]. This

correlation was corroborated by the occurrences of *P. bulloides* (OIS 5.5, 5.1, and the Holocene) and *S. rolshauseni*. (late OIS3-2).

### 3. Results

#### 3.1. Species Richness and Taphonomy

The foraminiferal fauna of core PS2138-1 comprises 75 species. Mean species number per sample is 11 (minimum 6 and maximum 19). Core PS2212-3 reveals a large species number of 124, yet mean species number per sample (excluding barren intervals) is only 2.5 (minimum 2 and maximum 15). In core PS2138-1 a considerable taphonomic loss of agglutinated foraminifera is observed, and agglutinated foraminifera are nearly absent in sediments older than the Younger Dryas. In both cores, carbonate dissolution affected the foraminiferal fauna during interglacial periods of enhanced paleoproductivity [Wollenburg and Mackensen, 1998a]. Intensive carbonate dissolution is also obvious in glacial, stadial sediments. However, although there is a varying taphonomic loss, all samples of core PS2138-1 still have a high number of species in common, a precondition for our reconstruction of environmental changes from benthic foraminiferal associations of core PS2138-1. Core PS2212-3 shows no consistent down-core taphonomic loss: Sediments with high carbonate contents are usually barren of agglutinated foraminifera, whereas only agglutinated foraminifera are observed in sediments above completely barren intervals. The environmental conditions of these purely agglutinated faunas are difficult to interpret since they have no real analog in the modern Arctic Ocean.

#### 3.2. Isotope Stratigraphy

The stable isotopic record of planktonic *N. pachyderma* (s) has been published in detail by Knies and Stein [1998] and Vogt [1997]. Although the global oxygen isotope signal of the surface water may be influenced by local meltwater events, the isotopic record of core PS2138-1 clearly shows evidence of OIS 1 through the upper part of OIS 6 [Knies et al., 2000] (Figure 2). The planktonic foraminiferal record of core PS2212-3 is less continuous than that of core PS2138-1, and extended periods, especially during glacial stages, are barren of any kind of microfossils (Figure 2). Oxygen isotope event 6.3 is indicated by a shift to low  $\delta^{18}$ O values of 3.7‰ for surface and 4.3‰ (*C. teretis*) for deep water masses (Figure 2). Oxygen isotope event 6.2 shows highest  $\delta^{18}$ O values in planktonic (4.7 and 4.4‰ in core PS2138-1 and PS2212-3, respectively) and benthic foraminifera (4.7 and 4.9‰ for *M. zaandami* and *C. teretis* (PS2138-1) and 5.0‰ for *O. tener* (PS2212-3). The low  $\delta^{18}$ O value (2.1‰) of planktonic foraminifera at 128.4 kyr is attributed to the influence of low isotopic deglacial water and is interpreted as representing the OIS 6/5 boundary (Termination II) [Knies et al., 2000; see also Hevrøy et al., 1996]. The same trend is obvious in  $\delta^{18}$ O values of benthic foraminifera where lowest  $\delta^{18}$ O values of 1.7 and 1.86‰ for *C. teretis* and *M. zaandami* are measured [see also Scott et al., 1989]. The  $\delta^{13}$ C values of *C. teretis* and *M. zaandami* also decrease to -1.3 and -2.3‰ (Figure 2). Substage 5.5 is indicated by low  $\delta^{18}$ O values of planktonic and benthic and low  $\delta^{13}$ C values of benthic foraminifera. The OIS 5/4 boundary is indicated by a marked shift in the oxygen isotope record of planktonic by +0.7 and +0.4‰ in cores PS2138-1 and PS2212-3, respectively, and of

