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# Living *Neogloboquadrina pachyderma* sin and its distribution in the sediments from Oman and Somalia upwelling areas

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#### Abstract

Microfaunal analysis of plankton nets collected offshore Oman/Yemen and sediment traps offshore Somalia shows that *Neogloboquadrina pachyderma* sin is abundant during the SW monsoon upwelling. The sediment traps recorded the highest flux (136 specimens  $m^{-2} day^{-1}$ ) and the highest relative frequency (3.55% of the total foraminifera assemblage) of the species during this period. During the intermonsoon it became less abundant and decreased in size, and only very few *N. pachyderma* sin were found in the water column during the NE monsoon. Sediment trap and Recent sediment data collected along a downslope transect off Somalia show that the species frequency decreases offshore. The highest concentrations of *N. pachyderma* sin in plankton nets off Oman/Yemen were found at a depth of 300–500 m. However, the oxygen isotope compositions of *N. pachyderma* sin at the depth of 300–500 m and from the surface 8 m are identical, and also similar to that of *Globigerina bulloides* which reflects properties of the upper 25 m of the water column. The carbon isotope values are relatively consistent within the studied samples from both areas except for the specimens from the surface water samples offshore Oman/Yemen. The data show that the  $\delta^{18}$ O ratio of *N. pachyderma* sin in the Arabian Sea reproduces, growths and calcifies in the upper 25 m of the water column, but possibly descends into deeper waters later during its life cycle. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: planktic foraminifera; upwelling; northwestern Indian Ocean; stable isotopes

### 1. Introduction

Left-coiling *Neogloboquadrina pachyderma* (*N. pachyderma* sin) strongly dominates planktic foraminiferal assemblages in polar areas (Bé and Tolderlund, 1971; Bandy, 1972; Cifelli, 1973) at temperatures below 7–9°C (Bé and Tolderlund, 1971; Bé and Hutson, 1977; Reynolds and Thunell, 1986). It has also been found living in a seasonal sea ice (Spindler, 1990). Right-coiling *N. pachyderma* (*N.*  pachyderma dex), also known as Neogloboquadrina incompta (Cifelli, 1973; Van Kreveld-Alfane, 1996), is generally found in association with Turborotalita quinqueloba and Globigerina bulloides in subpolar and transitional waters (Bé and Tolderlund, 1971; Cifelli, 1973).

*N. pachyderma* sin is common in 'polar' and 'subpolar' assemblages in the southern Indian Ocean in association with *G. bulloides* and *Globorotalia truncatulinoides* (Hutson and Prell, 1980). This assemblage dominates the sediments below the Subtropical and Antarctic convergences but has also been found

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in the sediments off the Arabian coast (Hutson and Prell, 1980). Hutson and Prell (1980) considered this assemblage to be indicative of regional upwelling and predicted that the same assemblage would be found offshore Somalia.

The association of *N. pachyderma* sin with coastal upwelling has recently been reported by various authors. Ufkes and Zachariasse (1993), Giraudeau and Rogers (1994), Little et al. (1997) and Ufkes et al. (1998) find high abundance of *N. pachyderma* sin in the cool and nutrient-rich waters of the Benguela Upwelling System (Southwest Africa). Ortiz and Mix (1992) observe increased fluxes of *G. bulloides* and *N. pachyderma* sin in response to a seasonal upwelling off Cape Blanco (the California Current region) in their nearshore sediment trap station.

Wells and Okada (1996) found increased relative abundance of *N. pachyderma* sin in glacial intervals of a sediment core taken off the southeastern Australian continental margin. These intervals also showed an increase in the relative abundance of the planktic foraminifera *G. bulloides* and *T. quinqueloba*, the benthic foraminifera *Bulimina aculeata* and low  $\delta^{13}$ C values of *Uvigerina*. Wells and Okada (1996) associated this interval with a period of strong upwelling and high surface-water productivity. In sediments of ODP Site 723A off the Oman Margin *N. pachyderma* sin was also found associated with supposedly enhanced upwelling (Naidu and Malmgren, 1996).

There is no general consensus on factors controlling the distribution of N. pachyderma. Reynolds and Thunell (1986) discuss the possibility of N. pachyderma distribution in association with specific surface water masses. Some studies (Reynolds and Thunell, 1986; Ufkes and Zachariasse, 1993) assume that the pattern is mainly controlled by a seasonal availability of appropriate food, i.e. diatoms. Ufkes and Zachariasse (1993) do not consider temperature to be an important factor. In contrast Giraudeau and Rogers (1994) find no direct relation between the distribution of N. pachyderma sin and phytoplankton biomass and conclude that sea surface temperature is the main factor. Ortiz et al. (1995) suggest that temperature is only an important control on a species distribution near the limits of its thermal tolerance while food and light are the main controlling factors under acceptable thermal conditions. N. pachyderma sin which has no symbionts would in this case mainly depend on an availability of food rather than light. Thunell et al. (1983) and Hemleben et al. (1989) believe that subsurfacedwelling species, including *N. pachyderma*, become more abundant when a shoaling event of the thermocline occurs and nutrient-rich, cool water causes an increase in primary production. Hilbrecht (1996, 1997) suggests that the distribution of *N. pachyderma* in high latitudes reflects its preference for dense surface waters with low vertical temperature gradients and little stratification.

