PALEOCEANOGRAPHY, VOL. 11, NO. 6, PAGES 679-699, DECEMBER 1996

Neogloboquadrina pachyderma (sinistral coiling) as paleoceanographic tracers in polar oceans: Evidence from Northeast Water Polynya plankton tows, sediment traps, and surface sediments

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Abstract. The abundance and chemistry of the planktonic foraminifera *Neogloboquadrina pachyderma* (sinistral coiling) have long been used as tools for monitoring polar surface ocean changes and for correlating these changes to atmospheric and thermohaline circulation fluctuations. However, due to its remote habitat, very little is known about how modern *N. pachyderma* (s.) respond to changing environmental conditions in the polar seas. Modern samples of *N. pachyderma* (s.) from the Northeast Water Polynya provide a means for studying how environmental conditions affect the vertical distribution and chemistry of this species. Highest abundances of *N. pachyderma* (s.) were associated with the chlorophyll maximum in the surface 20-80 m, where they are exploiting their primary food source. Evidence suggests that the addition of a calcite crust modifies the calcite tests of some *N. pachyderma* (s.) between 50 and 200 m, increasing shell density and modifying shell chemistry. The shell mass of encrusted forms is 3-4 times greater than the nonencrusted forms between 50 and 200 m. The oxygen isotope composition of *N. pachyderma* (s.) shells increase by 1.5‰ in response to local water column gradients. The $\delta^{13}C$ values of *N. pachyderma* (s.) are basically invariant with depth in this region, are consistently 1.0‰ depleted in comparison with the $\delta^{13}C$ for equilibrium calcite, and remain basically constant during the shell-thickening process. Mass balance calculations suggest that encrustation occurs at all depths, but abundance counts suggest that the process occurs mostly at the depth of the main pycnocline. Sediment fluxes of *N. pachyderma* (s.) occur during a 2-week bloom event and decrease to almost zero below complete ice cover. The decoupling of the processes controlling abundances and shell chemistry explain the discrepancies between transfer function and isotopically derived paleotemperature estimates of surface conditions, in some oceanic settings. The ability of $\delta^{18}O$ to record surface ocean conditions will depend on vertical water column gradients, as evidenced by the differences in core-top calibrations between the North and South Atlantic.

Introduction

Records of dust and $\delta^{18}O$ from Greenland and Antarctic ice cores reveal that both the northern and southern hemispheres have experienced numerous rapid changes in climate over the last 100,000 years [*Dansgaard et al.*, 1993; *Bender et al.*, 1994]. Sometimes occurring in less than 3 years over Greenland, $\delta^{18}O$ shifts of up to 7‰ from the ice core record have been interpreted as 10°C shifts in temperature [*Dansgaard et al.*, 1993; *Johnsen et al.*, 1992] and/or as changes in air mass sources to the Greenland ice sheet [*Charles et al.*, 1994]. A fundamental question in climate research is how these atmospheric mode changes are related to changes in the surface ocean and/or deepwater production changes.

The species *Neogloboquadrina pachyderma* (sinistral) (hereinafter referred to as *N. pachyderma* (s.)) dominates surface sediment assemblages of planktonic foraminifera in polar regions [*Imbrie and Kipp*, 1971; *Kipp*, 1976]. Specifically, north of the Arctic Front in the Greenland, Iceland, and Norwegian Seas, this species composes greater than 90% of the marine surface sediment assemblage [*Pflaumann et al.*, 1996]. Thus *N. pachyderma* (s.) provides an important ecological and geochemical proxy of past polar ocean temperature, salinity, sea ice, and nutrient conditions.

Paper number 96PA02617.
0883-8305/96/96PA-02617 $12.00

We studied a series of vertically stratified plankton tow samples collected from the northwest Greenland Sea in order to document the factors controlling both abundances and shell chemistry of *N. pachyderma* (s.). Today, the planktonic foraminiferal assemblage in this region is dominated by *N. pachyderma* (s.). We used a multiple opening/closing nets and environmental sensing system (MOCNESS) [*Wiebe et al.*, 1976], which takes plankton samples from discrete depth intervals while simultaneously measuring in situ temperature and salinity. We use these modern data from plankton tows, an underlying sediment trap, and underlying surface sediments in order to assess the modern ecology, vertical distribution, and calcification of *N. pachyderma* (s.).

Background

Paleoceanographic Application of *N. pachyderma* (s.)

The first applications of *N. pachyderma* (s.) as paleoceanographic proxy exploited the association between *N. pachyderma* (s.) and polar water masses. Early investigators of *N. pachyderma* determined that coiling direction, morphotypic variation, and degree of encrustation were correlated with water temperature, water mass, and latitude [*Ericson*, 1959; *Bandy*, 1960; *Kennett*, 1968; *Stehman*, 1972; *Srinivasan and Kennett*, 1974]. Most of these studies were completed on *N. pachyderma* (s.) from surface sediments and have been corroborated by plankton tow studies in the Atlantic, Pacific, and Indian Oceans [*Be and Tolderlund*, 1971; *Be*, 1977; *Be and Hutson*, 1977].

The tie between *N. pachyderma* (s.) and polar currents has been used as a basis for tracking the advance of the polar front down to 40°N in the North Atlantic during glacial maximum periods [*Ruddiman and McIntyre*, 1981]. On shorter timescales, abundance changes in *N. pachyderma* (s.) have been interpreted as temperature changes during rapid climate change events in the North Atlantic, such as the Younger Dryas [*Broecker et al.*, 1988; *Broecker et al.*, 1990]. Most recently, the abundance and stable isotope chemistry of *N. pachyderma* (s.) have been correlated with $\delta^{18}O$ changes in the Greenland ice cores [*Bond et al.*, 1993; *McManus et al.*, 1994; *Fronval et al.*, 1995; *Oppo and Lehman*, 1995], indicating that the mode changes in the North Atlantic surface ocean and atmosphere are interrelated.

The $\delta^{13}C$ and $\delta^{18}O$ of *N. pachyderma* (s.) have also been used to determine links between the surface, intermediate, and deep water circulation changes. Low-frequency changes in percent abundance, $\delta^{13}C$, and $\delta^{18}O$ of *N. pachyderma* (s.) in the polar North Atlantic have been correlated with shifts in deep ocean circulation [e.g., *Mix and Fairbanks*, 1985; *Jansen and Veum*, 1990; *Lehman and Keigwin*, 1992]. In the South Atlantic, the $\delta^{13}C$ of *N. pachyderma* (s.) has been used to relate changes in upwelling, surface productivity, and zones of maximum air-sea exchange to deep water circulation during the last glacial maximum [*Labeyrie and Duplessy*, 1985; *Keigwin and Boyle*, 1989; *Charles and Fairbanks*, 1990].

Several studies have attempted to calibrate the $\delta^{18}O$ of *N. pachyderma* (s.) with either sea surface temperatures (SST) or the $\delta^{18}O$ predicted for calcite formed in equilibrium with surface waters ($\delta^{18}O_{CALCITE}$) [*Duplessy et al.*, 1991; *Wu and Hillaire-Marcel*, 1994; *Charles and Fairbanks*, 1990]. The $\delta^{18}O$ of *N. pachyderma* (s.) from surface sediments shows basically a one-to-one correlation with $\delta^{18}O_{CALCITE}$ in the Southern Ocean (Figure 1a). In the North Atlantic region, one might argue that a one-to-one correlation also exists between the $\delta^{18}O$ of core-top *N. pachyderma* (s.) and the $\delta^{18}O_{CALCITE}$, given an offset of approximately 0.8‰. However, a significant amount of scatter exists in the data from the North Atlantic region, and the correlation coefficient is not as high (Figure 1b).

In the sedimentary record, similar discrepancies have been found between isotopically derived temperatures and SST estimates derived from ecological transfer functions. Downcore records from the North Atlantic show shifts in the percent abundance of *N. pachyderma* (s.) of 80-100% [*Bond et al.*, 1993]. According to percent abundance calibrations from core-top assemblages, these large shifts in the percent abundance of *N. pachyderma* (s.) equate to SST changes of at least 6°-8°C (Figure 1c) [*Imbrie and Kipp*, 1971; *CLIMAP*, 1981]. Oxygen isotope records from these same cores show no corresponding change in $\delta^{18}O$ of *N. pachyderma* (s.) which can be equated with temperature. In other words, while the percent abundance data suggest large changes in SST, the $\delta^{18}O$ of *N. pachyderma* (s.) suggests little or no change.

Hydrography of the Northeast Water Polynya

The Northeast Water (NEW) Polynya is a region of seasonally open water within the East Greenland Current (EGC) over the continental shelf off of eastern Greenland (Figure 2). The maximum areal extent of the polynya during summer 1992 was 18,000 km^2 [*Minnett*, 1995], a relatively modest size since the maximum recorded extent is 44,000 km^2 [*Wadhams*, 1981]. The polynya is open during the months of May-August and is otherwise in a region of complete ice cover during the remaining months. Within the polynya, ice cover remains patchy during the summer months, ranging from 0 to 100% ice cover. During the summer months, an anticyclonic gyre circulation dominates the central region of the polynya, over the Belgica Bank.

The upper 250 m of the water column in the polynya are characterized by large gradients in temperature and salinity. Two water masses compose most of the water column in the polynya. The Polar Water (PW) is characterized by low salinity ($S < 33$) water near the freezing point ($T < 0°C$) and occupies the surface layer to a depth of approximately 100 m [*Budeus and Schneider*, 1995]. During summer, insolation and ice melting warms and freshens the near surface PW, with salinities <32 and temperatures from 0.5° to 3.0°C. Waters between 100 and 200 m represent a region of mixing between the PW and the Return Atlantic Water (RAW), which is found below 200 m. The RAW is a warmer, more saline water mass ($T > 0°C$, $S > 34.9$) [*Budeus and Schneider*, 1995; *NEWater Steering Committee et al.*, 1993]. From the surface to 200 m, the salinity increases by approximately 3 (Figure 3a). The predicted change in $\delta^{18}O$ for calcite formed in equilibrium with seawater ($\delta^{18}O_{CALCITE}$) is greater than 3.5‰ between 0 and 200 m.

The NEW Polynya is characterized by relatively little vertical variation in PO_4 concentrations (Figure 3b; 0.6-1.3 μmol/kg) and low nitrogen concentrations (trace values) in

