

## Planktic Foraminiferal Content in a Mature Agulhas Eddy from the SE Atlantic: Any Influence on Foraminiferal Export Fluxes?

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**Key words:** Planktic foraminifera, Southeast Atlantic, Agulhas eddies, Interocean exchange, *Globorotalia menardii*.

### Abstract

The Agulhas eddies, large-scale rings of warm salty water, occasionally intrude into the Benguela Current system from the Indian Ocean and progress northwards across the Cape Basin and the Walvis Ridge. This inter-ocean exchange of heat and salt along the Cape of Good Hope is considered to play a crucial role for the global thermohaline circulation. Yet, the modern faunal composition of mature eddies from the northern Cape Basin and Walvis Ridge was uninvestigated in spite of the global importance of the Agulhas inflow, preventing firm micropalaeontological study of the palaeoceanographic variability of the ocean exchange in this area.

This paper describes the composition of the modern planktic foraminiferal assemblages collected from a mature Agulhas eddy when it entered into the northern Benguela Current system. The effect of the eddy's gradual decay on the foraminiferal communities in the upper water column is specifically examined, using plankton tow and CTD-rosette profiles, obtained within and outside the ring. In addition, exported foraminiferal fluxes beneath the eddy were investigated in order to determine their impact on the accumulation assemblages as recorded in sediment traps moored near the sea floor and in the core-top sediment from a box corer.

The examined mature eddy "W" was clearly evident on the satellite altimetry images by its elevated surface. It was distinguished from the surrounding ocean by a slightly higher salinity, deeper surface mixed layer and higher planktic foraminiferal standing stocks. Similar to planktic foraminiferal fauna in freshly formed eddies from the Agulhas retroflection, species such as *Globigerinoides trilobus* s.l., *Globigerinoides ruber*, *Orbulina universa*, *Globigerinella siphonifera* and *Globorotalia scitula* dominated in the ring "W" assemblages. However, *Globorotalia menardii*, a species previously believed to be characteristic for the Agulhas leakage into the S. Atlantic, was virtually absent in the eddy "W" fauna. Also *Globorotaloides hexagona*, a species endemic in Indian Ocean waters, was not found in the water column, in the export flux or underlying sediment. The February to July foraminiferal flux patterns recorded by the sediment traps mirror the February standing stocks from the water column. Here in contrast, the core-top results show dominance of intermediate/cold water species that originate from the seasonal spring bloom. This signal prevails in sediment to the extent that any potential Agulhas eddy signature in the sediment was overprinted.

### 1. INTRODUCTION

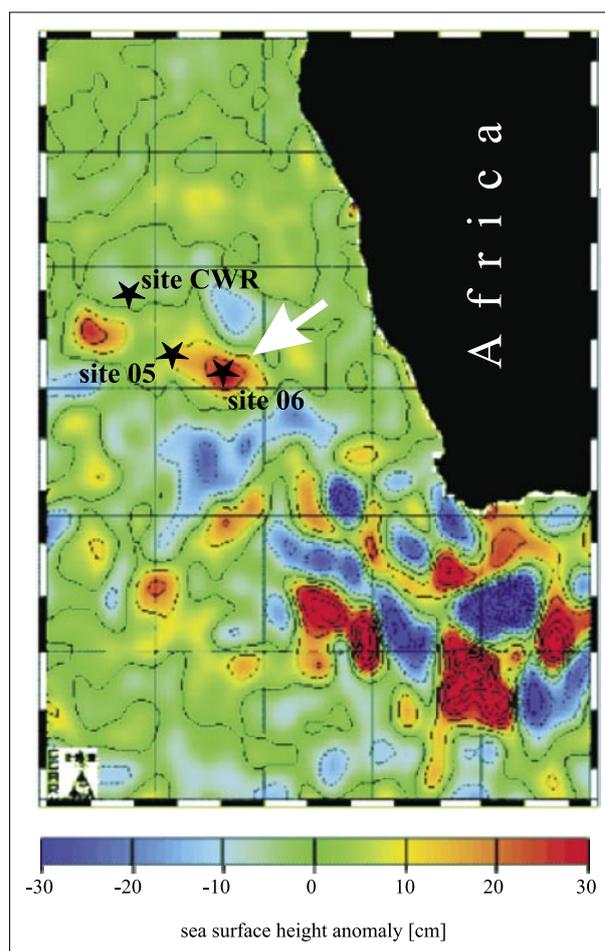
The oceanography of the southern part of the SE Atlantic is characterized by two prominent features: (1) the Benguela Current flowing northwards along the African continent, and (2) the inflow of the Indian Ocean water into the Atlantic around the Cape of Good Hope. The Benguela upwelling system (18–34°S) is nowadays one of the four major eastern boundary current regions of the World Oceans, distinguished by cold and nutrient rich water (PETERSON & STRAMMA, 1991; SHANNON & NELSON, 1996). In the Southern Cape Basin (the area where the Benguela Current originates), the warm, salty Agulhas Current intrudes from the Indian Ocean (PETERSON & STRAMMA, 1991). A greater part of the Agulhas Current water retrogrades back into the Indian Ocean, whereas a smaller part leaks into the SE Atlantic (LUTJEHARMS & VAN BALLEGOOYEN, 1988). This occurs in the form of large scale eddies that on average 5 to 7 times per year enter the Atlantic in the zone of Agulhas retroflection (GOÑI et al., 1997; SCHOUTEN et al., 2000). The Agulhas eddies are anti-clockwise rotating bodies that average 250 km in diameter and extend to a depth of 1000 m (LUTJEHARMS, 1996; VAN AKEN et al., 2003). Due to their rotational motion they are distinguished by an elevated surface relative to the surrounding ocean, traceable on satellite sea surface height (SSH) images (BYRNE et al., 1995). Once formed, the Agulhas eddies migrate northwards within the Benguela Current, gradually mixing with the surrounding water, losing heat and salinity. The decay of such a ring can take up to a few years, by the time they cross the central Walvis Ridge (SCHOUTEN et al., 2000). This addition of warm and salty water to the South Atlantic is an important element of the global thermohaline circulation (GORDON, 1985, 1996; DE RUIJTER et al., 1999) and one of the major controlling factors of the South Atlantic heat and salt budget (LUTJEHARMS, 1996; WEIJER et al., 1999). The effectiveness of the retroflection in generating warm eddies depends on the position of the subtropical front (DE RUIJTER, 1982). It may be assumed that this front moves northwards during glacial periods (BERGER & WEFER, 1996a), cutting off the supply of heat to the South Atlantic with direct consequences for the North Atlantic Deep Water formation (WEIJER et al., 2001). Due to such a decisive role of this system in the glo-

