

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Live foraminiferal faunas (Rose Bengal stained) from the northern Arabian Sea: links with bottom-water oxygenation

C. Cauille¹, K. A. Koho^{2,3}, M. Mojtahid¹, G. J. Reichart^{2,3}, and F. J. Jorissen¹

¹LPGN-BIAF, CNRS UMR6112, Laboratory of Recent and Fossil Bio-Indicators, Angers University, 2 Bd Lavoisier, 49045 Angers Cedex 01, France

²Utrecht University, Faculty of Geosciences, Department of Earth Sciences, Budapestlaan 4, 3584 CD Utrecht, the Netherlands

³Royal Netherland Institute for Sea Research (Royal NIOZ), Landsdiep 4, 1797 SZ 't Horntje, Texel, the Netherlands

Received: 19 August 2013 – Accepted: 6 September 2013 – Published: 23 September 2013

Correspondence to: C. Cauille (clemence.cauille@univ-angers.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Live (Rose Bengal stained) benthic foraminifera from the Murray Ridge, within and below the northern Arabian Sea Oxygen Minimum Zone (OMZ), were studied in order to determine the relationship between faunal composition, bottom-water oxygenation (BWO), pore-water chemistry and organic matter (organic carbon and phytopigment) distribution. A series of multicores were recovered from a ten-station oxygen (BWO: 2–78 μM) and bathymetric (885–3010 m depth) transect during the winter monsoon in January 2009. Foraminifera were investigated from three different size fractions (63–125 μm , 125–150 μm and > 150 μm). The larger foraminifera (> 125 μm) were strongly dominated by agglutinated species (e.g. *Reophax* spp.). In contrast, in the 63–125 μm fraction, calcareous taxa were more abundant, especially in the core of the OMZ, suggesting an opportunistic behaviour. On the basis of a Principal Component Analysis, three foraminiferal groups were identified, reflecting the environmental parameters along the study transect. The faunas from the shallowest stations, in the core of the OMZ (BWO: 2 μM), were composed of “low oxygen” species, typical of the Arabian Sea OMZ (e.g., *Rotaliatinopsis semiinvoluta*, *Praeglobobulimina* spp., *Bulimina exilis*, *Uvigerina peregrina* type *parva*). These taxa are adapted to the very low BWO conditions and to high phytodetritus supplies. The transitional group, typical for the lower part of the OMZ (BWO: 5–16 μM), is composed of more cosmopolitan taxa tolerant to low-oxygen concentrations (*Globocassidulina subglobosa*, *Ehrenbergina trigona*). Below the OMZ (BWO: 26–78 μM), where food availability is more limited and becomes increasingly restricted to surficial sediments, more cosmopolitan calcareous taxa were present, such as *Bulimina aculeata*, *Melonis barleeanus*, *Uvigerina peregrina* and *Epistominella exigua*. Miliolids were uniquely observed in this last group, reflecting the higher BWO. At these deeper sites, the faunas exhibit a clear depth succession of superficial, intermediate and deep-infaunal microhabitats, because of the deeper oxygen and nitrate penetration into the sediment.

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Oxygen minimum zones (OMZs) are present at intermediate water depths (250–1500 m) along the continental margin of the eastern Pacific, off southwest and north-west Africa, in the Bay of Bengal and in the northern Indian Ocean (Arabian Sea).

OMZs are defined as areas where the oxygen concentration in the water column is $< 22 \mu\text{M}$ (Levin, 2003; Helly and Levin, 2004). Mostly, they are also areas of high primary productivity where low-oxygen concentrations develop naturally and have persisted over geological timescales (Reichart et al., 1998), due to enhanced organic matter (OM) degradation. Where the OMZs intersect with the continental margin, the ocean floor is exposed to low-oxygen levels. Despite very low oxygen concentrations, protozoan and metazoan assemblages thrive in these environments (e.g. Jannink et al., 1998; Levin et al., 2000; Levin, 2003; Schumacher et al., 2007). These low-oxygen tolerant benthic assemblages can attain high densities, but have typically a low diversity (e.g. den Dulk et al., 1998; Jannink et al., 1998; Schumacher et al., 2007). The poor ventilation also impacts biogeochemical processes in the water column and within the sediment. This results in enhanced sequestration of organic material in the sediment. Consequently, OMZs are considered as important organic carbon sinks (e.g. Cowie, 2005; van der Weijden et al., 1999; Koho et al., 2013).

The intensity of the Arabian Sea OMZ is closely related to the Indian monsoon system (Wyrтки, 1973). During the summer (SW) monsoon (May to September), an intense coastal upwelling develops off the coast of Somalia, Oman and southwestern part of India. This upwelling triggers high biological productivity in the photic zone (e.g. Ryther and Menzel, 1965; Caron and Dennett, 1999; Rixen et al., 2000), leading to high export of organic carbon to intermediate water depths, where it is intensely recycled and remineralized. A second high biological productivity event occurs during the winter (NE) monsoon (e.g. Caron and Dennett, 1999; Rixen et al., 2000), due to convective mixing of the sea-surface water (Banse and McClain, 1986; Madhupratap et al., 1996). The intensity of the Arabian Sea OMZ is particularly strong, with oxygen concentrations

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



< 2 μM in its core (Paulmier and Ruiz-Pino, 2009). This is not only due to high biological productivity, but is also related to the semi-enclosed nature of the northern Arabian Sea (Wyrтки, 1973; Shetye et al., 1994), in combination with the renewal of intermediate waters by relatively oxygen-poor intermediate water-masses from the South and West (Swallow, 1984; Olson et al., 1993).

To date, only few studies have dealt with living (Rose Bengal stained) benthic foraminiferal faunas from the Arabian Sea OMZ. These studies have mostly focused on the Pakistan (Jannink et al., 1998; Maas, 2000; Erbacher and Nelskamp, 2006; Schumacher et al., 2007; Larkin and Gooday, 2009) and Oman margins (Stubbings, 1939; Hermelin and Shimmiel, 1990; Naidu and Malmgren, 1995; Gooday et al., 2000). In addition, Kurbjewit et al. (2000) and Heinz and Hemleben (2003, 2006) compared the foraminiferal distribution during different periods of the monsoonal cycle in the central, eastern and western parts of the Arabian Sea. Most of these studies described a general zonation of benthic foraminiferal faunas across the OMZ. However, since geochemical measurements were generally not included in these studies, no clear, specific correlations could be established with the controlling environmental parameters. Foraminiferal abundances and distributions are suggested to be controlled by organic matter supply and oxygen content. Oxygen and organic matter content are inversely correlated parameters which make their interpretation difficult.

Here, we explore for the first time the distribution and abundance of living benthic foraminiferal faunas from the Murray Ridge, Northern Arabian Sea. The Murray Ridge is a seamount with its top culminating in the core of the OMZ, and offers an ideal natural laboratory for investigation of biological process along BWO and organic carbon gradients. Live benthic foraminifera were investigated from three size fractions (63–125 μm , 125–150 μm and > 150 μm). Further, foraminiferal data were correlated with geochemical data obtained at the same stations from the studies of Kraal et al. (2012) and Koho et al. (2013), including BWO content, oxygen and nitrate pore water profiles, phytopigments concentrations and organic carbon, in order to examine the influence of environmental parameters on foraminiferal distribution along the study transect.

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2 Material and methods

2.1 Study area

During the interdisciplinary PASOM cruise (Process study on the Arabian Sea Oxygen Minimum Zone) in January 2009, a ten station transect was sampled along the Murray Ridge, north Arabian Sea (Fig. 1), along a strong oxygen gradient. The cruise was designed to cover a transect through the OMZ (885–3010 m), specifically targeting the transition zone from low oxygen to more oxic conditions below the OMZ. All sediment samples were retrieved with a multicorer, allowing the recovery of undisturbed surface sediment samples. The multicorer was equipped with eight cores measuring 6.6 cm in diameter and four cores measuring 10 cm in diameter. All cores collected for foraminiferal (\varnothing 6.6 cm) and geochemical analysis (\varnothing 6.6 cm and 10 cm) were retrieved from the same multicore cast. Most cores were sliced at 0.5 cm resolution down to 2 cm sediment depth, at 1 cm intervals between 2 and 6 cm and then every 2 cm intervals down to 10 cm. Only the cores used for pore water extraction and organic carbon (C_{org}) analyses were sliced differently: 0.5 cm intervals in the top 2 cm, 1 cm intervals down to 6 cm and 2 cm intervals down to 10 cm.