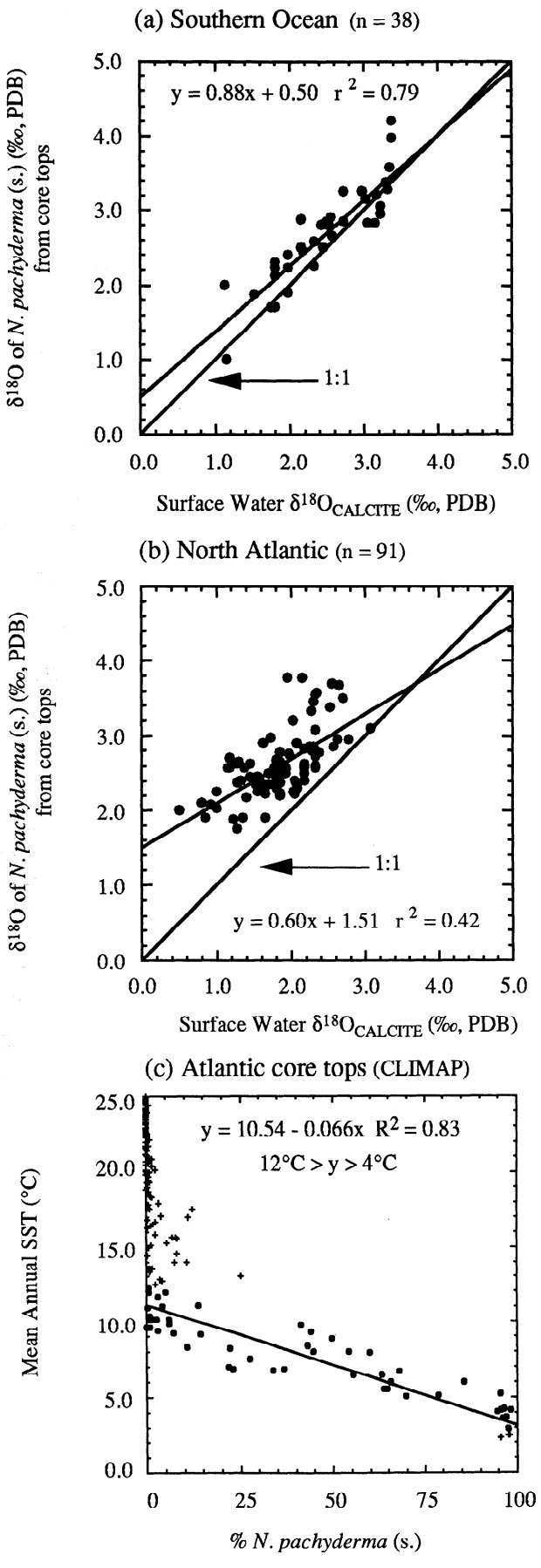

Figure 1. Values of $\delta^{18}O$ for calcite formed in equilibrium with surface waters ($\delta^{18}O_{CALCITE}$) are compared with measured values of $\delta^{18}O$ of *N. pachyderma* (s.). Dots represent the core-top oxygen isotope values on *N. pachyderma* (s.) from both locations, taken from published data compilations in (a) the Southern Ocean [*Keigwin and Boyle*, 1989; *Charles and Fairbanks*, 1990; *Niebler*, 1995] and (b) the North Atlantic-Norwegian Sea-Greenland Sea regions [*Kellogg et al.*, 1978; *Durazzi*, 1981; *Labeyrie and Duplessy*, 1985; *Mix and Fairbanks*, 1985; *Zahn et al.*, 1985; *Jansen and Veum*, 1990; *Duplessy et al.*, 1991; *Wu and Hillaire-Marcel*, 1994; *Sarnthein et al.*, 1995]. Values for $\delta^{18}O_{CALCITE}$ are calculated using summer SSTs from *Levitus and Boyer* [1994], and the salinity-$\delta^{18}O$ of water relationship is from *Duplessy et al.* [1991]. Lines indicate a 1:1 relationship between $\delta^{18}O_{CALCITE}$ and $\delta^{18}O$ of *N. pachyderma* (s.) and a least squares regression through the data. (c) Percent abundances of *N. pachyderma* (s.) in surface sediments are correlated with mean annual sea surface temperatures above the core sites in the North Atlantic. Solid circles are used in the least squares regression, and plus signs are from core tops not used in the regression (data taken from *CLIMAP* [1981] and *Prell* [1985]). These data demonstrate that the percent abundance of *N. pachyderma* (s.) represents an accurate recorder of SST between 4° and 12°C.

the euphotic zone [*Wallace et al.*, 1995a, b]. Photosynthesis is largely a function of the percentage of open water rather than ice thickness, but both nutrient concentrations and irradiance control the productivity within the polynya [*Smith*, 1995]. Chlorophyll *a* concentrations are lowest (<1 mg/kg) below complete ice cover but consistently peak between 20 and 60 m irregardless of percent ice cover. Transmissometer data also show peak particulate concentrations between 20 and 50 m. Particulate matter concentrations were large within the euphotic zone, primarily composed of diatomaceous material during late summer. The average depth of the 1% light level for all of the polynya stations is 31 ± 12 m, with a range from 12 to 67 m [*Smith*, 1995; *Smith et al.*, 1995]. The average rate of primary production in the polynya during 1992 was 0.21 g C m^{-2} d^{-1}, with maximum values of 1.1 g C m^{-2} d^{-1} [*Smith*, 1995]. While the average productivity is lower in the NEW Polynya (i.e., ~50% lower than average primary productivity measurements from the Fram Strait), the range encompasses that found in other Arctic systems [*Smith*, 1995].

Method

Foraminiferal Samples

All samples were taken in the NEW Polynya during the summers of 1992 and 1993 onboard the U.S. Coast Guard vessel *Polar Sea*. Vertically stratified plankton tow samples (mesh size, 150 μm) were collected from the NEW Polynya (Table 1; 76°-81°N, 9°-16°W) using a MOCNESS device [*Wiebe et al.*, 1976]. In this study, nets were sequentially opened and closed over discrete depth intervals between 0 and 300 m. In situ temperature and salinity were measured during towing, using a conductivity/temperature/depth (CTD) probe attached to the MOCNESS system. MOCNESS tow samples were stored in a 2% formaldehyde seawater solution, buffered with sodium tetraborate (borax) to prevent dissolution.

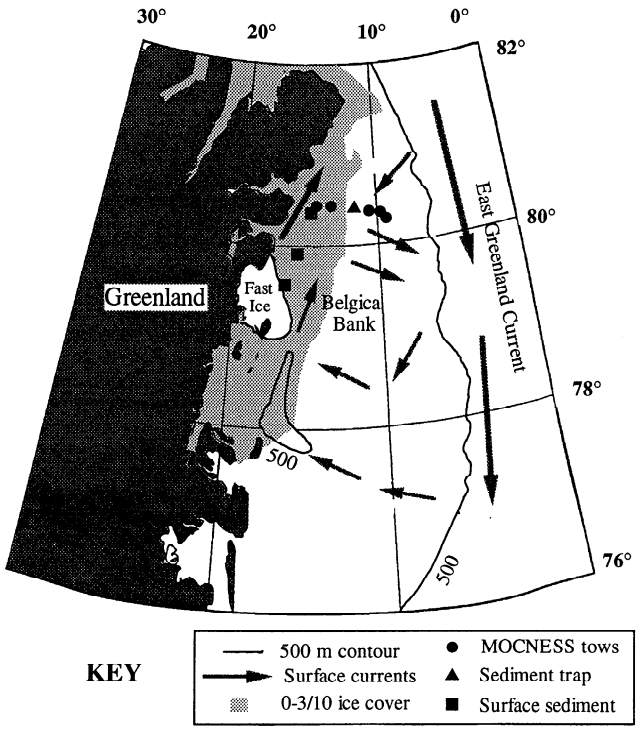

Figure 2. Location of multiple opening/closing nets and environmental sensing system (MOCNESS) plankton tow, sediment trap, and marine sediment samples taken from the Northeast Water (NEW) Polynya in the 1992, 1993 sampling seasons. The majority of samples were taken from the northern portion of the polynya. Arrows show major surface currents within and around the NEW Polynya. The NEW Polynya is located off the northeast coast of Greenland, and is fed directly by polar surface waters in the East Greenland Current. The lighter shaded region indicates the region of 0/10-3/10 concentration ice cover during July 1992 [from Smith et al. 1995].

Sample pH was maintained above 7.8. All foraminifera were counted and removed from splits of these samples using a pipette and were stored in the 2% buffered formaldehyde solution. Samples were split into equal fractions using a Folsom splitter.

Sediment trap samples were taken from a moored sediment trap with a collection area of 0.5 m^2. Five sediment trap samples were retrieved from sediment trap C (80.46°N, 11.02°W), deployed at 245 m in the northern trough of the polynya (Table 2). Trap samples were preserved in a 5% formaldehyde seawater solution buffered with sodium tetraborate. One-sixth splits of the total sample were counted for foraminiferal content. Benthic samples were collected using a 0.25-m^2 U.S. Naval Electronics Laboratory Mark III spade core. Undisturbed spade cores were subsampled using a 7-cm-diameter polycarbonate core (area, 38.5 cm^2) to a depth of 15-30 cm. Sediment samples were washed through a 63-μm-mesh sieve using tap water, and the coarse fraction was retained for planktonic foraminifera.

Foraminifera from plankton tows and sediment trap samples were rinsed in tap water to remove organic material. Specimens were then rinsed in distilled water and dried in vaccuo at <50°C for 2 hours. Prior to isotope analysis, foraminifera samples were vacuum roasted at 370°C for 1 hour. Duplicates of samples were prepared for analysis by cleaning with a H_2O_2 solution. These samples were soaked for 24 hours in a 30% H_2O_2 solution buffered to a pH of 7.8, before being rinsed, dried, and vacuum roasted.

For both isotope analyses and counting purposes, *N. pachyderma* (s.) were divided into two groups, depending on surface texture of the individual (Figure 4). Visual inspection was our only means of morphotype separation for this study. The first type of *N. pachyderma* (s.) has a heavily encrusted, crystalline surface [*Srinivasan and Kennett*, 1974; *Vilks*, 1975; *Reynolds and Thunell*, 1986]. The shells of these types are opaque, and the morphology tends to be more quadrate.

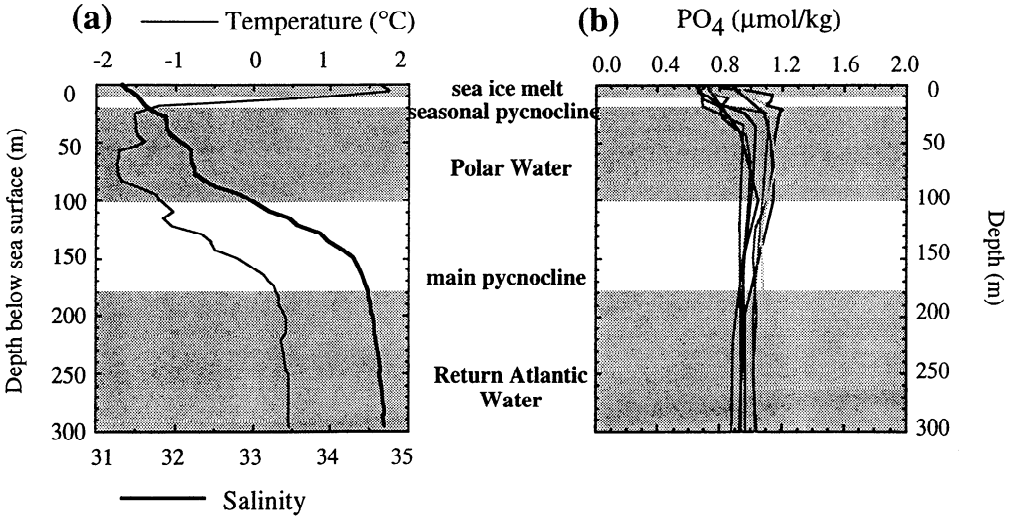

Figure 3. (a) Typical conductivity/temperature/depth (CTD) profile (MOCNESS Station 43D) from the NEW Polynya. The shading delineates the sea ice melt, the seasonal pycnocline, the Polar Water (PW), the main pycnocline, and the Return Atlantic Water (RAW) (nomenclature from *Budeus and Schneider* [1995]). (b) Concentrations of PO_4 (micromoles per kilogram) versus depth (meters) for the NEW Polynya MOCNESS stations used in this study [*Wallace et al.*, 1995a]. An approximate range in the PO_4 values at any given depth is about 0.2 μmol/kg. These stations all show a similar variability in PO_4 concentrations with depth.

Table 1. Station Locations Within the NEW Polynya

Station	Type	Date Taken	Time	Latitude, °N	Longitude, °W	Depth, m
92-4	MOCNESS	July 22, 1992	0211 UT	80.50	14.07	0-235
92-25C	MOCNESS	July 27, 1992	1109 UT	80.50	13.16	0-263
92-43A	MOCNESS	July 31, 1992	1232 UT	80.35	9.75	0-275
92-43D	MOCNESS	Aug. 1, 1992	2321 UT	80.30	9.65	0-250
93-36	MOCNESS	July 27, 1993	1740 UT	80.36	10.14	0-275
93-37A	MOCNESS	July 28, 1993	2329 UT	80.45	13.26	0-275
C	sediment trap	Aug. 9, 1992 to July 27, 1993		80.46	11.02	245
71 SC43	sediment			79.72	16.24	305
84	sediment			80.31	14.37	310
88	sediment			79.48	17.02	375

MOCNESS, multiple opening/closing nets and environmental sensing system.

The average mass per shell is 5.42 ± 1.12 μg. The second type of *N. pachyderma* (s.) has a smooth, shiny, reticulate surface. The latter chambers of the nonencrusted *N. pachyderma* (s.) are larger than earlier chambers, making the foraminifera less quadrate. The average mass per shell is 2.3 ± 0.7 μg. At least 10 encrusted individuals and thirty nonencrusted individuals were used to determine each average mass per shell measurement. Between one and seven of these measurements were made at each depth interval, in order to determine a mean mass at each depth. The left-coiling *N. pachyderma* make up greater than 95% of each sample.

Predicting $\delta^{18}O_{CALCITE}$ and $\delta^{13}C$ of ΣCO_2 for NEW Polynya Stations

In order to obtain a first-order $\delta^{18}O$-salinity relationship for water at our sites in the polynya, Stations 4-10 (80.275°N, 13.822°W) and 38-76 (80.150°N, 7.742°W) were analyzed for their oxygen isotope composition (Table 3). All water samples taken for $H_2{}^{18}O/H_2{}^{16}O$ analysis from the NEW Polynya were collected in 1993. A first-order $\delta^{18}O$-salinity relationship was determined based on these samples (Figure 5). This relationship was used to predict $\delta^{18}O$ of water for our stations in 1992, using the in situ salinity measurements taken from the MOCNESS CTD attached to the net system. The influence of sea ice melting is apparent in many of the surface (<40 m) samples analyzed from the polynya. However, comparison with additional data collected from the Fram Strait and the Greenland Sea demonstrates that the $\delta^{18}O$ of most of our water samples (S < 32.4) results from mixing between two sources. Mixing occurs between a less saline, polar outflow from the Fram Strait (S = 32.4, $\delta^{18}O$ = -2.53‰) and the warmer, more saline RAW of the West Spitsbergen Current (S = 34.92, $\delta^{18}O$ = 0.3‰). The $\delta^{18}O_{CALCITE}$ was calculated by applying an equilibrium calcite equation to the temperature and $\delta^{18}O$ of water for the two MOCNESS stations [*O'Neil et al.*, 1969].