bal ocean circulation and assumed high variability on the glacial–interglacial scale, the influence of the Agulhas eddies on the sedimentation patterns in the South Cape Basin was the subject of several palaeostudies (BERGER & WEFER, 1996b; FLORES et al., 1999; CHEN et al., 2002; RAU et al., 2002). Recently PEETERS et al. (2004) studied the modern system and provided firm evidence for the characteristic foraminiferal signature of a freshly formed eddy that allowed documentation of the inter-ocean exchange dynamics for the last 500 kyrs from the sediments of the southern Cape Basin.

Although sea surface temperature anomalies of Agulhas rings tend to disappear quickly (OLSON et al., 1992), satellite altimetry monitoring (e.g. TOPEX/Poseidon) documented that approximately two thirds of the eddies formed at the Agulhas retroflection cross over the northern Cape Basin and the central Walvis Ridge (e.g. GARZOLI & GORDON, 1996; GOŃI et al., 1997; SCHOUTEN et al., 2000). Such older eddies within northern Cape Basin surface waters have never been a subject of in-situ ecological studies. Therefore their faunal characteristics and the importance for sedimentation patterns are largely unknown. The purpose of this study is to determine for the first time the faunal and physical signature of a long-lived eddy and better understand the coupling between such oceanographic source signal in the water column and the exported flux directly below.

## 2. MATERIAL AND METHODS

The area of the Cape Basin off southwestern Africa has been monitored for spawning and decay of Agulhas rings since 1992 using TOPEX/Poseidon satellite altimetry (GRÜNDLINGH, 1995; GOŃI et al., 1997; SCHOUTEN et al., 2000). Aided by SSH images we sampled the centre of the long-lived eddy “W” in the northern Cape Basin during the first Mixing of Agulhas Rings Experiment (MARE) expedition in February 2000 (Fig. 1). Depth-stratified plankton tows were collected in the centre of the eddy (154 P–06), at its edge (154 P–05), and outside in the surrounding ocean (CWR) (Table 1; Figs. 1 & 2). Each station covered nine depth intervals from the upper 800 m of the water column. The plankton was collected using a Hydrobios Multi-net system modified for oblique towing and equipped with 100 µm plankton nets (LONČARIĆ, 2005). At the same sites, the entire water column was profiled using