The goal of this study is to determine the present-day distribution of *N. pachyderma* sin in the Arabian Sea in relation to the upwelling process. We also look into the questions of its depth habitat, food source, size distribution and stable isotopes composition as well as its preference to a specific area and/or stage within the major upwelling event. A full understanding of the ecology of *N. pachyderma* sin can provide a powerful tool for the reconstruction of the Arabian Sea upwelling history.

#### 2. Regional oceanography

The oceanographic circulation in the Arabian Sea is controlled by seasonal atmospheric changes. During winter (December–February) winds blow from the northeast (NE monsoon), in May they reverse directions and sharply increase in velocity leading to the southwest monsoon in the period June– September (JGOFS Report, 1994). The change in wind direction north of the equator results in a reverse of ocean currents. The changeovers from one monsoon regime to another takes place in about 4–6 weeks (Pickard, 1979).

The SW monsoon is the strongest of the two and induces one of the major western boundary currents, the Somali Current (Brown et al., 1989). The resulting Ekman transport causes a strong coastal upwelling offshore Arabia and Somalia (Bruce et al., 1980; Swallow, 1980; Schott et al., 1990).

The average winter surface temperatures are 25/26–28°C (Wyrtki, 1988). The water masses are well stratified; nutrient concentrations are low. During the intensive upwelling cool nutrient-rich waters are updoming along the coast of Somalia and Oman. One of the largest gyres develops annually offshore

Somalia between 4 and 12°N and extends as far as 58°E (Bruce et al., 1980). The source depth of upwelled water is about 200 m (Smith and Codispoti, 1980). The eddies are characterised by low sea surface temperatures, high concentrations of nitrate, dissolved silica and reactive phosphorus (Brown et al., 1980; Smith and Codispoti, 1980). During peak upwelling SSTs decrease to 14–22°C (Brown et al., 1980; Bruce et al., 1980; Smith and Codispoti, 1980; Wyrtki, 1988; Brummer, 1995).

#### 3. Material and methods

The data set used for the present study was collected during two R.V. *Tyro* cruises executed in 1992–1993 within the framework of the Netherlands Indian Ocean Program (NIOP, Van Hinte et al., 1995). The major areas of investigation were the Oman and Somalia coastal upwelling zones. Analysed samples were obtained by three types of devices: multinets, sediment traps and box-cores.

Plankton tow samples were collected along a transect perpendicular to the coast of Oman/Yemen (Fig. 1) using a Hydrobios multinet system equipped with 5 plankton nets (100  $\mu$ m). Five stations were sampled twice along this transect: once during August 1992 (SW monsoon, upwelling period) and again at the same locations during February 1993 (NE monsoon, non-upwelling period) (Fig. 1; Table 1). The nets are opened and closed consecutively during the upcast at five depth intervals i.e. 100-75, 75-50, 50-25, 25-10 and 10-0 m. In addition two deep casts, covering the depth intervals 500-300, 300-200, 200-150 and 150-100 m were taken. Samples were stored in borax-buffered formalin solution with pH >8.0, based on prefiltered seawater. After Folsom-spitting 75% of an original sample was shock-frozen in liquid nitrogen, freeze-dried and weighed. After combustion of the organic matter in a Low Temperature Asher ( $T < 100^{\circ}$ C), samples were wet-sieved into 5 fractions: 125-150, 150-250, 250-355, 355-500 and  $>500 \mu m$ .

The sediment traps and box-cores were collected along the Somalia continental slope (Fig. 1; Table 1). The sediment trap MST8-B was moored at 1265 m water depth, 268 m above sea floor. The sediment trap MST9-E was moored in the deep Somalia Basin south off Socotra (Fig. 1; Table 1) at 1032 m water depth, 3015 m above the sea floor. Both sediment traps provided a 9 months time-series record of particle fluxes throughout both the SW and NE monsoon and SW-NE intermonsoon periods (Tables 2 and 3). Each of the cups contains material collected over a period of one or two weeks. Samples were preserved in a pHbuffered solution of HgCl<sub>2</sub> in seawater added to the trap cups prior to mooring (for details see Brummer, 1995), wet-sieved over a 2 mm mesh and Folsomsplitted into a number of aliquots. Between 10 and 25% of the original sample was vacuum-filtered over a 0.45 µm filter and rinsed to remove the poisonous salts. The residue was resuspended in water, shockfrozen in liquid nitrogen, freeze-dried and weighed. After combustion of the organic matter in a Low Temperature Asher ( $T < 100^{\circ}$ C) it was wet-sieved and analysed in six fractions for MST8-B (100-125, 125-150, 150–250, 250–355, 355–500 and >500 µm), and three fractions for MST9-E (125-150, 150- $250, >250 \,\mu\text{m}$ ). In addition 100–125  $\mu\text{m}$  fraction of MST9-E sediment trap was checked for the presence of N. pachyderma sin.