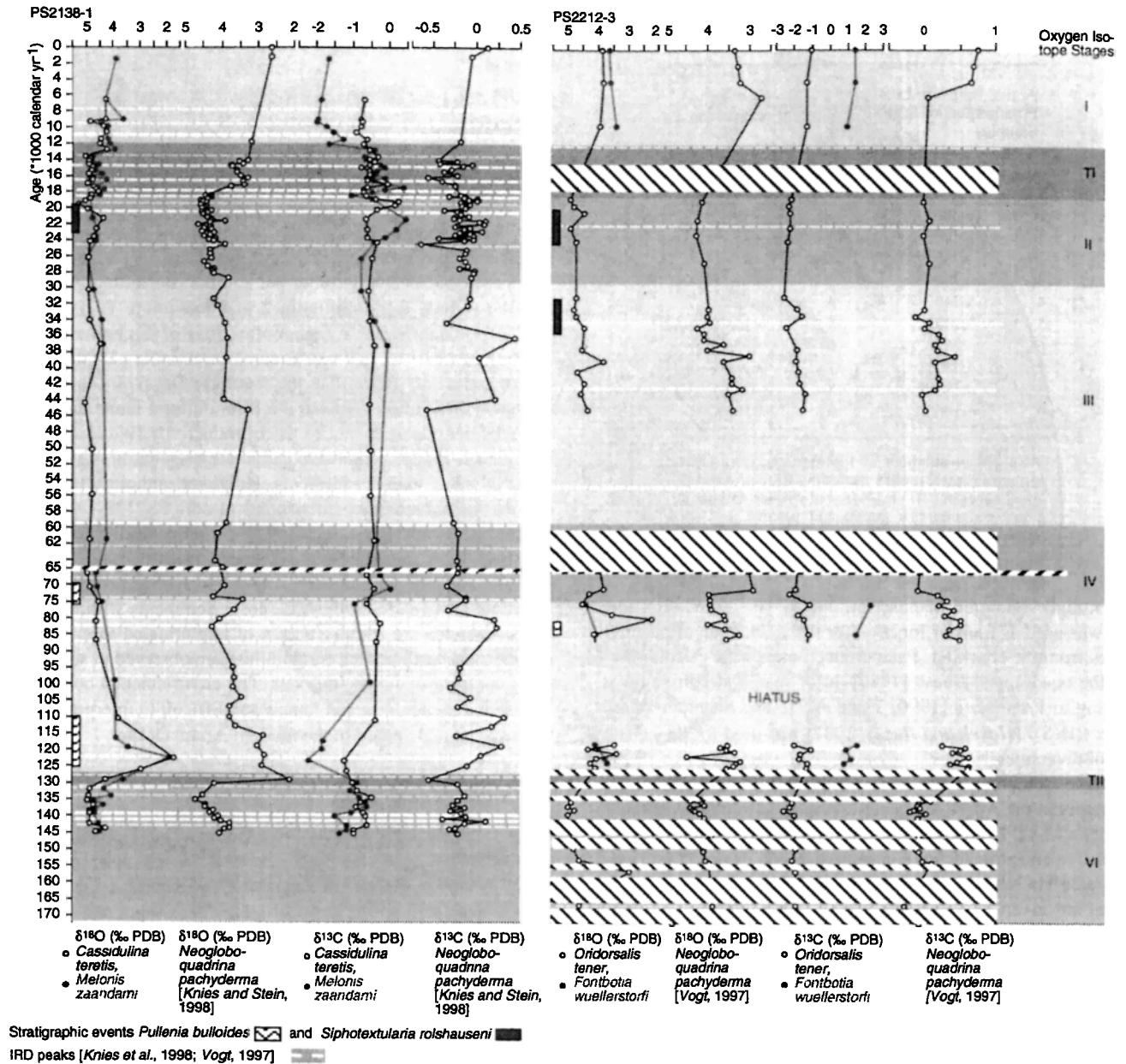


Figure 2. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  (percent Pee Dee belemnite (PDB)) values of benthic and planktonic foraminifera

benthic foraminifera by  $+0.2$ - $0.3$  and  $1\text{‰}$  in cores PS2138-1 and PS2212-3, respectively. At the same time, the  $\delta^{13}\text{C}$  values of benthic foraminifera increase by  $0.8$  and  $0.7\text{‰}$  in cores PS2138-1 and PS2212-3, respectively. The OIS 3/2 boundary is indicated by a shift to higher  $\delta^{18}\text{O}$  values in planktonic foraminifera. The onset of Termination I is dated at  $18.1$  ( $15.4$   $^{13}\text{C}$  kyr (PS2138-1), and well defined by the transition to low  $\delta^{18}\text{O}$  values in planktonic and prominent  $\delta^{13}\text{C}$  minima in benthic foraminifera. Although time resolution is low, samples of core PS2138-1 of OIS 2 and the Holocene were collected in time intervals of 200-300 years. The  $\delta^{18}\text{O}$  values of benthic and planktonic foraminifera usually show coincident variations (Figure 2). Lowest  $\delta^{18}\text{O}$  values correspond to sediments of Eemian and Holocene age. Eemian  $\delta^{18}\text{O}$  values are even lower than Holocene values. During OIS 2-4, 5.1-5.3, and 6,  $\delta^{18}\text{O}$  values are  $\sim 2$  and  $1\text{‰}$  higher in benthic and

planktonic foraminifera, respectively. No such trend is visible in the  $\delta^{13}\text{C}$  values of benthic and planktonic foraminifera (Figure 2). *Neoglobobquadrina pachyderma* show highest  $\delta^{13}\text{C}$  values within OIS 5, middle 3, and Holocene sediments following the Termination Ib. The  $\delta^{13}\text{C}$  values of *M. zaandami* and *C. teretis* show about the same general fluctuations, yet during OIS 6.3, 5.1, and the Termination Ib the  $\delta^{13}\text{C}$  values decrease of *M. zaandami* exceeds during the Eemian and the Holocene that of *C. teretis* by  $1$  by  $2\text{‰}$ , respectively.

### 3.3. Diversity

In core PS2138-1, in analogy to the modern Arctic Ocean [Wollenburg and Kuhnt, submitted manuscript, 2000], down-core benthic foraminiferal diversity fluctuations exhibit the same