2.2 Foraminiferal analyses

Onboard, samples were stained in Rose Bengal (Walton, 1952) in 95 % ethanol solution (1 g L^{-1}). They were gently shaken for several minutes and further stored in the Rose Bengal solution. In the laboratory, sediment samples were wet sieved into 150-, 125- and 63- μm fractions. To obtain a good staining, the samples were treated again with Rose Bengal for a minimum of 48 h. All well-stained foraminifera were picked wet (50 % ethanol – 50 % water) from $> 150 \mu\text{m}$ and 125–150 μm fractions from all levels until 10 cm depth under a binocular microscope. Foraminifera from the small size fraction (63–125 μm) were only investigated from the first centimetre of the sediment (0–0.5 cm and 0.5–1 cm).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The use of the Rose Bengal technique is an inexpensive and easy method (Walton, 1952; Bernhard, 1988, 2000). However, it has been shown that especially in low-oxygen settings, Rose Bengal may stain protoplasm of recently dead foraminifera (Corliss and Emerson, 1990; Bernhard, 2000). Therefore, to minimize the chance of bias in our counts of living foraminifera, very strict staining criteria were always applied. Specimens were considered living only when all chambers except the last one were well stained. Furthermore, doubtful specimens were compared with perfectly stained specimens of the same species and non-transparent agglutinated and miliolid taxa were broken to inspect their contents. Fragments of branching and tubular foraminifera (e.g. *Hyperammina*, *Rhizammina*) were not included in the data analyses because of their easily breakable tests, which makes it very difficult to quantify them correctly. Foraminiferal taxonomy was based on commonly used taxonomic reference works (e.g. Loeblich and Tappan, 1988; Jones, 1994) and on some taxonomic studies with emphasis on Arabian Sea and anoxic zones (e.g. Mass, 2000; Schumacher et al., 2007; Larkin and Gooday, 2009); see taxonomic appendix for more details.

For all stations, diversity indices, including species richness (S ; count of number of taxa in a sample), Shannon index ($H(S)$), and evenness (J) were calculated using the free statistical software “PAST” (PAleontological STatistics; Version 2.14; Hammer et al., 2001).

To better constrain the relationship between species variability and environmental conditions, Principal Component Analysis (PCA) was conducted using the free statistical software “R” (<http://cran.r-project.org/>). The PCA was run on geochemical/environmental data and on species that contributed for > 2 % to the total abundance of the entire database. Two PCA analyses were carried; the first one investigating the entire core (down to 10 cm, > 125 μm fraction), and the second one the top cm of the sediment (0–1 cm, > 63 μm fraction).

2.3 Dissolved oxygen and nitrate

In short, BWO concentrations water-column and bottom-water dissolved O₂ concentrations were measured with an oxygen sensor (Sea-Bird SBE43, accuracy 2%; Sea-Bird Electronics Inc., 2011) that was built into the framework of a conductivity, temperature and depth (CTD) profiler (all data published in Koho et al. (2013); see Fig. 2 for details).

The pore-water oxygen concentration was determined immediately following core recovery in a temperature controlled laboratory set up at in situ temperature (some data published in Kraal et al., 2012; see Fig. 2 for details). All measurements were done with Unisense oxygen microelectrodes (OXO100 or OXO50). The microelectrodes were two point calibrated at 100 % O₂ saturated seawater (bubbled with oxygen) and in a solution containing sodium ascorbate (0.1 M) to obtain the 0 % reading.

The details of pore-water extraction for nitrate analyses are outlined in Kraal et al. (2012). In short, sediment slicing was carried out in a N₂-purged glovebox in a temperature controlled laboratory set at in situ temperature (some data are published in Kraal et al., 2012; see Fig. 2 for details). Sediment samples were transferred to 50 ml plastic centrifuge tubes under N₂ atmosphere and centrifuged for 20 min at 4500 rpm outside the glovebox. The centrifuge tubes were then transferred back into the glovebox where the supernatant pore-water was filtered over 0.45 μm Teflon filters and frozen (−20 °C) until the analyses. Pore-water nitrate concentrations were measured by an autoanalyzer at the Royal Netherlands Institute for Sea Research (NIOZ) in Den Burg, Netherlands

2.4 Organic carbon and phytopigment analyses

The details of organic carbon analyses are outlined in Koho et al. (2013) (all data published in Koho et al., 2013; see Fig. 2 for details). In short, the sediment, from which the pore waters were extracted, was further used for solid phase analyses and frozen at −20 °C until analyses. In the laboratory, sediment was weighted, freeze-dried and decalcified by reacting twice with 1 mol L^{−1} HCl (4 h and 12 h). After two subsequent

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



rinses with ultrapure water, the decalcified samples were freeze-dried and organic C and N were measured with a CNS analyzer (Fisons Instruments NA 1500).

The phytopigments were extracted from a different core than the one used for C_{org} analyses. However, the core came from the same multicore cast. The details of phytopigment analyses are outlined in Koho et al. (2013). In short, the samples were stored at -80°C until analysed and freeze-dried prior to pigment extraction in 10 mL of acetone : water (90 : 10). The full pigment composition was obtained through application of high-performance liquid chromatography (HPLC) equipped with a C_{18} reverse phase column at the Royal Netherlands Institute for Sea Research (NIOZ – YERSEKE). The calibration was based on working standards prepared from commercially available compounds (DHI, Denmark). The pigment concentrations are reported per $\mu\text{g/g}$ of sediment.

3 Results

On the basis of BWO values, four consecutive zones can be distinguished: (1) the core of the OMZ, where BWO is around $2\ \mu\text{M}$ (Paulmier and Ruiz-Pino, 2009), (2) the lower part of the OMZ with $\text{BWO} < 22\ \mu\text{M}$ (Helly and Levin, 2004; Middelburg and Levin, 2009), (3) the dysoxic zone where BWO is between 22 and $45\ \mu\text{M}$ (Bernhard and Sen Gupta, 1999; Levin, 2003; Helly and Levin, 2004), and (4) relatively well-ventilated deeper “oxic” sites where BWO is $> 45\ \mu\text{M}$ (Bernhard and Sen Gupta, 1999; Levin, 2003). According to these definitions, our 885 m (PA1) and 1013 m (PA2) stations are located in the core of the OMZ, stations between 1172 and 1379 m (PA3, PA4 and PA5) depths are in the lower part of the OMZ, the 1495 m (PA6) station is located in the dysoxic zone, and stations from 1791 m to 3010 m (PA7, PA8, PA9 and PA10) are in the oxic zone (Fig. 2).

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.1 Environmental parameters

Details of the environmental parameters related to this study have been published in Kraal et al. (2012) and Koho et al. (2013). Here, some new data together with a summary of the existing data sets are presented in order to link them with the foraminiferal distribution and abundance (Fig. 2).

Organic carbon (C_{org}) and chlorophyll *a* (Chl *a*) contents, for the top first centimetre, progressively change along the study transect (Fig. 2; Koho et al., 2013). The highest concentrations ($C_{\text{org}} = 5.7 \text{ wt \%}$; Chl *a* = $2.6 \mu\text{g g}^{-1}$) are observed in the core of the OMZ (885 m and 1013 m). In the dysoxic (1495 m) and oxic zones (1791 m to 3010 m), C_{org} and Chl *a* values are lower, $< 2 \text{ wt \%}$ and $< 0.5 \mu\text{g g}^{-1}$, respectively (Fig. 2). Minimum concentrations ($C_{\text{org}} = 0.82 \text{ wt \%}$; Chl *a* = $0.1 \mu\text{g g}^{-1}$) are found at the deepest site (3010 m). Generally, C_{org} and Chl *a* concentrations decrease with increasing water depth and BWO.

The oxygen penetration depth into the sediment increases along the transect and is strongly related to the BWO content ($r^2 = 0.8$) (Fig. 2). At the shallowest site (885 m, $\text{BWO} \sim 2 \mu\text{M}$), within the OMZ, oxygen penetration is about 0.1 cm whereas at the deepest site (3010 m, $\text{BWO} \sim 78.3 \mu\text{M}$) oxygen is available until 1.8 cm depth. The nitrate penetration depth shows weaker yet relatively strong regression with the BWO content ($r^2 = 0.4$), increasing from the 1.2 cm at 885 m (OMZ site) to 7.5 cm at 3010 m (oxic site).

3.2 Foraminiferal assemblages of the 0-10 cm interval (> 125 μm fraction)

3.2.1 Total abundance

Foraminiferal abundances for the whole cores (down to 10 cm) were investigated in three different size fractions: 125–150 μm , > 150 μm and > 125 μm (Fig. 3a), the > 125 μm fraction being the sum of the first two. All size fractions show a similar dis-

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tribution of foraminiferal absolute abundance, and no clear trend is seen along the transect (Fig. 3a).