A series of 8 box-cores (902-908 and 915) was collected along a transect perpendicular to the coast of Somalia (Fig. 1; Table 1). The shallowest box-core 902B is located on the upper slope at a depth of 459 m, about 50 km offshore. The deepest core, 915B, was recovered from a depth of 4035 m, at approximately 250 km offshore. Box-cores 905B and 915B were collected at the locations of sediment traps MST8 and MST9, respectively. On board the upper centimeter of each box-core was stored in a bottle with a 60% ethanol/Rose Bengal solution (Troelstra et al., 1995). In the laboratory the samples were splitted by means of a wet splitter (Fritsch 'Rotary sample devider' laborette 27) to obtain a representative amount of material for the analysis of microfauna and wet-sieved over 125  $\mu$ m mesh sieve.

All samples obtained were split with an Otto microsplitter to an appropriate size, and at least 200 planktic foraminifera were counted per fraction.

Stable isotopes were analysed for 6 samples of *N.* pachyderma sin which contained 13 to 78 specimens (Table 4). Specimens from the plankton tows of Station 313 off Oman were measured from the size fractions 125–150 and 150–250  $\mu$ m in the deep cast (300–500 m water depth) and 125–150  $\mu$ m in the



- Locations of plankton tow samples offshore Yemen/Oman (Stations 308-313 sampled during upwelling period and 917-922 sampled during non-upwelling period)
- ▼ Locations of sediment traps MST8-B and MST9-E offshore Somalia
- Locations of box-cores 902-908 and 915 offshore Somalia, station numbers increase with a depth

Fig. 1. Map showing locations of plankton tow stations 308–313 and 917–922 (Oman/Yemen transect), sediment traps MST8-B and MST9-E and box-cores 902–908 and 915 (Somalia transect).

shallow cast (0–8 m water depth). *N. pachyderma* sin from box-cores 902B and 905B and sediment trap MST8-B collected offshore Somalia were measured in the size fraction  $125-250 \mu$ m. The weight of *N. pachyderma* sin was measured before the iso-

tope analysis was performed (except for the surface sample from Station 313 offshore Oman).

Isotope composition of *N. pachyderma* sin from the deep cast of the plankton tows was measured at the Geological Institute, University of Bremen.

Table 1	
List of the samples	

Type of the	Station	Date of the	Latitude	Longitude	Depth
sample		sampling	(N)	(E)	(m)
Multinet	308	19.08.92	16°08	52°30	98-72, 72-48, 48-23, 23-0
Multinet	309	19.08.93	16°06	52°47	50-28, 28-18, 18-8, 8-0
Multinet	310	20.08.92	16°02	52°44	74-49, 49-23, 23-8, 8-0
Multinet	310 dc	20.08.93	16°01	52°45	498–298, 298–200, 200–148, 148–98
Multinet	311	21.08.92	16°02	52°46	96-75, 74-50, 50-23, 23-8, 8-0
Multinet	313	21.08.92	15°54	53°01	100-75, 74-50, 49-24, 24-10, 8-0
Multinet	313 dc	22.08.92	15°52	53°00	498-300, 300-199, 196-150, 148-99
Multinet	922	27.02.93	16°09	52°31	100-77, 77-52, 52-26, 26-12, 12-0
Multinet	920	27.02.93	16°05	52°39	102-78, 78-53, 53-27, 27-11, 11-0
Multinet	920 dc	27.02.93	16°04	52°42	501-303, 303-202, 202-153, 153-103
Multinet	919	26.02.93	16°00	52°44	102-77, 77-52, 52-26, 26-10, 10-0
Multinet	918	26.02.93	15°58	52°49	103-78, 78-52, 52-27, 27-12, 12-0
Multinet	917	25.02.93	15°54	52°57	102-78, 78-52, 52-27, 27-12, 12-0
Multinet	917 dc	25.02.93	15°53	53°00	502-302, 302-203, 203-153, 153-101
Sediment trap	MST8-B	07.06.92-14.02.93	10°45.444′	51°56.655′	1265
Sediment trap	MST9-E	07.06.92-21.02.93	10°43.068′	53°34.422′	1032
Box-core	902B	February/March, 1993	10°46.72′	51°34.64′	459
Box-core	903B	February/March, 1993	10°46.97′	51°39.48′	789
Box-core	904B	February/March, 1993	10°47.27′	51°46.23′	1194
Box-core	905B	February/March, 1993	10°54.94′	51°56.65′	1567
Box-core	906B	February/March, 1993	10°48.70′	52°07.76′	2020
Box-core	907B	February/March, 1993	10°48.24′	52°14.96′	2807
Box-core	908B	February/March, 1993	10°46.66′	52°54.88′	3572
Box-core	915B	February/March, 1993	10°41.37′	53°31.41′	4035

Table 2 Sediment trap MST8-B

Sample	Start sampling	End sampling	Number of days of sampling
MST8-B2	07/06/92	21/06/92	14
MST8-B3	21/06/92	05/07/92	14
MST8-B4	05/07/92	19/07/92	14
MST8-B5	19/07/92	02/08/92	14
MST8-B6	02/08/92	16/08/92	14
MST8-B7	16/08/92	30/08/92	14
MST8-B8	30/08/92	06/09/92	7
MST8-B9	06/09/92	13/09/92	7
MST8-B10	13/09/92	27/09/92	14
MST8-B11	27/09/92	11/10/92	14
MST8-B12	11/10/92	25/10/92	14
MST8-B13	25/10/92	08/11/92	14
MST8-B14	08/11/92	22/11/92	14
MST8-B15	22/11/92	06/12/92	14
MST8-B16	06/12/92	20/12/92	14
MST8-B17	20/12/92	03/01/93	14
MST8-B18	03/01/93	17/01/93	14
MST8-B19	17/01/93	31/01/93	14
MST8-B20	31/01/93	14/02/93	14

