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Surface water conditions in the Northern Benguela Region (SE Atlantic) during the last 450 ky reconstructed from assemblages of planktonic foraminifera

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Abstract

Planktonic foraminiferal records from Site 1083 (ODP Leg 175) were used to investigate changes in surface water conditions in the Northern Benguela Region over the past 450 ky. The assemblages of planktonic foraminifera are dominated by four species: sinistral coiling *Neogloboquadrina pachyderma*, dextral coiling *N. pachyderma*, *Globigerina bulloides* and *Globorotalia inflata*. Besides, tropical species deliver a small contribution to the assemblage.

The most prominent temporal variations, displayed by *N. pachyderma* (s+d), represent changes in the coastal upwelling and the presence of cold, nutrient rich waters over the core site. *Neogloboquadrina pachyderma* (s+d) shows cyclic variability in the eccentricity and, to a less extent, precession frequencies. The changes indicate increased upwelling intensity in glacial maxima and precession maxima, and correlate well with the wind-strength record of Stuut et al. (2002). During glacial maxima, steep temperature gradients over the Southern Hemisphere caused strong SE trade winds and strong upwelling. Precession maxima cause a weak monsoonal circulation, more zonal SE trade winds, strong coastal upwelling, and nutrient-rich surface waters over ODP Site 1083.

Advection of Angola Current (AC) surface water into the Walvis Basin, indicated by the tropical species, occurs when the Angola Benguela Front (ABF) is positioned southward. Occasionally, this happened during glacial maxima, as can be explained with the reconstructed and predicted meridional movements of the ABF. The amount of AC water was never sufficient to suppress the marine biological production at the core site.

The contribution of Benguela Current (BC) water, reflected by *Globorotalia inflata*, is greatly determined by the upwelling. In periods of strong upwelling, the BC influence is suppressed.

In several glacial substages, the temperature of the upwelling South Atlantic Central Water (SACW) may have been increased, as suggested by the dominance of *Neogloboquadrina pachyderma* (d) in the upwelling record. This phenomenon may be due to intensified subduction in the central South Atlantic that induces the formation of SACW, or to larger contributions of Eastern SACW to the upwelling water.

Around 250-200 ky BP, a long-term shift to higher productivity occurred that is absent in the upwelling record. It was accompanied with a transition from a precession and obliquity variability to an eccentricity dominated variability in the

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Globorotalia inflata (BC) record. The shift was probably connected to a long-term southward shift of the circumpolar oceanic frontal systems south of the African continent. © 2004 Elsevier B.V. All rights reserved.

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1. Introduction

The Benguela region is one of the world's largest coastal upwelling areas. It plays a vital role in the transfer of heat and salt from the Indian into the Atlantic Ocean, which is a critical factor in driving the global conveyor belt (Lutjeharms et al., 2001). Therefore, the variations in the Benguela Current system are likely to affect the climate on a global scale. Hydrographically, the region can be separated in the Northern Benguela Region (NBR), north of 28°S, where the upwelling is perennial and the Southern Benguela Region (SBR) with a seasonal upwelling in spring and summer (Lutjeharms and Meeuwis, 1987).



Fig. 1. Overview of surface currents in the SE Atlantic Ocean and core positions. After Lutjeharms and Stockton (1987). AC=Angola Current, ABF=Angola-Benguela Front, BOC=Benguela Oceanic Current, BCC=Benguela Coastal Current, SAC=South Atlantic Current, AGC=Agulhas Current. Striped area=coastal upwelling, shaded area=filaments of upwelled water.

Most of the previous work in the Benguela region focussed on the coastal upwelling (e.g. Oberhänsli, 1991; Schneider et al., 1995; Little et al., 1997a,b; Ufkes et al., 2000; Chen et al., 2002). The objective of this study is to reconstruct the variations of the surface water masses in the Northern Benguela Region after the Mid-Pleistocene transition, and to investigate their driving processes. Besides upwelling, the most dominant oceanographic process in the NBR, other important features are the leakage of warm Angola Current (AC) water from the north, and the influence of variations in the SBR introduced by the Benguela Current (BC). We will assess the impact of these three features by comparing our faunal records with existing records from the Angola Basin and the Southern Cape Basin. The influences of the variations in these processes on marine productivity will be discussed.

2. Hydrography

The Southeast Atlantic atmospheric and oceanic current system (Fig. 1) has been reviewed in detail by Peterson and Stramma (1991). The atmospheric circulation in this area is dominated by a large semipermanent high-pressure cell over the South Atlantic, the South Atlantic Atmospheric High (SAAH), a low-pressure cell over southern Africa during the austral summer, and the Intertropical Convergence Zone (ITCZ) over central and southern Africa. This system gives rise to the southeast trade wind that is the driving force behind a large-scale coastal upwelling system and the main oceanic current in this area, the BC. The cold BC is an eastern boundary current flowing to the north. The primary source of its water is the South Atlantic Current with the Agulhas Current and Subantarctic Surface Water as additional sources (Fig. 1). South of Walvis Ridge, the BC splits in a coastal (Benguela Coastal Current, BCC) and an oceanic branch (Benguela Oceanic Current, BOC). North of the Walvis Ridge, where the BC meets the warm southward flowing AC, a frontal zone, the Angola Benguela Front (ABF), develops. The ABF moves seasonally between 14° and 17°S (Meeuwis and Lutjeharms, 1990) and forms the northern boundary of the Benguela system. Shannon et al. (1986) have described intrusions

of warm AC water from the north along the Namibian shelf, the so-called "Benguela niños." These result in a rise of the sea surface temperature on the shelf and are associated with a decline in upwelling activity and marine biological productivity in the Northern Benguela Region. From the south, subtropical Indian Ocean water enters the Atlantic in large, 200–300-km-wide eddies called Agulhas Rings, contributing a large amount of Indian Ocean water

Tab	le	1	

Reference	Minimum	Maximum
Globigerina bulloides (d'Orbigny, 1826)	6.2	49.8
Globigerina digitata (Brady, 1879)	0	0.6
Globigerina falconensis (Blow, 1959)	0	2.1
Globigerina glutinata (Egger, 1893)	0	11.8
Globigerina quinqueloba (Natland, 1938)	0	5.8
Globigerinella siphonifera	0	2.6
(d'Orbigny, 1839)		
Globigerinella calida (Parker, 1962)	0	3.7
Globigerinoides trilobus (Reuss, 1850)	0	2
Globigeroides ruber r. (d'Orbigny, 1839)	0	1.5
Globigeroides ruber w.	0	2.9
Globigeroides sacculifer (Brady, 1877)	0	0.8
Globigeroides tenellus (Parker, 1958)	0	1.8
Globorotalia crassaformis d.	0	4.2
(Galloway and Wissler, 1927)		
Globorotalia crassaformis s.	0	0.4
Globorotalia hirsuta d. (d'Orbigny, 1839)	0	1.4
Globorotalia hirsuta s.	0	0.3
Globorotalia inflata (d'Orbigny, 1839)	0	39.9
Globorotalia menardii (d'Orbigny, 1826)	0	0.4
Globorotalia scitula (Brady, 1881)	0	4.1
Globorotalia truncatulinoides d.	0	3
(d'Orbigny, 1839)		
Globorotalia truncatulinoides s.	0	1.6
Globorotaloides hexagonus	0	0.4
(Natland, 1938)		
Globoturborotalita rubescens	0	0.5
(Hofker, 1959)		
Neogloboquadrina dutertrei	0	5.9
(d'Orbigny, 1839)		
Neogloboquadrina pachyderma d.	2.3	80.5
(Ehrenberg, 1861)		
Neogloboquadrina pachyderma s.	0	85.4
Orbulina universa (d'Orbigny, 1839)	0	11.4
Pulleniatina obliquiloculata	0	0.5
(Parker and Jones, 1865)		
Sphaeroidinella dehiscens	0	0.5
(Parker and Jones, 1865)		

Minimum and maximum abundances are given in percentage.

to the BC and the Atlantic Ocean (Schouten et al., 2000).

The coastal upwelling takes place all along the coast of southwestern Africa. The water wells at 100–300 m depth from the South Atlantic Central Water (SACW) that is formed by subduction in the central South Atlantic (Tomczak and Godfrey, 1994) and the Eastern South Atlantic Central Water (ESACW) that is formed by advection with Agulhas Current water (Mohrholz et al., 2001). The upwelling is concentrated in a number of cells over the shelf (Shannon, 1985; Lutjeharms and Meeuwis, 1987). From these cells, filaments of the cold and nutrient-rich upwelled waters penetrate far, op to 1200 km, into the ocean (Lutjeharms and Stockton, 1987). In the NBR, the perennial upwelling shows a maximum intensity during the late austral winter and early

spring, while the seasonal upwelling in the SBR is at its maximum during the austral spring and summer (Lutjeharms and Meeuwis, 1987). The upwelling in the SBR is stronger and, due to admixture of Antarctic Intermediate Water to the SACW, the upwelled waters in the SBR are cooler than in the NBR.