In the $> 125 \mu\text{m}$ fraction, total live foraminiferal abundance varies from ~ 90 to ~ 970 ind/50 cm², the two extremes being observed in the two sites from the core of the OMZ (at 885 m and 1013 m, respectively). The lower OMZ stations (1172 m, 1306 m and 1379 m) show values from 215 ind/50 cm² to 450 ind/50 cm², the dysoxic site (1495 m) contains ~ 970 ind/50 cm², whereas the oxic sites (1791 m to 3010 m) show densities varying from ~ 400 ind/50 cm² to ~ 870 ind/50 cm² (Fig. 3a).

Agglutinated foraminifera are dominant at all stations. They always constitute more than half of the total assemblage (Fig. 3a). In the lower part of the OMZ (stations at 1172, 1306 and 1379 m), they attain $\sim 70\%$ on average. Abundance of hyaline taxa varies along the transect without a clear pattern. Miliolids are only present at the oxic sites (1791 m to 3010 m depth), constituting less than 14 % of total standing stocks.

3.2.2 Diversity and dominance

A total of 191 species have been identified, of which 71 are agglutinants, 99 are hyaline and 21 are miliolid species. Species richness (S) differs considerably between the OMZ stations (core and lower part) and the dysoxic sites (1495 m) (Fig. 3a). The lowest number of species (17) is observed at 1013 m depth, in the core of the OMZ. At the dysoxic site (1495 m) a maximum of 68 species is recorded. At the oxic sites (1791 m to 3010 m), species richness is more constant, with about 50 species at all stations (Fig. 3a). The species richness trend follows generally that of the total abundance ($r^2 = 0.5$), suggesting that the number of foraminifera found is largely determined by the sample size. However, in general higher S coincides with a higher Shannon index ($H(S)$) and a lower evenness (J) (Fig. 3a). Species are also distributed fairly evenly at all sites evenness varying from 0.4 to 0.6 (Fig. 3a).

Shannon diversity ($H(S)$) is minimal in the core of the OMZ (2.3 to 2.5). It is higher at the dysoxic and oxic sites, where values around 3.0 are observed. Maximum $H(S)$

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



values are observed in the lower part of the OMZ at 1379 m ($H(S) = 3.1$) and more oxygenated site at 2470 m ($H(S) = 3.2$) (Fig. 3a).

3.2.3 Distribution patterns of individual species

Foraminiferal species distribution shows important changes along the transect (Fig. 4), although some agglutinated species, such as *Reophax agglutinans*, *Reophax micaceus* and *Lagenaminna difflugiformis* are found at most of the stations.

In the core of the OMZ, where oxygen and nitrate penetration are very shallow (~ 0.1 cm and ~ 1.3 cm respectively) faunal density maximum is concentrated in the upper 1.5 cm (Fig. 4). Nevertheless, at both sites, living foraminifera are found down to 3–4 cm. The fauna of both stations is dominated by the agglutinated species *Reophax agglutinans*, *Lagenaminna difflugiformis*, *Ammodiscus* sp., *Cribrostomoides* cf. *jeffreysii*, *Verneuilinella propinqua*, *Reophax dentaliniformis* and *Hormosina guttifer* and the hyaline species *Uvigerina peregrina* type *parva*, *Rotaliatinopsis semminvoluta*, *Praeglobobulimina* sp., *Fursenkoina mexicana*, *Bulimina exilis*, *Chilostomella oolina*, *Gyroidina soldanii* and *Fursenkoina* sp.

In the lower part of the OMZ (1172 to 1379 m), maximum densities are consistently observed in the first cm of the sediment, but small numbers of stained specimens are present down to 6–8 cm depth (Fig. 4). Here, the oxygen and nitrate penetration depth increase to 0.6 cm and 3.5 cm depth, respectively. The faunas of this zone are dominated by the agglutinated species *Reophax* cf. *spiculifer*, *Reophax agglutinans*, *Lagenaminna difflugiformis* and *Verneuilinella propinqua* and the hyaline species *Bulimina* cf. *mexicana*, *Ehrenbergina trigona*, *Melonis barleeanus*, and *Uvigerina peregrina*. The infaunal taxa are dominated by agglutinated taxa, among which several *Reophax* species, whereas only some scarce individuals of the hyaline taxa *Chilostomella oolina* and *Fursenkoina* sp. are found deeper in the sediment (3–4 cm).

At the dysoxic (1495 m) and oxic (1791 to 3010 m) stations, live foraminifera are found down to 10 cm depth (Fig. 4), although maximum densities are recorded in the oxygenated first two cm of the sediment (Fig. 4).

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



At the dysoxic site (1495 m), *Lagenammia difflugiformis*, *Reophax agglutinans*, *Bulimina aculeata*, *Uvigerina peregrina* dominate the fauna. Both *B. aculeata* and *U. peregrina* show two in-sediment maxima here: in the first half cm, which is well oxygenated and at 3–5 cm depth, below the oxygen and nitrate penetration depth.

At the oxic sites (1791 m to 3010 m), miliolid taxa appear (Fig. 4). Among these, *Pyrgo murrhina* is most frequent and is found at the 1970 and 2470 m sites (Fig. 4). Other species, with maxima close to the sediment surface, include *Uvigerina peregrina*, *Lagenammia difflugiformis*, *Bulimina aculeata*, and *Reophax agglutinans*. Also the density of intermediate and deep infaunal species increases at these sites. *Melonis barleeanus* is found down to 3–4 cm (1791 to 2470 m) and *Fursenkoina* sp. is found in small numbers from 1791 to 2470 m, down to the 6–8 cm level. Furthermore, *Reophax* species are found down to 10 cm depth regardless of the absence of oxygen and nitrate in the sediment. Different species are found at 3010 m site. Here, faunas are dominated by agglutinated species, such as, *Hormosina guttifera*, *Reophax agglutinans* and *Lagenammia difflugiformis*, and by the hyaline *Oridorsalis umbonata*.

3.3 Foraminiferal faunas of the 63–125 μm fraction (0–1 cm)

3.3.1 Total foraminiferal abundance and diversity

The 63–125 μm fraction has only been examined in the topmost 1 cm from the same cores-site investigated for the $> 125 \mu\text{m}$ fraction (Fig. 3b). In the first cm, all investigated size fractions (63–125 μm , $> 125 \mu\text{m}$) show a similar pattern, and no clear trend is seen along the transect (Fig. 3b).

On average, foraminiferal abundances in the $> 63 \mu\text{m}$ fraction of the 0–1 cm level (Fig. 3b) are at least twice as high as the densities in the $> 125 \mu\text{m}$ fraction. The abundance of small (63–125 μm) foraminifera is particularly high in the core and lower part of the OMZ and at the dysoxic station (1495 m) where this fraction accounts for 62–84 % of the total foraminiferal abundance (Fig. 5). At the oxic stations (1791 m to 3010 m), foraminifera of the 63–125 μm fraction and $> 125 \mu\text{m}$ fraction are more even; the 63–

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



125 μm fraction contributing for 44–49 % of the total assemblage. At 3010 m, the 63–125 μm is dominant again, accounting for ~ 67 % of the total fauna (Fig. 5).

In general, the 63–125 μm fraction is dominated by calcareous taxa (~ 30 – 65 %). Consequently, in the > 63 μm fraction, the relative abundance of calcareous taxa is higher than in the > 125 μm fraction (Fig. 3b).

Similarly to > 125 μm fraction (top 10 cm), Shannon diversity ($H(S)$) of the > 63 μm fraction (top 1 cm) is relatively low (2.8) in the core of the OMZ (885 m and 1013 m), but increases to 3.3 to 3.5 at deeper sites (1172 m, 1306 m and 1379 m) (Fig. 3b). Species richness has a similar trend as $H(S)$ (Fig. 3b). Evenness values do not show a very clear trend, although low evenness values are generally found where high values of species richness and $H(S)$ are recorded. In general, all diversity indices are systematically higher when the 63–125 μm size class is included (Fig. 3b).

3.3.2 Faunal composition of the > 63 μm fraction (0–1 cm level)

Figure 5 shows the species distribution along the transect for the > 63 μm fraction (0–1 cm only). As expected, the foraminiferal species repartition observes important change between sites.

Small hyaline species, such as *Bolivina seminuda* and *Nuttalides pusillus*, are common in the OMZ core (885–1013 m). In addition, small individuals of *Uvigerina peregrina* type *parva* are abundant. The agglutinated species *Trochammina* sp.1, *Veleronoides wiesneri* and *Reophax bilocularis* are also only observed abundantly in the 63–125 μm fraction. As in the larger size classes, many OMZ taxa are either restricted to these sites, or occur only in very low abundances at deeper sites.