Specimens were dissolved in 100% orthophosphoric acid at 75°C and measured with a Finnigan MAT 251 mass spectrometer combined with an automated carbonate preparation line. Analytical precision is better than 0.07‰ for  $\delta^{18}$ O and 0.04‰ for  $\delta^{13}$ C. Specimens from MST8-B5 sediment trap and sediment samples 902B and 905B were analysed at the Free University in Amsterdam. They were dissolved in 100% orthophosphoric acid at 80°C and measured with a MAT 251 mass spectrometer connected to an automated carbonate preparation line (Bremen type). The external analytical precision of the laboratory standard is 0.08‰ for the oxygen and 0.04‰ for the carbon isotope analysis. All values are reported against PDB using NBS19 and 20 for calibration of the reference gas. Thirteen specimens of N. pachyderma sin from the upper water column collected off Oman were measured at The Applications and Research Laboratory of Micromass UK Ltd in Manchester, where samples ranging in size from 5 to 20 µg calcite can be analysed. Specimens were

Table 3 Sediment trap MST9-E

Sample	Start sampling	End sampling	Number of days of sampling
MST9-E2	07/06/92	21/06/92	14
MST9-E3	21/06/92	05/07/92	14
MST9-E4	05/07/92	19/07/92	14
MST9-E5	19/07/92	26/07/92	7
MST9-E6	26/07/92	02/08/92	7
MST9-E7	02/08/92	09/08/92	7
MST9-E8	09/08/92	16/08/92	7
MST9-E9	16/08/92	23/08/92	7
MST9-E10	23/08/92	30/08/92	7
MST9-E11	30/08/92	06/09/92	7
MST9-E12	06/09/92	13/09/92	7
MST9-E13	13/09/92	27/09/92	14
MST9-E14	27/09/92	11/10/92	14
MST9-E15	11/10/92	25/10/92	14
MST9-E16	25/10/92	08/11/92	14
MST9-E17	08/11/92	22/11/92	14
MST9-E18	22/11/92	06/12/92	14
MST9-E19	06/12/92	20/12/92	14
MST9-E20	20/12/92	03/01/93	14
MST9-E21	03/01/93	17/01/93	14
MST9-E22	17/01/93	31/01/93	14
MST9-E23	31/01/93	14/02/93	14
MST9-E24	14/02/93	21/02/93	7

dissolved in 100% orthophosphoric acid at 90°C and analysed using a Micromass Multicarb automated carbonate device interfaced to an Optima stable isotope ratio mass spectrometer with micro volume dual inlet. The external analytical precision of the laboratory standard is 0.06‰ for the oxygen and 0.04‰ for the carbon isotope analysis. The values are reported against PDB using NBS19 for calibration of the reference gas.

In order to interpret isotopic composition of N.

pachyderma sin we calculated equilibrium calcite values using the temperature and isotopic composition from direct measurements of the surface waters according to the paleotemperature equation of Epstein et al. (1953). The linear relation of  $\delta^{18}$ O of water with salinity was established as

 $\delta^{18} O_w = -8.98 + 0.26S,$ 

where *S* is the salinity in per mil (G. Ganssen, pers. commun., 1998). We calculated the  $\delta^{18}$ O of the water from the salinity measurements for the depths where the vertical plankton samples were taken.

# 4. Morphology of *Neogloboquadrina pachyderma* sin

*N. pachyderma* sin is a relatively small foraminifera with 4–5 globular chambers in the final whorl. We observed it only in the size range from 100 to 250  $\mu$ m. Chambers of *N. pachyderma* are subspherical to ovate, closely embracing and rapidly increasing in size. The final chamber is often elongated and has a rim or a bulla-like cover over much of the umbilicus. The aperture of *N. pachyderma* is umbilical, interiomarginal and varies from a low to high arch. The species is non-spinose.

*N. pachyderma* sin from the Arabian Sea (Plate 1) reveals all the morphological features generally attributed to *N. pachyderma* (Bandy, 1972; Saito et al., 1981), except for the lack of a thick calcite crust which usually gives this species its characteristic robust appearance. In our material, including sediment samples, we find *N. pachyderma* sin being similar to what Bandy (1972, p. 306) describes as "specimens from the upper part of the water column". Our speci-

Table 4

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Sample	Type of the sample	Size fraction	Number of specimens analysed	Average weight of 1 specimen (µm)	$\delta^{13}C$	δ <sup>18</sup> Ο
313-4-5	plankton tow	125-150	13	-	0.69	-1.95
313-dc-1	plankton tow	125-150	69	1.09	-1.61	-1.90
313-dc-1	plankton tow	150-250	56	1.40	-1.35	-1.93
MST8-B5	sediment trap	125-250	78	1.17	-1.50	-1.42
902B	sediment	125-250	40	1.06	-1.69	-1.55
905B	sediment	125-250	36	1.13	-1.33	-1.38

mens have relatively thin and lobulate tests compared to the Recent forms from the Arctic Ocean (Kohfeld et al., 1996, fig. 4b and c), antarctic and subantarctic areas (Bandy, 1972, pl. 7, figs. 1–7), the North Pacific Ocean (Reynolds and Thunell, 1986, pl. 2, figs. 1–6) and the North Atlantic (Van Kreveld-Alfane, 1996, pp. 94–95, pl. 9, figs. 1–15).