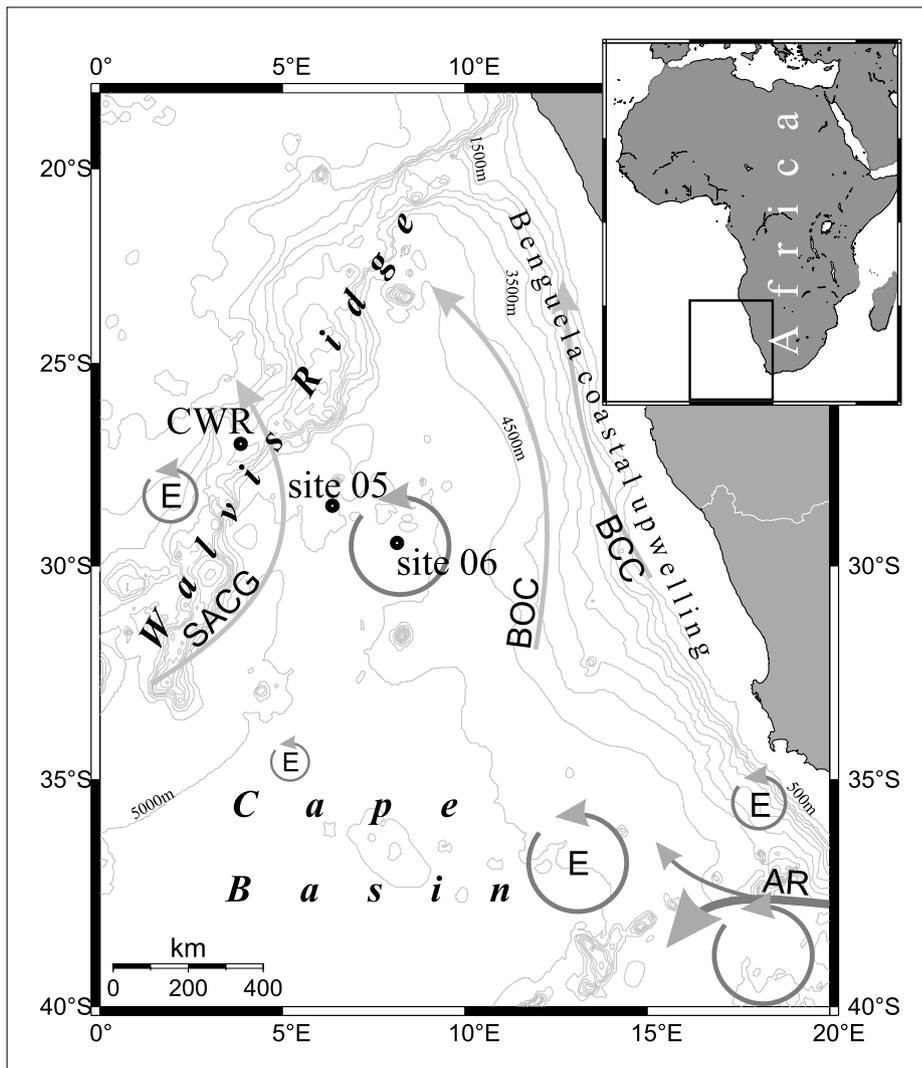


**Fig. 1** Sea surface altimetry image (TOPEX/Poseidon; positive anomaly in red, negative in blue) from February 18, 2000 and location of three sampling stations from this study. The centre of eddy “W” (marked by an arrow) was at the time of sampling (February 22, 2000) exactly at station 06.

a Neill–Brown CTD-rosette sampler (VETH, 2000). In addition, two Technicap PPS5 sediment traps were moored 250 m above the sea floor, one below the centre of the eddy at site 06 (water depth 5036 m), and another outside the eddy at the CWR site (water depth 2700 m). The traps had a sampling area of 1 m<sup>2</sup> and collected an integrated 6-months sample of pelagic particles settling to the sea floor. For processing of foraminiferal samples from traps and plankton tows, and the taxonomic determination, the procedure described in LONČARIĆ et al. (2005, 2006a, b) has been followed. The foraminiferal standing stocks are calculated following the method from LONČARIĆ (2005) and LONČARIĆ et al.

**Table 1** Position of the stations and sampling techniques applied in this study.

station	coordinates [°]		sampling technique			
	lat.	long.	pl. tows	CTD	sed. trap	box core
CWR	27.0 S	3.9 E	+	+	+	+
05	28.8 S	6.3 E	+	+		
06	29.2 S	8.2 E	+	+	+	



**Fig. 2** Location of the study sites with the regional bathymetry and hydrography. Legend: BOC – Benguela Oceanic Current; BCC – Benguela Coastal Current; SACG – South Atlantic Central Gyre; AR – Agulhas Retroflection; E – Agulhas eddies. Map created by OMC at [www.aquarius.geomar.de](http://www.aquarius.geomar.de).

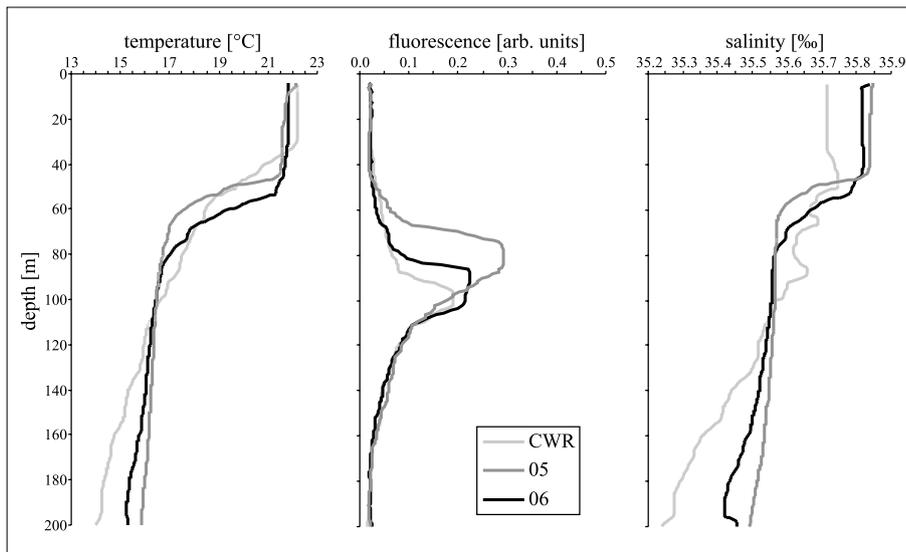
(2006a). In addition to the plankton tow, CTD-rosette and sediment trap sampling, we also recovered the bottom sediments using a box corer at the CWR site during the MARE III cruise (February 2001; station 174 P-03/6). The sampling and processing of the box core and its stratigraphy are described in LONČARIĆ (2005). The results of the foraminiferal analysis from the uppermost 0.5 cm of the sediment are presented here.