In the lower part of the OMZ, small hyaline species, *Gyroidina* sp.2, *Bolivina* aff. *dilatata*, *Bolivina* sp. 1, *Nuttalides pusillus*, *Gavelinopsis translucens* and *Epistominella exigua*, are abundant. In addition, as in the > 125 μm fraction, *Reophax* species are common at these sites (Fig. 5).

The foraminiferal assemblages at the dysoxic site (1495 m) and in the oxic zone (1791 m to 3010 m) show high abundances of *E. exigua*, *G. subglobosa*, *Nuttalides*

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



spp., *U. peregrina*, *M. barleeanus*, *Pullenia* spp., *Reophax* spp. and *Cribrostomoides* spp. (Fig. 5). Of these taxa, only *Nuttalides* spp. is largely restricted to the 63–125 μm fraction and others are also found in abundance in the $> 125 \mu\text{m}$ fraction. At the deepest and best ventilated sites (1970 and 2470 m depth), *Pyrgo murrhina*, *Pyrgoella sphaera* and *Pyrgo lucernula* are the best represented miliolid taxa (Fig. 5).

3.4 Foraminiferal assemblages and relation to environmental parameters: principal component analyses (PCA)

Our PCA analysis is based on the relative abundances of the dominant species ($> 2\%$) in the $> 125 \mu\text{m}$ (0–10 cm) size fraction and the geochemical data (Fig. 6). Axis 1 explains about $\sim 33\%$ and axis 2 about 15% of the total variance. Three faunal groups are clearly identified in the PCA analyses (Fig. 6). Group 1 is characterized by species living in the core and lower part of the OMZ (Figs. 4 and 6), and plot together with high C_{org} and pigment values. Group 2 mainly consists of species present in the lower part of the OMZ and in the dysoxic zone (Fig. 6). It seems to represent a transitional assemblage between the faunas of the OMZ and of the oxic sites (Fig. 6). Finally, group 3 contains the species dominating the faunas at the deeper, oxic sites. They plot together with high BWO, nitrate and oxygen penetration and water depth.

A second PCA analysis was performed on the basis of the relative abundance data of dominant species in the $> 63 \mu\text{m}$ fraction (0–1 cm). As in the PCA presented above, three very similar groups were obtained (see Supplement C), with only few changes in species composition (e.g. *Nuttalides pusillus*, *Bolivina* spp.) are observed. Due to the similarity of the two PCA analyses, only the PCA based on the $> 125 \mu\text{m}$ size will be discussed further. We feel this one is more robust as it is based on the complete core with foraminifera analysed down to 10 cm depth in sediment. Moreover, most paleoceanographic studies are based on $> 125 \mu\text{m}$ fraction.

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Discussion

4.1 Environmental conditions and their implications to benthic foraminifera

The organic carbon availability in the benthic environment depends to a large degree on primary production (PP) in the surface waters, and the subsequent flux of organic remains to the seafloor. In the Arabian Sea, these parameters are strongly linked to the monsoonal cycle. The SW (June–September) and NE (December–March) monsoons lead to intense seasonal changes of surface hydrography and vertical particle flux to the deep-sea (Nair et al., 1989; Haake et al., 1993; Rixen et al., 1996). Nutrient enrichment in surface waters, and thus maximum PP, occur during times of moderate to strong winds associated with SW and NE monsoons (Banse and McClain, 1986; Banse, 1987; Rao et al., 1989). Intensity of the NE and SW monsoon, and also the ensuing PP, show important interannual variability (Wyrтки, 1973; Burkill et al., 1993). Our samples were taken in January 2009, during the winter NE monsoon, when PP was quite high (surface Chl *a* ~ 0.5–0.7 mg m⁻³, www.nasa.gov). During the intermonsoon (April–May and October–November), PP is lower at this site (Chl *a* ~ 0.3–0.5 mg m⁻³, www.nasa.gov) and higher during the summer SW monsoon (Chl *a* ~ 0.7–0.1 mg m⁻³, www.nasa.gov).

Benthic foraminifera generally respond to the quantity and quality of the organic material arriving to the sea-floor (e.g. Jorissen et al., 2007; Mojtaħid et al., 2009). In our samples, the percentage of C_{org}, an integrative parameter indicative of OM quantity (Fig. 2) shows a clear exponential decline with increasing BWO content (Koho et al., 2013). Chl *a* content, giving somewhat more information about the quality of OM available for benthic organisms, describes a decrease with increasing depth and BWO content (Fig. 2). Other parameters that could potentially influence benthic foraminiferal distribution are the oxygen concentration in the bottom waters, and the oxygen and nitrate penetration into the sediment, which have been partly described by Kraal et al. (2012). These three parameters are strongly interdependent and related to amount of C_{org} arriving at the seafloor and its degradation in the sediment during the early di-

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



agenesis. This results in a progressive increase in oxygen and nitrate penetration into the sediment with increasing water depths and BWO and decreasing C_{org} .

4.2 Foraminiferal densities and diversities

Despite food availability generally considered as the main ecological parameter controlling the foraminiferal distribution and abundance on continental margin settings (e.g. Jorissen et al., 1995, 2007; Koho, 2008), the standing stocks of foraminifera on the Murray Ridge do not show a clear trend with any other measured environmental parameter, including C_{org} , Chl *a*, BWO or water depth (Figs. 2 and 3). This observation appears to be in contrast with previous studies of foraminifera from the Arabian Sea OMZ where a decreasing of the TSS with water depth was observed (Jannink et al., 1998; Schumacher et al., 2007; Fig. 7). However, since very few environmental parameters were included in these studies, a genuine comparison of foraminiferal abundances remains difficult. The work of Schumacher et al. (2007) was performed off the Pakistan continental margin during the spring intermonsoon (March-April 2003) from 136 m to 1870 m depths. When comparing foraminiferal abundances from similar depths, higher values are observed in our study transect (Fig. 7). We would expect the opposite since sea-surface Chl *a* content ($\sim 1\text{--}2.5\text{ mg m}^{-3}$; www.nasa.gov) and BWO were higher during the sampling time of Schumacher et al. (2007) (Fig. 7). The study of Jannink et al. (1998) investigated two transects (from 500 to 2000 m depths) from the Pakistan margin (fall intermonsoon, October 1992), which showed large differences (a 4-fold difference) in foraminiferal abundances (Fig. 7). The authors tentatively explained it by the different sampling times: a three week time lag between the two samplings would have led to a very different OM input. Our data are generally similar to foraminiferal abundances from Jannink et al. (1998), especially in transect I (Fig. 7). Kurbjeweit et al. (2000) compared six sites (from 1916 to 4425 m) across the Arabian Sea during the fall intermonsoon (September/October 1995). Although only two sites are comparable with our transect ($\sim 1916\text{ m}$ and $\sim 3100\text{ m}$), similar foraminiferal abundances are observed (Fig. 7).

When the finer size fraction (63–125 μm , first cm only) is also examined, foraminiferal TSSs increase considerably (Fig. 3b). Small-sized foraminifera account for up to 72 % of the total assemblage at the OMZ sites whereas at deeper sites they count for 54 % (Fig. 5). Similar observations were made in the Pakistan margin of the Arabian Sea OMZ (Jannink et al., 1998; Larkin and Gooday, 2009). The dominance of small foraminifera could partly be due to pulsed C_{org} supplies likely favouring small sized opportunistic taxa (e.g., Fontanier et al., 2005).

Unlike foraminiferal TSSs, diversity parameters show somewhat clearer trends along the studied transect (Fig. 3). Within the OMZ, diversity tends to be lower than at deeper sites, which is in agreement with previous studies in the area (Jannink et al., 1998; Schumacher et al., 2007). The lower diversity in the core and lower part of the OMZ could be the result of a disappearance of species sensitive to very low oxygen concentrations. Alternatively, it could be that the very high (and potentially episodic) food input favours opportunistic taxa, thereby decreasing the diversity indices. Although most benthic foraminifera are supposed to be insensitive to low BWO down to at least 22 μM (1 mLL^{-1}) (Jorissen et al., 2007), the very low concentrations in the core of the OMZ are probably beyond the tolerance levels of many species.

4.3 Dominance of agglutinated species along the study transect

The high proportion of agglutinated species (up to 72 %) along the studied transect seems independent of the BWO or C_{org} content. Indeed, some agglutinated species (*Reophax* spp. and *Lagenammima difflugiformis*) are present all along the transect. Earlier studies from the Arabian Sea have not observed such a high dominance of agglutinated foraminifera. Although, Kurbjeweit et al. (2000) described a strong dominance of agglutinated species at the deepest sites of their transect. However, these sites were located below our depth-transect between 1916 to 4425 m.