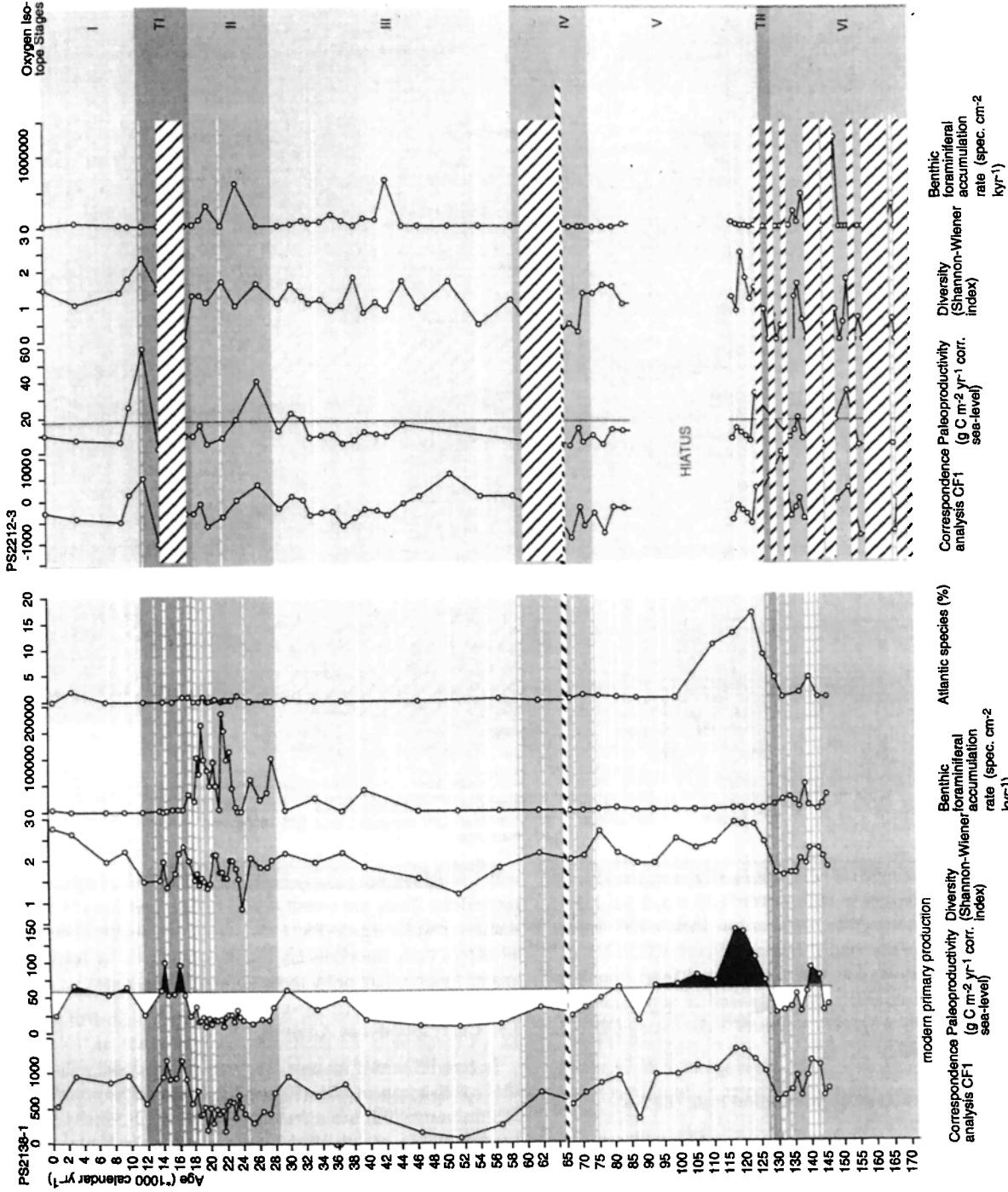


Figure 3. Correspondence analysis factor values (CF1), calculated paleoproductivity, Shannon-Wiener index, benthic foraminiferal accumulation rate, and percentage of "Atlantic species."

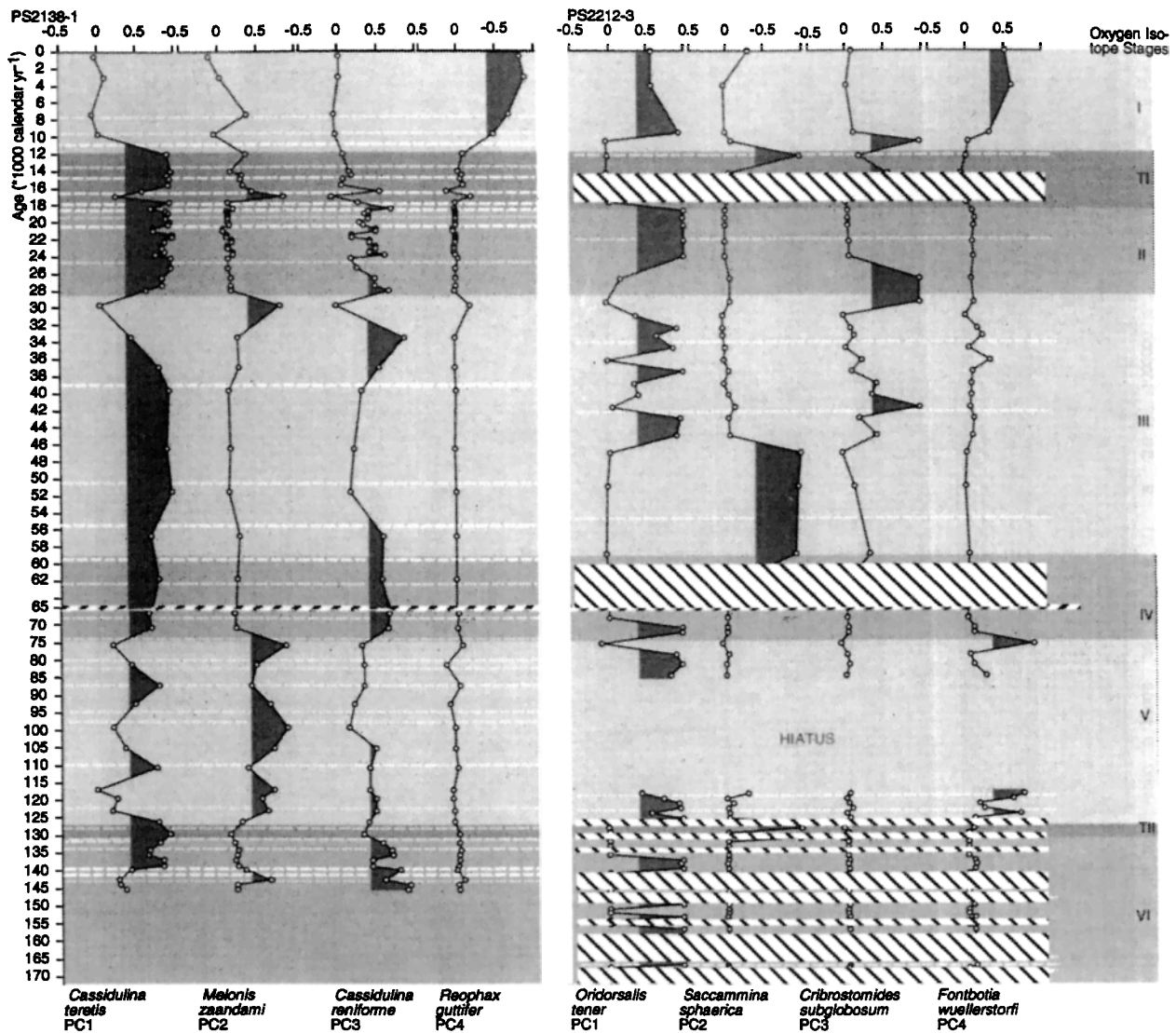


Figure 4. Distribution of foraminiferal principal component association, highest PC factor loadings.

trends as changes in sample CF1 (Figure 3). High sample CF1 are matched by high diversities in sediments of OIS 6.3, 5.5-5.3, 5.1, late 3.1, and the Termination Ia, whereas low sample CF1 are revealed from low diversity stadial faunas. In core PS2212-3, diversity shows rapid down-core fluctuations, and apart from Termination I to Holocene sediments in general is non-parallel to changes in sample CF1. Highest diversities occur during OIS 5.5, 5.1, and Termination Ia.

#### 3.4. Benthic Foraminiferal Accumulation Rate (BFAR)

The BFAR shows large fluctuations (0-184,887, with mean of 28,653, and 0-1,289,121, with mean of 61,526, species per 10 cm<sup>3</sup> kyr<sup>-1</sup> in cores PS2138-1 and PS2212-3, respectively) (Figure 3). Extremely low BFAR are revealed from OIS 4 and interglacial and interstadial sediments of OIS 5, 3, and the Holocene, whereas highest BFAR correspond to glacial stadials OIS 6, 3, and 2. Sediments with high BFAR reveal a diverse calcareous foraminiferal fauna. Even small calcareous tests are usually bright and clear, with no signs of dissolution. In contrast, sediments

with low BFAR are usually depleted in small-sized calcareous foraminifera. Tests are usually dull, brittle, and heavily edged at shallower water depth (PS2138-1). In coincidence, at deeper water depths these intervals are usually comprised by solely agglutinated foraminifera or by foraminiferal barren zones.