Above 40 m, the $\delta^{18}O$ of water will be a result of mixing between the PW end-member, sea ice melt, and possibly some continental meltwater. The decrease in surface salinities without an associated decrease in $\delta^{18}O$ of water suggests that these samples are predominantly influenced by sea ice melting. Applying our $\delta^{18}O$-salinity relationship to all surface samples may result in an underestimation of the $\delta^{18}O$ of water in the surface 40 m, which in turn may result in an underestimation of the $\delta^{18}O_{CALCITE}$. In the surface 0-20 m, seasonal warming of this surface layer by about 4°C will decrease the $\delta^{18}O_{CALCITE}$ by approximately 1‰. Because we cannot further quantify mixing between sea ice melt, PW, and continental ice melt without additional $\delta^{18}O$ of water data, we have shaded the range in which we expect to find the actual value of $\delta^{18}O_{CALCITE}$ (see Figure 8).

Table 2. Fluxes of *N. pachyderma* (s.) Collected by a Time Series Sediment Trap in the NEW Polynya

Cup	Dates Open	Duration, days	Total*	Encrusted*	Nonencrusted*
C1	Aug. 1, 1992 to Aug. 9, 1992 and Sept. 6, 1992 to July 27, 1993	332	32	15	16
C3	Aug. 9, 1992 to Aug. 14, 1992	5	528	168	338
C5	Aug 14, 1992 to Aug. 24, 1992	10	803	382	412
C6	Aug. 24, 1992 to Sept. 3, 1992	10	192	73	109
C7	Sept. 3, 1992 to Sept. 5, 1992	2	120	63	51

*Number per square meter per day.

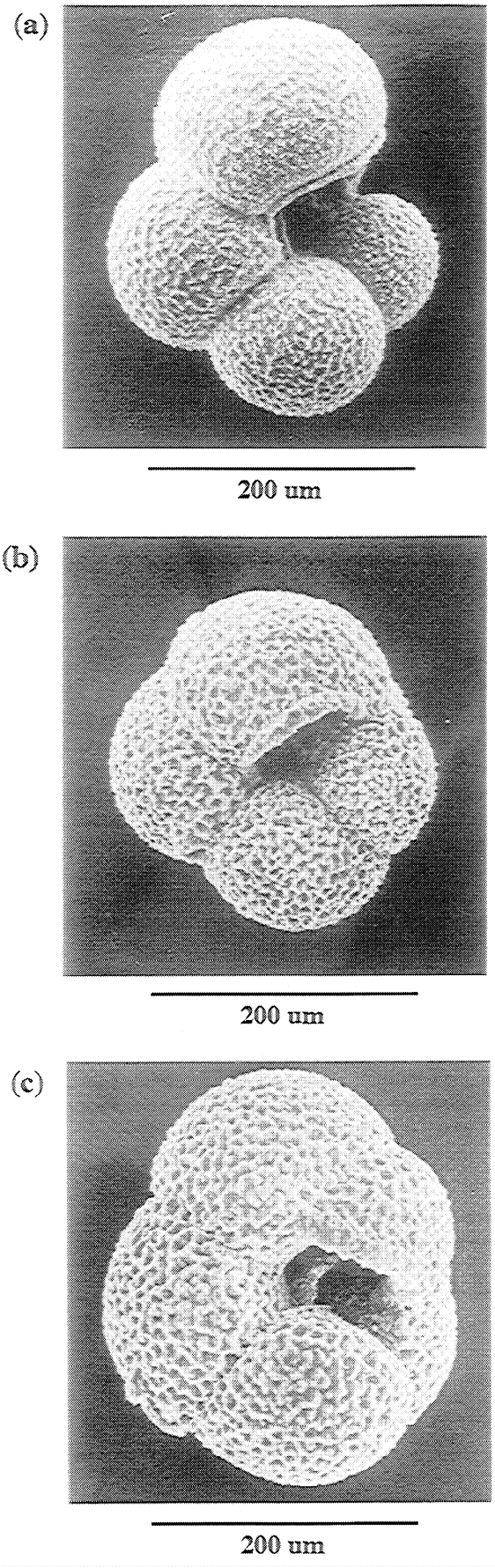

Figure 4. Scanning electron micrograph images (200X) demonstrate the physical differences between the (a) nonencrusted and (b) encrusted forms of *N. pachyderma* (s.) found in the NEW Polynya plankton tow samples (c) Encrusted form found in Arctic surface sediments. Scale bars are all 200 μm. Close examination (2500X) of these same specimens shows varying degrees of encrustation on *N. pachyderma* (s.). (d) Nonencrusted *N. pachyderma* (s.) from the water column shows the beginnings of encrustation (white calcite) around shell pores. (e) Encrusted *N. pachyderma* (s.) from the water column show an increasing density of calcite crust around shell pores. (f) *N. pachyderma* (s.) found in Arctic surface sediments show an even greater amount of encrustation. Scale bars are all 20 μm. Figures 4a, 4b, 4d, and 4e are taken from Station 92-43A, 150-200 m in the water column. Figures 4c and 4f are taken from Ocean Drilling Program (ODP) Site 911B, 80.5°N, 8.2°E, 900 m.

Table 3. Oxygen Isotope Values Measured on Water From the NEW Polynya, July 1993

Sample	Pressure, mbar	Temperature, °C	Salinity	$\delta^{18}O$ (‰, SMOW)
		Station 4, CTD 10, 80.28°N, 13.82°W		
3084	2	1.830	32.010	-2.871
3083	10	0.450	32.315	-2.748
3082	14	-0.720	32.367	-2.478
3081	20	-1.517	32.406	-2.558
3080	34	-1.683	32.424	-2.502
3079	50	-1.733	32.434	-2.557
3078	60	-1.745	32.442	-2.508
3077	74	-1.680	32.581	-2.248
3076	98	-1.593	32.879	-1.864
3075	148	-0.784	34.060	-0.593
3074	199	0.074	34.554	-0.113
3073	261	0.567	34.706	-0.006
		Station 38, CTD 76, 80.15°N, 7.74°W		
3742	2	1.161	30.840	-2.536
3741	3	0.213	31.288	-2.540
3740	5	0.390	31.165	-2.508
3739	8	-0.341	31.549	-2.415
3738	13	-0.491	31.607	-2.558
3737	20	-0.790	31.792	-1.999
3736	30	-0.447	32.186	-1.804
3735	60	-1.655	32.395	-2.262
3734	100	-1.433	32.937	-1.640
3733	149	-0.299	34.317	-0.245
3732	201	0.329	34.701	0.227
3731	300	0.384	34.850	0.346

Reproducibility of North Atlantic Deep Water standards is 0.03‰. Values for Station 4 were measured on July 24, 1993, at 2:16pm LT, and values for Station 38 were measured on July 31 at 2:16pm LT. CTD, conductivity/temperature/depth measurement.

Samples of $\delta^{13}C$ of ΣCO_2 were not measured as part of either of the U.S. *Polar Sea* cruises, but measurements of $\delta^{13}C$ of ΣCO_2 were taken during the 1993 RV *Polarstern* cruise to the NEW Polynya. MOCNESS Stations 43A and 43D, sampled in 1992, are at the same location as *Polarstern* Station PS2425 (80.14°N, 10.6°W). Because PO_4 profiles from all of the MOCNESS stations have the same characteristics (Figure 3b), we have used this *Polarstern* station as a rough estimate of the $\delta^{13}C$ of ΣCO_2 at all of our MOCNESS stations (A. Mackensen, unpublished data, 1995). The effect of gas exchange for CO_2 inventories was negligible throughout the polynya during the period of the 1992 cruise [*Yager et al.*, 1995]. Thus we expect that the effects of air-sea exchange upon the carbon isotope composition of ΣCO_2 is minimal. For comparison with the $\delta^{13}C$ of *N. pachyderma* (s.) from the MOCNESS stations , we have added the 1.0 ± 0.2‰ offset to the $\delta^{13}C$ of ΣCO_2 in order to determine the $\delta^{13}C$ for calcite formed in equilibrium with seawater [*Romanek et al.*, 1992].

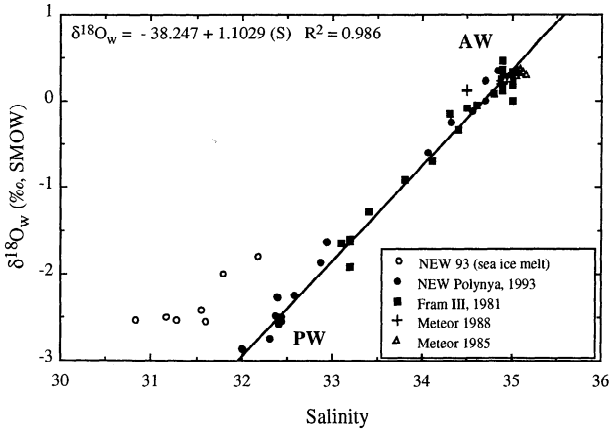

Figure 5. Values of $\delta^{18}O$ (‰, SMOW) versus salinity for water samples from the Fram Strait (Fram III [*Ostlund and Hut*, 1984]), the Greenland Sea (Meteor 1985 and 1989 [*Bauch*, 1995]), and the NEW Polynya. We have compared the NEW data with that from the Fram Strait and the Greenland Sea in an attempt to establish a mixing line between the Polar Water (PW) in the polynya and Atlantic Water (AW). Open circles represent samples that are affect by sea-ice melt, in the surface 40 m, and are not included in the regression.

Stable Isotope Analyses

For the $H_2{}^{18}O/H_2{}^{16}O$ analysis, 2 mL of water from each sample were purged with CO_2 in order to strip the samples of all other gases. The samples were then equilibrated with the CO_2 gas at 35°C for 10 hours before analysis. Oxygen isotope analyses were performed on a VG Prism II mass spectrometer, with an automated sampler designed at Lamont-Doherty Earth Observatory (LDEO). Reproducibility of North Atlantic Deep Water (NADW) standards was 0.03‰. Isotope analyses on carbonate samples were performed on a Finnegan 251 MAT mass spectrometer at LDEO using an automated carbonate analysis device designed at LDEO. Samples for stable isotope analyses were composed of at least 10 encrusted and

30 nonencrusted *N. pachyderma* (s.). Standard masses were measured for each run to encompass the range of masses of the foraminiferal samples (usually 40-180 μg). Measurement error of the foraminifera samples analyzed is 0.07‰ for oxygen and 0.05‰ for carbon, based on replicate analyses of our working standard.

Results

A comparison of foraminiferal abundances and chlorophyll demonstrates that the maximum abundances of *N. pachyderma* (s.) occur at or just below the depth of the maximum chlorophyll concentrations (Figure 6; Table 4). Chlorophyll concentrations are overlain on these plots with bold lines and represent chlorophyll measurements made in several bottle casts at each station [*Wallace et al.*, 1995a]. Maximum chlorophyll concentrations occur between 20 and 60 m depth, with values ranging between 2 and 11 μg/kg. Foraminifera found within these depths have green protoplasm. At four stations, maximum abundances of *N. pachyderma* (s.) occur between 20 and 80 m. At Station 93-36, maximum *N. pachyderma* (s.) abundances occur between 60 and 100 m. At Station 4, both chlorophyll concentrations and foraminiferal abundances are minimal. Significant concentrations of total *N. pachyderma* (s.) are still found below the chlorophyll maximum zone.