In the studied samples the majority of *N. pachyderma* belongs to the left-coiling variety, and only very few specimens of *N. pachyderma* dex were identified.

# 5. Distribution of *Neogloboquadrina pachyderma* sin in the water column and sediment samples

#### 5.1. Multinets (Oman/Yemen area)

On the Oman/Yemen transect the highest concentrations of *N. pachyderma* sin were observed during upwelling in the deep cast at Station 313 (approximately 90 km distance from the coast) (Fig. 2; Table 1). Its frequency decreases from 6 specimens  $m^{-3}$ between 500 and 300 m water depth to only 0.5 specimens  $m^{-3}$  in the upper 25 m. *N. pachyderma* sin was also found in the deep cast at Station 310 but in lower concentrations. In the shallow casts from the other stations (upper 100 m) *N. pachyderma* sin occurs rarely.

Virtually no *N. pachyderma* sin were found in the multinets from the non-upwelling season; out of 33 studied samples only three contained the species in extremely low concentrations.

#### 5.2. Sediment traps (Somalia area)

In both sediment traps *N. pachyderma* sin was mainly found during upwelling (Figs. 3 and 4). Most of the species occur in the size fraction 100–125  $\mu$ m (only counted for MST8-B). Its highest flux of 136 specimens m<sup>-2</sup> day<sup>-1</sup> in the residue >125  $\mu$ m was recorded in MST8-B between July 5 and 19, 1992 (Fig. 3). It is associated with minimum SSTs, a high



Fig. 2. Temperature profile and concentration (number of specimens/ $m^3$ ) of *N. pachyderma* sin in the water column along the Oman/Yemen transect in August 1992. Concentration of *N. pachyderma* sin in the water column in February 1993 is always less than 0.063 specimens/ $m^3$ .



flux of upwelling indicator G. bulloides, low fluxes of Globigerinoides ruber and Globigerinoides sacculifer (species which prefer stratified water masses), low diversity and low equitability in the planktic foraminifera assemblage (Conan and Brummer, in press). In the same period (from June 21 till August 2) N. pachyderma sin also increased in size: the contribution of the specimens  $>125 \,\mu m$  is the highest compare to other months, and among those 88.0% are larger than 150 µm. The highest relative abundance of the species in the total planktic foraminifera assemblage has been observed over the period July 19-August 16. Later in the season the species became smaller: up to 38.8% of the specimens in the period from August 30 till September 27 were found in the fraction  $125-150 \mu m$ . At the end of September both flux and relative abundance of N. pachyderma sin decreased (Fig. 3). From the end of September N. pachyderma sin was only present in the residue  $<150 \,\mu m$ .

A peculiar peak in the flux of small specimens of *N. pachyderma* sin between September 27 and October 25 corresponds to increased fluxes of the small species *T. quinqueloba*, *Globigerina rubescens*, *Tenuitella iota*, *Dentigloborotalia anfracta*, *Tenuitella parkerae*, high numbers of juvenile benthic foraminifera and skeletal fragments (Conan and Brummer, in press). That can be explained by lateral transport of fine resuspended sediment material from the shelf or upper slope off Somalia. After November 8 the species was observed in very low numbers and only in fraction 100–125  $\mu$ m.

Similar to MST8-B the highest frequency of *N. pachyderma* sin in MST9-E was recorded at the period of lower SSTs, which indicate the maximum of upwelling intensity from June 21 till September 27, 1992. A first peak occurred between August 2 and August 9 (28 specimens  $m^{-2} day^{-1}$ ) and a second between August 30 and September 6 (32 specimens

Plate 1

- 2. Umbilical view, multinet 313/AC/1.
- 3. Spiral view, multinet 313/4/2.
- 4. Umbilical view, sediment trap MST8-B3.
- 5. Spiral view, sediment trap MST8-B3.
- 6. Umbilical view, surface sediments from 905B.
- 7. Spiral view, surface sediments from 905B.

m<sup>-2</sup> day). In terms of the relative abundance *N.* pachyderma sin only reached 1.0% in the period from July 26 till August 9. It was not observed in the residue larger than 150  $\mu$ m in most of the samples, with a few exceptions (Fig. 4). The species was also sporadically present in the period between September 27 and February 14. However, the flux of the species was very low and consists of maximally 1 to 3 *N. pachyderma* sin m<sup>-2</sup> day<sup>-1</sup>. Additional checks of the MST9 samples in the fraction 100–125  $\mu$ m confirm the presence of the species in the water column during the non-upwelling season.