#### 3.5. Correspondence Analysis

In core PS2138-1, samples show fluctuating CF1 values of 67-1317, with mean of 676 (Figure 3). Extraordinary high sample CF1 values (>700) are referred to OIS 6.3, 5.5-5.3, 5.1, late 3.1, Termination Ia, and the Holocene excluding the Younger Dryas, and the core top sample. Stadial sediments reveal about one third lower sample CF1. Extraordinary high sample CF1 are observed in coincidence with the immigration of Atlantic species (*Epistominella pusilla*, *Discorbinella berthelothi*, and *Pullenia* spp.), low  $\delta^{13}\text{C}$  values of benthic, and in parallel or slightly lagging, low  $\delta^{18}\text{O}$  values of planktonic and benthic foraminifera (Figure 2). In core PS2212-3, CF1 values fluctuate between -1024 and 1129, with a mean at -224. Extraordinary high sample CF1 are calcu-



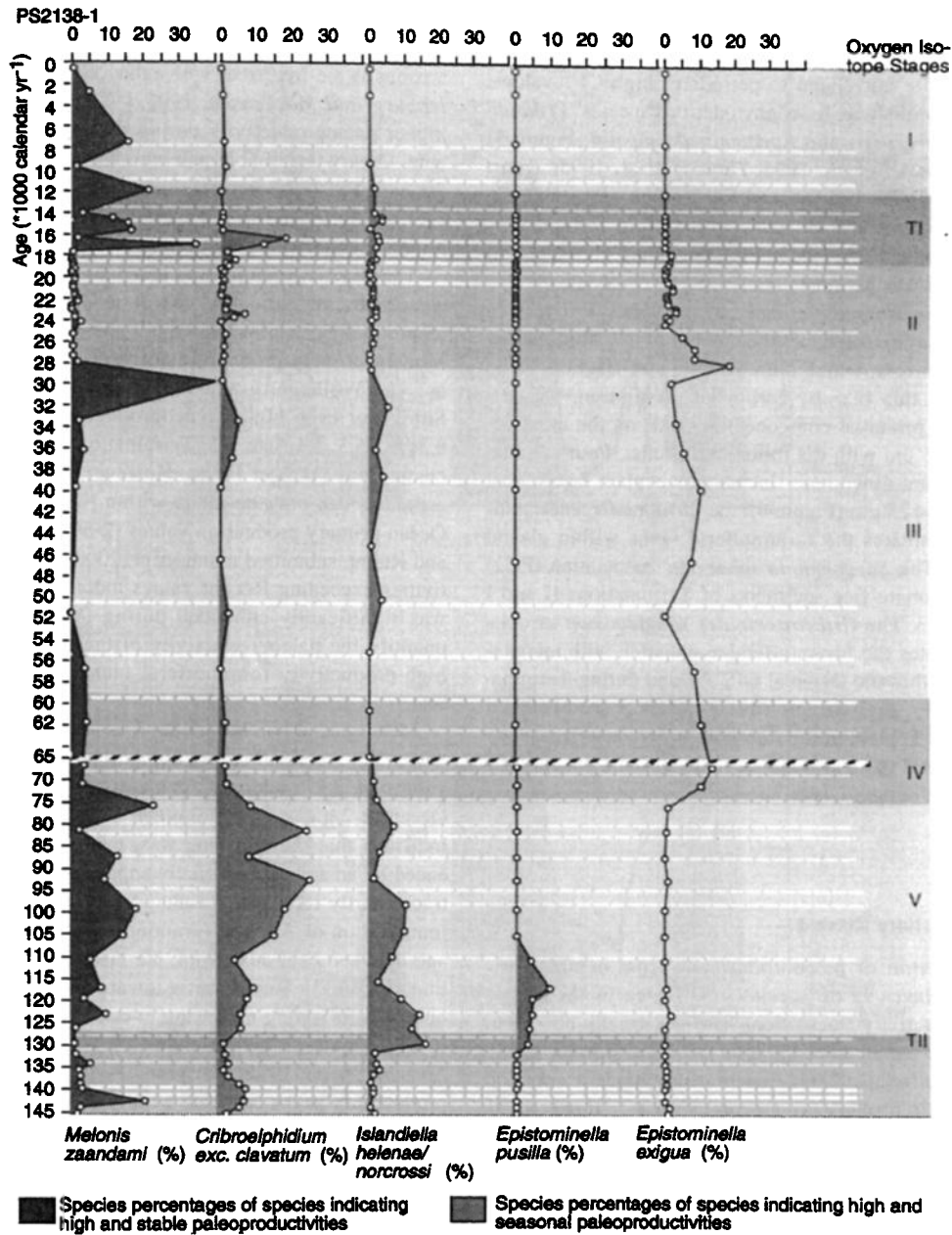


Figure 5. Core PS2138-1 species abundances (percent) of phytodetritus-related species. Given CF1 values show species contribution to CF1; high CF1 values indicate high positive relation to paleoproductivity.

lated for low-diversity (two to three species) agglutinated faunas (Figure 4). In stadials these sequences are dominated by *Saccammina sphaerica*, *S. socialis* and *Rhabdammina* spp. (*S. sphaerica* principal component association, see section 3.6.), and have no analog in the modern Arctic Ocean. In contrast, interstadial agglutinated faunas are dominated by the *Cribrostomoides subglobosum* PC association (see section 3.6.), which is a common association of seasonally ice-free areas of the modern Arctic Ocean [Wollenburg and Mackensen, 1998a].