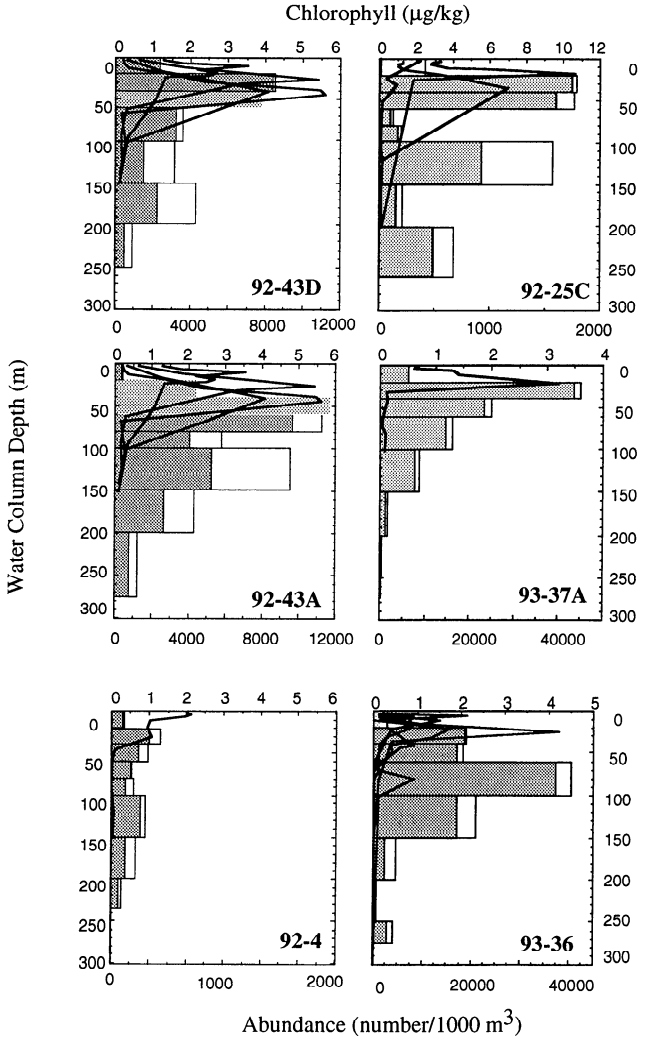

Figure 6. Vertical distribution of *N. pachyderma* (s.) at five MOCNESS stations within the polynya. Note the different axes scales used for each station. The bold line represents chlorophyll a profiles (micrograms/kilogram) measured at each station within the polynya [*Wallace et al.*, 1995a]. The shaded bars show abundances (number/1000 m^3) of nonencrusted *N. pachyderma* (s.) while the open bars represent abundances of encrusted individuals. Lightly shaded bars without outlines represent poorly preserved samples in which foraminifera suffered extensive dissolution. Counts of total foraminifera could still be made on these samples. With the exception of 1993 Station 36, peak abundances of *N. pachyderma* (s.) occur between 20 and 80 m water depth, at or just below the zone of maximum chlorophyll concentrations.

Comparison between plankton tow, sediment trap, and surface sediment abundances demonstrates several important points (Figures 7a-7d). First, between 0 and 80 m, nonencrusted *N. pachyderma* (s.) make up greater than 95% of the water column assemblage. Second, the encrusted forms increase from 0% to 25-40% of the total *N. pachyderma* (s.) assemblage between 50 and 275 m. This increase is driven by an increase in the absolute concentrations of encrusted *N. pachyderma* (s.) (maximum between 100 and 150 m), as well as a dramatic decrease in the concentrations of nonencrusted *N. pachyderma* (s.). Nonencrusted and encrusted *N. pachyderma* (s.) abundances are concentrated in different parts of the water column. While the nonencrusted forms are found mostly in the cold mixed layer above the main pycnocline, abundances of encrusted *N. pachyderma* (s.) peak within the main pycnocline (Figure 7b). Third, the relative percent of encrusted *N. pachyderma* (s.) in sediment trap samples varies from 40 to 60%. These percentages are slightly higher than the values found at the greatest depth intervals in the plankton tows and drastically higher than the percentages of encrusted forms found in the surface (0-80 m) tows. Finally, nonencrusted *N. pachyderma* (s.) are completely absent in the surface sediment samples taken from the NEW Polynya. Surface textures of the encrusted forms found in the sediments were pitted, which is suggestive of dissolution.

Measurements of average shell mass of encrusted *N. pachyderma* (s.) are 3-4 times greater than nonencrusted forms in the uppermost 200 m. The average mass of nonencrusted forms does not change throughout the water column (Figure 7c). The average mass of encrusted *N. pachyderma* (s.) increases from 4 to 7 μg between 30 and 175 m.

Comparison of $\delta^{18}O$ of *N. pachyderma* (s.) and $\delta^{18}O_{CALCITE}$ for all stations demonstrates three important points (Figure 8; Table 4). First, the $\delta^{18}O$ of both encrusted and nonencrusted *N. pachyderma* (s.) changes with depth in the water column, increasing approximately 1.5‰ between 50 and 200 m. This increase in the $\delta^{18}O$ of *N. pachyderma* (s.) corresponds to the changes in $\delta^{18}O_{CALCITE}$, with some offset. The $\delta^{18}O$ of *N. pachyderma* (s.) are consistently lighter than $\delta^{18}O_{CALCITE}$, and the nonencrusted forms are consistently lighter than the encrusted forms. Second, between 200 and 275 m, the $\delta^{18}O$ values of water column *N. pachyderma* (s.) converge on the $\delta^{18}O$ values measured from underlying sediment trap samples. The range of $\delta^{18}O$ values of *N. pachyderma* (s.) from sediment traps and surface sediments in the NEW Polynya are 1.9-2.5‰. Finally, the *N. pachyderma* (s.) from 200 m and those

Table 4. Abundances and Isotope Values of *N. pachyderma* (s.) From MOCNESS Stations, and Fluxes and Isotope Values of *N. pachyderma* (s.) from Sediment Trap C, Within the NEW Polynya

Sample	Depth, m	Split counted, %	Abundance, number/1000m^3		$\delta^{18}O$, ‰ PDB		$\delta^{13}C$, ‰ PDB	
			Encrusted	Nonencrusted	Encrusted	Nonencrusted	Encrusted	Nonencrusted
92-4-N9	0-20	24.646	11	102	----	----	----	----
92-4-N8	20-40	24.730	90	340	----	----	----	----
92-4-N7	40-60	48.486	83	242	----	----	----	----
92-4-N6	60-80	44.336	6	178	----	----	----	----
92-4-N5	80-100	44.922	77	123	----	----	----	----
92-4-N4	100-148	44.336	42	262	----	----	----	----
92-4-N3	148-200	47.070	89	128	----	----	----	----
92-4-N2	200-235	44.141	26	66	----	----	----	----
92-25C-N9	0-21	48.510	400	20	3.01	----	0.54	----
					3.05		0.55	
					3.08		0.57	
					2.93		0.57	
92-25C-N8	21-40	48.706	40	1748	----	1.10	----	0.71
						1.07		0.68
						1.05		0.69
						1.11		0.69
						1.56		0.78
						1.16		0.67
						1.07		0.59
92-25C-N7	40-59	48.633	170	1604	----	1.24	----	0.66
						1.26		0.64
						1.36		0.68
						1.36		0.77
92-25C-N6	59-80	47.266	20	110	----	1.06	----	0.66
92-25C-N5	80-100	47.270	20	172	----	1.20	----	0.55
92-25C-N4	100-149	47.168	640	929	1.42	1.30	0.64	0.63
					1.39	1.24	0.64	0.60
					1.57		0.80	
					1.56		0.77	
92-25C-N3	149-200	44.433	60	152	1.82	1.89	0.46	0.39
92-25C-N2	200-258	49.270	180	490	2.78	2.00	0.37	0.31
93-36-N9	0-20	25.000	*	1130*	----	----	----	----
93-36-N8	20-40	25.000	900	18660	----	1.01	----	0.60
						0.88		0.48
93-36-N7	40-60	25.000	1000	17110	----	0.90	----	0.51
93-36-N6	60-100	25.000	2820	37230	----	0.91	----	0.61
93-36-N5	100-150	25.000	3710	17040	1.38	1.31	0.52	0.60
					1.13	1.41	0.46	0.65
93-36-N4	150-200	25.000	2220	2210	1.70	1.69	0.51	0.51
					2.01	1.63	0.51	0.43
93-36-N3	200-250	25.000	330	430	2.37	1.77	0.41	0.35
93-36-N2	250-275	25.000	1170	2830	1.62	1.34	0.55	0.36
93-37A-N8	20-40	25.000	824	43400	----	----	----	----
93-37A-N7	40-60	25.000	825	23400	----	----	----	----
93-37A-N6	60-100	25.000	726	16800	----	----	----	----
93-37A-N5	100-146	25.000	970	7700	----	----	----	----
93-37A-N4	146-199	25.000	539	1210	----	----	----	----
93-37A-N3	199-248	25.000	87	290	----	----	----	----
93-37A-N2	248-273	25.000	32	80	----	----	----	----
92-43A-N9	0-20	30.489	40	351	----	1.14	----	0.94
92-43A-N8	20-40	24.91	*	4030*	----	----	----	----
92-43A-N7	40-60	24.91	*	11700*	----	----	----	----
92-43A-N6	60-80	24.623	1590	9661	----	1.06	----	0.66
92-43A-N5	80-100	24.632	1740	4074	1.30	1.20	0.62	0.55
					1.64		0.60	
92-43A-N4	100-150	24.262	4310	5260	1.92	1.36	0.45	0.43
					1.79	1.33	0.50	0.37
					1.76	1.52	0.51	0.46
					1.67	1.34	0.60	0.37

Table 4. (continued)

Sample	Depth, m	Split counted, %	Abundance, number/1000m^3		$\delta^{18}O$, ‰ PDB		$\delta^{13}C$, ‰ PDB	
			Encrusted	Nonencrusted	Encrusted	Nonencrusted	Encrusted	Nonencrusted
92-43A-N3	150-200	23.535	1650	2644	2.50	----	0.44	----
					2.53		0.47	
					2.46		0.48	
					2.58		0.47	
					2.56		0.47	
92-43A-N2	200-275	23.56	470	780	2.89	2.75	0.42	0.28
					3.04	2.64	0.48	0.23
						2.95		0.34
92-43D-N9	0-19	24.844	23	2359	----	0.82	----	0.76
92-43D-N8	19-38	24.633	97	8506	----	0.87	----	0.59
92-43D-N7	38-60	24.781	*	7781*	----	----	----	----
92-43D-N6	60-100	24.351	366	3552	1.36	1.13	0.64	0.79
92-43D-N5	100-149	22.023	1596	3115	1.87	1.29	0.60	0.23
92-43D-N4	149-198	23.488	2037	4244	2.62	2.38	0.53	0.48
92-43D-N3	198-248	23.488	429	857	2.68	2.43	0.49	0.33
					2.38		0.54	

Sample	Duration, days	Split counted, %	Flux, number m^{-2} d^{-1}		$\delta^{18}O$, ‰ PDB		$\delta^{13}C$, ‰ PDB	
			Encrusted	Nonencrusted	Encrusted	Nonencrusted	Encrusted	Nonencrusted
Trap C1	332	16.667	15	16	2.60	----	0.51	----
					2.32		0.59	
Trap C3	5	16.667	168	338	2.26	1.97	0.48	0.29
Trap C5	10	16.667	412	382	2.59	----	0.52	----
Trap C6	10	16.667	110	74	2.29	----	0.51	----
Trap C7	2	16.667	52	64	2.54	----	0.39	----

For all encrusted *N. pachyderma* (s.) measurements, at least 10 individuals were used. For each nonencrusted *N. pachyderma* (s.) analysis, more than 30 individuals were used.

*Samples in which carbonate was too dissolved (due to insufficient buffering when samples were archived) to permit isotope analyses. Counts of total foraminifera could still be made in the samples and are listed in the nonencrusted *N. pachyderma* (s.) column.

found in sediment traps have oxygen isotope signatures that bear little resemblance to the values representing the temperature and salinity conditions found in the surface 50 m of the water column. Instead, the $\delta^{18}O$ of *N. pachyderma* (s.) continue to change between 0 and 200 m, and the *N. pachyderma* (s.) found in the sediment traps appear to reflect water column values found at approximately 80-120 m.

Both the $\delta^{13}C$ of ΣCO_2 and the $\delta^{13}C$ of *N. pachyderma* (s.) change minimally between 50 and 200 m (Figure 9). Between 50 and 200 m, the $\delta^{13}C$ of *N. pachyderma* (s.) average 0.50±0.14‰; sediment trap and surface sediment values average 0.46±0.10‰. The $\delta^{13}C$ of ΣCO_2 at *Polarstern* Station PS2425 average 0.66±0.20‰ between 0 and 150 m, and the deepest samples are within the range of $\delta^{13}C$ of *N. pachyderma* (s.) values found in the surface sediments. The $\delta^{13}C$ of ΣCO_2 shows a slight maximum ($\Delta\delta^{13}C$ = 0.3‰) at the depth of the chlorophyll maximum, perhaps due to enrichment in ^{13}C resulting from local productivity. However, with the possible exception of one station (92-25C), the same trend is not resolvable in the plankton tow data. Inorganic precipitation studies using calcite show that the $\delta^{13}C$ for calcite formed in equilibrium with seawater should be 1.0±0.2‰ greater than the $\delta^{13}C$ of ΣCO_2 [*Romanek et al.*, 1992]. However, the $\delta^{13}C$ of *N. pachyderma* (s.) from the MOCNESS plankton tows share remarkably similar values with $\delta^{13}C$ of ΣCO_2 measurements from the NEW Polynya. In other words, the $\delta^{13}C$ of *N. pachyderma* (s.) are slightly more than 1‰ depleted compared with the $\delta^{13}C$ of equilibrium calcite.