3. Material and methods

ODP Site 1083 was drilled during ODP leg 175 in the Northern Cape Basin (20°53' S 11°13' E) at 2190 m water depth (Fig. 1). The sediments consist of moderately bioturbated clayey nannofossil ooze. Samples were taken from three Holes 1083A, 1083B and 1083D to obtain a complete stratigraphic inter-



Fig. 2. Age model for the upper 44 m of Site ODP 1083, based on the correlation of CORTEX measurements in core MD 962094. Oxygen isotope data and element counts of MD 962094 from Stuut et al. (2002). cps = counts/s, mcd = meters composite depth, t1 = tie point 1 according to Table 2. Shaded intervals indicate glacial stages.

val. For the analysis of planktonic foraminiferal assemblages in this core, a total of 99 samples were taken from the upper 40 m, freeze-dried, weighted and subsequently disintegrated in tap water. Thereafter, the samples were sieved over 63, 150 and 600 µm mesh sieves. The 150-600 µm size fraction was used in the analysis. From this size fraction, a split was made that contained at least 200 specimens of planktonic foraminifera. Planktonic foraminifera were counted and classified according to the taxonomies of Kennett and Srinivasan (1983) and Hemleben et al. (1989). A total of 26 species of planktonic foraminifera was identified (Table 1). In addition, the total number of benthic foraminifera, and benthicand planktonic foraminiferal fragments in the split were counted, to test the effect of selective dissolution on the assemblages (Appendix A).

A composite section of the three holes was analyzed with the XRF scanner CORTEX (Jansen et al., 1998) to obtain a high-resolution record of seven element counts. The Fe and Ca counts were used for the temporal correlation with similar data

Table 2
Tie points used for correlating Fe and Ca records of MD 962094 and
ODP 1083

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ODP 1083 depth (mcd)	MD 962094 age (ky)	Tie point
1.24	12.10	t1
2.28	19.18	t2
3.80	33.83	t3
6.95	69.36	t4
8.95	86.86	t5
12.50	134.24	t6
16.60	175.26	t7
17.74	189.85	t8
19.44	199.68	t9
20.02	211.80	t10
20.60	226.63	t11
21.34	235.02	t12
22.50	245.87	t13
23.06	253.81	t14
24.36	272.63	t15
27.26	299.73	t16
29.76	329.10	t17
31.08	341.18	t18
32.66	353.19	t19
33.44	360.81	t20
34.16	365.38	t21
36.54	389.38	t22
37.90	403.13	t23

from the nearby core MD 962094 (Fig. 1) for which an age model was developed based on oxygen isotope stratigraphy. The isotope data are given in Appendix B. The records of Fe were shown to make a good correlation tool in cores throughout the Northern Cape Basin (Stuut, 2001) and the Ca records also display the same trends in both cores. Thus we were able to construct a reliable age model for the studied interval of ODP Site 1083 by correlating peaks in both records (Fig. 2; Table 2). According to the age model, the average sedimentation rate is 10 cm/ky over the past 450 ky, ranging between 4 and 17 cm/ky.

Cross-spectral analysis was performed on the different faunal records using the Analyseries software package by Paillard et al. (1996). We compared the faunal records with the stacked δ^{18} O of MD 962094. Cross-spectral estimates are based on 5-ky linear interpolated time series for the time interval between 6 and 454 ky BP. We used a Bartlett window with 30 lags, which resulted in a band width of 0.01 cycles/ky.

4. Present-day distribution of planktonic foraminifera

Four species of planktonic foraminifera dominate the assemblages in the coretop samples from the southwestern African shelf: the sinistral coiling *Neogloboquadrina pachyderma*, dextral coiling *N. pachyderma*, *Globigerina bulloides* and *Globorotalia inflata* (Fig. 3; Giraudeau, 1993).

Nowadays *Neogloboquadrina pachyderma* (s) is the most abundant species in polar surface waters. In the Benguela region this species is abundant in cold, high-nutrient upwelled waters (Ufkes and Zachariasse, 1993; Ufkes et al., 1998) and it shows abundance maxima in sediments below the upwelling cells. This implies that a high abundance of *N. pachyderma* (s) can be related to increased upwelling intensity, transport of polar waters to the Walvis Ridge by the BC or both. Little et al. (1997a) reported that peak abundances of *N. pachyderma* (s) observed in piston cores from the NBR are not present in cores in the SBR. Therefore, a high abundance of this species at ODP Site 1083 is considered to indicate enhanced coastal upwelling of cold nutrient-rich waters in the NBR.



Fig. 3. Present-day distribution of planktonic foraminifera in surface sediments on the SE African shelf. After Giraudeau (1993). Modified from Ufkes et al. (2000).

Neogloboquadrina pachyderma (d) occurs in subpolar and transitional environments. It is also abundant in surface waters in coastal upwelling cells and in upwelling filaments. This is reflected by increased abundance of this species in surface sediments below these environments. It is more abundant in the surface sediments from the NBR than in the SBR (Giraudeau, 1993; Ufkes et al., 1998).

Globigerina bulloides is also an upwelling species, being abundant in various subtropical to subpolar upwelling regions of the world. Its distribution in the SE Atlantic and surface sediments on the SE African shelf is comparable to that of *Neogloboquadrina pachyderma* (d) although it is more abundant in warmer waters (Giraudeau, 1993; Ufkes et al., 1998). Both *N. pachyderma* (d) and *G. bulloides* are living in the transitional environment between the upwelling cells and the BOC. Here *N. pachyderma* (d) represents the colder and more nutrient-rich waters and *G. bulloides* is found in warmer and less fertile waters (Oberhänsli, 1991; Schmidt, 1992; Giraudeau, 1993; Pflaumann et al., 1996; Ufkes et al., 1998).

Of the four dominant species, *Globorotalia inflata* represents the most oligotrophic conditions. It is most abundant in surface waters in temperate regions where it prefers well-mixed water masses with a

deep mixed layer. In the SE Atlantic, the species is abundant in the surface waters of the ABF and the BOC (Oberhänsli et al., 1992; Ufkes et al., 1998; Kemle-von Mücke and Oberhänsli, 1999). It is the most successful species in the transitional environment between the Benguela system and the South Atlantic subtropical gyre. Further south, it is the most abundant species in the transitional zone between the subtropical and subantarctic water masses (Rau et al., 2002). In the surface sediments it is more abundant in the SBR than in the NBR. Also Walvis Ridge surface sediments may contain high abundances of *G. inflata* (Schmidt, 1992).

Ten species that are characteristic for equatorial and central gyre water masses are combined into one group. This group contains species preferring warm surface waters and a well stratified water column and includes: *Globigerinoides ruber* (pink + white varieties), *Globigerinoides sacculifer*, *Globigerinoides trilobus*, *Globigerinella siphonifera*, *Globigerinella calida*, *Globorotalia crassaformis*, *Globorotalia menardii*, *Globigerina rubescens* and *Globigerinoides tenellus*. (Oberhänsli et al., 1992; Ufkes et al., 1998; Kemle-von Mücke and Oberhänsli, 1999). Species from this group are referred to as tropical species further on.

5. Results

5.1. Downcore distribution of planktonic foraminifera

Four species (*Neogloboquadrina pachyderma* (s), *N. pachyderma* (d), *Globigerina bulloides* and *Globorotalia inflata*) make up more than 85% of planktonic foraminiferal assemblages in ODP Site 1083 (Fig. 4). Other species reaching abundances higher than 2% are the ones in the tropical species group, as well as *Neogloboquadrina dutertrei*, *Orbulina universa* and *Globigerinata glutinata*. The latter three species will not be considered any further because of their overall low abundances.

Neogloboquadrina pachyderma (s) shows the most pronounced variations in its relative abundance, between 0% and 85% with an average of 17% (Fig. 4).

The maximum abundances occur in distinct peaks during several glacial and interglacial stages.

Neogloboquadrina pachyderma (d) is the most abundant species throughout the core. It has an average contribution of 38% varying between 2% and 80% (Fig. 4). The glacial to interglacial variations of *N. pachyderma* (d) and *N. pachyderma* (s) are absent and weak, respectively. If, however, the two species are grouped, their abundance curve shows a distinct glacial–interglacial pattern, with the highest abundances in glacial stages.

The pattern of *Globigerina bulloides* also shows glacial-interglacial variations, but with highest abundances mostly during interglacials, with additional maxima during the glacial stages MIS 6 and MIS 8 (Fig. 4). The average relative abundance is 25%, the values varying between 6% and 50%.



Fig. 4. Relative abundance of planktonic foraminifera in ODP 1083 and δ^{18} O curve of MD 962094 (Stuut et al., 2002; Appendix B). Shaded intervals indicate glacial stages.