### 3. THE EDDY “W”

In October 1999 the Agulhas eddy named “W” was one of the most prominent features on the sea surface height images of the Cape Basin (available at: [http://ibis.grdl.noaa.gov/SAT/hist/tp\\_products/topex.html](http://ibis.grdl.noaa.gov/SAT/hist/tp_products/topex.html)). It was situated in the central Cape Basin, at the approximate latitude of Cape Town. During the austral spring and early summer it migrated northwards by approximately 5° latitude and lost its intensity. The SSH image of February 18, 2000 (Fig. 1) was used for pinpointing station 06, in the centre of the ring. The eddy “W” remained at

site 06 for approximately two weeks, and then migrated westwards over the Walvis Ridge. In May 2000 it disappeared from the SSH images. During April/May 2000 another smaller Agulhas eddy was in the vicinity, south of site 06. However, this eddy disintegrated before fully reaching the site. Although situated centrally within the “Agulhas Eddy Corridor” (GARZOLI & GORDON, 1996; SCHOUTEN et al., 2000), the CWR site was not crossed by the fleeting eddies during the entire sediment trap sampling period (February–July 2000).

The crucial assumption being made here is that SSH anomalies in the southeastern Atlantic Ocean are indeed Agulhas rings (SCHOUTEN et al., 2000). It has been shown without question that the gross SSH variability in the Cape Basin only arises from passing Agulhas rings (GARZOLI & GORDON, 1996; GARZOLI et al., 1996). In addition, e.g. VAN AKEN et al. (2003) have demonstrated by extensive seagoing hydrographic investigations, the relationship between TOPEX/Poseidon SSH anomalies and in-situ measured properties of the rings. Most of the time, the SSH position of the ring centre is within 50 km, or half a degree, of the



**Fig. 3** Temperature, fluorescence and salinity profiles for the upper 200 m of the water column measured by the CTD-rosette sampler at three study sites from Figs. 1 & 2.

actual centre (SCHOUTEN et al., 2000). SeaWiFS satellite images of the surface chlorophyll-a concentration (LONČARIĆ, 2005; LONČARIĆ et al., 2006b) show that all stations sampled in this study were oligotrophic, outside the direct influence of the Benguella upwelling at the time of the plankton towing. Yet, tongues of nutrient-rich water spreading from the Benguela upwelling zone did approach station 06 from July to September 2000 (LONČARIĆ et al., 2006b).

## 4. RESULTS

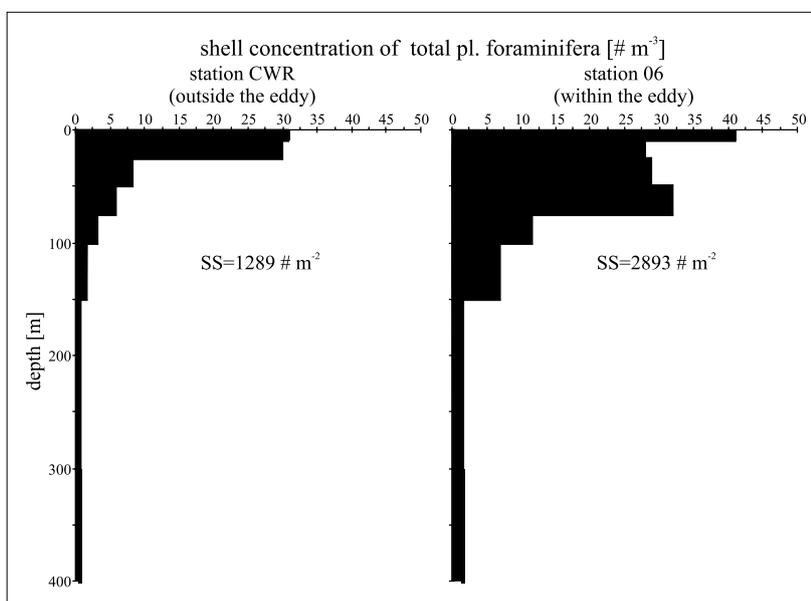
### 4.1. Physical properties

During plankton tow sampling and CTD-rosette profiling (February 22, 2000; station 06) the eddy “W” was situated in the northern Cape Basin. It was eminently distinguishable on the SSH image by its elevated sur-