Data from the moored sediment trap show that maximum fluxes of *N. pachyderma* (s.) occur in early August, in one 2-week-long bloom event (Figure 10). Fluxes decrease to almost zero under complete ice cover. This result is consistent with sediment trap results from other polar regions (Figure 11), which show maximum fluxes occurring as a 2-week- to 3-month-long bloom during summer in the Southern Ocean [*Donner and Wefer*, 1994]. This brief period of production of *N. pachyderma* (s.) has been also observed in the North Pacific, during the spring bloom [*Reynolds and Thunell*, 1986]. A temporal trend is not discernible in either the carbon or oxygen isotope signals of the sediment trap *N. pachyderma* (s.). Average $\delta^{13}C$ values are 0.47±0.10‰, and average $\delta^{18}O$ values are 2.36±0.23‰.

Discussion

Depth Habitat of *N. pachyderma* (s.)

Because of its encrustation, *N. pachyderma* (s.) has been classified as a "deep dweller" by many investigators and is ex-

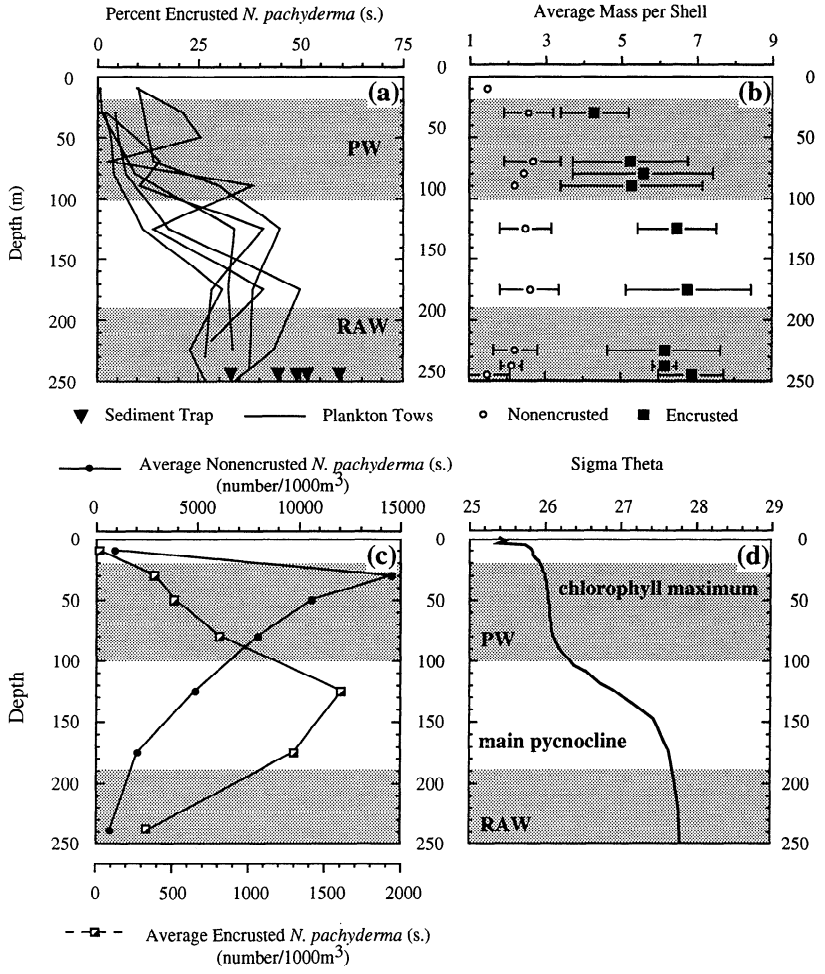

Figure 7. (a) Percent abundance of encrusted *N. pachyderma* (s.) versus depth demonstrates an increase in the percentage of encrusted forms below the PW. Sediment trap assemblages (solid triangles) contain even greater percentages of encrusted forms. (b) The average concentrations of the two types of *N. pachyderma* (s.) for all stations demonstrate that the increase in the percent encrusted *N. pachyderma* (s.) is the result of both an increase in the encrusted abundances and a decrease in abundances of the nonencrusted forms. (c) A comparison of the average mass per shell (1992-1993) versus depth shows that the encrusted tests (solid squares) are 3-4 times heavier than the nonencrusted ones (open circles). While the nonencrusted shells have a constant mass with depth, the mass of the encrusted forms increases from ~4 to 7 μg between 50 and 200 m. Average measurements were made on 10 encrusted and 30 nonencrusted individuals; standard deviations represent 1σ (n=2-10) variability of all measurements made from the polynya samples at each depth interval. (d) Sigma theta versus depth for a representative station in the polynya [from *Wallace et al.*, 1995a]. Shaded regions in all plots indicate the depth range of the seasonal pycnocline, the PW, the main pycnocline, and the RAW. Comparison with sigma theta demonstrates that maximum average masses and abundances of encrusted *N. pachyderma* (s.) are associated with the main pycnocline.

pected to grow and calcify below 200 m water depth [*Be*, 1960; *Boltovskoy*, 1971; *Aksu and Vilks*, 1988; *Hemleben et al.*, 1989]. However, these studies have all inferred calcification depth, based mostly on isotope analyses from surface sediment specimens. *Vilks* [1975] first compared surface plankton tow samples (0-200 m) with sediment samples in the Arctic Ocean and suggested that only the older, larger, encrusted shells are preserved in sediment assemblages. The first direct study of the depth habitat of *N. pachyderma* (s.) using stratified plankton tows demonstrated that *N. pachyderma* (s.) lives in the surface 100 m north of 83°N in the Arctic Ocean [*Carstens and Wefer*, 1992].

Previous investigators have developed an ecological model which explains that asymbiotic foraminifera respond to changes in phytoplankton concentrations [*Fairbanks and Wiebe*, 1980]. According to several MOCNESS studies, maximum abundances of non-symbiont-bearing planktonic foraminifera are found in association with the chlorophyll maximum zone, which they exploit as a food source zone [*Fairbanks and Wiebe*, 1980; *Fairbanks et al.*, 1982; *Ravelo et al.*, 1990]. The MOCNESS plankton tow samples from the NEW Polynya indeed show peak abundances of total *N. pachyderma* (s.) at 20-80 m, in conjunction with the chlorophyll maximum zone. The green protoplasm of the individuals

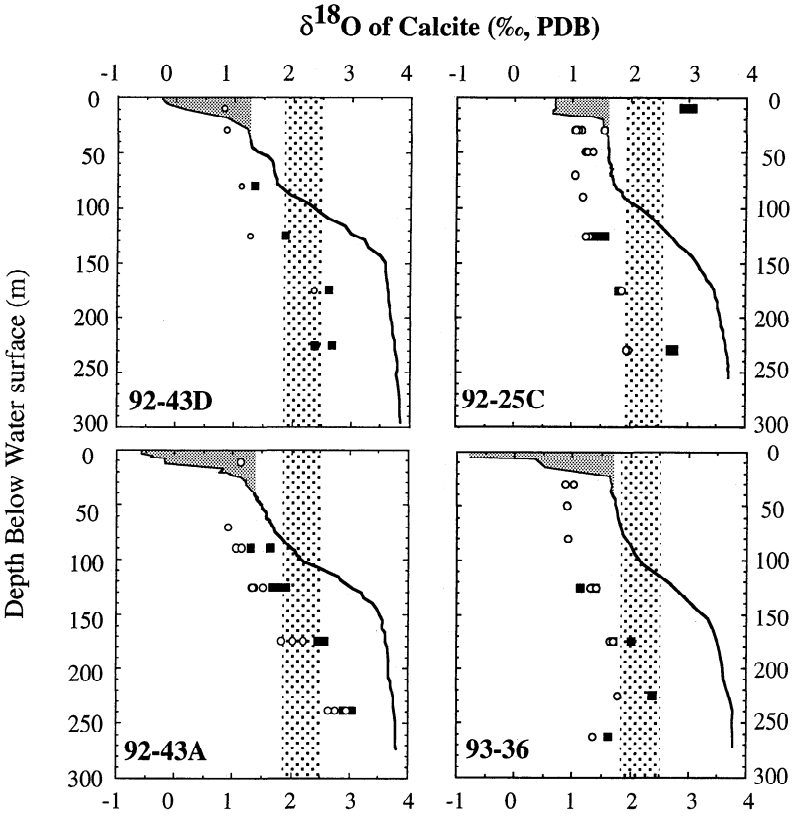

Figure 8. Oxygen isotope composition of *N. pachyderma* (s.) for four sites within the NEW polynya. Solid line represents the $\delta^{18}O$ predicted for calcite formed in equilibrium with sea water, using the *O'Neil et al.* [1969] equation as formulated by *McCorkle et al.* [1990]: $\delta^{18}O_{CALCITE}$ (‰, Pee Dee Belemnite) = 2.78 x 10^6 T^{-2}(°K) - 33.0857 + ($\delta^{18}O_W$ - 0.27). The $\delta^{18}O$ of water ($\delta^{18}O_W$) is predicted from salinity, using the relationship shown in Figure 5. The stippled area represents the range of $\delta^{18}O$ of *N. pachyderma* (s.) measured in sediments and sediment trap samples from the polynya. Open circles represent nonencrusted individuals, while solid squares represent encrusted individuals. The shaded region between 0 and 40 m represents the region in which our prediction of $\delta^{18}O_{CALCITE}$ may be uncertain, due to the influence of sea-ice melt.

found at these depths suggests that they are ingesting either phytoplankton or detrital chlorophyll particles. This hypothesis is further supported by transmission electron micrograph (TEM) studies on *N. pachyderma* (s.), which show feeding vacuoles containing diatoms, silica fragments, and abundant algal cells undergoing digestion [*Gowing*, 1989].

While these data support the ecological model of *Fairbanks and Wiebe* [1980] for the most part, additional environmental controls appear to contribute to the observed distributions of *N. pachyderma* (s.) in the NEW Polynya. In the previous MOCNESS studies, *N. dutertrei* and *G. sacculifer* abundances show a major increase at the depth of the deep chlorophyll maximum zone, with major decreases in abundances both above and below the deep chorophyll maximum zone. In this study, while abundances generally reach peak concentrations at the chlorophyll maximum zone (Figures 6 and 7), *N. pachyderma* (s.) abundances sometimes remain high even below the chlorophyll maximum zone. Several factors could contribute to this difference. First, the chlorophyll data and MOCNESS plankton tows were not collected simultaneously. At each station, the chlorophyll data reflect several casts collected as many as 12 hours before or after the MOCNESS deployments. Second, the MOCNESS plankton tow samples, particularly at Station 93-36, could be capturing a foraminiferal bloom that has already occurred and begun to sink. Between 20 and 100 m at Station 93-36, the $\delta^{18}O$ of *N. pachyderma* (s.) show remarkably consistent values of approximately 1.0‰ (Figure 8). These $\delta^{18}O$ data suggest that the *N. pachyderma* (s.) may have dropped from the chlorophyll maximum zone without adding calcite, following a bloom. In this case, the depth zone in which the foraminiferal ecology is controlled may be narrower than the MOCNESS abundance data indicate.

Additional physical constraints in the polynya environment could also explain the relatively high abundances found below the chlorophyll maximum zone following these bloom events. The sharp density gradient of the main pycnocline provides a lower barrier to settling for the nonencrusted foraminifera (Figure 7). As a result, high abundances of nonencrusted forms may be observed throughout the mixed layer, but higher concentrations are usually found in association with the chlorophyll food source located between 20 and 60 m.

Encrustation Process in *N. pachyderma* (s.)

One distinguishing characteristic of *N. pachyderma* (s.) specimens found in marine sediments is the thick calcite crust.