The average flux of *N. pachyderma* sin over the studied period was more than 4 times higher in MST8 than in MST9 (Figs. 3 and 4). The percentage contribution of the larger specimens (>150  $\mu$ m) to all *N. pachyderma* sin >125  $\mu$ m is on average 81.9% in MST8 and only 4.0% in MST9.

#### 5.3. Sediment samples (Somalia area)

Box-core top samples of the Somalia transect were analysed in the size fraction  $>125 \ \mu m$ . In terms of both concentrations and relative abundance, a maximum of N. pachyderma sin occurs in box-core 902B (Fig. 5). In this sample the concentration of the species is approximately 250 specimens per gram dry sediment, and its relative abundance reaches almost 11% of the total planktic foraminifera assemblage. Both number and percentage decrease gradually offshore (Fig. 5). N. pachyderma sin is absent in 907B and 908B and observed again in very low concentrations in 915B. The distribution pattern of N. pachyderma sin in the sediments resembles that of T. quinqueloba and to a lesser extent of G. rubescens, T. iota and D. anfracta (E. Ivanova, unpubl. data). The latter are also relatively frequent in the sediments of the upper slope.

# 6. Weight and isotope composition of *Neogloboquadrina pachyderma* sin

*N. pachyderma* sin were weighed and their stable isotope ratios were determined for two samples from the deep multinet cast and one sample of the shallow multinet cast at station 313 from the Oman/Yemen area as well as one sample from sed-

Neogloboquadrina pachyderma sin.  $\times 400$ .

<sup>1.</sup> Umbilical view, multinet 313/4/2.



Fig. 3. Fluxes and relative abundance of *N. pachyderma* sin in sediment trap MST8-B, plotted against days of years 1992 + 1993, from June 7, 1992 to February 14, 1993. Data on SSTs are after Conan and Brummer (in press).

iment trap MST8-B5 and two surface sediment samples from the Somalia area (Table 4). The heaviest specimens are *N. pachyderma* sin from the size fraction 150–250  $\mu$ m of the deep multinet cast 313-dc-1 (Oman/Yemen transect). Their average weight is 1.4  $\mu$ g which is more than 20% heavier then *N. pachyderma* sin from the same sample in the size fraction 125–150  $\mu$ m. *N. pachyderma* sin from the sediment trap sample MST8-B5 offshore Somalia are slightly

heavier than those from the sediment samples (Table 4).

Oxygen isotope values of three samples from the Somalia basin are within the standard deviation of the machine and range from -1.38 to -1.55%. They are similar to  $\delta^{18}$ O of *G. bulloides* from the top sediments of box-cores 902B and 905B, which have values of -1.31 and -1.36%, respectively.

Oxygen isotope values of N. pachyderma sin from



Fig. 4. Fluxes and relative abundance of *N. pachyderma* sin in sediment trap MST9-E, plotted against days of years 1992 + 1993, from June 7, 1992 to February 14, 1993. Data on SSTs are after Conan and Brummer (in press).

the multinet sample collected offshore Oman are about 0.5‰ lighter than offshore Somalia. However, they are the same for the three analysed samples and also very similar to  $\delta^{18}$ O of *G. bulloides* at the same station, ranging from -2.22 to -1.57‰ (F. Peeters, unpubl. data). The  $\delta^{18}$ O values of *N. pachyderma* sin and *G. bulloides* correspond to the calculated equilibrium calcite values of the upper 25 m of the water column (Fig. 6; Table 4).

The  $\delta^{13}$ C values of all measured *N. pachyderma* 

sin, except for the sample from the upper 8 m of the water column offshore Oman, are similar and range from -1.33 to -1.69% (Table 4). They show a similarity with those of *G. bulloides*, which vary from -1.68 to -1.61% in the core top sediments offshore Somalia and from -2.57 to -1.84% in the water column of Station 313 offshore Oman.  $\delta^{13}$ C values of *N. pachyderma* sin form the upper 8 m at Station 313 are 0.69\%, which is more than 2% heavier than the rest of the samples.



in total foraminifera assemblage >125  $\mu$ m

Fig. 5. Distribution of N. pachyderma sin in surface sediments of box-cores along the Somalia transect.

#### 7. Discussion

*N. pachyderma* sin is a relatively small species in the Arabian Sea. The highest frequency of the species was observed in the 100–125  $\mu$ m size fraction of the sediment trap MST8-B collected offshore Somalia. In both Somalia and Oman/Yemen offshore areas it was generally less abundant between 125 and 250  $\mu$ m and never recorded in >250  $\mu$ m fraction. It explains why *N. pachyderma* sin was not commonly observed in the water column of the Arabian Sea during previous studies which were based



Fig. 6. Calculated  $\delta^{18}$ O values of equilibrium calcite in the water column (after Peeters and Ganssen, unpubl. data) and measured  $\delta^{18}$ O values of *N. pachyderma* sin at Station 313, Oman/Yemen transect.

on the material larger than 200 µm (Bé and Hutson, 1977; Duplessy et al., 1981; Zahn, 1985).