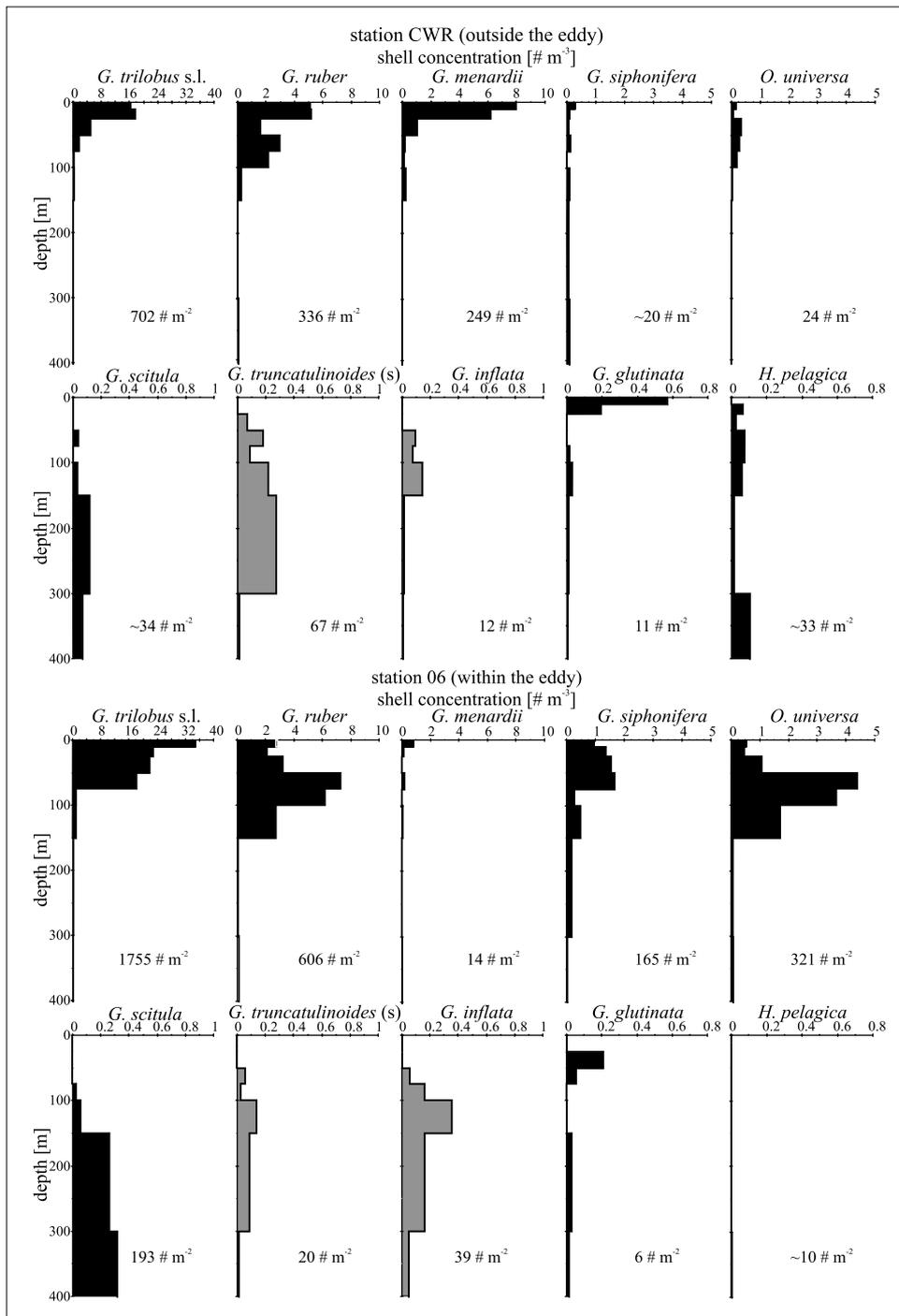
face (Fig. 1). Although clearly recognisable on the TOPEX/Poseidon satellite image, the CTD profiles taken in the centre of the eddy (station 06) and outside in the open ocean (CWR station) were similar (Fig. 3). The similar temperature of the surface mixed layer ( $\sim 22^{\circ}\text{C}$ ) and prominent deep fluorescence maximum at  $\sim 100$  m characterised both profiles. In both cases the fluorescence maximum was below the surface mixed layer. The centre of the eddy differed from the surrounding water by  $\sim 0.1\text{‰}$  higher salinity, deeper surface mixed layer (60 m in the ring vs. 35 m outside) and by a somewhat broader and stronger fluorescence maximum (Fig. 3).

### 4.2. Foraminiferal assemblages

The foraminiferal concentration profiles in the upper 800 m of the water column collected by plankton tows



**Fig. 4** Shell concentration of total planktic foraminifera sampled by plankton tows within eddy “W” (right panel) and in the surrounding oligotrophic gyre (left panel). Numbers refer to the total foraminiferal shell standing stocks in the productive zone calculated following the method described in LONČARIĆ (2005) and LONČARIĆ et al. (2006a).



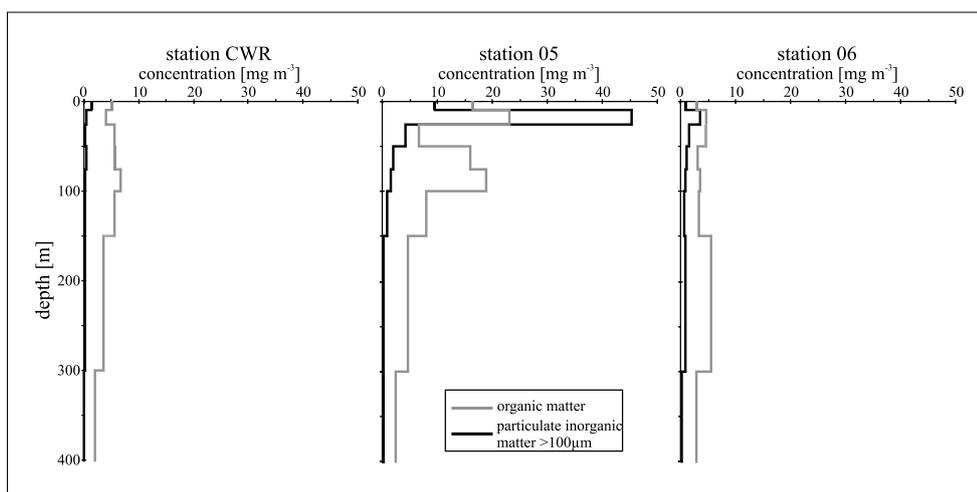
**Fig. 5** Shell concentration profiles of 10 major foraminiferal species from the plankton tows sampled within and outside eddy "W" given for the upper 400 m of the water column. Species given in black belong to the typical Agulhas leakage fauna (PEETERS et al., 2004). Numbers refer to the standing stocks in the productive zone of the particular species calculated following the method from LONČARIĆ (2005) and LONČARIĆ et al. (2006a).