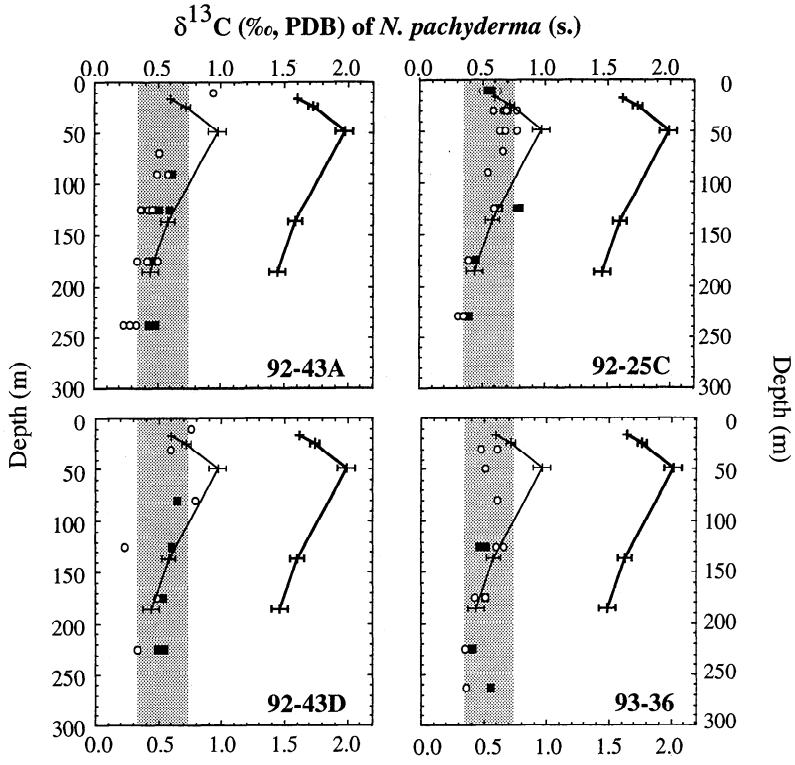

Figure 9. Carbon isotope composition of *N. pachyderma* (s.) for the same four sites within the polynya as in Figure 8. The $\delta^{13}C$ of equilibrium calcite is indicated by the bold line. The $\delta^{13}C$ of ΣCO_2 (light line) was taken from 1993 R/V *Polarstern* Station PS2425 (A. Mackensen, personal communication, 1995). The stippled area, open circles and solid squares are the same as in Figure 8.

In the NEW Polynya plankton tow samples, the abundances of the encrusted forms increase at the depth of the main pycnocline (Figure 7). These observations are consistent with other Arctic Ocean studies, which show an increase in the secondary calcification of *N. pachyderma* (s.) with depth in the water column [*Carstens and Wefer*, 1992]. Several processes could explain the relationship between the nonencrusted *N. pachyderma* (s.), mostly found in the surface 20-80 m, and the encrusted foraminifera, whose peak abundances are found at the depth of the main pycnocline.

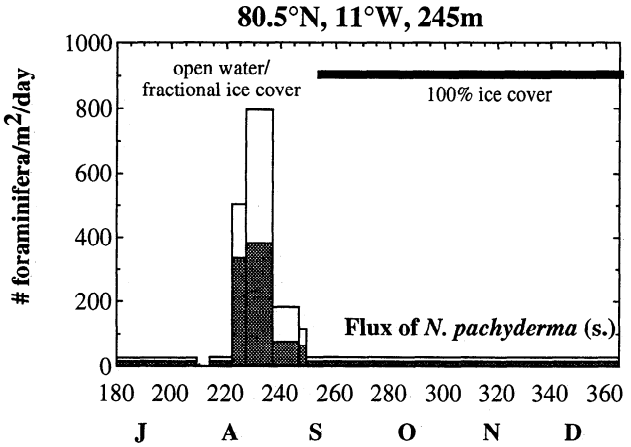

Figure 10. *N. pachyderma* (s.) fluxes from trap C within the NEW Polynya. The trap was deployed from August 1992 to July 1993. The major fluxes of both nonencrusted and encrusted *N. pachyderma* (s.) occur in a single pulse in late August. Encrusted (open bars) and nonencrusted (shaded bars) *N. pachyderma* (s.) each make up approximately 50% of the sediment trap assemblage. Other species are negligible. Solid line shows times with 100% ice cover.

One hypothesis to explain this increase in encrusted forms with depth is that the nonencrusted *N. pachyderma* (s.) add a calcite crust as part of their life cycle. In the tropical species *Globigerinoides sacculifer*, a similar type of encrustation is associated with gametogenesis. Prior to gamete release and reproduction, the tropical species adds irregular calcite deposits covered by a smooth veneer to its chambers [*Be*, 1980; *Hemleben et al.*, 1989]. This crust can account for as much as one third of the shell mass of *G. sacculifer* [*Be*, 1980]. It is possible that the crust of *N. pachyderma* (s.) is also gametogenic in nature. In this case, the addition of a calcite crust results in a change in shell density, which in turn results in the descent of the encrusted forms below the mixed layer and into the main pycnocline.

Encrustation could be a gradual process beginning at or near the surface and continuing to a depth of approximately 200 m in the water column. The increase in average shell mass of the encrusted *N. pachyderma* (s.) supports this suggestion (Figure 7c; Table 5). An implication of this hypothesis is that the addition of shell mass with depth should result in an integration of *N. pachyderma* (s.) shell chemistry across the depth range of encrustation. In terms of paleoceanographic reconstructions, the encrustation process would result in the largest de-

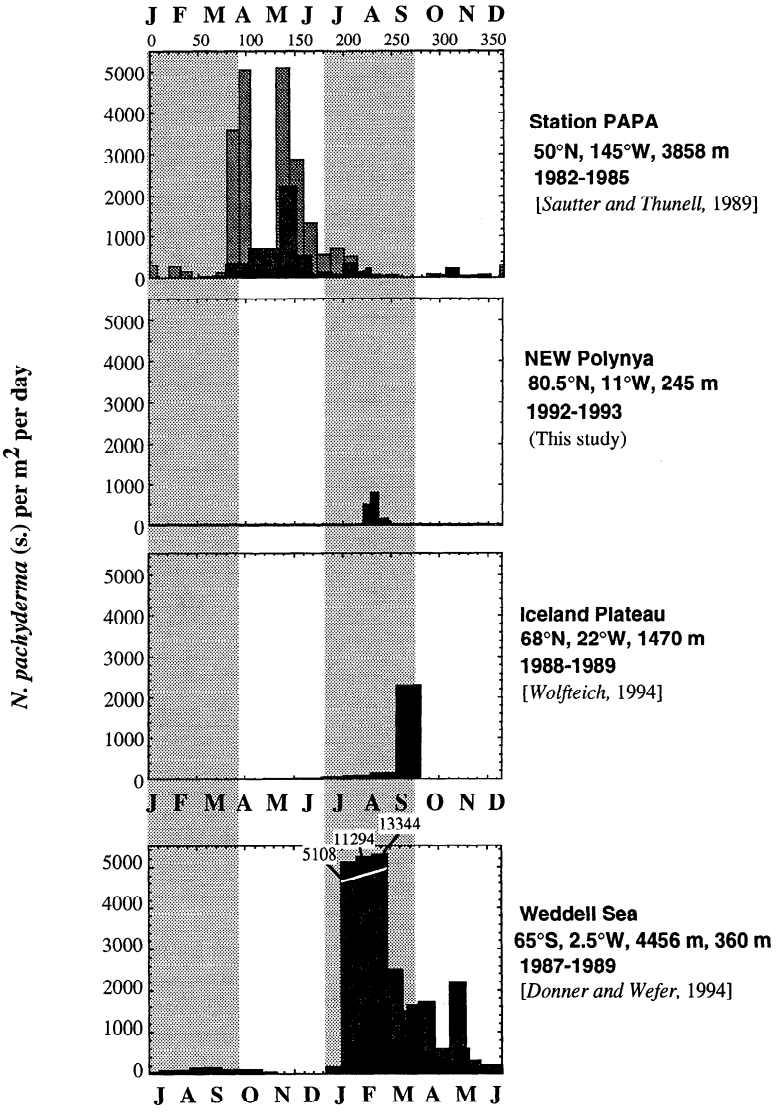

Figure 11. Fluxes of *N. pachyderma* (s.) measured in sediment traps from Station PAPA in the North Pacific [*Sautter and Thunell*, 1989], the NEW Polynya, the Iceland Plateau [*Wolfteich*, 1994], and the Weddell Sea [*Donner and Wefer*, 1994]. Highest fluxes are found at the Weddell Sea moorings, during February and March, austral summer. Durations of maximum fluxes vary from 1 week to 1 month. While polar peaks occur in summer, the maximum flux at the subpolar station (Station PAPA) occurs in spring. Alternating shading across all four plots aligns winter, spring, summer, and autumn seasons.

viations from surface conditions in regions with sharp hydrographical gradients.

Alternatively, encrustation (i.e., transformation from nonencrusted to encrusted forms) could occur all at once but at a variety of depths in the water column. Our data demonstrate that while the mass of the nonencrusted forms does not change throughout the water column, the isotopic composition of the nonencrusted forms increases by at least 1‰ between 0 and 200 m. These data suggest that the nonencrusted *N. pachyderma* (s.) are living and calcifying throughout the water column. In this case, even though encrustation occurs at all depths, the peak abundances of the encrusted forms are found in the main pycnocline (100-200 m). Therefore the isotopic signal recorded in the sediment trap and marine sediments is biased toward this depth interval of the main pycnocline. Furthermore, the isotopic signal of the encrusted forms will be a combination of the shell chemistry of the primary and crustal calcite at a given depth interval.

These different hypotheses of encrustation can be tested using a simple mass balance calculation, assuming that the bulk shell composition is a result of two-component mixing between the nonencrusted and encrusted shell calcite. On the basis of this assumption, we can formulate two equations which describe the mass and chemistry of *N. pachyderma* (s.):

$$M_P + M_C = M_T$$

$$M_P C_P + M_C C_C = M_T C_T,$$

where M_P, M_C, and M_T are the masses of primary calcite, calcite crust, and the total shell mass, respectively, and C_P, C_C,

and C_T represent the shell chemistry of these same components.

Previous investigators have completed extensive measurements of size and mass of planktonic foraminifera in order to accurately estimate the proportions of primary and secondary (crusted) calcite [*Lohmann,* 1995]. Detailed measurements of shell mass, shell size, and the associate isotope chemistry would be required to accurately determine the proportions of crust and primary calcite. These measurements were not made for this study. Instead, we shall assume that the nonencrusted *N. pachyderma* (s.) approximates the mass and shell composition of the primary calcite, and the encrusted *N. pachyderma* (s.) approximates the mass and shell composition of the total, bulk shell. On the basis of these assumptions, we can then estimate changes in the mass and chemical composition of the added crust.

We can then use these mass balance equations to estimate the isotopic composition of the calcite crust, based on these hypotheses (Table 5). First, we assume that the whole crust is added at any depth level throughout the water column. In this case, for any given depth

$$C_C = (M_T C_T - M_P C_P) / (M_T - M_P)$$

In the second case, we assume that the whole crust is added at any given depth interval, but that all of the primary calcite of the nonencrusted foraminifera were formed in the depth range of 20-80 m. Here we set M_P and C_P to the values found at 30 m. In the final case we assume that all of the primary calcite was added above 70 m, that crust addition begins at 70 m, and that it is then added gradually with depth (see Table 5). We calculate the composition of the crust added from one depth interval to the next using the change in mass and isotopic composition of the encrusted *N. pachyderma* (s.) between each depth interval. In comparing the calculated crust chemistry from these cases (Table 5), we see that the first two hypotheses present reasonable isotope values for calcite crust. However, the third case presents isotope values ranging from -4 to +99‰ for the oxygen isotope composition of the added calcite crust, which are unrealistic values given the $\delta^{18}O_{CALCITE}$ predicted for the ambient water. Thus it seems more reasonable that the crust is not added gradually throughout the water column but perhaps all at once. Because the peak abundances are found in the main pycnocline (100-200 m), the isotopic signal of the encrusted forms found in the marine sediments is biased toward the realm of the main pycnocline.

These calculations all assume that the encrustation process converts nonencrusted *N. pachyderma* (s.) into older, encrusted forms. An alternative hypothesis that must be considered is that nonencrusted and encrusted forms are two different morphotypes entirely, occupying two distinct environments. The nonencrusted forms are found in the mixed layer, well above the main pycnocline, whereas the encrusted morphotypes are associated with the main pycnocline. Indeed, the relatively constant offset between the nonencrusted and encrusted forms, for both $\delta^{18}O$ and $\delta^{13}C$, might suggest that we are observing a constant "vital effect" offset between these two morphotypes. While this hypothesis is possible, we believe the other possibilities are more likely for a number of reasons. First, examination of the surface textures using scanning electronic microscopy demonstrates the process of

Table 5. Average Mass and Isotope Composition per Shell versus Depth for All Stations.