The sediment trap (Somalia area) record shows that *N. pachyderma* sin is present in the Arabian Sea all year around. However, it is far more abundant during the upwelling compared to the non-upwelling period when it only occurs in very low numbers in the finest size fraction (100–125  $\mu$ m). In sediment trap sample MST8-B4 collected over the period from July 5 till 19 we recorded the highest flux of *N. pachyderma* sin. At the same time there was an increase in the flux of biogenic silica and other planktic foraminifera species, in particular the well known upwelling indicator *G. bulloides*. Conan and Brummer (in press) estimate that about two weeks are needed for the foraminifera to reproduce and to settle down from the surface to the depth of the sediment trap. Thus the high flux of *N. pachyderma* sin actually corresponds to the end of June–beginning of July, a period characterised by dropping SSTs, the development of an upwelling gyre and increasing primary productivity.

Generally lower frequencies and unstable fluxes of *N. pachyderma* sin as well as its smaller size were observed in MST9-E compared to MST8-B. We think that the major reproduction niche of *N. pachyderma* sin offshore Somalia is within the coastal upwelling zone.

Extremely low fluxes of small *N. pachyderma* sin were observed in the sediment traps collected during the non-upwelling period off Somalia simultaneously with the low concentrations in deep multinets off Oman. This suggests that the non-upwelling period, characterised by a strong thermocline, high SSTs and low nutrients concentrations, is not a period of active reproduction and growth of *N. pachyderma* sin.

The sediment samples show an in/offshore distribution pattern of *N. pachyderma* sin similar to the sediment traps. The highest concentrations and relative abundance of the species are found in the shallowest part of the transect. A similar pattern was previously observed by Ortiz and Mix (1992) in sediment trap study off Cape Blanco (the California Current region) and Giraudeau and Rogers (1994) in sediment samples from the Benguela upwelling system. Little et al. (1997) also attribute the distribution of *N. pachyderma* sin in the Benguela upwelling system to the 'inshore, eutrophic, nutrient-rich, cooler' newly upwelled waters.

The highest concentration of *N. pachyderma* sin in the water column offshore Oman is found at a depth of 300–500 m at the deepest Station 313, during the upwelling period. It is also present in lower concentrations in the upper part of the water column. If 300–500 m is the actual depth habitat of *N. pachyderma* sin in the Western Arabian Sea than it may feed at least during a part of their life cycle on detrital material rather than on diatoms as was suggested by Hemleben et al. (1989), Reynolds Sautter and Thunell (1989) and Ufkes and Zachariasse (1993).

Another possible explanation for a high concentration of N. pachyderma sin at the depth of 300–

500 m is that not all of the specimens (or even none of them) were living at the time they were collected. They could be a relict of a reproduction bloom from a few weeks previously. This scenario would explain our oxygen isotopic data and also be in agreement with Ufkes and Zachariasse (1993) who found high concentrations of the species in the surface mixed layer off the Southwest African coast.

Ortiz et al. (1996) also observe high frequency of N. pachyderma sin deep in the water column in the California Current, however, the species was also present in the surface water. High concentrations of N. pachyderma sin at a great depth could be a migration pattern within the water column in relation to its growth and reproductive cycle. The migration of the species to a greater depth in the later life stages was mentioned by Kohfeld et al. (1996) in their study of net samples east off Greenland. They show that N. pachyderma sin reaches peak abundance at 20-80 m water depth in association with a chlorophyll maximum zone, but later it moves deeper in the water column where it increases the calcite mass of its shell 3-4 times and modifies the shell chemistry. None of the specimens we find in our samples have the massive calcite crust. The largest specimens are found in the fraction 150-250 µm and on average they are about 22% heavier than the ones from the size fraction 125-150 µm. There is, however, no difference in the oxygen isotopic composition of the specimens from those two size intervals. The data of the isotopic analysis show that N. pachyderma sin in all the studied samples calcified in the upper 25 m of the water column.

The oxygen isotope composition of foraminifera shells generally reflects the temperature and  $\delta^{18}O_w$ of the ambient water (Kroon and Ganssen, 1989 and references therein). However, currently there is a discussion about whether *N. pachyderma* sin also has an offset in  $\delta^{18}O$  as well as in  $\delta^{13}C$ . For example, Bauch et al. (1997) observed a 1‰ offset in the  $\delta^{18}O$  of *N. pachyderma* sin as a result of the 'vital effect'. Ortiz et al. (1996) discuss the possibility of a -0.7‰ offset in connection with temperature determined kinetic disequilibrium processes. We observe a constant  $\delta^{18}O$  signature of *N. pachyderma* sin within two studied areas. The  $\delta^{18}O$  value of *N. pachyderma* sin from the upper 8 m in the water column offshore Oman is the same as the  $\delta^{18}O$  ratio of equilibrium calcite calculated for this depth and consistent with the measurements from the deep cast (Fig. 6; Table 4). Thus we infer that in the Arabian Sea *N. pachyderma* sin calcifies in the uppermost water column in equilibrium with ambient water.

Offshore Somalia steep temperature gradients and intense mixing in the upwelling cells result in large vertical/horizontal temperature variations that range from 18 to 25°C in the upper 25 m of the water. The  $\delta^{18}$ O values of *N. pachyderma* sin from both sediment trap and two sediment samples collected offshore Somalia are between -1.38 and -1.55%. These values are also well within the range of the equilibrium calcite calculated for the surface 25 m of the water column.