The ecological preferences of agglutinated foraminifera are not well understood. It has been suggested that they are less dependent on fresh food input than calcareous taxa (e.g. Koho, 2008; Phipps, 2012a). Therefore, agglutinated taxa could colonise en-

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



vironments less suitable for calcareous taxa (Phipps, 2012a). A clear decline is seen both in the quality and quantity of OM along our study transect (Koho et al., 2013). Therefore, the lower OM quality could limit calcareous species and favour the expansion of agglutinated ones.

Alternatively, the abundance of agglutinated foraminifera may be related to the carbonate chemistry of the study setting. Due to the enhanced organic matter recycling and associated CO₂ release into the pore waters, the benthic habitat may become acidified (Berger, 1970). This acidification would make carbonate minerals less stable and thus the habitat would be less suitable for hyaline foraminifera. Visual inspection of samples revealed relatively poorly preserved (planktonic) foraminifera. This was especially evident in samples from the transitional setting towards more ventilated sites. Furthermore, the bottom water carbonate saturation index (Ω) was also calculated to be < 1, suggesting calcite under saturation, at four sites (885 m, 1306 m, 1791 m, 1970 m) (Reichart, unpublished data).

Previous work on agglutinated foraminifera has also suggested that in general, agglutinated foraminifera are less tolerant to low-oxygen conditions than calcareous foraminifera (Moodley et al., 1997; Gooday et al., 2000, 2001, 2009; Neira et al., 2001). However, the strong dominance of agglutinated species at all stations of our BWO gradient implies the contrary; they appear to be just as tolerant of strongly oxygen depleted conditions as calcareous taxa.

4.4 Species zonation

Three faunal groups were identified by PCA analyses (Fig. 7). These three groups are very distinct in their faunal composition, which present a clear succession along the transect, mainly reflecting the change of BWO and OM. Group 1 is characterised by the taxa inhabiting the core of the OMZ, Group 2 the lower OMZ and Group 3 the dysoxic and oxic taxa. In the following three paragraphs, we will discuss the ecology of the dominant taxa of each of these three groups.

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.4.1 Taxa dominating the faunas in the core of the OMZ

In the PCA, these taxa plot together with positive values of quantitative C_{org} and OM quality indicator (Chl *a*). This suggests that they are favoured by a high content of relatively fresh OM. The OMZ taxa are mainly composed of hyaline species, which are exclusively found in the OMZ (*Bulimina exilis*, *Uvigerina peregrina* type *parva*, *Rotaliatinopsis semiinvoluta*, *Praeglobobulimina* sp. and *Fursenkoina* sp.) (Fig. 6). Also some agglutinated species plot in this group (*Reophax agglutinans*, *Reophax dentaliniformis*, *Cribrostomoides* cf. *jeffreysii* and *Ammodiscus* sp.), which is not surprising since agglutinated taxa represent ~ 70 % of the TSS (> 125 μ m fraction) in the OMZ (from 885 m to 1306 m) (Fig. 3a).

Among the agglutinated taxa, only two species appear strictly restricted to the OMZ: *Ammodiscus* sp. and *Cribrostomoides* cf. *jeffreysii* (Fig. 4). *C.* cf. *jeffreysii* has been described by Maas (2000) and Schumacher et al. (2007) in the core of the OMZ. Also the presence of *Ammodiscus* sp. in the OMZ is consistent with previous observations from the Arabian Sea (e.g. Jannink et al., 1998; Maas, 2000; Schumacher et al., 2007), which characterised this taxon as highly tolerant to low-oxygen conditions and feeding on relatively fresh OM. *Ammodiscus* sp. was described as *A. cretaceous* from 233 m to 902 m water depths by Maas (2000).

Reophax agglutinans, was present along the whole depth transect, however in the PCA analyses showed affinity to OMZ taxa. The omnipresence of this taxon suggests that it is less dependent on the availability of labile OM, than other species characterising the core of the OMZ.

Calcareous taxa in general present a much clearer species succession than agglutinated ones (Fig. 4), and therefore appear to be more sensitive to the ecological parameters (BWO and OM quantity and quality). These observations also suggest that these hyaline species are very tolerant to low-oxygen conditions. *Bulimina exilis* is one of the most common species encountered in the core of the OMZ from the North-Eastern Arabian Sea (Jannink et al., 1998; Schumacher et al., 2007; Larkin and Gooday, 2009).

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Previous studies have demonstrated that this taxon thrives under conditions of high input of relatively fresh phytodetritus (Caralp, 1989; Jannink et al., 1998) and is able to survive in environments that are very low in oxygen (e.g. Jannink et al., 1998; Mass, 2000). Further, *B. exilis* is a common species of high productivity and/or low-oxygen environments in the OMZ of SW Africa (Schmiedl et al., 1997) and off Cape Blanc (Morigi et al., 2001). Another common species in this group is *R. semiinvoluta*, which occurs only at the 885 m and 1172 m stations. Our data confirms previous findings of *R. semiinvoluta* in the Arabian Sea (Jannink et al., 1998), and suggest that this species is specific to the OMZ of the Arabian Sea, and adapted to live under very low-oxygen conditions with a strong and intermittent flux of fresh organic matter. In a paleoceanographic study of the Arabian Sea, den Dulk et al. (1998), suggested that *R. semiinvoluta* may rapidly respond to changes in BWO, occurring at the base of the OMZ where it could thrive seasonally. However our data cannot confirm this hypothesis due to the fact that the samples reflect a single moment in time rather than a time series. *Praeglobobulimina* sp. is also only present at the 885 m and 1013 m sites. This specie is similar to the one described in den Dulk et al. (2000), Maas (2000) and Schumacher et al. (2007). Likewise, in these studies, *Praeglobobulimina* sp. is restricted to the core of the OMZ. Therefore, we suggest it is adapted to the very low oxygen conditions and may feed on relatively fresh OM.

Uvigerina peregrina inhabits a wide range of continental slope and margin environments, including relatively low-oxygen environments (e.g. Jannink et al., 1998; Maas, 2000; Schumacher et al., 2007) but also relatively well-ventilated sites (e.g. Fontanier et al., 2005; Koho, 2008; Mojtahid et al., 2010). It abounds in settings with relatively highly OM content (e.g. Lutze and Colbourn, 1984, Hermelin and Shimmield, 1990; Schmiedl and Mackensen, 1997) but also in areas with more moderate OM enrichment (e.g. Fontanier et al., 2005; Mojtahid et al., 2010). It has been described previously as a dominant faunal element in the Arabian Sea OMZ (e.g. Hermelin and Shimmield, 1990; Jannink et al., 1998; Gooday et al., 2000; Schumacher et al., 2007). In this study, we observed two different morphotypes of *U. peregrina* (Fig. 8). Specimens found in the

core of the OMZ are somewhat smaller, smoother and have weakly developed lower costae. They correspond to *U. peregrina* forma *parva* of Lutze (1986) (Figs. 3–4 and 8). At deeper sites, specimens have larger and higher costae and become more spinose (Figs. 1–2 and 8). These specimens present morphotypes from typical *U. peregrina* sensu stricto to *U. auberiana* (d'Orbigny, 1839) (fully spinose specimens). A similar morphological variation in *U. peregrina* has been noted in the Eastern Atlantic (e.g. Lutze, 1986; Schönfeld, 2006; Koho, 2008; Gooday and Jorissen, 2012). *Uvigerina peregrina* forma *parva* and *U. peregrina* do not occur together. *U. peregrina* type *parva* is only present in the core of the OMZ where BWO is very low and where food availability is probably much higher, whereas *U. peregrina* occurs from 1306 to 2407 m (Fig. 4). Because most of the deeper sites show a continuous variability from *U. peregrina* s.s. to *U. auberiana*, they have been counted together as *U. peregrina*. These two taxa appear to be indicative of slightly higher BWO and lower OM supplies.

4.4.2 Dominant taxa of the lower OMZ

These taxa are focussed at the 1172 m and 1306 m sites, where the BWO content is between ~ 5 and $\sim 17 \mu\text{M}$ (Fig. 6), and where C_{org} content is still high (3.5–2.80 wt %). The major species of this group are: *Reophax* cf. *spiculifer*, *Ehrenbergina trigona*, *Pullenia bulloides*, *Globocassidulina subglobosa*, *Cribrostomoides bradyi*, *Bulimina* cf. *mexicana* and *Verneuilinulla propinqua*. In the literature, most of these species have been described as tolerant to relatively low-oxygen conditions (e.g. den Dulk et al., 1998, 2000; Jannink et al., 1998; Schumacher et al., 2007).