In the relative abundance curve of *Globorotalia inflata*, the last two glacial-interglacial cycles are also well visible, with highest abundances during the interglacials (Fig. 4). Before 250–200 ky BP, however, the values vary at higher frequencies than after that time. The average relative abundance is 12% with maxima of 40% and minima of 0%.

The contribution of the tropical species group is small, with an average of 2% varying between 0% and 10% (Fig. 4). At first sight, this group seems to follow a glacial–interglacial pattern with the highest abundances in the interglacial stages. The minima, however, do not coincide with the glacial maxima, and the peaks and lows appear to precede the glacial and interglacial maxima by 15 to 20 ky.

5.2. Cross-spectral analysis

The most obvious cyclic variability revealed by cross-spectral analysis of the faunal records with the oxygen isotope record of MD 962094 is near the 100- ky^{-1} frequency band, which is the dominant frequency in ice volume variations (Hays et al., 1976). This cyclicity is most pronounced in the power spectra of *Globigerina bulloides*, *Neogloboquadrina pachy-derma* (s+d) and the tropical species group (Fig. 5). *N. pachyderma* (s+d) and *G. bulloides* are in phase with the oxygen isotope curve or slightly precede it. Cross-spectral analysis of the tropical species group with oxygen isotopes shows that minimum abundance of the tropical species is leading maximum ice volume by 10 ± 2 ky.

The power spectra of *Neogloboquadrina pachyderma* (s), *N. pachyderma* (s+d) and *Globorotalia inflata* show coherent peaks near 19 ky. Although the precession signal in temperature, productivity and wind strength-related records from this area usually shows up as a 23-ky cycle (Schneider et al., 1996; Stuut et al., 2002), we consider the 19-ky cyclicity in the spectral diagram of the *N. pachyderma* (s+d) record precession related. The discrepancy may be caused by differences in the age models and our relatively low sampling resolution (~ 5 ky).

In the power spectra of *Globorotalia inflata* and the tropical species a peak appears around 40 ky, indicating a relation with obliquity with maximum abundances during obliquity maxima. Also the spectral diagrams of *Neogloboquadrina pachyderma* (d). and *N. pachyderma* (s+d) show a small peak near this period. The spectral diagrams of *N. pachyderma* (s+d) and of the tropical species show a peak near 28 ky.

6. Discussion

6.1. Preservation

Of the four dominant species, Globigerina bulloides is most susceptible to dissolution while the other three are considered dissolution-resistant. The tropical group is also dominated by species sensitive to dissolution. In the Cape Basin, the dissolution varies in glacial cycles with dissolution maxima during glacial stages (Howard and Prell, 1992). The dissolution indicators in ODP Site 1083, the fragmentation index and the ratio between planktonic and benthic foraminifera (p-b ratio), show the same variability (Fig. 6A). So any abundance variation showing a glacial-interglacial variability might be caused by selective dissolution of fragile species (Berger, 1970; Le and Thunnel, 1996). In order to test this possibility, we plotted the relative abundances of the foraminiferal species with the fragmentation index (Fig. 6B) and the p-b ratio. The comparison with the fragmentation index shows no correlation for the dominant species, the largest correlation coefficient applies to the dissolution-sensitive tropical species group ($r^2 = 0.20$ only). The comparison with the p-b ratios gives similar results. Apparently, selective dissolution plays only a minor role in the species composition. We conclude that the assemblage variations primarily reflect the changing surface water conditions at this site during the studied time interval.

6.2. Upwelling signal

The *Neogloboquadrina pachyderma* (s+d) record appears to give the most reliable upwelling signal. It shows a good correlation with the productivityrelated total organic carbon (TOC) (Fig. 7) and SST records from the nearby core GeoB1028-5 at Walvis Ridge. The interpretation is corroborated by the frequency spectra of the records. *Neogloboquadrina pachyderma* (s+d) varied in the precession



Fig. 5. Spectral diagrams of different species of planktonic foraminifera in ODP 1083. The bandwidth is 0.01 cycles/ky. Dashed lines indicate coherence with the δ^{18} O record of MD 962094; dashed horizontal lines indicate the 80 % confidence level with the δ^{18} O record. Cyclicities coherent with the δ^{18} O record at the 80% confidence level are indicated in ky.

(23 ky⁻¹) and eccentricity (100 ky⁻¹) frequencies while the obliquity signal (41 ky⁻¹) is very weak (Fig. 5), and the same spectrum is observed in the TOC and SST records of core GeoB 1028-5 (Schneider et al., 1996). The *N. pachyderma* (s+d) record, moreover, shows a good correlation with the aeolian grain size record of the nearby core MD 962094 from Walvis Ridge analyzed by Stuut et al.

(2002) (Figs. 1 and 7). During periods of intensified trade winds, indicated by larger aeolian grain sizes, the coastal upwelling of nutrient-rich waters was stronger, which is shown by contemporary higher abundances of *N. pachyderma* (s+d) in ODP Site 1083. The *N. pachyderma* (s+d) record correlates much better with this aeolian record than the *N. pachyderma* (s) upwelling record proposed by Little





Fig. 7. Relative abundance of *Neogloboquadrina pachyderma* (s+d) in ODP 1083, TOC in core GeoB 1028-5 (Schneider et al., 1996) and size of aeolian dust in core MD 962094 (Stuut et al., 2002). For the last 60 ky, the dust data are given as five-point moving-average values because of the high resolution of the original data. Asterisks indicate high values of *N. pachyderma* (s+d) that are absent in the *N. pachyderma* (s) record. Shaded intervals indicate glacial stages.

et al. (1997a,b). This is particularly clear for the high *N. pachyderma* (s+d) values at 285–240, 188, 115–105, 72, and 42 ky BP that are absent in the *N. pachyderma* (s) record in ODP1083 as well as in the cores described by Little et al. (1997a,b). Apparently, *N. pachyderma* (s) was displaced by *N. pachyderma* (d), which suggests that the SST was higher at these times (Oberhänsli et al., 1992; Giraudeau, 1993; Ufkes et al., 1998) like at 430, 375, 351, and

301 ky BP. The displacement might be caused by the leakage of warm water from the Agulhas Current or higher temperatures of the upwelled SACW. In the case of leakage, some contribution of tropical species would be expected, which apparently was not the case (Fig. 4). Consequently, it is the upwelling SACW that must have been less cold at these times. If so, the peaks indicate either larger contributions of ESACW to the upwelling water or

Fig. 6. (A) Dissolution indicators (fragmentation index and plankton/benthos ratio) in ODP 1083. Shaded intervals indicate glacial stages. (B) Scatter plots of relative abundance of planktonic foraminifera and fragmentation index.

variations in the stratification of the water column in the central South Atlantic. If the latter is the latter is the case, it suggests that intensified atmospheric circulation enhances the subduction that induces the formation of SACW.

The most pronounced variations in the Neogloboquadrina pachyderma (s+d) record are related to the glacial-interglacial 100-ky cycle. During glacial stages, steeper temperature gradients over the Southern Hemisphere resulted in stronger SE trade winds and increased coastal upwelling (Schneider et al., 1996). The precessional 23-ky cyclicity in the coastal upwelling can be explained by the variations in the zonality of the Benguela Current controlled by the summer insolation at low latitudes. During a precession minimum, the boreal summer insolation was high, which caused a strong monsoonal circulation. This configuration weakens the zonal intensity of the trade winds (Fig. 7b) (McIntyre et al., 1989; Schneider et al., 1996). As a result, the transport of cold upwelled water in filaments over the Walvis Ridge was reduced, as indicated by the N. pachyderma (s+d) record, and the productivity was lowered as shown by the TOC record in GeoB 1028-5.

6.3. Warm-water signal

The increase and decrease of upwelling can explain the downcore abundance pattern of the tropical species. During weak upwelling, less cold and nutrient-rich waters were transported to the core site. This resulted in a greater influence of the warm, lownutrient water masses originating from the South Atlantic gyre and the Angola Current. During glacial maxima, on the other hand, intense upwelling resulted in large amounts of cold waters originating from the coast and less influence of warmer water masses.

There is, however, a phase difference between the glacial-interglacial cycle of the upwelling species and the tropical species. This phase difference is most obvious in glacial maxima, where the minimum abundance of tropical species precedes the maxima in the ice volume and the abundance of the upwelling species by 15-20 ky. A 15-20-ky lead of the lowest SST over the largest global ice volume is typical in tropical SST records due to the amplitude modulation

of the precession signal by the eccentricity cycle. This signal, however, needs to be transported by surface water advection to show up at subtropical latitudes (Schneider et al., 1999).