### 3.6. Principal Component Analyses

The down-core fluctuations of benthic foraminiferal species abundances at site PS2138-1 are reflected by fluctuating domi-

nances of four benthic foraminiferal PC associations (factors) in the PC analyses of the  $>63 \mu\text{m}$  fraction. These four factors explain 89.58% of the total variance (Figure 4): The modern *Reophax guttifer* association (PC4) characterizes post-Younger Dryas sediments ( $<9.7$  kyr). Glacial intervals are usually dominated by the low-diversity *Cassidulina teretis* association (PC1). The factor loadings of the *C. teretis* PC association are generally negatively correlated to the CF1 values of the correspondence analysis (Figures 3 and 4). The *C. reniforme* association (PC3) characterizes stadial sediments of OIS 6, 4, and 3. *C. reniforme* PC factor loadings are highest during periods of high  $\delta^{18}\text{O}$  values of benthic and planktonic foraminifera and extremely low during maximum ice-rafted debris (IRD) ( $>2$  mm) deposition events within OIS 2 and 6. The *Melonis zaandami* association (PC2) characterizes the

foraminiferal fauna within OIS 6.3, 5.5, 5.3, 5.1, 3.1, and Termination 1a (Figure 4). Highest PC factor loadings of the *M. zaandami* association are correlated to periods of high CF1 values. With increasing dominance, first "phytodetritus species" (*Islandiella helenae*, *I. norcrossi*, and *Epistominella pusilla*; Figure 5) [Gooday, 1994; Smart et al., 1994; Thomas et al., 1995; Smart and Gooday, 1997] then species related to high and stable  $C_{org}$  fluxes (*C. exc. clavatum* and *M. zaandami*) [Caralp, 1989] essentially contribute to the *M. zaandami* PC association.

Core PS2212-3 was periodically affected by carbonate dissolution, resulting in purely agglutinated assemblages. Progressive carbonate dissolution first reduces the number of tiny, thin-walled calcareous foraminifera, which dominate the size fraction <125  $\mu$ m. To minimize this bias by carbonate dissolution, we performed a separate principal component analysis on the more robust fraction > 125  $\mu$ m with the following results: Four associations with significant down-core fluctuations explain 84.54 % of the total variance >125  $\mu$ m (Figure 4); the *Oridorsalis tener* association (PC1) dominates the foraminiferal fauna within glacial OIS 2, 4, and 6. The *Saccammina sphaerica* association (PC2) characterizes carbonate-free sediments of Terminations II and I and the older OIS 3. The *Cribrostomoides subglobosum* association (PC3) dominates the foraminiferal association with increasing CF1 values within the terminal OIS 3.1 and during Termination 1. Additionally, high factor loadings of PC3 are observed within middle OIS 3. Finally, the *Fontbotia wuellerstorfi* association (PC4) dominates the foraminiferal fauna in sediments of OIS 5.5, 5.1, and post-Younger Dryas.

## 4. Discussion

### 4.1. Paleoproductivity Record

The reconstruction of paleoproductivity from benthic foraminiferal assemblages is of special importance in the Arctic Ocean since productivity fluctuations here are usually not documented by organic carbon accumulation [Knies and Stein, 1998]. We applied the correlation function between modern core top samples and modern primary production values ( $C_{org}$  flux =  $0.291 \times 10^{(CF1)}$ ) to down core CF1 in order to estimate paleoproductivities (Figure 3). This method requires fossil communities similar or close to the modern fauna to calculate reliable paleoproductivities. The use of parallel analyses (diversity, Q mode PC analyses) helps to trace problematic core sections, where fossil assemblages significantly deviate from the modern record. Core PS2212-3 reveals extended intervals affected by corrosive water masses, as indicated by the species composition. In the modern Arctic Ocean carbonate dissolution and oxygen depletion are related to areas with enhanced productivity. Arctic Ocean deep waters are well ventilated, and agglutinated foraminifera are only rare faunal components in deep-sea thanatocoenosis. In applying the modern "transfer function" to the foraminiferal fauna of core PS2212-3, extraordinarily high paleoproductivity is calculated for foraminiferal faunas dominated by agglutinated foraminifera. Core sections dominated by *Saccammina sphaerica*, *S. socialis*, and *Rhabdammina* spp. (*S. sphaerica* PC association, see below) have no analog in the modern Arctic Ocean. They likely represent relict faunas, and the calculated high paleoproductivity values are unreasonable. We excluded these intervals from paleoproductivity calculations (Figure 3). In contrast, the increase in paleoproductivity within upper OIS 3.1 and Termination 1a coincides with

the occurrence of the *Cribrostomoides subglobosum* PC association. In the modern Arctic Ocean this association is restricted to seasonally ice-free areas with enhanced primary production [Wollenburg and Mackensen, 1998a]. Therefore at least the shift to higher paleoproductivity during these periods seems to be reliable. Otherwise reliable paleoproductivities cannot be evaluated for core PS2212-3 because the down-core faunal change is not exclusively related to changes in paleoproductivity but to environmental conditions not represented in the modern data set.

The benthic foraminiferal associations of core PS2138-1 more closely resemble the modern Arctic Ocean fauna. Calculated paleoproductivity varies between 7 and 150  $g C m^{-2} yr^{-1}$  (Figure 3). Modern primary production at the core position is about 59  $g C m^{-2} yr^{-1}$  [Wollenburg and Kuhnt, submitted manuscript, 2000]. Similar or even higher paleoproductivity is calculated for OIS 6.3, 5.5-5.3, 5.1, late 3.1, Termination 1a, and the Holocene excluding the Younger Dryas. However, reliable paleoproductivity estimates can only be made within the range of modern Arctic Ocean primary production values (2-59  $g C m^{-2} yr^{-1}$ ) [Wollenburg and Kuhnt, submitted manuscript, 2000]. Calculated paleoproductivities exceeding recent values indicate that paleoproductivity was significantly enhanced during these periods; however, to quantify the paleoproductivity of these intervals would require high-productivity foraminiferal faunas within the modern data set.

Mean glacial paleoproductivities are about one third of recent values but are significantly higher than mean primary production values of the modern permanently ice-covered central Arctic Ocean (2-3  $g C m^{-2} yr^{-1}$ ) [English, 1961; Zheng et al., 1998]. This indicates that the core site was, even during the glacial, influenced by an at least seasonally enhanced primary production. Extraordinarily high paleoproductivity is observed at times of the immigration of Atlantic foraminiferal species, indicating a linkage between heat advection, ice coverage, and primary production (Figure 5). Rapid shifts toward high paleoproductivity are observed following meltwater events at 15.4-12 and 10-8  $^{14}C$  kyr (18.1-14 and 11.7-9 calendar kyr) [e.g., Stein, et al., 1994; Elverhøi et al., 1995; Nørgaard-Pedersen, 1997, 1998]. These productivity peaks coincide with low  $\delta^{18}O$  values of benthic and planktonic foraminifera and high IRD supply (Figure 2). Increasing paleoproductivity is indicated initially by an increase in "phytodetritus species" then by species related to enhanced and more stable paleoproductivity [Gooday, 1988, 1994; Gooday and Turley, 1990; Smart et al., 1994; Thomas et al., 1995; Smart and Gooday, 1997]. Accordingly, decreasing paleoproductivity is indicated by an increase of species of the *C. teretis* association, related to moderate seasonal paleoproductivity.