Depth, m	Average Mass Per Shell, µg				Nonencrusted Average Isotope Composition, ‰			Encrusted Average Isotope Composition, ‰			$\delta^{18}O$, ‰				$\delta^{13}C$, ‰			
	Non-encrusted, M_P	N	Encrusted, M_T	N	$\delta^{18}O$, C_P	$\delta^{13}C$, C_P	N	$\delta^{18}O$, C_T	$\delta^{13}C$, C_T	N	Crust, C_C*	Crust, C_C†	Crust, C_C‡	Crust, C_C*	Crust, C_C†	Crust, C_C‡	Crust, C_C*	Crust, C_C†	Crust, C_C‡
10	1.5	1	----		0.98±0.23	0.85±0.13	2	(3.02±0.06)	(0.56±0.02)	4									
30	2.6±0.6	4	4.1±0.9	2	1.09±0.19	0.65±0.08	10	----	----		----	----	----	----	----	----	----	----	----
50	2.6± 0.8	2	4.22	1	1.22±0.19	0.65±0.09	5	----	----		----	----	----	----	----	----	----	----	----
70	2.7±0.7	2	5.2±1.5	2	0.99±0.11	0.59±0.11	2	----	----		----	----	----	----	----	----	----	----	----
80	2.5±0.2	2	5.6±1.9	2	1.02±0.15	0.71±0.14	2	1.34	0.65	1	1.6	1.6	1.7	0.6	0.6	0.7			
90	2.2±0.2	2	5.3±1.9	2	1.13±0.08	0.54±0.04	3	1.47±0.24	0.61±0.01	2	1.7	1.8	-0.9	0.7	0.6	2.3			
125	2.5±0.7	6	6.5±1.0	6	1.34±0.08	0.48±0.15	9	1.59±0.24	0.59±0.12	11	1.7	1.9	3.6	0.7	0.6	0.8			
175	2.6±0.8	7	6.8±1.6	7	1.95±0.27	0.44±0.06	7	2.31±0.38	0.48±0.03	9	2.5	3.0	24.7	0.5	0.4	0.5			
225	2.2±0.6	3	6.2±1.5	3	2.04±0.28	0.34±0.02	3	2.58±0.20	0.44±0.07	4	2.9	3.6	-4.2	0.5	0.3	0.4			
238	2.1±0.3	3	6.2±0.3	2	2.42±0.73	0.30±0.06	4	2.52±0.78	0.48±0.07	3	2.6	3.5	99.0	0.6	0.4	30.9			
245*	1.5±0.6	4	6.9±0.9	9	1.97	0.29	1	2.44±0.15	0.51±0.07	10	2.6	3.2	1.7	0.6	0.4	0.8			
262	----		5.5	1															

At least 10 encrusted individuals and 30 nonencrusted individuals were used to determine each average shell measurement. Numbers in parentheses indicate number of samples (N) used to determine each average. Error bars show 1σ. Measurements from 245 m depth are taken from sediment trap samples. The possible isotopic compositions of the crust are then estimated using the mass balance calculations described below.

* Isotopic composition of crust added to the nonencrusted *N. pachyderma* (s.), for each depth interval: $C_C = (M_T C_T - M_P C_P) / (M_T - M_P)$.

† Isotopic composition of crust added at each depth interval, to nonencrusted *N. pachyderma* (s.) formed at 30 m: $C_C = [M_T C_T - M_{P(30\ m)} C_{P(30\ m)}] / [M_T - M_{P(30\ m)}]$.

‡ Isotopic composition of crust added between each successive depth interval, assuming that crust is added gradually at each depth interval, as determined by the change in average shell mass: $C_C = [M_{T(Z_{i+1})} C_{T(Z_{i+1})} - M_{T(Z_i)} C_{T(Z_i)}] / [M_{T(Z_{i+1})} - M_{T(Z_i)}]$, where Z_i, Z_{i+1} are successive depth intervals. Crust addition begins between 70 and 80 m and is initially added to nonencrusted *N. pachyderma* (s.) formed at 70 m.

crust addition (Figures 4d-4f). A comparison of surface textures in three different stages of encrustation shows the calcite veneer present on the nonencrusted *N. pachyderma* (s.) and two additional cases in which encrustation appears to have increased. Additionally, "cracking open" the encrusted *N. pachyderma* (s.) under a dissecting microscope reveals an internal morphology similar to the nonencrusted specimens. Third, mass versus size measurements on plankton samples from the 1993 NEW polynya cruise (D. Nuernberg and K. Kohfeld, unpublished data, 1996) seem to suggest an encrusting process similar to that observed in *G. truncatulinoides*, where the addition of shell crust does not change the size but increases the shell density of the foraminifera (Figure 12) [*Lohmann*, 1995]. Finally, the transformation from nonencrusted to encrusted *N. pachyderma* (s.) provides a logical explanation for the difference in the proportions of nonencrusted and encrusted forms between the sediment trap and plankton tow samples. However, to conclusively prove this would require either ribosomal RNA-based taxonomy on both morphotypes or definitive observations of the crust addition process in culture experiments.

Sediment Fluxes

What becomes important for marine sediment studies is the transfer of the water column planktonic foraminiferal assemblage to the marine sediments. Both the isotopic data and the relative abundances from the sediment trap samples reflect

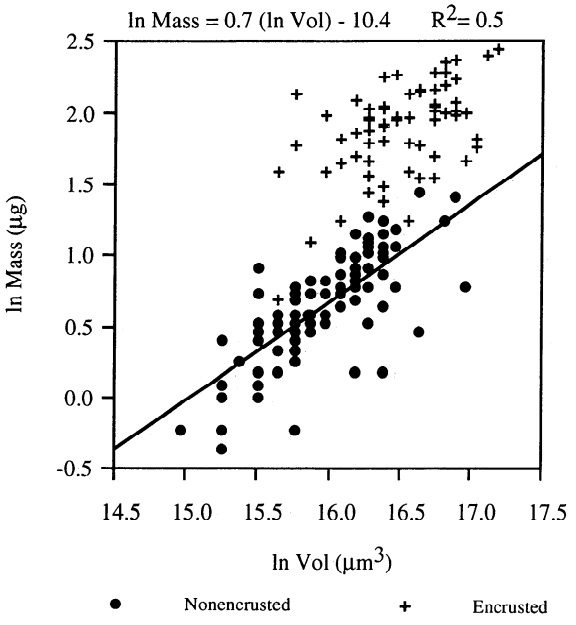

Figure 12. Mass versus volume (cubic micrometers) measurements made on single *N. pachyderma* (s.) for 1993 plankton tow and sediment trap samples. The mass of nonencrusted *N. pachyderma* (s.) appears correlated with the corresponding volumes. Encrusted forms show greater mass per volume than nonencrusted forms, suggesting that the crust addition increases shell density (data from K. Kohfeld and D. Nuernberg, manuscript in preparation, 1996). This increase in shell density may explain the deeper depth habitat of the encrusted forms.

conditions observed in the deepest plankton tow samples. However, the maximum concentrations of planktonic foraminifera are found between 0 and 100 m in the water column. There are several possible explanations for what happens to the relatively shallow-dwelling nonencrusted *N. pachyderma* (s.): (1) transformation to encrusted forms, (2) dissolution in the sediments, and (3) predation by larger invertebrates above the main pycnocline. The first possibility is that some of these nonencrusted *N. pachyderma* (s.) are transformed into encrusted forms. The evidence supporting this hypothesis is explored in the previous section. Interestingly, the large percentages of nonencrusted foraminifera still present in the deepest plankton tows (50-75%) and in the sediment traps (~50%) suggest that not all mature *N. pachyderma* (s.) add a thick calcite crust. This situation may be analogous to the sac-like chamber observed on some but not all specimens of *G. sacculifer* in marine sediments. The second possibility is dissolution. Whether there are two morphotypes, or juveniles transforming to adults, it is possible that the thin-shelled, nonencrusted foraminifera are dissolving in the sediments. Dissolution is certainly the most probable explanation for the absence of nonencrusted forms in marine sediments, where even the tests of the encrusted forms appear pitted. The final possible explanation is predation by larger organisms above the main pycnocline. Indeed, a variety of invertebrates in the plankton tows were observed to have foraminiferal tests in their guts. Both shell-thickening processes and predation upon planktonic foraminifera have been observed in other MOCNESS studies [*Fairbanks and Wiebe*, 1980; *Fairbanks et al.*, 1982]. Any of these explanations are possible, and we expect that some combination of the three truly represent what is occurring.

The sediment trap data provide a means of quantifying the fluxes of foraminifera from the water column to marine sediments. Low abundances of *N. pachyderma* (s.) in the water below permanent ice cover are found in both the Arctic and Antarctic [*Carsola*, 1953; *Spindler and Dieckmann*, 1986; *Carstens and Wefer*, 1992]. While high abundances of *N. pachyderma* (s.) have been found in some Antarctic sea ice samples, these same high concentrations have not been discovered in Arctic sea ice [*Spindler and Dieckmann*, 1986]. In spite of this difference, in both the Southern and Arctic Oceans, fluxes of *N. pachyderma* (s.) to marine sediments decrease to zero below complete ice cover [*Donner and Wefer*, 1994]. In both hemispheres, the sediment trap data suggest that the abundances and fluxes of *N. pachyderma* (s.) are tied to periods of increasing primary productivity, or to spring blooms events [*Reynolds and Thunell*, 1986; *Donner and Wefer*, 1994]. Maximum carbon fluxes to the sediments in the NEW Polynya, as recorded in sediment traps, occur between August and September (I. D. Walsh et al., Particle dynamics and a conceptual model of the flow field in the Northeast Water Polynya, submitted to *Continental Shelf Research*, 1996). Likewise, data from sediment trap C from the NEW Polynya show maximum fluxes of *N. pachyderma* (s.) occurring at the same time as the maximum carbon fluxes to the sediments. All of these studies show brief (2 weeks to 1 month) blooms of *N. pachyderma* (s.) to the sediments. This brief period of production may limit the use of *N. pachyderma* (s.) for reconstructing surface ocean conditions.

Vital Effects on $\delta^{13}C$ of *N. pachyderma* (s.)

The carbon isotope composition of ΣCO_2 in surface waters is controlled by several factors, specifically (1) changes in biological uptake and regeneration of organic matter, (2) changes in air-sea exchange [*Mook et al.*, 1974; *Charles and Fairbanks*, 1990; *Broecker and Maier-Reimer*, 1992; *Charles et al.*, 1993], (3) mixing of water masses with different "preformed" values of $\delta^{13}C$ [*Oppo and Fairbanks*, 1987; *Lynch-Stieglitz et al.*, 1994], and (4) global ocean reservoir changes in $\delta^{13}C$ of ΣCO_2 (0.3-0.4‰ decrease during the last glacial maximum (LGM) [*Duplessy et al.*, 1988]). To use geochemical and abundance information from *N. pachyderma* (s.) requires an understanding of how this polar planktonic foraminifer calcifies, thereby recording changes in its environment.

Overprinted upon the observed $\delta^{13}C$ changes are the vital effects of a given species of planktonic foraminifera. In other words, the $\delta^{13}C$ of *N. pachyderma* (s.) will include both the changes in $\delta^{13}C$ of ΣCO_2 of the environment and any microhabitat effects caused by the life cycle of the individual foraminifera. Several studies have examined isotopic compositions on varying size fractions of planktonic foraminifera from marine sediments, demonstrating that $\delta^{18}O$ and $\delta^{13}C$ composition can be size dependent [*Berger et al.*, 1978; *Curry and Matthews*, 1981; *Williams et al.*, 1981; *Fairbanks et al.*, 1982; *Bouvier-Sougmagnac and Duplessy*, 1985; *Oppo and Fairbanks*, 1989; *Billups and Spero*, 1995; *Ravelo and Fairbanks*, 1995]. Determining the vital effect upon the isotopic composition of foraminifera is important for isolating the portion of the isotopic signal that is related to external, hydrographic changes. Studies on symbiont-bearing tropical foraminifera, for example, demonstrate that the magnitude of the vital effect can increase the $\delta^{13}C$ of the shell by as much as 1.5‰, when shell mass increases fourfold [*Oppo and Fairbanks*, 1989]. Initial studies of size fractionation in *N. pachyderma* (s.) have shown no consistent offset in size [*Charles and Fairbanks*, 1990], unlike studies for *O. universa*, *N. dutertrei*, and *G. sacculifer* [*Oppo and Fairbanks*, 1990; *Spero and Lea*, 1993]. However, more recent studies have demonstrated a size-dependent variability in isotopic composition of *N. pachyderma* (s.) in some regions, with differences of 0.3‰ for $\delta^{18}O$ and up to 0.8‰ for $\delta^{13}C$, between the 150-250 mm and the >250 mm size fractions [*Donner and Wefer*, 1994].

In the NEW Polynya, where virtually no vertical gradient in $\delta^{13}C$ is predicted, the $\delta^{13}C$ of *N. pachyderma* (s.) remains basically invariant as shell mass increases threefold. This same observation has been made for the majority of non-symbiont-bearing foraminiferal species examined in the tropical Atlantic [*Ravelo and Fairbanks*, 1995]. These data suggest that the vital effect upon $\delta^{13}C$ of *N. pachyderma* (s.) does not increase with shell mass. Thus it is possible that changes in shell mass will not cause the $\delta^{13}C$ of added calcite to diverge from the $\delta^{13}C$ of ΣCO_2 in the water, and in the presence of a gradient in $\delta^{13}C$ of ΣCO_2, the $\delta^{13}C$ of *N. pachyderma* (s.) will likewise reflect an integration of the uppermost 200 m. However, further studies in regions with gradients in $\delta^{13}C$ of ΣCO_2 are needed. Additionally, we still observe the vital effect offset from the $\delta^{13}C$ of "equilibrium calcite," which may or may not be consistent from region to region.