This phase difference indicates that the AC supplied the warm surface waters during the glacial maxima for the following reason. There are three possible warm-water sources: the Angola Current, the South Atlantic subtropical gyre, and Indian Ocean water supplied by the BC. Because the BOC had a more zonal or oceanward direction during the glacial maxima (Schneider et al., 1995), the coastward transport from the subtropical gyre to Site 1083 is an unlikely source. Also the supply from the Indian Ocean can be ruled out, because no signs of warm-water advection were found in the SBR during the glacial stages MIS 2 and MIS 10 (Giraudeau et al., 2001; Chen et al., 2002; Rau et al., 2002). This leaves the AC in the north as the only source for the advection of warm surface waters during the glacial stages.

This interpretation is corroborated by an alkenone-derived SST record from the upper slope off Namibia further south (GeoB 1712-4, 23.3°S, 998 m) (Kirst et al., 1999; Schneider et al., 1999). Kirst et al. inferred that warm AC-water intrusions followed the meridional shifts of the Angola Benguela Front (ABF) reported by Jansen et al. (1996). This explains why the minimum SST occurred 45–50 ky BP, 30 ky before the last glacial maximum, when the ABF was at its northernmost position (Fig. 8). Our tropical species record shows that AC waters can be traced further oceanward than the upper slope, as so does the transitional SST pattern in the next deeper core further south at 1967 m (GeoB 1711-4) studied by Kirst et al. (1999).

The record of the meridional ABF movements deviates from the global ice-volume record because it has strong 100-ky, 23-ky and 15-ky components, and not much power in the 41-ky obliquity band (Jansen et al., 1996). To test the AC origin of the tropical species, we extrapolated the ABF movements back to 460 ky BP by extrapolation and addition of the 100-ky and 23-ky components (Fig. 8). The extrapolation shows a good agreement with the tropical record, and appears to predict the lead of its 15–20-ky lows over the maxima in global ice volume.



Fig. 8. Relative abundance of the tropical species group in ODP 1083 and predicted position of the Angola-Benguela Front (ABF). Shaded intervals indicate glacial stages.

Oberhänsli (1991), otherwise, indicated warm intrusions of AC water during MIS 11, sporadically in MIS 8 to MIS 6, and in MIS 5. This reconstruction was based on the increased abundance of *Neogloboquadrina dutertrei*. Her record of warmwater indicators (Fig. 8a: warm signal, in Oberhänsli, 1991), however, has the same appearance as our record of tropical species. It would not change much if *N. dutertrei* and *Globorotalia inflata*, the species that are not included in our tropical group, were excluded from it. Moreover, the only considerable difference occurs in MIS 9, where an increased *N. dutertrei* contribution is not accompanied with more tropical species. Because this observation is based on two samples only (284 and 295 ky BP), we consider the tropical species from Site 1083 as the best available signal of warm AC-water intrusions.

6.4. Benguela Current signal

The influence of the BOC, as indicated by our *Globorotalia inflata* record, is for a large part, the result of the local wind strength and direction and associated changes in the upwelling system. When this system intensifies, the influence of the BOC is reduced. The importance of BOC water at ODP Site 1083 also decreases with more zonal trade winds, because then also the BOC will be more zonally directed. Therefore, the influence of the Benguela Current is expected to have increased during interglacials when the upwelling was weaker and the BOC more meridional. Indeed, during the last 200 ky the record of *G. inflata* shows maximum abundances during warm episodes when the upwelling was weak.

The abundance record of Globorotalia inflata also indicates a change in the variation pattern in the BOC at 250-200 ky BP, from a high-frequency variation related to the earth's precession and obliquity cycles to a lower one dominated by the eccentricity cycle (Fig. 9). Before, the 23-ky precessional amplitude was 50% larger and the 100-ky eccentricity amplitude four times smaller than after that time, while the obliquity amplitude was slightly larger. This change is observed neither in the upwelling indicators nor in the tropical species at ODP Site 1083. A similar transition, from high-frequency variability to glacial-interglacial variability, was observed by Giraudeau et al. (2001) in the Southern Cape basin. Furthermore, Rau et al. (2002) provided evidence for a shift to lower wind stress and higher sea surface temperatures in a core located south of South Africa in this period. These authors suggest that these changes were caused by a southward shift of the Antarctic circumpolar fronts.

We hypothesise a causal relationship between the positions of these fronts and the characteristics of the BC. If so, the change in the dominant frequencies of the variations in the BC would support a more northern position of the fronts before 250–200 ky



Fig. 9. Relative abundance of *Globorotalia inflata* in ODP 1083 and its 100-ky and 23-ky filtered components (dashed lines). Shaded intervals indicate glacial stages.

BP. When the fronts were situated relatively north, the smaller high-frequency variations in the positions of these fronts, related to the earth's precession and obliquity, could be transferred to the BC. When, however, the fronts were situated further south, small high-frequency movements were less readily recorded in the BC because the distance between the fronts and the BC was too large. In this way, the position of circumpolar fronts south of Africa may influence the water mass characteristics of the BC, because it regulates the inflow of Indian Ocean water, subpolar water, and water from the transitional zone between the subtropical and subantarctic water masses into the BC.

6.5. Link between water-mass and productivity variations in the NBR

Of the three major signals identified, the upwelling signal, warm-water signal and BOC signal, the upwelling signal correlates best with the TOC record of marine productivity on the eastern Walvis Ridge S. West et al. / Marine Micropaleontology 51 (2004) 321-344

(Schneider et al., 1996; core GeoB 1028-5). The correlation indicates that upwelling was the most important biological production process during the last 400 ky. There was, however, also a shift to higher TOC values at 250-200 ky BP, especially during the glacial stages MIS 6, and MIS 2 to MIS 4 (Fig. 7). Because this shift is absent in the upwelling record of *Neogloboquadrina pachyderma* (s+d), a part of the productivity must be induced by other processes than upwelling. Warm AC water intrusions from the north, leading to decreased productivity (Kirst et al., 1999), may be excluded as a cause, because there is no similar long-term transition in the tropical species record (Fig. 4). The shift, however, occurred simultaneously with the long-term change in the BOC, indicated by the transition in the dominant frequencies in the Globorotalia inflata record, which we attribute to a long-term southward shift of the Antarctic circumpolar fronts. We suggest, therefore, that changing hydrographical conditions in the SBR related to this shift affected the productivity in the NBR.

7. Conclusions

Three assemblages of planktonic foraminifera in ODP Site 1083 reflect the surface water conditions in the Northern Cape Basin during the late Quaternary. They show variations in the water produced by coastal upwelling, water transported by the Benguela Current (BC), and water originating from the Angola Current (AC). Selective dissolution plays only a minor role in the species composition.

The *Neogloboquadrina pachyderma* (s+d) record gives the most reliable upwelling signal. It varies mainly in the eccentricity and, to a less extent, precession frequency, with highest productivity during glacial and precessional maxima. The upwelling record is well correlated with the nearby aeolian grain-size record of Stuut et al. (2002), showing that intensified and more zonal trade winds induce a stronger coastal upwelling of nutrient-rich waters.

The contribution of the BC water is greatly determined by the upwelling. In periods of strong upwelling the BC influence is suppressed. The tropical species reflect the leakage of warm AC water through the Angola-Benguela Front (ABF) in the north. Also this AC signal is partly a rest signal after the upwelling signal. A considerable AC contribution, however, was occasionally recorded during glacial maxima, and there is a 15–20 ky lead of the AC signal over the upwelling signal. These differences are determined by the phase of the reconstructed and predicted meridional movements of the ABF.

In several glacial substages, the upwelling signal is dominated by *Neogloboquadrina pachyderma* (d), suggesting higher sea surface temperatures. Probably, the upwelling South Atlantic Central Water (SACW) has been less cold at these times. This phenomenon may be due to larger contributions of Eastern SACW to the upwelling water or to variations in the stratification of the water column in the central South Atlantic. If the latter is the latter case, it suggests that intensified atmospheric circulation enhances the subduction that induces the formation of SACW.

A long-term shift to higher productivity occurs around 250–200 ky BP that is absent in the upwelling record. It is accompanied with a transition from a precession and obliquity variability to an eccentricity dominated variability in the BC record. The shift is probably connected to the long-term southward shift of the circumpolar oceanic frontal systems south of the African continent indicated by Rau et al. (2002).