Paleoproductivity values calculated for core PS2138-3 are correlated to the growth and decay of the Svalbard ice sheet as indicated by ice-rafted debris analysis, radiocarbon dating, and stable  $\delta^{18}O$  analysis [Elverhøi et al., 1995; Mangerud et al., 1996; Knies et al., 1998]. Late Weichselian ice advances beyond the present coastline at 22  $^{14}C$  kyr (25.9 calendar kyr) and 18  $^{14}C$  kyr (21.5 calendar kyr) [Elverhøi et al., 1995] are reflected by decreasing paleoproductivities of 14 and 9  $g C m^{-2} yr^{-1}$  (Figure 6). Stepwise ice retreat from the outer shelf starting at 14.8  $^{14}C$  kyr (17.5 calendar kyr), followed by a second retreat between 13 and 12  $^{14}C$  kyr (15.1-14 calendar kyr) is documented by increased paleoproductivity values of 54 and about 100  $g C m^{-2} yr^{-1}$  [Elverhøi et al., 1995]. The  $\delta^{13}C$  values of the intermediate to deep infaunal *M. zaandami* are negatively correlated to paleoproductivity (correla-



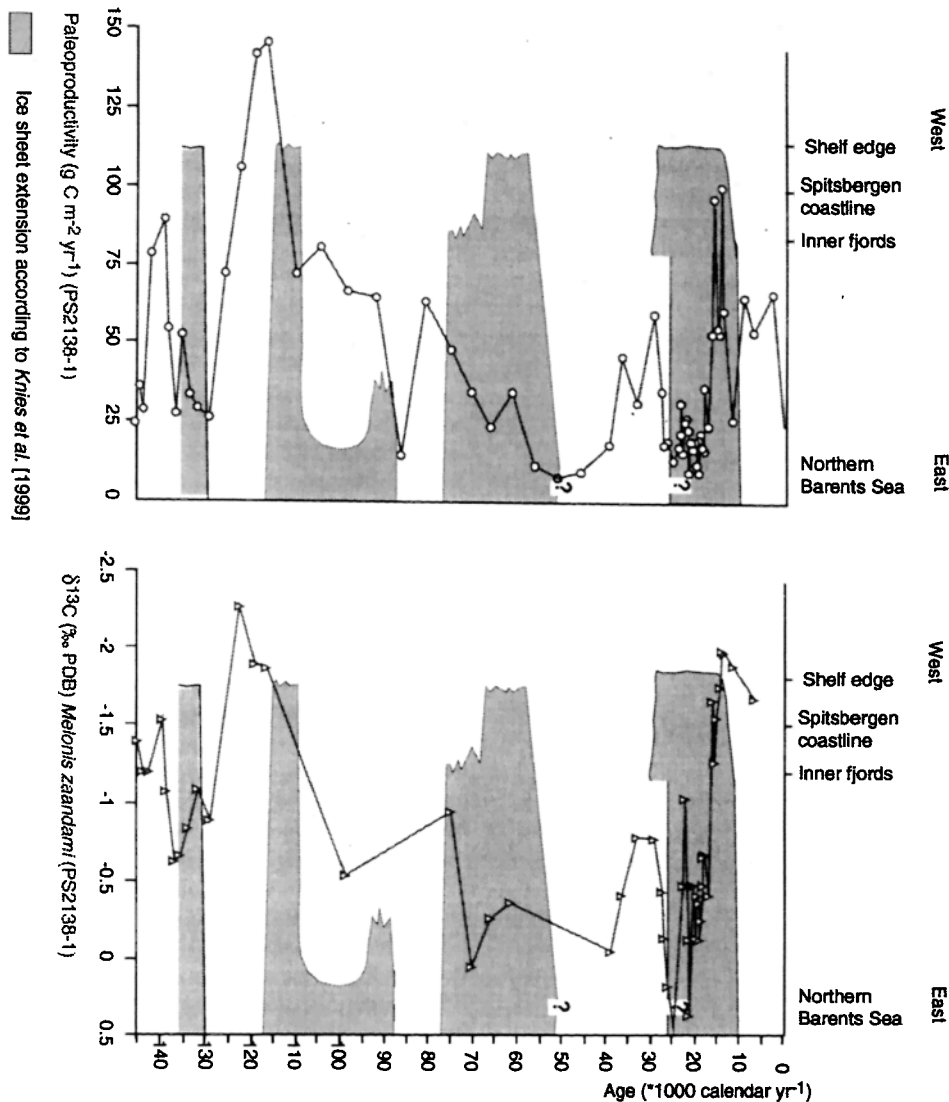


Figure 6. Estimated paleoproductivity,  $\delta^{13}\text{C}$  (percent PDB) value of *Melonis zaandami*, and the down-core distribution of the *C. reniforme* association compared to the ice sheet extensions.

tion coefficient  $r = 0.77$ ) (Figure 6) [see also Mackensen et al., 2000]. *Cassidulina teretis* prefers a shallow infaunal habitat [Wollenburg and Mackensen, 1998b]. Therefore the  $\delta^{13}\text{C}$  value of this species also should predominantly reflect pore water-dissolved inorganic carbon isotopic composition. However, the mean  $\delta^{13}\text{C}$  value of *C. teretis* matches values reported by Scott et al. [1989] and Hevrøy et al. [1996] from the eastern Canadian Margin and central Yermak Plateau, where paleoproductivity and related carbon flux are low. Epibenthic foraminifera were only found in two samples in low numbers. Therefore it was not possible to calculate the difference between bottom water and pore water  $\delta^{13}\text{C}$  values. However, our data show that pore water  $\delta^{13}\text{C}$  depletion reflects changes in paleoproductivity quite reliably.

Additional qualitative information on paleoproductivity can be obtained by diversity measurements. Similar to the modern conditions [Wollenburg and Mackensen, 1998a; Wollenburg and Kuhnt, submitted manuscript, 2000], down-core benthic foraminiferal diversity fluctuations are correlated to changes in pa-

leoproductivity within the generally oligotrophic environment of the Arctic Ocean: High paleoproductivity is reflected by high diversity, whereas low productive glacial periods are documented by low-diversity faunas.