Although *G. subglobosa* is a major species in the lower part of the OMZ, it is also found in small numbers at deeper sites. *G. subglobosa* is known to have a cosmopolitan character; it is found in the Atlantic Ocean (Gofas, 1978; Weston, 1982; Murray et al., 1986), in the central Pacific (Gofas, 1978) and in the Indian Ocean (Lagoe, 1977; Corliss, 1983b; Peterson, 1984). Its presence in the small fraction at deepest sites can be explained by the opportunistic behaviour: rapid colonization of episodic fresh phytodetritus (Jorissen et al., 2007 and reference therein). The environmental preferences

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of *E. trigona* are poorly known. Along the sampled transect this species is only present at the 1306 and 1379 m sites. The presence of *E. trigona* in the lower part of the OMZ is consistent with the observations of Hermelin and Shimmiedl (1990), who found this species at mid bathyal depths (770 m, 955 m and 1048 m) within and below the core of the OMZ. These authors also suggested that *E. trigona* could be an endemic species to the Arabian Sea OMZ environment. If so, *E. trigona* could be an indicator species for the lower part of the OMZ, which would make it a potential tracer for past variability of the base of the OMZ.

Little is known about ecological preferences of agglutinated species in this group (*R.cf. spiculifer*, *C. brady*, *V. propinqua*). However, based on our data, these species may be tolerant to relatively low-oxygen condition, with elevated levels of OM still available.

The depth limit of the lower OMZ has been shown to vary over geological history (e.g. Reichart et al., 1997, 1998; den Dulk et al., 2000; Schmiedl and Leuschner, 2005). Den Dulk et al. (2000) observed fluctuations in the depth of the OMZ based on the benthic foraminiferal assemblages during the last 225 000 years. Further, Schmiedl and Leuschner (2005) suggested these vertical shifts of the OMZ boundary through time correspond to the combined effects of enhanced OM fluxes and changes in the intensity of deep-water circulation. The foraminifera living in this transitional environment at the lower part of the OMZ can be used to track these changes in the past and aid in reconstruction of OMZ dynamics. The presence of both cosmopolitan (e.g. *Pullenia bulloides* and *Cribrostomoides brady*) and potentially endemic species (*Ehrenbergina trigona*), make this assemblage unique to Arabian Sea.

4.4.3 Taxa dominant at more oxygenated deeper sites

Rather diverse foraminiferal assemblages, including miliolids, hyaline and agglutinated species (Fig. 6), are found at all deeper sites, with BWO > 26 μM . At these sites, OM availability is lower, as is indicated by the lower Chl *a* and C_{org} contents (Fig. 2).

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Live foraminiferal
faunas from the
northern Arabian Sea**

C. Cauille et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

This third group defined by the PCA analysis is mainly dominated by agglutinated species such as *Lagenammina difflugiformis*, *Reophax micaceus*, *Hormosina guttifer*, *Reophax subfusiformis* and *Trochammina* spp. The increase in proportions of agglutinated species towards deeper waters is usually attributed to increasingly oligotrophic conditions, resulting in a change in OM quantity and quality (e.g. Ohga and Kitazato, 1997; Schmiedl et al., 1997; Kurbjeweit et al., 2000; Koho, 2008; Phipps et al., 2012). However, this assemblage contains also hyaline taxa, the most common ones being *Bulimina aculeata*, *Oridorsalis umbonata*, *Melonis barleeanus*, *Epistominella exigua* and *Uvigerina peregrina*. The presence of *B. aculeata* below the OMZ is consistent with previous studies of the Arabian Sea (e.g., Zobel, 1973; Jannink et al., 1998). *O. umbonata* has been observed in various well-oxygenated environments. Mackensen et al. (1995) relate this species to environments with low food supply. Also, the conspicuous occurrence of the intermediate infaunal taxon *M. barleeanus* suggests a relative dominance of refractory OM (Caralp, 1989; Koho et al., 2013) whereas the presence of *E. exigua* suggests episodic fresh phytodetritus reaching the seafloor (Gooday et al., 1996). *E. exigua* is mainly present in the 63–125 μm size fraction (Fig. 5) below the OMZ. However the OM data here, do not suggest the presence of fresh OM. Hence, *E. exigua* may also feed on more refractory OM. In our dataset, miliolids (*Pyrgo murrhina*, *Pyrgoella sphaera*, *Pyrgo lucernula*) are absent from the core and lower part of the OMZ, and are exclusively found in fair numbers below the OMZ. Similar observations have been made in other Arabian Sea studies (e.g. Jannink et al., 1998; den Dulk et al., 2000; Schumacher et al., 2007). In general, miliolids are rare or absent in oxygen deficient environments (e.g. Mullineaux and Lohmann, 1981; Nolet and Corliss, 1990; Jorissen et al., 1995) thereby implying that they could be more sensitive to oxygen stress compared to other species. In a study of two piston cores collected from 920 m and 1470 m, Den Dulk et al. (2000) suggested that a high abundance of miliolids could reflect periods of periodically increased BWO. In fact, Den Dulk et al. (2000) speculate that the percentage of miliolids could be a robust proxy for reconstructing past changes in bottom and pore-water oxygenation. However, miliolid tests, due their high Mg/Ca

ratio, are more sensitive to alkalinity changes of the bottom-water. Acidic bottom waters, such as those in the core of the OMZ potentially would result in the loss of these shells.

4.5 Vertical distribution

5 Generally, highest foraminiferal abundances are found in the first cm of the sediment. Towards deeper sites, with increased BWO and deeper oxygen and nitrate penetration into the sediment, the vertical range of the foraminiferal faunas increases. Only at the 885 m station, the density maximum was not found in the topmost level, but in the 1–1.5 cm interval, roughly corresponding to the depth of maximum nitrate penetration (Fig. 4). However, the very similar composition of the upper three half cm samples, with an absence of exclusively infaunal taxa, suggests that this deeper maximum could be an artifact, due to the mixing of the very soupy superficial sediment during sample retrieval. In the lower part of the OMZ (1172 to 1379 m), oxygen penetration is only 1 to 6 mm, whereas living foraminifera are present in fair numbers down to 2 to 5 cm depth. This maximum microhabitat depth roughly corresponds to the maximum depth of nitrate penetration (2.5 to 3.5 cm). At 1495 and 1791 m depths, substantial numbers of living foraminifera are found until 5 to 6 cm depth, much deeper than maximal oxygen and nitrate penetration. At the deepest sites, the living fauna tends to be limited to the upper 3 cm of the sediment. At 3010 m depth, the living faunas become very scarce below 3 cm, well above the limit of nitrate penetration. These species distribution may also be influenced by macrofaunal bioturbation, which may have transported some specimens below or above their preferential living-depth. However, both calcareous and agglutinated foraminifera show an exponential decrease in standing stock toward sediment-depth.

25 The distribution of calcareous and agglutinated foraminifera in the sediment appears to be systematically different. While the calcareous taxa are mainly concentrated in the first three cm (0–3 cm depth), the agglutinated species are mostly present down to 10 cm. In the core of the OMZ, *Bulimina exilis* and *Fursenkoina mexicana* display

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



clear infaunal maxima, the latter species occurring deeper than the first one (Fig. 4). At 885 m depth, *B. exilis* is present in maximum numbers in the 1.5–2 cm level, slightly deeper than the maximum nitrate penetration, whereas *F. mexicana* occurs between 1.5 and 3 cm depth, in completely anoxic conditions. Another *Fursenkoina* species is present at stations between 1791 and 2470 m, where it occurs in low numbers in a deep infaunal microhabitat, in completely anoxic sediments between 4 and 8 cm depth. Consistent with our study, *B. exilis*, *F. mexicana* and *Fursenkoina* sp. are mainly described as intermediate and deep infaunal taxa living below the oxygen penetration depth (Jorissen et al., 1998). *Melonis barleeanus* appears in fairly high numbers in intermediate infaunal microhabitats at all stations from 1495 to 3010 m depth. Its microhabitat depth mimics the oxygen penetration depth, and gradually deepens from 0 to 1 cm at 1495 m, 0.5/1 to 3 cm at 1791 and 1970 m, and 2 to 3 cm at 3010 m depth. The occurrence of *M. barleeanus* below the oxygen penetration depth and above the nitrate penetration depth is consistent with numerous previous studies (e.g. Jorissen et al., 1995, 1998; Koho, 2008; Mojtahid et al., 2010). It appears that this species is able to thrive in absence of oxygen as long as nitrate is present in the pore-water. The presence of intermediate and deep infaunal taxa in anoxic sediments could be explained by a facultative anaerobic metabolism of the concerned species. It is possible that in absence of oxygen, these taxa are able to shift to nitrate reduction. Such a facultative anaerobic metabolism is also envisaged for some of the species living in the core of the OMZ, where the BWO is very low. It has been demonstrated recently that many foraminiferal species accumulate intracellular nitrate in low-oxygen settings (Pina-Ochoa et al., 2009). However, until now, nitrate respiration has only been shown for a limited number of taxa (Risgaard-Petersen et al., 2006; Piña-Ochoa et al., 2010; Koho et al., 2011). Unfortunately, no measurements of denitrification rates have been performed for the dominant species of the Arabian Sea OMZ so that the possibility of an anaerobic metabolism of some of the dominant OMZ taxa remains speculative.