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Depth	Age	<i>N</i> .	<i>N</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	Total						
(mcd)	(ky BP)	pachyderma	pachyderma	bulloides	inflata	ruber	ruber	sacculifer	trilobus	siphonifera	calida	crassaformis	crassaformis	menardii	rubescens	tenellus	tropical
		(d)	(s)			(r)	(w)					(d)	(s)				species
0.38	6.2	48.0	0.4	22.0	20.6	0.4	0.9	0	0	0.9	0	0	0	0	0	0.4	2.7
0.88	9.6	34.2	0	34.2	19.5	0.6	2.7	0	0	1.5	0	0	0	0	0	0.2	4.9
1.38	13.1	42.0	0.5	39.6	9.2	0	1.9	0	0	1.9	0	0	0	0	0	0	3.9
1.68	15.1	19.9	47.1	18.0	2.4	0.3	0.6	0	0	0	1.8	0	0	0	0	0	2.8
2.28	19.2	18.8	63.0	6.8	5.2	0	1.6	0	0	0	0.5	0	0	0	0	0	2.1
2.88	25.0	49.8	17.1	17.5	6.9	0	0.4	0	0	0	1.5	0	0	0	0	0.4	2.2
3.48	30.7	23.5	55.3	10.6	3.0	0	0.4	0	0	0.4	0.4	0	0	0	0	0	1.1
3.88	35.1	26.2	28.4	17.5	8.7	0	0.4	0	0	0	0	0	0	0	0	0	0.4
4.29	39.4	38.7	29.6	19.5	2.4	0	0.3	0	0	0	0	0	0	0	0	0	0.3
4.79	45.0	29.5	40.3	14.9	7.3	0	0	0	0	0.7	0	0	0	0	0	0.3	1.0
5.29	50.6	19.2	53.0	15.4	5.6	0	0.9	0	0	0.4	0	0	0	0	0	0	1.3
5.79	56.3	50.2	20.6	18.7	5.3	0	0	0	0	0	0	0	0	0	0	0	0
6.29	61.9	47.4	1.2	38.9	7.3	0	0	0	0	1.2	0	0	0	0	0	0.2	1.4
6.79	67.6	44.1	4.9	36.4	7.3	0	0	0	0	0	0	0.4	0	0	0	0	0.4
7.29	72.3	69.7	6.1	11.8	7.0	0	0.4	0	0	0	0	0	0	0	0	0	0.4
7.79	76.7	33.7	1.9	35.2	21.1	0	0	0	0	2.6	0	0	0	0	0	0	2.6
8.29	81.1	27.3	1.0	33.0	31.6	0.3	0	0	0	1.7	0	0	0	0	0	0	2.0
8.79	85.5	27.4	1.3	37.6	30.4	0	0.8	0	0	0.8	0	0	0	0	0	0.4	2.1
9.29	91.4	26.5	1.1	35.6	24.8	0	1.1	0	0	1.7	0	0	0	0	0	0.3	3.1
9.79	98.1	17.0	32.0	33.3	9.2	0	0.3	0	0	0.3	0	0	0	0	0	0	0.7
10.29	104.7	47.9	0.7	32.9	11.9	0	1.4	0	0	1.4	0	0	0	0	0	0	2.8
10.79	111.4	33.9	2.3	46.8	14.0	0	0	0	0	0.8	0	0	0	0	0	0.5	1.3
11.09	115.4	54.1	1.2	30.2	10.3	0	0	0	0	0	0.4	0	0.4	0	0	0	0.8
11.39	119.4	29.2	2.1	32.3	29.6	0	1.7	0	0	0	1.7	0	0	0	0	0	3.4
11.69	123.4	23.1	37.0	27.5	8.5	0	0.9	0	0.2	0.2	0.7	0	0	0	0	0	2.1
11.99	127.4	52.9	2.5	7.8	17.2	0.4	2.0	0	2.0	0.4	3.7	0	0.4	0.4	0	0	9.4
12.29	131.3	68.3	7.5	14.2	4.1	0.4	0	0	0	0	0.7	0.4	0.4	0	0	0	1.9
12.59	135.1	24.7	59.3	6.2	3.6	0.5	0	0	0	0	0	0	0	0	0	0.5	1.0
13.19	141.1	58.3	6.0	18.3	6.0	0.5	1.8	0	0	0.5	1.4	0	0	0	0	0	4.1
13.59	145.1	49.8	5.7	25.1	6.6	0	0.5	0	0	0	0	0	0	0	0	0	0.5
13.98	149.0	49.0	13.5	21.4	6.3	0	0	0	0	0	0	0	0	0	0	0.5	0.5
14.38	153.0	41.7	1.9	39.8	5.6	0	0	0	0	1.6	0	0	0.3	0	0	0.3	2.2
14.88	158.0	67.7	5.7	16.2	4.8	0	0.9	0	0	0	0	0	0	0	0	0	0.9
15.38	163.1	37.7	13.5	32.3	10.0	0	0.3	0	0	0	0	0	0	0	0	0	0.3
15.88	168.1	34.2	37.8	16.5	2.4	0	0	0	0	0.3	0	0	0.3	0	0	0	0.6
16.38	173.1	39.8	13.2	22.6	12.4	0	0.4	0	0	0.4	0	0	0	0	0	0.4	1.1
16.88	178.8	35.3	11.6	24.7	18.6	0	1.4	0	0	0.9	0	0	0	0	0	0	2.3
17.38	185.2	80.5	4.1	10.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0

Appendix A. Relative abundance of planktonic foraminifera (%), plankton/benthos ratio and fragmentation index for the upper 43 m of ODP 1083. mcd=meters composite depth

Ap	pend	ix A	(continued)
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G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	Ν.	О.	Р.	<i>S</i> .	Undetermined	p-b	Fragmentation
digitata	falconensis	glutinata	quinqueloba	hirsuta	hirsuta	scitula	truncatulinoides	truncatulinoides	hexagonus	dutertrei	universa	obliquiloculata	dehiscens		ratio	index
				(d)	(s)		(d)	(s)								
0	0	2.7	0	0	0	0	0	0.4	0	1.8	0.9	0	0	0.4	1.00	0.23
0	0	3.6	0	0.2	0	0	0.6	0	0	0.2	1.5	0	0	1.1	1.00	0.15
0	0.5	1.9	0	0	0	0.5	0	0	0	0.5	0	0	0	1.4	0.99	0.13
0	0	2.1	5.8	0	0	0.3	0	0	0	0	0	0	0	1.5	0.96	0.20
0	0	1.6	0.5	0	0	0	0	0	0	0	1.0	0	0	1.0	0.91	0.25
0	0	1.8	2.9	0	0	0.7	0	0.4	0	0	0.4	0	0	0.4	0.88	0.32
0	0	2.3	2.3	0	0	0.4	0	0	0	0	0	0	0	1.5	0.92	0.25
0	0	2.6	3.1	0	0	0.4	0	0	0	0.9	11.4	0	0	0.4	0.98	0.38
0	0	1.7	0	1.4	0	0	0	0	0	1.0	4.5	0	0	0.7	0.95	0.34
0	0	2.1	0	0	0	0	0	0	0	1.0	3.1	0	0	0.7	0.94	0.36
0	0	1.7	0	0	0	0.4	0	1.3	0	0.9	1.3	0	0	0	0.83	0.50
0	0	1.9	0.5	0	0	0	0	1.4	0	0.5	1.0	0	0	0	0.81	0.37
0	0	1.0	0.6	0.2	0	0	0	0.6	0	0.4	0.4	0	0	0.6	0.93	0.29
0	0.4	2.8	1.6	0	0	0	0	0	0	0.8	0.8	0	0	0.4	0.83	0.36
0	0	1.3	0.4	0	0	0	0	0.9	0	1.3	0	0	0	0.9	0.93	0.41
0	0	3.3	0	0	0	0.4	0	1.1	0	0	0.4	0	0	0.4	0.97	0.28
0	0	4.0	0	0	0	0	0	0	0	0	0.7	0	0	0.3	0.97	0.34
0	0	0	0.4	0	0	0	0	0.4	0.4	0	0	0	0	0	0.96	0.21
0	0.3	3.7	0.3	0	0.3	0	0.6	0.3	0	0.3	2.0	0	0	1.1	0.93	0.35
0	0	3.4	0.3	0	0	0	0.7	0	0	0	1.7	0	0	1.4	0.98	0.25
0	0.3	2.4	0	0	0	0	0	0	0	0	0.3	0	0	0.7	0.99	0.23
0	0	1.0	0	0	0	0	0	0	0	0.3	0.3	0	0	0.3	0.98	0.24
0	0	2.5	0	0	0	0	0	0	0	0.4	0	0	0	0.4	0.98	0.25
0	0	1.7	0	0.3	0.3	0	0	0	0	0.3	0.3	0	0	0.3	0.99	0.27
0	0	1.2	0	0	0	0	0	0	0	0	0.2	0	0	0.5	0.99	0.19
0	0	4.1	0	0	0	0	0	0.4	0.4	1.6	2.0	0	0	1.6	0.99	0.17
0	0	0.4	0.4	0	0	0	0	0	0	2.6	0.4	0	0	0.4	0.96	0.21
0	0	1.0	0	0	0	0.5	0	0	0	2.6	0	0	0	1.0	0.92	0.16
0	0	1.8	0.9	0	0	0.9	0.5	0	0	0	0.5	0	0	2.8	0.90	0.35
0	0.5	4.3	4.3	0	0	0	0.5	0	0	0	0.5	0	0	2.4	0.85	0.33
0	0	4.2	3.1	0	0	0	0	0	0	0	1.0	0	0	0.5	0.83	0.29
0	0	3.0	1.6	0.5	0	0.3	0.5	0	0	0	1.1	0	0	1.9	0.96	0.16
0	0	1.7	0.9	0	0	0	0	0.4	0	0	0.4	0	0	1.3	0.88	0.34
0.3	0	1.6	1.0	0.3	0	0.3	0	0	0	0	1.0	0	0	1.3	0.94	0.36
0	0	2.9	1.8	0	0	0.9	0	0.6	0	0	0.9	0	0	1.5	0.89	0.39
0	0	4.9	1.9	0	0	0.8	0.4	1.1	0	0	1.1	0	0	0.8	0.92	0.37
0.5	0	3.3	1.9	0	0	0.5	0	0.5	0	0	0.9	0	0	0	0.90	0.41
0	0.4	1.2	0	0	0	0	0	0	0	0.8	0.4	0	0	0.8	0.81	0.36