BFAR are commonly used in paleoproductivity reconstructions [e.g., Herguera and Berger, 1991; Loubere, 1997]. In the Arctic Ocean, however, severe calcite dissolution significantly limits the applicability of this method. Both studied cores show rapid BFAR fluctuations. Low BFAR are observed within periods of enhanced productivity of interglacials and interstadials and the peak of glacial stadials. In contrast, highest BFAR correspond to periods of low productivity, such as glacial stadials. Extremely low BFAR in the shallow core PS2138-1 (995 m) coincide with low BFAR or foraminiferal barren zones in the deep core PS2212-3 (2495m). In core PS2212-3 these intervals are solely comprised by agglutinated foraminifera, whereas corroded and heavily etched calcareous foraminifera constitute the foraminiferal fauna of core PS2138-1. This indicates that taphonomic

loss by carbonate dissolution significantly decreased the original BFAR, especially during stadials when corrosion increased with increasing water depth. Intensive carbonate dissolution is commonly observed in areas with high organic carbon fluxes in the Arctic Ocean and its adjacent seas [Steinsund and Hald, 1994; Hald and Steinsund, 1996]. Enhanced paleoproductivity may also have caused intensified carbonate dissolution during OIS 6.3, 5.5 to 5.3, 3.1, the Termination Ia, and the Holocene. However, low BFAR observed within low-productivity periods during stadials may be related to corrosive bottom waters. This needs to be taken into consideration when using accumulation rates of coccoliths or planktonic foraminifera as a paleoproductivity indicator in the Fram Strait and the northern Nordic Seas [e.g., Dokken and Hald, 1996; Hald and Aspeli, 1997; Hebbeln and Wefer, 1997].

#### 4.2. Fluctuating Paleocological Conditions Related To The Svalbard/Barents Sea Ice Sheet Extension: Evidence From Foraminiferal PC Associations

Two foraminiferal PC associations of core PS2138-1 and three associations of core PS2212-3 are analogous to associations observed in the modern Arctic Ocean [Wollenburg and Mackensen, 1998a; Wollenburg and Kuhnt, submitted manuscript, 2000]:

In shelf to slope environments with increased productivity and intense carbonate dissolution in autumn and winter [Hald and Steinsund, 1996; Hald et al., 1996] the foraminiferal fauna is dominated by agglutinated species. These environments are represented by the *Reophax guttifer* association at ~1000 m and by the *Cribrostomoides subglobosum* association at 2500 m water depth [Scott and Vilks, 1991; Bergsten, 1994; Wollenburg and Mackensen, 1998a]. In core PS2138-1 the dominance of the *R. guttifer* association in post-Younger Dryas sediments thus indicates enhanced seasonal  $C_{org}$  accumulation and autumn carbonate dissolution. In core PS2212-3 the *C. subglobosum* association dominates the foraminiferal fauna during the terminal OIS 3.1 and Terminations Ia and Ib.

The modern *Oridorsalis tener* association is confined to the permanently ice-covered, low-productivity continental rise [Wollenburg and Mackensen, 1998a]. It occurs only in deep water core PS2212-3 (2550 m water depth) during stadials and low-productivity periods of the Eemian and the Holocene (Figure 4).

The calcareous *Fontobotia wuellerstorfi* association characterizes seasonally ice-free areas of enhanced seasonal primary production [Sarnthein and Altenbach, 1989; Wollenburg and Mackensen, 1998a] with less intense carbonate dissolution at the seafloor. This association dominates the foraminiferal fauna in core PS2212-3 during OIS 5.5 and 5.1 and after the Younger Dryas. High numbers of *F. wuellerstorfi* during OIS 5 and late Holocene times are common and well documented in the Nordic Seas [e.g., Belanger, 1982; Streeter et al., 1982; Haake and Pflaumann, 1989; Nees and Struck, 1994].

In the modern Arctic Ocean the distribution of the *Cassidulina teretis* association is restricted to seasonally ice-free areas [Wollenburg and Mackensen, 1998a]. *C. teretis* has been interpreted as an opportunistic species, well adapted to strong seasonal fluctuations in food supply [Gooday and Lambshead, 1989]. In core PS2138-1 the *C. teretis* association characterizes glacial stadials, indicating significant seasonal primary production pulses even during glacial periods. Nevertheless, the *C. teretis* association is still negatively correlated to annual paleoproductivity estimates (Figures 3 and 4).

During periods of enhanced and stable paleoproductivity, mobile infaunal to deep infaunal species of the *Melonis zaandami* association predominate (*Cribrorhynchium exc. clavatum*, *Melonis zaandami*, *Stainforthia* spp., and *Fursenkoina fusiformis*) [Wollenburg and Mackensen, 1998b] (Figures 4 and 5). The *M. zaandami* association (PS2138-1; PC2) has no analog in the modern Arctic Ocean. *M. zaandami* is a predominantly deep infaunal living species related to high  $C_{org}$  fluxes and more stable primary production values [Caralp, 1989; Korsun and Polyak, 1989; Corliss, 1991; Mackensen et al., 1995; Wollenburg and Mackensen, 1998b]. In core PS2138-1, highest factor loadings of the *M. zaandami* association coincide with enhanced paleoproductivity within OIS 6.3, 5.5, 5.3, 5.1, 3.1, and Termination Ia (Figures 3 and 4). Maximum occurrences of this association follow high abundances of the glacier terminus-related *C. reniforme* association in OIS 6.3, 3.1, and Termination Ia. In OIS 5 sediments, below and above significant occurrences of the *M. zaandami* PC association, high numbers of the ice edge-related species *C. excavatum clavatum* are found [Mudie et al., 1984; Hald et al., 1994; Polyak and Solheim, 1994; Alve, 1995]. High abundances of ice edge-related species probably characterize phases of ice sheet advances or retreats at the core position. *M. zaandami* dominates during the phases of stable high paleoproductivity at the ice edge.