The agglutinated species here are mainly composed of *Reophax* species (*Reophax agglutinans*, *Reophax dentaliniformis*, *Reophax micaceus*) and *Lagenammmina difflugi-*

formis (Fig. 4). Unlike hyaline taxa, the distribution of these agglutinated taxa does not seem to follow a geochemical boundary. Instead their distribution appears to be independent of oxygen and nitrate penetration depth. Phipps (2012a) suggested that most agglutinated taxa have lower trophic requirements than calcareous taxa which would enable them to live in deeper, more food-limited sediment layers. Alternatively, some authors suggested that agglutinated species would prefer living deeper in the sediment to avoid competition with calcareous species (e.g., Buzas et al., 1989; Van der Zwaan et al., 1999; Gooday, 2003; Phipps, 2012a).

5 Conclusions

Foraminiferal standing stocks from the Murray Ridge do not show any clear correlation with any of the measured environmental parameters. This observation is inconsistent with previous studies from the Arabian Sea. The standing stocks appear to reflect a complex mix of the environmental parameters, which cannot be directly uncoupled here.

The diversity of benthic foraminifera change with bottom water oxygenation. The lowest diversities are generally seen in the core of the OMZ and the highest in the lower part of the OMZ and the deeper more ventilated sites. The prevailing, extremely low oxygen concentrations in the core of the OMZ ($BWO \pm 2 \mu M$) may limit the occurrence of species in this zone, leading to low diversity assemblage

Agglutinated foraminifera form a dominant part of the foraminiferal assemblage in the Murray Ridge. Up to 72 % of the species assemblage is made of agglutinated taxa. Their distribution seems independent of the BWO and they are present in all sites, including the core of the OMZ. Therefore, agglutinated foraminifera appear to be equally tolerant to oxygen depletion than hyaline taxa. In the Murray Ridge, the dominance of agglutinated taxa may be related to relatively corrosive bottom water conditions as a result of enhanced organic matter cycling, limiting the occurrence of hyaline species. In

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



addition, the agglutinated foraminifera may be favoured by the relatively refractory OM present in the lower OMZ and at the more oxic sites.

Three clear foraminiferal zones were observed across the study transect: (i) species inhabiting the core of the OMZ, (ii) species observed in the transitional zone, including the lower part of the OMZ and the dysoxic area, (iii) species found in the relatively oxic sites. The distribution of these groups is closely tied to environmental parameters, including redox conditions and food availability. In further application, these three groups can be used to reconstruct the OMZ dynamics in the Arabian Sea.

Supplementary material related to this article is available online at
[http://www.biogeosciences-discuss.net/10/15257/2013/
bgd-10-15257-2013-supplement.zip](http://www.biogeosciences-discuss.net/10/15257/2013/bgd-10-15257-2013-supplement.zip).

Acknowledgements. Ship time on R/V *Pelagia* was provided by the PASOM project financed by the Netherlands Organization for Scientific Research (NWO; grant number 817.01.015). We are very grateful to the SCIAM laboratory for the foraminiferal SEM images. The second author acknowledges NWO-ALW (Earth and Life sciences council) for funding (grant number 820.01.011 to G. J van der Zwaan).



The publication of this article
is financed by CNRS-INSU.

References

Banse, K.: Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea, *Deep-Sea Res.*, 34, 713–723, 1987.

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Banse, K. and McClain, C. R.: Winter blooms of phytoplankton in the Arabian Sea as observed by the Coastal Zone Colour Scanner, *Mar. Ecol.-Prog. Ser.*, 34, 201–211, 1986.
- Barranguet, C., Kromkamp, J., and Peene, J.: Factors controlling primary production and photosynthetic characteristics of intertidal microphytobenthos, *Mar. Ecol.-Prog. Ser.*, 173, 117–126, 1998.
- Bernhard, J. M.: Postmortem Vital Staining in Benthic Foraminifera; Duration and Importance in Population and Distributional Studies, *J. Foramin. Res.*, 18, 143–146, doi:10.2113/gsjfr.18.2.143, 1988.
- Bernhard, J. M. and Sen Gupta, B.: Foraminifera of oxygen-depleted environments, in: *Modern Foraminifera*, edited by: Sen Gupta, B., Kluwer Academic, Dordrecht, 200–216, 1999.
- Bernhard, J. M.: Distinguishing Live from Dead Foraminifera: Methods Review and Proper Applications, *Micropaleontology*, 46, 38–46, doi:10.2307/1486179, 2000.
- Berger, W. H.: Planktonic foraminifera: Selective solution and lysocline, *Mar. Geol.*, 8, 111–138, 1970.
- Burkill, P. H., Mantoura, R. F. C., and Owens, N. J. P.: Biogeochemical cycling in the northwestern Indian Ocean: a brief overview, *Deep-Sea Res. Pt. II*, 40, 643–649, 1993.
- Buzas, M. A., Collins, L. S., Richardson, S. L., and Severin, K. P.: Experiments on predation, substrate preference, and colonization of benthic foraminifera at the shelfbreak off the Ft. Pierce Inlet, Florida, *J. Foramin. Res.*, 19, 146–152, 1989.
- Caralp, M. H.: Abundance of *Bulimina exilis* and *Melonis barleeaanum*: relationship to the quality of organic matter, *Geo-Mar. Lett.*, 9, 37–43, 1989.
- Caron, D. A. and Dennett, M. R.: Phytoplankton growth and mortality during the 1995 northeast monsoon and spring intermonsoon in the Arabian Sea, *Deep-Sea Res. Pt. II*, 46, 1665–1690, 1999.
- Corliss, B. H.: Distribution of Holocene deep-sea benthonic foraminifera in the southwest Indian Ocean, *Deep-Sea Res.*, 30, 95–117, 1983b.
- Corliss, B. H. and Emerson, S.: Distribution of Rose Bengal stained deep-sea benthic foraminifera from the Nova Scotian continental margin and Gulf of Maine, *Deep-Sea Res.*, 37, 381–400, 1990.
- Cowie, G.: The biogeochemistry of Arabian Sea surficial sediments: A review of recent studies, *Prog. Oceanogr.*, 65, 260–289, doi:10.1016/j.pocean.2005.03.003, 2005.
- Den Dulk, M., Reichart, G. J., Memon, G. M., Roelofs, E. M. P., Zachariasse, W. J., and van der Zwaan, G. J.: Benthic foraminiferal response to variations in surface water pro-

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

ductivity and oxygenation in the northern Arabian Sea, *Mar. Micropaleontol.*, 35, 43–66, doi:10.1016/S0377-8398(98)00015-2, 1998.

Den Dulk, M., Reichart, G., van Heyst, S., Zachariasse, W., and Van der Zwaan, G.: Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 161, 337–359, doi:10.1016/S0031-0182(00)00074-2, 2000.

Erbacher, J. and Nelskamp, S.: Comparison of benthic foraminifera inside and outside a sulphur-oxidizing bacterial mat from the present oxygen-minimum zone off Pakistan (NE Arabian Sea), *Deep Sea Res. Pt. I*, 53, 751–775, doi:10.1016/j.dsr.2006.02.003, 2006.

Fontanier, C., Jorissen, F. J., Chaillou, G., Anschutz, P., Grémare, A., and Griveaud, C.: Live foraminiferal faunas from a 2800 m deep lower canyon station from the Bay of Biscay: Faunal response to focusing of refractory organic matter, *Deep Sea Res. Pt. I*, 52, 1189–1227, doi:10.1016/j.dsr.2005.01.006, 2005.

Gofas, S.: Une approche du paléoenvironnement océanique: les foraminifères benthiques calcaires traceurs de la circulation abyssale, Ph.D. thesis, University of Western Brittany, France, 1978.

Gooday, A. J.: Epifaunal and shallow infaunal foraminiferal communities at three abyssal NE Atlantic sites subject to differing phytodetritus input regimes, *Deep-Sea Res. Pt. I*, 43, 1395–1421, 1996.

Gooday, A. J.: Benthic foraminifera (Protista) as tools in deep-water palaeoceanography: a review of environmental influences on faunal characteristic, *Adv. Mar. Biol.*, 46, 1–90, 2003.