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Depth	Age	Ν.	Ν.	<i>G</i> .	G.	G.	G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	Total
(mcd)	(ky BP)	pachyderma	pachyderma	bulloides	inflata	ruber	ruber	sacculifer	trilobus	siphonifera	calida	crassaformis	crassaformis	menardii	rubescens	tenellus	tropical
		(d)	(s)			(r)	(w)					(d)	(s)				species
17.88	190.7	72.2	1.3	17.2	5.3	0	0	0	0.4	0.9	0	0	0	0	0	0	1.3
18.38	193.6	35.0	1.2	30.5	25.6	0	0.4	0	0	0	0	0	0	0	0	0	0.4
18.88	196.4	46.4	1.0	26.6	12.8	0	0.7	0	0.3	0.3	1.4	0	0	0	0	1.4	4.2
19.38	199.3	34.3	0.4	35.1	20.3	1.5	0.4	0	0.7	0	0.4	0	0.4	0	0	0.4	3.7
19.63	204.1	35.4	1.0	30.8	15.2	1.0	1.5	0	0.5	0.5	1.0	0	2.0	0	0	1.5	8.1
19.88	208.9	38.9	0.3	34.3	11.3	0	1.6	0.8	0	0.5	3.5	0	2.4	0	0	0.8	9.7
20.13	214.9	33.5	4.8	36.2	10.5	0	0.6	0	0	0.3	3.3	0	1.8	0	0	0.6	6.6
20.38	221.0	50.8	5.8	28.9	5.5	0	0.6	0	0	2.2	0	0	0	0	0	0	2.8
20.63	225.4	42.9	5.9	18.5	24.9	0	0	0	0.5	0.5	0.5	0	0.5	0	0	0	2.0
20.88	229.8	35.2	9.2	24.0	17.1	0.7	0.7	0	0	0.3	1.0	0	1.0	0	0	0	3.6
21.38	235.4	39.3	0.9	46.2	3.8	0.3	0.6	0	0	0.3	1.2	0	0.3	0	0	0.3	3.0
21.88	240.1	76.2	0.3	9.1	2.0	0.3	1.8	0	0.3	0.6	1.2	0	0.8	0	0	0.6	5.7
22.38	244.8	52.9	1.8	32.0	8.9	0	0	0	0	0.4	0	0	0	0	0	0	0.4
22.88	251.3	51.0	0.5	24.4	15.6	0	0	0	0	0	0	0	0.3	0	0	0.3	0.5
23.13	254.8	53.1	4.3	25.4	8.6	0	0.5	0	0	0	0.5	0	0	0	0	0	1.0
23.38	258.4	21.3	28.5	19.7	22.9	0	0.4	0	0	0	1.2	0	0	0	0	0	1.6
23.63	262.1	40.6	2.8	30.7	15.5	0	0.8	0	0.4	0	0	0	0	0	0	0	1.2
23.88	265.7	52.9	4.4	18.6	10.8	0	1.5	0	0	1.5	2.0	0	0	0	0	0	4.9
24.13	269.3	53.4	1.4	19.7	14.9	0	0.5	0	0	0	0	0	0	0	0	0	0.5
24.38	272.9	59.8	5.5	20.5	5.5	0	0	0	0	0	1.2	0	0	0	0	0	1.2
24.63	275.2	37.2	1.4	15.1	39.0	0	0	0	0	0	0	0	0	0	0	0	0
24.88	277.6	45.6	7.0	29.8	12.1	0	0	0	0	0	0	0	0	0	0	0	0
25.13	279.9	45.3	9.4	22.9	16.7	0	0	0	0	0	0	0	0	0	0	0	0
25.38	282.3	31.9	1.4	49.8	9.9	0	0	0	0	0	0.5	0	0	0	0	0	0.5
25.63	284.7	67.1	0.7	14.4	12.0	0	0	0	0	0	0	0	0	0	0	0	0
25.88	287.0	48.3	0.9	27.4	16.7	0	0	0	0	0.9	0	0	0	0	0	0	0.9
26.38	291.8	17.1	1.2	47.5	26.1	0	0	0	0	0	1.2	0	0	0	0	0.4	1.6
26.88	296.5	37.9	1.0	35.4	16.9	0	0	0	0.5	1.0	0.5	0	0	0	0	0	2.1
27.38	301.9	42.9	9.4	31.4	8.9	0	0	0	0	0	0	0	0	0	0	0	0
27.88	307.7	44.1	0.5	37.6	4.2	0	0.5	0	0	0	0	0	0	0	0	0	0.5
28.38	313.1	29.2	16.0	37.3	8.0	0	0	0	0	0	1.9	0	0	0	0	0	1.9
28.88	319.0	4.5	49.2	13.1	21.1	0	0.5	0	0	0.5	2.5	0	0	0	0	0	3.5
29.38	324.8	3.1	40.2	29.3	19.7	0	0.4	0	0	0.4	2.6	0	0	0	0.4	0.4	4.4
29.88	330.0	4.5	26.5	27.5	26.5	0.5	1.5	0.5	0.5	0	3.5	0	0	0	0	0.5	7.0
30.38	334.8	5.6	30.6	21.4	28.6	0	1.5	0	2.0	1.0	2.0	0	0.5	0	0.5	0	7.7
30.88	339.4	12.1	48.8	18.8	11.3	0	0.8	0	0	0.4	0	0	0	0	0	0.4	1.6
31.38	343.5	13.9	56.5	16.2	7.9	0	0.9	0	0	0.5	0	0	0	0	0.5	0	1.9
31.88	347.3	29.3	19.1	23.3	19.4	0	0	0	0.4	0.4	1.8	0	0	0	0	0	2.5