(Figs. 4–6) were compared with the export fluxes from the sediment traps and the accumulation flux from the core top sediment (Fig. 7). The selected stations represent the foraminiferal assemblages within the eddy (station 06) and the surrounding oligotrophic gyre (CWR station), respectively. In addition, quantitative analysis of the plankton tow samples was performed at station 05, situated at the moment of sampling at the eddy's edge (Fig. 1).

#### 4.2.1. Water column fauna

In February 2000 the foraminiferal standing stock within the eddy "W" was more than two times higher than in

the surrounding oligotrophic ocean (Fig. 4). The highest total foraminiferal concentrations were restricted to the surface mixed layer (SML) at both stations. Yet, within the eddy, the foraminiferal concentrations showed two maxima, one within the uppermost tow interval and another at the base of the SML. In contrast, by February 2000 the surrounding ocean was characterised by a shallow SML (Fig. 3) and high foraminiferal concentrations were restricted to the uppermost 25 m (Fig. 4). The standing stocks at both stations were dominated by tropical, shallow-dwelling species such as *Globigerinoides trilobus* s.l. and *Globigerinoides ruber* (Figs. 5 & 7). *Orbulina universa*, *Globigerinella siphonifera* and



**Fig. 6** Concentration of organic and particulate inorganic matter larger than 100 µm from the plankton tows sampled at three study sites from Figs. 1 & 2. The organic matter is calculated as dry bulk weight minus weight of the ashed residue.

*Globorotalia scitula* were frequent only within the eddy and showed maximum concentrations in the subsurface. Remarkably, the tropical *Globorotalia menardii* was virtually absent within the eddy, while this species was the third most abundant in the surrounding ocean where it showed the second highest concentration in the uppermost tow interval. For the other species, deep-dwelling *Globorotalia truncatulinoides* (sin) and *Globorotalia inflata* showed similar concentrations and vertical distributions at both sites, whereas *Globigerinita glutinata* and *Hastigerina pelagica* were rare. Quantitative analysis performed on the tow material collected at station 05 (Fig. 1), showed significantly increased plankton standing stocks compared to not only the surrounding ocean, but also to the centre of the eddy (Fig. 6). The concentration of organic matter was approximately 5 times higher, and the concentration of the particulate inorganic matter exceeded 15 to 45 times the values from the eddy and the surrounding area, respectively (Fig. 6).