The *Cassidulina reniforme* association (PS2138-1; PC3) characterizes sediments deposited during glacial stadials. High abundances of *Cassidulina reniforme* are usually related to glaciomarine shelf and upper slope environments [Sejrup and Guibault, 1980; Mudie et al., 1984; Hald and Vorren, 1987; Polyak and Solheim, 1994; Seidenkrantz et al., 1995; Hald and Aspeli, 1997]. The species often dominates the proximal glacier environment and inner fjords of Svalbard [Hansen and Knudsen, 1992; Hald and Korsun, 1997], and thus should be able to tolerate extended periods of dysoxic or anoxic bottom waters [Alve, 1990]. In core PS2138-1, highest factor loadings of the *C. reniforme* association are correlated with high  $\delta^{18}O$  values of planktonic and benthic foraminifera, indicating an extended sea ice cover and stable high global ice volume during these periods. During OIS 2 highest  $\delta^{18}O$  values are measured from intervals dominated by the *C. reniforme* PC association, whereas  $\delta^{18}O$  values of ~1‰ lower are accompanied by low or near-zero PC factor loadings of the *C. reniforme* PC association. Periods of dominating *C. reniforme* association correspond reasonably well with times of maximum glacial ice sheet extension (Figure 6). At greater water depths (core PS2212-3) the *C. reniforme* association is replaced by barren zones during glacial maxima.

Sediments above the glacial maximum barren zones are dominated by the *Saccammina sphaerica* association (*S. sphaerica*, *S. socialis*, and *Rhabdammina* spp.), which commonly contains attached agglutinated foraminifera and individuals covered with iron manganese crusts. Similar assemblages were interpreted as recolonization faunas in extreme environments of strong oxygen depletion [Kaminski et al., 1995] or high current activities [Kaminski, 1985; Kaminski and Schröder, 1987; Kuhnt et al., 2000]. There is no analog to the *S. sphaerica* association in the modern Arctic Ocean. However, high numbers of *S. sphaerica* are observed in Arctic slope environments exposed to seasonal anoxia and iron manganese mobilization (J. Wollenburg, personal observation, 1999). Encrusting agglutinated foraminifera are nearly the only forms colonising indurated sediments within the hydrothermal vent area of the Juan de Fuca Ridge, where they may prefer

FeMn-rich surfaces [Jonasson and Schröder-Adams, 1996]. The predominantly attached *Saccammina* spp. of core PS2212-3 may have had a similar preference or were able to tolerate the dysoxic environmental conditions associated with FeMn precipitation. The *S. sphaerica* association may be either a relict fauna caused by an extensive carbonate dissolution at greater water depths or a fauna recolonizing a formerly anoxic environment (foraminiferal barren zones) under dysoxic conditions. This association generally occurs on top of foraminiferal barren zones and characterizes the initial ice sheet retreat of peak glacial periods (Figure 6).

#### 4.3. Glacial Paleoceanography

Temperate, saline Atlantic water masses were advected to the Arctic Ocean during OIS 6.3, 5.5, and 1. This is indicated, at the sites under investigation by high numbers of "Atlantic" foraminifera and indicators of seasonal ice-retreat (e.g., phytodetritus species and modern analog agglutinated associations). These periods of strong Atlantic warm water advection are characterized by maxima in paleoproductivity, and low  $\delta^{18}\text{O}$  values of planktonic and benthic foraminifera, as well as low  $\delta^{13}\text{C}$  values of endobenthic foraminifera (Figures 2 and 3). During these times of low  $\delta^{18}\text{O}$  values for both benthic and planktonic foraminifera brine release probably was enhanced, and ice formation must have been strong. This probably resulted in the subsequent buildup of thick sea ice. In addition, the moisture supply provided by the water vapor of open water areas during times of brine formation may have favored the accumulation of snow on the adjacent ice sheet and may have triggered the progression of the continental ice sheet [Hebbeln et al., 1994].

Sediments with highest  $\delta^{18}\text{O}$  values are dominated by the *C. reniforme* association referred to as the modern glacier front environment at intermediate water depths. This finding supports the idea of an immediate advance of the ice sheet after cold Atlantic water advection [Hebbeln et al., 1994; Hebbeln and Wefer, 1997]. At deep water sites (core PS2212-3) these heavily ice-covered periods are usually documented by intervals barren of foraminifera, indicating decreased deep water ventilation. This finding is in accordance with former assumptions of a strongly reduced Atlantic water advection and a reduced deep water renewal in the Nordic Seas and the Arctic Ocean during parts of the last glacial [Kellogg et al., 1978; Gard and Backman, 1990].

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## 5. Summary

The combined analyses of planktonic and benthic oxygen and carbon isotopes, diversity, BFAR, correspondence, and Q mode principal component analyses of two long cores in the marginal Arctic ocean revealed the following.

1. The annual amount and seasonality of paleoproductivity in the Arctic Ocean is reflected by benthic foraminiferal assemblages. In core PS2138-1, periods during which the ice sheet approached or retreated from the core site are dominated by PC associations related to highly seasonal organic carbon fluxes (*R. guttifer*, *C. teretis*, and *C. reniforme*). In contrast, stable and high productivity at the ice edge are reflected by the *M. zaandami* PC association. At site PS2212-3, enhanced paleoproductivity is inferred from the *F. wuellerstorfi* and *C. subglobosum* PC associations.

2. The accumulation rate of benthic foraminifera (BFAR) in the Arctic Ocean during the last 145 kyr shows no significant correlation to paleoproductivity estimates.

3. Site PS2138 was at least seasonally ice-free during the entire last 145 kyr. Even the lowest paleoproductivity estimates of  $7 \text{ g C m}^{-2} \text{ yr}^{-1}$  within core PS2138-1 are still higher than values of  $\sim 2 \text{ g C m}^{-2} \text{ yr}^{-1}$  for the modern permanently ice-covered Arctic Ocean. High paleoproductivity values, exceeding the maximum productivity in the seasonally ice-free modern Arctic Ocean, are calculated for OIS 6.3, 5.5-5.3, and Termination Ia. Lowest paleoproductivity values are calculated for sediments of OIS 6, OIS 4, the early OIS 3, and OIS 2.

4. Temperate saline Atlantic water has entered the Arctic Ocean within OIS 6.3, 5.5, and the Holocene. Cold, less saline Atlantic or GIN Seas water may have entered the Arctic Ocean in coincidence to the Nordway events of the Nordic Seas. During stagnating Atlantic water advection, unusually low paleoproductivity values are observed in the Arctic Ocean, indicating increasing ice coverage. Deep water was poorly ventilated during these periods, and the deeper site (PS2212-3) became exposed to corrosive bottom waters.

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W. Kühnt, Department of Geosciences, D-24118 Kiel, Germany

A. Mackensen and J.W. Wollenburg, Alfred-Wegener-Institute on Polar- and Marine Research, P.O. Box 120161, Columbusstrasse, D-27515 Bremerhaven, Germany (jwollenburg@awi-bremerhaven.de)

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