The $\delta^{18}O$ of *N. pachyderma* (s.) in Marine Sediments

An important issue which needs to be addressed is how well the results from the NEW Polynya can be generalized to whole ocean conditions potentially recorded by *N. pachyderma* (s.) and preserved in marine sediments. In the study region of the NEW Polynya, the water column is characterized by a sharp gradient in $\delta^{18}O_{CALCITE}$ and virtually no change in the $\delta^{13}C$ of ΣCO_2 between 50 and 200 m. While the hydrographic regime of a polynya is not characteristic of the global ocean, this regime bears similarity to hydrographic conditions found in the Arctic and in the East Greenland Current. Indeed, similar results using *N. pachyderma* (s.) from plankton tows have been found in the Arctic Ocean, where the average depth of calcification appears to lie between 100 and 200 m, based on $\delta^{18}O_{CALCITE}$ (D. Bauch et al., Oxygen isotope composition of *Neogloboquadrina pachyderma* (sin.) in the Arctic Ocean, submitted to *Marine Geology*, 1996, hereinafter referred to as D. Bauch et al., submitted manuscript, 1996). The conditions found in the NEW Polynya may be similar to those conditions expected in regions with seasonal sea ice covers, at a sea ice edge, and polar regions influenced by summer meltwater. A paleoceanographic analog might be the glacial to deglacial conditions hypothesized for the Nordic Seas [*Koc and Jansen*, 1994] or the regions of the North Atlantic during Heinrich events [*Bond et al.*, 1993], or even during the maximum advance of the polar front [*Ruddiman and McIntyre*, 1981]. In all of these paleoceanographic examples, the sediment assemblages are composed of greater than 90% *N. pachyderma* (s.).

Additionally, even if the hydrographic conditions are not the same, can we generalize about the patterns of shell calcification in *N. pachyderma* (s.)? In the polynya, the process of encrustation appears to occur predominantly at the depth of the main pycnocline, 100-200 m. Thus marine sediment values will reflect an integrated average of water column conditions through the depth of maximum abundances. The process of encrustation could respond to the depth of main thermocline or pycnocline in all regions. Recent sediment trap and plankton tow studies from the Sea of Okhotsk, the Arctic Ocean, and the California Current have suggested that *N. pachyderma* (s.) calcify at the depth of the main thermocline, varying between 40 and 200 m [*Alderman*, 1996; *Ortiz et al.*, 1996; D. Bauch et al., submitted manuscript, 1996]. If this is the case, then the geochemistry of *N. pachyderma* (s.) will rarely and only selectively reflect surface ocean conditions and will depend strongly upon the depth and magnitude of the vertical hydrographic gradients.

Excursions in $\delta^{18}O$ of *N. pachyderma* (s.) from deep-sea core records are frequently interpreted as changes in sea surface salinity, resulting from the influence of glacial meltwater in both the North Atlantic [*Jones and Keigwin*, 1988; *Lehman and Keigwin*, 1992; *Koc and Jansen*, 1994; *Stein et al.*, 1994] and Southern Oceans [*Labeyrie et al.*, 1986]. Using the discrepancies between the transfer function SSTs and the $\delta^{18}O$, some studies have attempted to calculate changes in the $\delta^{18}O$ of water in order to estimate salinity. The calculations of $\delta^{18}O$ of water have been used to estimate North Atlantic surface salinity decreases of as much as 1-2 during the last glacial maximum [*Duplessy et al.*, 1991; *Duplessy et al.*, 1992].

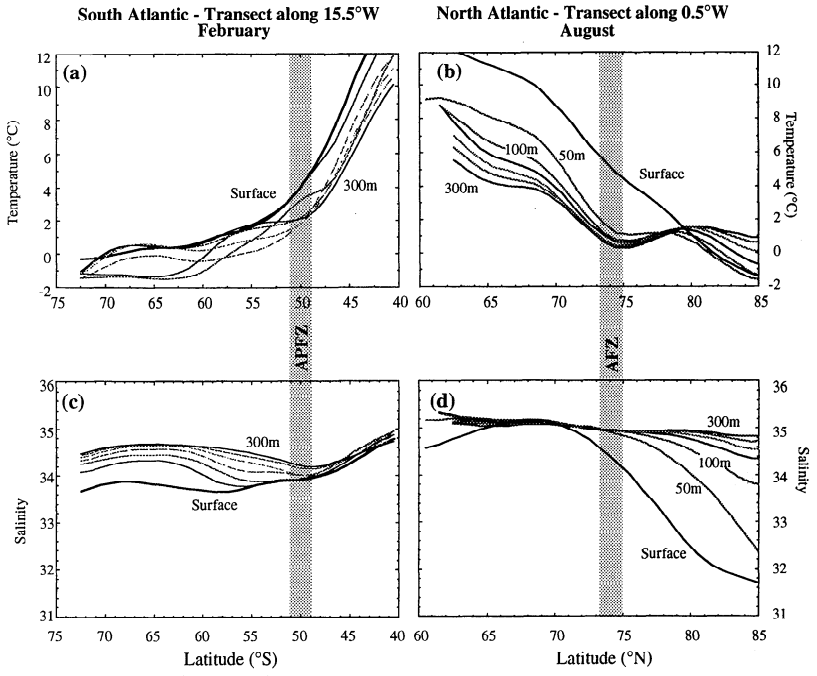

Figure 13. Comparison of temperature and salinity transects from the South Atlantic (along 15.5°W) and the North Atlantic (along 0.5°W) [*Levitus and Boyer*, 1994]. The curves represent temperature (Figures 13a and 13b) and salinity (Figures 13c and 13d) values at 50 m depth intervals between 0 and 300 m, for the months of maximum foraminiferal flux to the sediments in both hemispheres [*Donner and Wefer*, 1994; *Wolfteich*, 1994]. For both temperature and salinity, these transects demonstrate the difference in water column hydrography between these two regions. Specifically, the Southern Ocean is more homogeneous with depth, with smaller ranges in temperature and salinity between 0 and 300 m.

Our results suggest that sea surface temperature and salinity conditions are not generally recorded in the $\delta^{18}O$ of *N. pachyderma* (s.) where the upper 200 m are stratified but instead depend on the water column temperature and salinity gradients present where *N. pachyderma* (s.) is calcifying. For example, an examination of water column characteristics between 0 and 300 m in the North and South Atlantic demonstrates how we might expect water column variability to affect the shell chemistry of *N. pachyderma* (s.) (Figures 13a-13d). In both temperature and salinity, the Southern Ocean section exhibits more homogeneous water column characteristics with depth than the North Atlantic section. Specifically, temperature ranges between the surface and 300 m reach 2°-4°C in the South Atlantic (Figure 13a), while the temperature ranges in the North Atlantic regions are as large as 8°C between 0 and 300 m (Figure 13b). Similarly, the salinity gradients between 0 and 300 m are less than 1 across the South Atlantic transect (Figure 13c). On the other hand, in the Norwegian and Greenland Seas, the observed salinity gradients are as large as 3.5 (Figure 13d).

From these average hydrographic differences between the North and South Atlantic, we might predict that the $\delta^{18}O$ of *N. pachyderma* (s.), which is roughly a function of temperature and salinity during calcification, will be more likely to reflect surface ocean conditions in the Southern Ocean. Indeed, previous studies in the Southern Ocean have shown a good correlation between surface temperature and the $\delta^{18}O$ of *N. pachyderma* (s.) found in surface sediments (Figure 1a) [*Charles and Fairbanks*, 1990]. Given an offset of approximately 0.8‰, one might argue that a one-to-one correlation exists between the $\delta^{18}O$ of *N. pachyderma* (s.) and $\delta^{18}O_{CALCITE}$ for surface waters in the North Atlantic regions (Figure 1b). However, the correlation coefficient for the North Atlantic data is not as high, undoubtedly the result of greater stratification in temperature and salinity in the North Atlantic regions. Specific studies of *N. pachyderma* (s.) from core tops in the Norwegian Sea have suggested that *N. pachyderma* (s.) reflects surface ocean conditions between 0 and 50 m south and east of the Arctic Front [*Johannessen et al.*, 1994]. The hydrographic data shown in Figure 13 suggests that this might be expected in regions south of the Arctic Front. Still, even in this region where salinities are relatively homogeneous with depth, the temperature gradients of approximately 6-8°C would result in a $\delta^{18}O_{CALCITE}$ range of approximately 1.4-1.8‰ in the surface 300 m. In the Norwegian Sea region 1.4‰ of this variability occurs between 0 and 100 m. This variability in surface ocean stratification could explain the lower degree of correlation found in the North Atlantic region. In general, for all polar oceans, we suggest that the ability of *N. pachyderma* (s.) to record surface ocean conditions depends on vertical hydrographic gradients present in the region where *N. pachyderma* (s.) adds this calcite crust. Surface ocean conditions are most likely to be recorded by *N. pachyderma* (s.) in regions with deep surface mixed layers (>300 m) and minimal seasonal temperature changes.

Conclusions

Modern, vertically stratified plankton tow samples from the Northeast Water (NEW) Polynya illustrate the decoupling of the processes that control foraminiferal productivity and shell chemistry. Highest abundances of *N. pachyderma* (s.) were found associated with the chlorophyll maximum zone in the surface 20-80 m, where they are exploiting their primary food source. The addition of a calcite crust modifies the calcite tests of some *N. pachyderma* (s.) between 50 and 200 m, increasing shell density and modifying shell chemistry. Shell mass of encrusted individuals are 3-4 times greater than the nonencrusted individuals. Between 50 and 200 m, the oxygen isotope composition of *N. pachyderma* (s.) increases by 1.5‰ in response to local water column gradients. Abundances of encrusted *N. pachyderma* (s.) increase at the depth of the main pycnocline (100-200 m). Mass balance calculations suggest that encrustation occurs at all depths, but abundance counts suggest that the process occurs mostly at the depth of the main pycnocline (100-200 m).

Comparison with previous sediment trap studies demonstrates that the sediment fluxes of *N. pachyderma* (s.) occur during 2 weeks to 1 month, a brief period which is likely tied to phytoplankton bloom events. Sediment fluxes of *N. pachyderma* (s.) decrease to almost zero below complete ice cover.

Unlike symbiont-bearing species of planktonic foraminifera, the "vital effect" of *N. pachyderma* (s.) appears to remain constant during the shell-thickening process. The isotopic composition of *N. pachyderma* (s.) integrates hydrographic conditions in the surface 200 m of the water column. While $\delta^{13}C$ for calcite formed in equilibrium with seawater has been shown to be 1.0±0.2‰ greater than the $\delta^{13}C$ of ΣCO_2 [*Romanek et al.*, 1992], we see no offset between the $\delta^{13}C$ of *N. pachyderma* (s.) and the $\delta^{13}C$ of ΣCO_2 measurements from the NEW Polynya.

These results have implications for the use of $\delta^{18}O$ of *N. pachyderma* (s.) in paleoceanographic studies. These data help to explain the discrepancies between transfer function and isotopically derived paleotemperature estimates of surface conditions in some oceanic settings. The ability of $\delta^{18}O$ of *N. pachyderma* (s.) to record surface ocean conditions depends on vertical stratification where shell calcification is occurring, as evidenced by the differences in core-top calibrations between the North and South Atlantic.

Acknowledgments. Samples were collected as part of the U.S. NEWater project, funded by NSF. We thank G. T. Rowe for providing sediment samples from the NEW Polynya, W. O. Smith for providing chlorophyll and light intensity data, and A. Mackensen for providing unpublished $\delta^{13}C$ of ΣCO_2 from the 1993 R/V *Polarstern* cruise to the NEW Polynya. D. Nuernberg cheerfully agreed to share unpublished size measurements on *N. pachyderma* (s.). J. Wright assisted with stable isotope analyses in the Fairbanks isotope laboratory at LDEO, and P. Lane, C. Ashjian, and E. Schwartzing assisted with data and sample collection at Brookhaven National Laboratory. Special thanks to D. Breger (LDEO) for her assistance with SEM images. This work has greatly benefited from helpful suggestions of J. Ortiz, J. Lynch-Stieglitz, J. McManus, R. F. Anderson, D. Nuernberg, K. Miller, and three anonymous reviewers. This work was supported by a NASA Global Change Research Fellowship to K.E.K. and NSF grant OCE 92-04143 to R.G.F. This is LDEO Publication 5545.

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(Received January 19, 1996; revised August 15, 1996;
accepted August 21, 1996.)