#### 4.2.2. Export fluxes

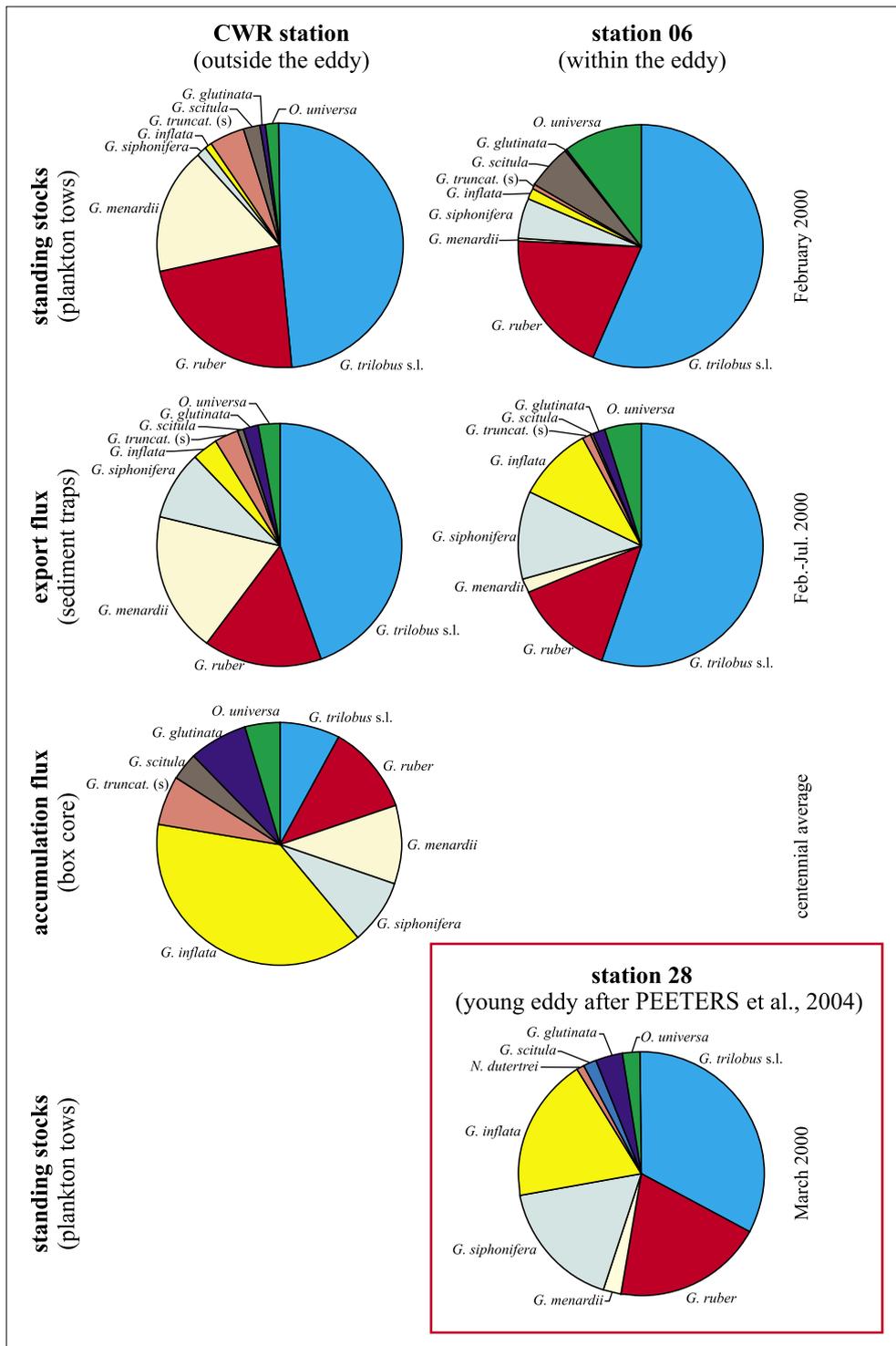
The relative abundances of major species from the plankton tow and sediment trap assemblages were strikingly similar in spite of the long sampling interval of the traps, covering an integrated 6-month period from February to July 2000 (Fig. 6). Absence of coloured, opaque or fragmented foraminiferal tests at both trap sites and pronounced lunar cyclicity observed for fragile *Hastigerina pelagica* at the CWR site (LONČARIĆ et al., 2005) testified to the accuracy of flux sampling and complete preservation of foraminiferal shells due to the pH buffered collecting cups (LONČARIĆ et al., 2006b) and relatively fast settling of specimens >150 µm considered in this study (TAKAHASHI & BÉ, 1984). As in the water column standing stocks, the warm-water species *G. trilobus* s.l. and *G. ruber* also dominated the exported flux intercepted by the traps at both sites. The assemblages from the CWR site situated outside the eddy “W” were generally in agreement with the previously published results from the upper water column and surface sediment characteristic for the S.

Atlantic Subtropical Gyre (e.g. BÉ & TOLDERLUND, 1971; NIEBLER & GERSONDE, 1998; KEMLE-VON MÜCKE & HEMLEBEN, 1999). Only minor differences between the plankton tow and sediment trap assemblages were manifested by the increased relative abundance in the export flux of *G. siphonifera* at the CWR site, and by the increased relative abundance of *G. inflata*, together with *G. siphonifera* at site 06, respectively. In contrast, *O. universa* and *G. scitula* showed higher relative abundance in the water column within the eddy “W” than in the export flux beneath.

#### 4.2.3. Core-top sediment assemblages

Since the water depth at site 06 (5036 m) is deeper than that of the calcite lysocline (i.e. the depth at which calcite becomes undersaturated or the level of the onset of carbonate dissolution) and the Carbonate Compensation Depth (i.e. the depth below which the rate of calcite dissolution exceeds the rate of deposition) we sampled the sediment surface only at the shallow CWR site (2700 m). The <sup>14</sup>C and <sup>210</sup>Pb analyses showed that the topmost sediment at the CWR site is modern in age and the mixing rates are very low (LONČARIĆ, 2005).

The centennial average accumulation flux preserved in the Walvis Ridge sediment differed in foraminiferal assemblage from those in the export flux and standing stocks sampled at the same site. In contrast to the composition of the fauna in the water column standing stocks and in the sediment trap fluxes, which were dominated by *G. trilobus* s.l. and *G. ruber*, approximately one third of the normalised foraminiferal assemblage in the uppermost 0.5 cm of the sediment was composed of *G. inflata* (Fig. 7). Also some other secondary species within the water column and export flux assemblages such as sinistral *G. truncatulinoides*, *G. glutinata* and *G. scitula* showed a significant increase in the relative abundance within the surface sediment. In addition to the conventional enumeration of foraminiferal species, which considers on average 300 shells per sample, more than 5000 foraminiferal shells from the sieve size fraction >150 µm in the CWR surface sediment were



**Fig. 7** Relative abundance of 9 major foraminiferal species normalised to 100%, sampled within and outside eddy "W", in the water column (February plankton tows), export flux (integrated February to July sediment traps) and accumulation flux (core top sediment). The assemblages characteristic for a young Agulhas eddy from the southern Cape Basin are given for comparison (bottom right – after PEETERS et al., 2004).

randomly analysed in search for *Globorotaloides hexagona*, a species endemic to the Indian Ocean. Yet, this species was neither recognised in the sediment sample, nor in the traps or plankton tows.