The carbon isotope ratio of planktic foraminifera is clearly out of equilibrium with the ambient water (Kroon and Ganssen, 1989 and references therein). Preliminary estimations of the  $\delta^{13}$ C values in the water column at the Station 313 offshore Oman are about 1.2‰ at the surface and decrease by approximately 1.2‰ within the first 25 m depth (G. Brummer, unpubl. data). It implies that N. pachyderma sin from the surface water offshore Oman has an offset of approximately -0.5% (Table 4). This is less than observed by Kohfeld et al. (1996) from Northeast Water Polynia where N. pachyderma sin was consistently 1.0% depleted in comparison with the  $\delta^{13}$ C for equilibrium calcite. The two samples from the deeper cast of the same station are 2.04-2.3‰ lighter in carbon isotopes compared to the surface sample. The explanation can be found in a large shift of  $\delta^{13}$ C of values with an increasing depth and/or a very dynamic and rapidly changing trophic environment at the surface. Thus, for example, N. pachyderma sin from the deep cast could have calcified at the surface under different conditions one or two weeks ago. The  $\delta^{13}$ C values of *N. pachyderma* sin from the deeper Oman multinet sample (300-500 m) show more similarity to those from the sediment trap and core top sediments collected offshore Somalia than with the surface sample from the same Station offshore Oman.

The seasonal pattern of *N. pachyderma* sin in the Western Arabian Sea is clearly pronounced. It is present in the water column all year around, but grows and reproduces only during 3–4 months related to the upwelling period. *N. pachyderma* sin is

known to survive unfavorable conditions for at least a few months. It lives in polar regions where a strong seasonality provides only a few productive months per year. For example, sediment trap material collected off East Greenland suggests that the flux of N. pachyderma sin is almost zero below complete ice cover, and only rises during a period of 2 to 4 weeks each year, likely tied to phytoplankton bloom events (Kohfeld et al., 1996). N. pachyderma sin can probably adjust to the rapidly changing environmental conditions of the Arabian Sea by means of the same mechanism that it uses in the high latitudes. Being passive at least half of the year, it is brought up by upwelled waters and dispersed offshore at gyre margins during the SW monsoon. The lower temperature and a great availability of food create conditions suitable for reproduction and growth of the species. This would explain the high fluxes of N. pachyderma sin and the greater test size of the specimens from the sediment traps collected in the upwelling season, in particular from trap MST8, which is closer to the center of upwelling than MST9.

### 8. Conclusions

The results of our study indicate that the occurrence of *N. pachyderma* sin offshore Somalia and Oman is strongly related to upwelling. Therefore almost all *N. pachyderma* sin found in the sediments are produced during the upwelling period, and its isotope composition reflects properties of the seasonal water masses.

*N. pachyderma* sin is 'dormant' over a large period of the year (NE monsoon), in analogy with the modern arctic *N. pachyderma* sin. It is present in extremely low concentrations, only in the <125  $\mu$ m fraction. We assume it survives a few hundred meters deep in the water column and only with the beginning of SW monsoon *N. pachyderma* sin is brought up to the surface by upwelling waters. There, in the surface 25 m within a zone of coastal upwelling, it grows and reproduces. This conclusion is based on  $\delta^{18}$ O of *N. pachyderma* sin compared to  $\delta^{18}$ O of calcite equilibrium values in the water column, similarity of oxygen isotope ratios of *N. pachyderma* sin to that of *G. bulloides* and association of the species with chlorophyll maximum zone (Kohfeld et

al., 1996) which is close to the surface during the SW monsoon in the Arabian Sea (Brummer, 1995). The species is transported by the dynamic upwelling gyre as far as 250 km offshore, but its abundance and size decreases rapidly. The carbon isotope signal of *N. pachyderma* sin in the Arabian Sea is at least 0.5‰ and possibly even more depleted compare to the values in the water column.

We can think of two possible explanations for the high frequency of *N. pachyderma* sin observed in the deep multinets. Our preferred explanation is that the distribution could be attributed to some sort of migration pattern connected to the life cycle of *N. pachyderma* sin, where a long 'resting stage' at a greater depth precedes a short reproduction period near the surface. Alternatively, we may not be dealing with living specimens but with a flux, i.e. remains of a reproduction bloom of 1-2 weeks earlier.

The relation of *N. pachyderma* sin to upwelling in the Arabian Sea is as clear pronounced as that of *G. bulloides*. We suggest that its absolute and relative frequencies in marine sediment can be used for the interpretation of past upwelling intensity in the area.

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### Appendix A. Taxonomic list

Taxonomy follows Parker (1962), Saito et al. (1981) and Kroon (1991).

Dentigloborotalia anfracta (Parker, 1967) Globigerina bulloides d'Orbigny, 1826 Globigerina rubescens Hofker, 1956 Globigerinoides ruber (d'Orbigny, 1839) Globogerinoides sacculifer (Brady, 1877) Globorotalia truncatulinoides (d'Orbigny, 1839) Neogloboquadrina incompta (Cifelli, 1961) Neogloboquadrina pachyderma (Ehrenberg, 1861) Tenuitella iota (Parker, 1962) Tenuitella parkerae (Brönniman and Resig, 1971) Turborotalita quinqueloba (Natland, 1938)

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