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Appendix A	A (continued)	
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G.	<i>G</i> .	<i>G</i> .	G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	Ν.	О.	Р.	<i>S</i> .	Undetermined	p-b	Fragmentation
digitata	falconensis	glutinata	quinqueloba	hirsuta	hirsuta	scitula	truncatulinoides	truncatulinoides	hexagonus	dutertrei	universa	obliquiloculata	dehiscens		ratio	index
				(d)	(s)		(d)	(s)								
0	0	0.4	0	0	0	0	0	0	0	0	1.8	0	0	0	0.56	0.52
0	0.4	2.0	1.2	0	0	0.4	0	0.8	0	0.8	1.2	0	0	0.4	0.96	0.32
0	0	4.8	1.0	0	0	0.3	0	0.7	0	0.3	0.3	0	0	1.4	0.97	00.0
0	0.4	3.0	0.7	0	0	0.4	0.4	0	0	0	1.1	0	0	0.4	0.97	0.28
0	0.5	4.5	0.5	0	0	1.0	0	0	0	1.0	1.5	0	0	0	0.94	0.23
0	0.8	2.7	0.8	0	0	0.8	0	0	0	0.3	0.3	0	0	0	0.99	0.28
0	2.1	3.3	0.3	0	0	0.3	0.3	0	0	1.2	0.3	0	0	0.6	0.93	0.16
0.3	0.3	2.5	0.6	0	0	0.6	0	0.9	0	0.3	0.3	0	0	0.3	0.95	0.28
0	0.5	1.5	1.0	0	0	0	0	0.5	0	0	2.0	0	0	0.5	0.83	0.38
0	0	3.3	3.9	0	0	0.7	0	0	0	0.3	1.0	0	0	1.6	0.96	0.25
0	0	3.0	0.3	0	0	0.6	0.3	0.3	0	0.3	0.9	0	0	1.2	0.92	0.45
0	0	3.4	0	0	0	0.2	0	0	0	1.7	1.1	0	0	0.5	0.97	0.19
0	0	2.2	0.4	0	0	0.4	0	0	0	0.9	0	0	0	0	0.95	0.34
0.3	0	4.9	0.5	0	0	0.5	0	0	0	1.1	0.5	0	0	0	0.86	0.41
0	0	3.8	0.5	0	0	0	0.5	0.5	0	1.0	0.5	0	0	1.0	0.92	0.36
0	0	1.6	2.4	0	0	0	0	0	0	0	0	0	0	2.0	0.84	0.36
0	0.4	3.6	0	0.4	0	2.0	0	0.8	0	0.4	0.8	0	0	0.8	0.85	0.40
0.5	0	2.5	2.9	0	0	0	0	0	0	0	0.5	0	0	2.0	0.88	0.32
0	0	4.8	2.9	0	0	0	0	0	0	0.5	1.4	0	0	0.5	0.80	0.41
0	0	3.5	0	0	0	0	0	0	0	2.0	0.8	0	0	1.2	0.61	0.42
0	0	4.6	0.5	0	0	0.5	0	0	0	0	0.9	0	0	0.9	0.65	0.52
0	0	2.8	0	0	0	0.9	0	0	0	0	1.4	0	0	0.5	0.77	0.45
0	0.5	2.6	0	0	0	1.0	0	0	0	0	1.0	0	0	0.5	0.74	0.52
0	0	3.8	0	0	0	0	0	0	0	0	1.4	0	0	1.4	0.63	0.56
0	0	2.7	0	0	0	0.3	0	0	0	0.3	1.0	0	0	1.4	0.79	0.32
0	0	4.3	0	0	0	0	0	0	0	0	0.9	0	0	0.9	0.94	0.40
0	0	2.7	0	0	0	0.4	0	1.6	0	0	0.8	0	0	1.2	0.87	0.45
0.5	0	3.1	0.5	0	0	0	0	0	0	0	1.0	0	0	1.5	0.93	0.44
0	0	2.6	1.0	0	0	1.0	0	0	0	0.5	1.0	0	0	1.0	0.86	0.43
0.5	0	5.6	0	0	0	0.5	0	1.4	0	0	3.8	0	0	0.9	0.89	0.32
0	0	3.8	0	0	0	1.4	0	0	0	0.5	0.5	0	0	1.4	0.94	0.31
0	0	1.5	0.5	0	0	0.5	0	0	0	0	4.5	0	0	1.5	0.99	0.27
0	0	0.4	0	0	0	0.9	0	0	0	0	0.4	0	0	1.7	0.95	0.23
0	0	0.5	0	0	0	0.5	0	0	0	0	6.0	0	0	1.0	0.97	0.20
0	0	3.1	0.5	0	0	0	0	0	0	0	1.0	0.5	0	1.0	0.98	0.27
0	0	1.6	1.6	0	0	0.8	0	1.2	0	0	1.2	0	0	1.2	0.87	0.40
0	0	0.5	0.9	0	0	0.9	0	0	0	0.5	0.9	0	0	0	0.71	0.44
0	0	1.4	1.8	0	0	0.4	0	0.4	0	0.4	0.4	0.4	0	1.4	0.92	0.38

(continued on next page)

Appendix A (continued)

Depth (mcd)	Age	N. nachydarma	N.	G.	G.	G.	G.	G.	G. trilobus	G.	G.	G.	G.	G. manardii	G.	G.	Total
(mea)	(Ky DI)	(d)	(s)	ounones	injiaia	(r)	(w)	succunjer	11 1100113	sipnonijeru	cunuu	(d)	(s)	menaran	rubescens	ieneiius	species
32.38	351.1	59.0	11.8	14.2	6.1	0	0.5	0	0	0.9	0.5	0	0	0	0	0	1.9
32.88	355.3	31.3	32.9	15.7	10.4	0	0.4	0	0	0	2.4	0	0	0	0	0	2.8
33.38	360.2	7.7	70.5	8.1	8.5	0	0	0	0	0	0	0	0	0	0	0	0
33.88	363.6	42.4	34.6	12.6	6.3	0	0	0	0	0	0	0	0	0	0	0	0
34.38	367.6	18.1	22.3	11.4	39.9	0	0	0	0	0	0.5	0	0	0	0	0	0.5
34.66	370.4	44.3	24.4	15.4	10.9	0	0	0	0	0	0	0	0	0	0	0	0
35.16	375.5	57.9	20.1	9.7	3.4	0	0.5	0	0.2	0.2	0.5	0	0	0.2	0	0	1.6
35.66	380.5	49.8	5.8	22.3	13.6	0	0	0	0	0	0.3	0	0	0	0	0.3	0.6
36.16	385.5	46.0	5.4	22.0	19.2	0	0	0	0	0.6	0.3	0	0	0	0	0.6	1.6
36.66	390.6	13.4	20.3	33.7	13.4	0	0	0	0	0	0	0	0	0	0	0	0
37.16	395.6	3.5	53.4	26.4	1.5	0	1.5	0	0	0	1.8	0	0.6	0	0	0	3.8
37.66	400.7	19.0	27.1	34.1	3.3	0	1.1	0	0	0	2.6	0	0	0.4	0	0.4	4.4
38.16	405.5	47.7	1.0	29.7	0	0	2.9	0	0	0.3	2.3	0	2.3	0.3	0	0	8.2
38.56	409.0	38.0	2.7	42.7	2.7	0.3	0.9	0	0	2.1	0	0	0	0	0	0	3.3
39.06	413.5	38.5	1.8	42.0	1.1	0	0.7	0	0	0	1.4	0	4.2	0	0	1.8	8.1
39.56	418.0	49.1	2.2	33.0	8.7	0	1.2	0	0	0.5	0.5	0	1.0	0	0	0.2	3.5
40.06	422.5	55.5	0.7	23.4	14.7	0	0	0	0	0	0	0	0	0	0	0.3	0.3
40.56	427.0	73.0	6.1	11.6	2.5	0	0.2	0	0	0.5	0	0	0	0	0	0	0.7
41.06	431.8	18.4	47.9	21.0	5.5	0	0	0	0	0	0	0	0	0	0	0	0
41.56	436.7	22.2	46.2	18.2	6.2	0	0	0	0	0	0.4	0	0	0	0	0	0.4
42.06	442.8	2.3	85.4	7.4	2.9	0	0	0	0	0	0	0	0	0	0	0	0
42.56	448.8	7.9	77.6	10.5	1.3	0	0	0	0	0	0	0	0	0	0	0	0
43.06	454.9	56.8	8.6	19.8	6.5	0	0	0	0	0	0	0	0	0	0	0.6	0.6

G.	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	<i>G</i> .	Ν.	О.	Р.	<i>S</i> .	Undetermined	p-b	Fragmentation
digitata	falconensis	glutinata	quinqueloba	hirsuta	hirsuta	scitula	truncatulinoides	truncatulinoides	hexagonus	dutertrei	universa	obliquiloculata	dehiscens		ratio	index
				(d)	(s)		(d)	(s)								
0	0	3.8	0	0	0	0.5	0	1.4	0	0	0.5	0	0	0.9	0.90	0.31
0	0	2.0	0	0	0	0	0	0.4	0	2.0	1.6	0	0	0.8	0.83	0.21
0	0	3.4	1.3	0	0	0	0	0.4	0	0	0	0	0	0	0.91	0.38
0	0	0.5	0.5	0	0	0.5	0	0.5	0	0.5	0.5	0	0	1.0	0.75	0.32
0	0	4.7	0.5	0	0	0	0	0	0	0	1.6	0	0	1.0	0.69	0.42
0	0	3.0	0	0	0	0	0	0	0	0.5	0.5	0	0.5	0.5	0.70	0.48
0	0	4.8	0.5	0	0	0.5	0	0.5	0	0	0.2	0	0	0.9	0.96	0.20
0	0.3	1.6	0	0	0	0.3	0	0.3	0	4.2	0.3	0	0	0.6	0.96	0.26
0	0	2.2	0	0	0	0	0	0	0	2.2	1.0	0	0	0.3	0.87	0.31
0	0	11.8	0	0	0	4.1	0.4	0	0	0.8	0.8	0	0	1.2	0.73	0.52
0.3	0	3.5	0.3	0	0	0	0	0.3	0	5.0	1.2	0	0	0.9	0.84	0.32
0	0	4.4	0	0	0	0	0	0.7	0	5.9	0.4	0	0	0.7	0.93	0.34
0	0.3	6.2	0.3	0	0	0.7	0	0.3	0	1.6	2.0	0	0	2.0	0.92	n.d.
0	0	3.6	0	0	0	0.3	3.0	0	0	0	1.2	0	0	2.7	0.92	0.30
0	0	1.1	0	0	0	0.7	0.4	0.4	0	3.2	2.1	0	0	0.7	0.94	0.27
0.2	0.5	0.5	0.2	0	0	0.5	0.7	0.2	0	0	0.2	0	0	0.2	0.93	0.20
0	0.3	2.3	0.3	0	0	0.7	0.7	0.3	0	0.7	0	0	0	0	0.96	0.13
0	0	3.4	0.5	0	0	0.9	0.5	0	0	0.5	0.2	0	0	0.2	0.86	0.17
0.3	0	3.2	0.6	0	0	0.6	0	1.0	0	1.0	0.3	0	0	0	0.95	0.18
0	0	5.1	0	0	0	0	0	0.7	0	1.1	0	0	0	0	0.82	0.24
0	0	0.6	0	0	0	0	0	0.3	0	0.3	0	0	0	0.9	0.99	n.d.
0	0	1.8	0.4	0	0	0	0	0.4	0	0	0	0	0	0	0.90	n.d.
0.6	0	3.6	0.3	0	0	1.5	0	0	0	1.5	0	0	0	0.3	0.93	n.d.