## 5. DISCUSSION

The physical properties of a young, freshly formed eddy from the Agulhas retroflection zone in the south-

ern Cape Basin have been recently studied *in situ* by VAN AKEN et al. (2003). This eddy was distinguished from the surrounding water by higher temperature and salinity values, and a deeper surface mixed layer. The foraminiferal assemblages of a young Agulhas eddy were characterized by high standing stocks and the dominance of tropical-subtropical species (PEETERS et al., 2004). The most dominant among 10 characteristic Agulhas leakage species were *G. trilobus* s.l., *G. ruber* and *G. siphonifera* (PEETERS et al., 2004).

Due to a strong air–sea interaction (OLSON et al., 1992), the positive sea surface temperature anomaly disappeared by the time eddy “W” reached the northern Cape Basin. Yet, the ring was still clearly visible on SSH images (Fig. 1). Although the eddy lost some of its original physical and faunal signatures during its migration, that took more than a year from the Indian to the Atlantic Ocean, several characteristics were still recognizable. It was distinguished from the surrounding ocean by a deeper surface mixed layer, higher salinity and higher foraminiferal standing stocks (Figs. 3 & 4). The foraminiferal assemblages were dominated by the same species (i.e. *G. trilobus* s.l., *G. ruber* and *G. siphonifera*), characteristic of a freshly formed ring (Fig. 7). However, the contrast between the physical and faunal characteristics of eddy “W” and the surrounding oligotrophic water of the subtropical gyre was weak (Fig. 5). It is mostly difficult therefore to clearly identify a mature eddy based only on foraminiferal assemblages, without additional support from the satellite-derived sea surface altimetry, though this is not due to faunal changes.

In a number of palaeostudies on Cape Basin sediments, *G. menardii* was attributed to have originated in the Indian Ocean and its presence in the sediment record was interpreted as indicative for the “open Cape valve” (BERGER & WEFER, 1996b; RAU et al., 2002), i.e. an interconnection between the Indian and Atlantic Ocean. Our results suggest that this species does not belong to the typical mature ring fauna. Instead in the ring assemblages, an order of magnitude higher standing stock of *G. menardii* has been found in the adjacent subtropical gyre (Fig. 5). In addition, this species does not appear in the modern, freshly formed Agulhas eddies in relative abundances higher than 2% (PEETERS et al., 2004, supplementary information S5). Therefore it is more likely that during interglacials, when ocean fronts shifted southward (BERGER & WEFER, 1996a), this species re-seeded the Cape Basin from the subtropical Atlantic, rather than from the Indian Ocean (see fig. 3 from BERGER & WEFER, 1996b). This implies that the reappearance of *G. menardii* in the sediment records of the Cape Basin, and in particular in its northern part, cannot be directly interpreted as evidence for the opening and closing of the “Cape valve”.

Surprisingly high concentrations of organic and particulate inorganic matter were recorded at station 05, situated at the edge of the eddy “W” (Fig. 6). These concentrations were not only higher than in the surrounding oligotrophic ocean, but also compared to the centre of the eddy, suggesting a significantly increased productivity and high faunal standing stocks. The flow velocities of the rotating eddy increase with the distance from its centre to the inner edge, where they drop due to the friction with the surrounding water. The velocities are highest at the top of the thermocline and decrease with depth (VAN AKEN et al., 2003). Therefore, drastically increased standing stocks recorded at station 05 may be the result of an “upwelling type” process in the

turbulent zone at the interface between the eddy and the surrounding water. Such a mixing process could introduce nutrients from the subsurface into the surface mixed layer, enhancing productivity in the otherwise predominantly oligotrophic environment.

The integrated February–July export fluxes recorded by the sediment traps at stations CWR and 06 mirror to a large extent the water column standing stocks from February 2000 (Fig. 7). This suggests stable conditions in the productive zone during the entire period of trap sampling. The increased dominance of *G. inflata* in the deposition fluxes, coupled with decreasing foraminiferal diversity and abundance of the warm water species, accompany the transition from oligotrophic to mesotrophic conditions along the west–east Benguela trophic gradient (LONČARIĆ, 2005; LONČARIĆ et al., 2006b). Therefore increased export fluxes of *G. inflata* suggest increased productivity, in particular at site 06 situated ca. 200 km closer to the Benguela upwelling zone. Such enhanced productivity occurred probably at the end of the sampling period when this site encountered the filaments of nutrient-rich water spreading from the Benguela upwelling zone or, more likely, subsurface nutrients became available due to the wind-induced winter deepening of the surface mixed layer (LONČARIĆ et al., 2006b). Alternatively, the higher relative abundance of *O. universa*, *G. scitula* and *G. ruber* in the February water column of the same site appear related to the passing eddy.

The dominance of *G. inflata* and distinct assemblages of the CWR core-top sediment, in contrast to the February plankton tow and February to July sediment trap assemblages (Fig. 7), indicate a strong overprint by the seasonal bloom. Approximately 25% of the annual flux in this area is deposited during the short, but prominent austral spring maximum in October (LONČARIĆ et al., 2006b). This seasonal event dilutes the already very weak Indian Ocean signal that remained in the mature eddy and makes it untraceable in the fossil record. In all studied samples specimens of *G. hexagona* were absent. This species is endemic to the Indian Ocean waters, but present in low abundance in the zone of Agulhas retroflexion and in the freshly formed Agulhas rings (PEETERS et al., 2004). Therefore, the fingerprint of Indian Ocean inflow cannot be firmly traced by the foraminiferal assemblages in the water column and surface sediments of the northern Cape Basin and the central Walvis Ridge.

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