Appendix A (continued)

Appendix B. δ^{18} O data of *G. inflata* in core MD 962094. The data for the upper 15 m are from Stuut et al. (2002)

Denth	δ ¹⁸ Ω	Depth	δ ¹⁸ Ω												
(m)	(%)	(m)	(%)	(m)	(‰)	(m)	(%)								
0.03	0.30	2.58	1.75	5.18	1.25	7.78	0.67	10.33	0.46	12.93	1.63	15.48	0.44	18.18	1.08
0.08	0.25	2.63	1.44	5.23	1.47	7.83	1.09	10.38	0.48	12.98	1.49	15.53	0.88	18.23	1.65
0.13	0.47	2.68	1.63	5.28	1.34	7.88	0.89	10.48	0.65	13.03	1.25	15.58	0.94	18.28	1.29
0.18	0.80	2.73	1.53	5.33	1.01	7.93	1.08	10.53	0.62	13.08	1.58	15.63	1.22	18.33	1.43
0.23	0.72	2.78	1.55	5.38	1.14	7.98	1.54	10.58	0.78	13.13	1.43	15.68	1.51	18.38	1.30
0.28	0.43	2.83	1.63	5.43	1.27	8.03	1.64	10.63	0.87	13.18	0.82	15.73	1.19	18.43	1.45
0.33	0.33	2.88	1.11	5.48	1.30	8.08	1.87	10.68	0.75	13.23	0.89	15.78	1.73	18.48	1.51
0.38	0.47	2.93	1.65	5.53	0.69	8.13	1.69	10.73	0.72	13.28	1.17	15.83	1.45	18.53	1.08
0.43	0.67	2.98	1.12	5.58	0.89	8.18	2.05	10.78	0.60	13.33	1.22	15.88	1.29	18.58	1.17
0.48	0.23	3.03	1.04	5.63	0.92	8.23	2.12	10.83	0.63	13.38	1.01	15.93	2.51	18.63	1.05
0.53	0.56	3.08	1.67	5.68	0.83	8.28	2.02	10.88	0.89	13.43	1.10	15.98	2.14	18.68	1.01
0.58	0.41	3.13	1.31	5.73	0.72	8.33	1.89	10.93	0.76	13.48	1.02	16.03	2.12	18.73	1.24
0.63	0.57	3.18	1.45	5.78	0.67	8.38	1.78	10.98	1.18	13.53	1.30	16.13	1.45	18.78	1.12
0.68	0.54	3.23	1.46	5.83	0.81	8.43	1.89	11.03	0.81	13.58	0.88	16.18	1.45	18.83	0.89
0.73	0.72	3.28	1.78	5.93	1.18	8.48	1.92	11.08	1.35	13.63	1.30	16.23	1.67	18.88	0.84
0.78	1.40	3.33	1.31	5.98	0.96	8.53	2.15	11.13	1.09	13.68	1.31	16.28	1.48	18.93	0.53
0.83	1.51	3.38	1.53	6.03	1.35	8.58	1.82	11.18	1.66	13.73	1.43	16.33	1.62	18.98	0.55
0.88	1.14	3.43	1.54	6.08	1.54	8.63	1.91	11.23	1.92	13.78	1.37	16.38	1.85	19.03	0.67
0.93	1.14	3.48	1.67	6.13	1.19	8.68	2.01	11.28	1.68	13.83	1.71	16.43	1.75	19.08	0.58
0.98	1.48	3.53	1.45	6.18	1.21	8.73	1.71	11.33	1.22	13.88	1.71	16.48	1.90	19.13	0.55
1.03	1.58	3.58	1.37	6.23	1.26	8.78	1.89	11.38	1.38	13.93	1.55	16.53	2.03	19.18	0.82
1.08	1.54	3.63	1.01	6.28	1.29	8.83	1.97	11.43	1.62	13.98	1.67	16.58	1.80	19.23	0.82
1.13	1.96	3.68	1.53	6.33	1.30	8.88	1.42	11.48	1.77	14.03	1.60	16.63	2.09	19.28	0.42
1.18	1.79	3.73	1.69	6.38	1.05	8.93	2.01	11.53	2.00	14.08	1.51	16.68	1.98	19.33	0.81
1.23	1.48	3.78	1.50	6.43	0.97	8.98	1.45	11.58	1.44	14.13	1.68	16.73	1.97	19.38	1.00
1.28	2.14	3.83	1.59	6.48	1.11	9.03	1.74	11.63	1.40	14.18	1.54	16.78	1.88	19.43	0.91
1.33	1.83	3.88	1.44	6.53	1.16	9.08	1.70	11.68	1.24	14.23	1.48	16.83	2.03	19.48	1.00
1.38	1.66	3.93	1.57	6.58	1.36	9.13	1.52	11.73	1.27	14.28	1.16	16.88	2.08	19.53	0.87
1.43	1.80	3.98	1.45	6.63	1.51	9.18	1.74	11.78	1.42	14.33	1.02	16.93	1.87	19.58	0.82
1.48	1.92	4.03	1.36	6.68	1.09	9.23	1.74	11.83	1.78	14.38	1.18	16.98	1.75	19.63	1.14
1.53	1.85	4.08	1.55	6.73	1.01	9.28	1.57	11.88	1.40	14.43	0.85	17.03	1.96	19.68	0.85
1.58	2.00	4.13	1.55	6.78	1.24	9.33	1.25	11.93	1.72	14.48	0.58	17.08	1.63	19.73	1.48
1.63	1.41	4.18	1.49	6.83	0.74	9.38	1.42	11.98	1.93	14.53	0.74	17.18	1.50	19.78	1.00
1.68	1.92	4.23	1.55	6.88	0.92	9.43	1.40	12.03	1.88	14.58	0.88	17.23	1.53	19.83	1.04
1.73	1.88	4.28	1.58	6.93	0.84	9.48	1.61	12.08	2.42	14.63	1.07	17.28	1.45	19.88	0.99
1.78	1.70	4.33	1.33	6.98	1.12	9.53	1.47	12.13	2.46	14.68	0.98	17.33	1.27	19.93	1.10
1.83	1.75	4.38	1.35	7.03	0.91	9.58	1.49	12.18	2.01	14.73	0.94	17.38	1.54	19.98	1.53
1.88	1.34	4.43	1.41	7.08	1.45	9.63	1.44	12.23	2.16	14.78	0.86	17.43	1.35	20.03	1.57
1.93	1.50	4.48	1.33	7.13	1.44	9.68	1.52	12.28	1.53	14.83	0.71	17.48	1.47	20.08	1.44
1.98	1.95	4.53	1.00	7.18	1.29	9.73	1.28	12.33	1.85	14.88	0.97	17.53	1.68	20.13	1.23
2.03	1.83	4.58	1.49	7.23	1.13	9.78	1.43	12.38	1.82	14.93	0.96	17.58	1.59	20.18	1.18
2.08	1.70	4.63	1.73	7.28	0.91	9.83	1.50	12.43	1.53	14.98	0.61	17.63	1.76	20.23	1.68
2.13	1.54	4.68	1.58	7.33	0.60	9.88	1.67	12.48	2.05	15.03	0.83	17.68	1.48	20.28	1.56
2.18	1.59	4.73	1.58	7.38	0.06	9.93	1.79	12.53	2.08	15.08	0.81	17.73	1.84	20.33	1.77
2.23	1.49	4.78	1.57	7.43	0.37	9.98	1.55	12.58	2.37	15.13	0.57	17.78	1.48	20.38	1.92
2.28	1.47	4.83	1.74	7.48	-0.01	10.03	1.64	12.63	2.05	15.18	0.64	17.83	1.69	20.43	2.15
2.33	1.53	4.88	1.65	7.53	0.05	10.08	1.23	12.68	1.98	15.23	0.12	17.88	1.17	20.48	2.53
2.38	1.63	4.93	1.96	7.58	0.01	10.13	0.81	12.73	1.98	15.28	0.34	17.93	1.19	20.53	2.43
2.43	1.75	4.98	1.95	7.63	-0.01	10.18	1.45	12.78	2.40	15.33	0.46	17.98	1.05		
2.48	1.73	5.03	1.67	7.68	0.35	10.23	1.13	12.83	2.08	15.38	0.38	18.03	1.12		
2.53	1.65	5.08	1.77	7.73	0.10	10.28	0.99	12.88	2.10	15.43	0.74	18.13	1.21		

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