Gooday, A. J. and Jorissen, F. J.: Benthic Foraminiferal Biogeography: Controls on Global Distribution Patterns in Deep-Water Settings, *Annual Review of Marine Science*, 4, 237–262, doi:10.1146/annurev-marine-120709-142737, 2012.

Gooday, A. J., Bernhard, J. M., Levin, L. A., and Suhr, S. B.: Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas, *Deep Sea Res. Pt. II*, 47, 25–54, doi:10.1016/S0967-0645(99)00099-5, 2000.

Gooday, A. J., Kitazato, H., Hori, S., and Toyofuku, T.: Monothalamous Soft-Shelled Foraminifera at an Abyssal Site in the North Pacific: A Preliminary Report, *J. Oceanogr.*, 57, 377–384, doi:10.1023/A:1012447015771, 2001.

Gooday, A. J., Levin, L. A., Aranda da Silva, A., Bett, B. J., Cowie, G. L., Dissard, D., Gage, J. D., Hughes, D. J., Jeffreys, R., Lamont, P. A., Larkin, K. E., Murty, S. J., Schumacher, S.,

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Whitcraft, C. and Woulds, C.: Faunal responses to oxygen gradients on the Pakistan margin: A comparison of foraminiferans, macrofauna and megafauna, *Deep-Sea Res. Pt. II*, 56, 488–502, doi:10.1016/j.dsr2.2008.10.003, 2009.

5 Hammer, Ø., Harper, D., and Ryan, P. D.: PAST: Palaeontological statistics software package for education and data analysis, *Palaeontol. Electron.*, 4, 1–9, 2001.

Haake, B., Ittekkot, V., Rixen, T., Ramaswamy, V., Nair, R. R., and Curry, W. B.: Seasonality and interannual variability of particle fluxes to the deep Arabian Sea, *Deep-Sea Res.*, 40, 1323–1344, 1993.

10 Heinz, P. and Hemleben, C.: Regional and seasonal variations of recent benthic deep-sea foraminifera in the Arabian Sea, *Deep-Sea Res. Pt. I*, 50, 435–447, doi:10.1016/S0967-0637(03)00014-1, 2003.

Heinz, P. and Hemleben, C.: Foraminiferal response to the Northeast Monsoon in the western and southern Arabian Sea, *Mar. Micropaleontol.*, 58, 103–113, doi:10.1016/j.marmicro.2005.10.001, 2006.

15 Helly, J. J. and Levin, L. A.: Global distribution of naturally occurring marine hypoxia on continental margins, *Deep-Sea Res. Pt. I*, 51, 1159–1168, doi:10.1016/j.dsr.2004.03.009, 2004.

Hermelin, J. O. R. and Shimmield, G. B.: The importance of the oxygen minimum zone and sediment geochemistry in the distribution of Recent benthic foraminifera in the northwest Indian Ocean, *Mar. Geol.*, 91, 1–29, 1990.

20 Jannink, N. T., Zachariasse, W. J., and Van der Zwaan, G. J.: Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea), *Deep-Sea Res. Pt. I*, 45, 1483–1513, doi:10.1016/S0967-0637(98)00027-2, 1998.

Jones, R. W.: *The Challenger Foraminifera*, Oxford University Press, Oxford, New-York. Tokyo, 149 pp., 1994.

25 Jorissen, F. J., de Stigter, H. C., and Widmark, J. G. V.: A conceptual model explaining benthic foraminiferal microhabitats, *Mar. Micropaleontol.*, 26, 3–15, doi:10.1016/0377-8398(95)00047-X, 1995.

Jorissen, F. J., Wittling, I., Peypouquet, J. P., Rabouille, C., and Relexans, J. C.: Live benthic foraminiferal faunas off Cape Blanc, NW-Africa: Community structure and microhabitats, *Deep-Sea Res. Pt. I*, 45, 2157–2188, doi:10.1016/S0967-0637(98)00056-9, 1998.

30 Jorissen, F. J., Fontanier, C., and Thomas, E.: Chapter Seven Paleoceanographical Proxies Based on Deep-Sea Benthic Foraminiferal Assemblage Characteristics, in: *Developments in Marine Geology*, vol. 1, edited by: Hillaire, C. and De Vernal, M. and A., 263–325, Elsevier,

available at: <http://www.sciencedirect.com/science/article/pii/S1572548007010123>, (last access: 14 August 2013), 2007.

Koho, K. A.: The dynamic balance between food abundance and habitat instability: benthic foraminifera of Portuguese margin canyons, 2008.

5 Koho, K. A., Piña-Ochoa, E., Geslin, E., and Risgaard-Petersen, N.: Vertical migration, nitrate uptake and denitrification: survival mechanisms of foraminifers (*Globobulimina turgida*) under low oxygen conditions, *FEMS Microbiol. Ecol.*, 75, 273–283, 2011.

Koho, K. A., Nierop, K. G. J., Moodley, L., Middelburg, J. J., Pozzato, L., Soetaert, K., van der Plicht, J., and Reichart, G.-J.: Microbial bioavailability regulates organic matter preservation in marine sediments, *Biogeosciences*, 10, 1131–1141, doi:10.5194/bg-10-1131-2013, 2013.

10 Kraal, P., Slomp, C. P., Reed, D. C., Reichart, G.-J., and Poulton, S. W.: Sedimentary phosphorus and iron cycling in and below the oxygen minimum zone of the northern Arabian Sea, *Biogeosciences*, 9, 2603–2624, doi:10.5194/bg-9-2603-2012, 2012.

15 Kurbjeweit, F., Schmiedl, G., Schiebel, R., Hemleben, C., Pfannkuche, O., Wallmann, K., and Schäfer, P.: Distribution, biomass and diversity of benthic foraminifera in relation to sediment geochemistry in the Arabian Sea, *Deep Sea Res. Pt. II*, 47, 2913–2955, doi:10.1016/S0967-0645(00)00053-9, 2000.

Lagoe, M. L.: Recent benthic foraminifera from the Central Arctic Ocean, *J. Foramin. Res.*, 7, 106–129, 1977.

20 Larkin, K. E. and Gooday, A. J.: Foraminiferal faunal responses to monsoon-driven changes in organic matter and oxygen availability at 140 and 300 m water depth in the NE Arabian Sea, *Deep Sea Res. Pt. II*, 56, 403–421, doi:10.1016/j.dsr2.2008.05.037, 2009.

Levin, L.: Oxygen minimum zone benthos: adaptation and community response to hypoxia, 2003.

25 Levin, L. A., Gage, J. D., Martin, C., and Lamont, P. A.: Macrobenthic community structure within and beneath the oxygen minimum zone, NW Arabian Sea, *Deep Sea Res. Pt. II*, 47, 189–226, doi:10.1016/S0967-0645(99)00103-4, 2000.

Loeblich, Jr., A. R. and Tappan, H.: Foraminiferal Genera and their classification, Van Nostrand Rheinhold Company, New York, 970 pp., 1988.

30 Lutze, G. J.: *Uvigerina* species of the eastern North Atlantic, in: Atlantic-European Oligocene to Recent *Uvigerina*, edited by: Van der Zwaan, G. J., Jorissen, F. J., Verhакten, P. J. J. M., and von Daniels, C. H., *Utrecht Micropaleontological Bulletins*, 35, 21–46, 1986.

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Live foraminiferal
faunas from the
northern Arabian Sea**

C. Cauille et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Lutze, G. F. and Coulbourn, W. T.: Recent benthic foraminifera from the continental margin of northwest Africa: Community structure and distribution, *Mar. Micropaleontol.*, 8, 361–401, 1984.

5 Maas, M.: Verbreitung lebendgefärbter benthischer Foraminiferen in einer intensivierten Sauerstoffminimumzone, Indo-Pakistanischer Kontinentalrand, nördliches Arabisches Meer (Distribution of Rose Bengal stained benthic foraminifera within an intensified oxygen minimum zone, Indo-Pakistan Continental Margin, Northwest Arabian Sea), *Meyniana*, 52, 101–128, 2000.

10 Mackensen, A., Schmiedl, G., Harloff, J., and Giese, M.: Deep-sea foraminifera in the Southern Atlantic Ocean: ecology and assemblage generation, *Micropaleontology*, 41, 342–358, 1995.

Madhupratap, M., Prasanna Kumar, S., Bhattahiri, P. M. A., Dileep Kumar, M., Raghukumar, S., Nair, K. K. C., and Ramaiah, N.: Mechanisms of the biological response to winter cooling in the northeastern Arabian Sea, *Nature*, 483, 549–552, 1996.

15 Middelburg, J. J. and Levin, L. A.: Coastal hypoxia and sediment biogeochemistry, *Biogeochemistry*, 6, 1273–1293, doi:10.5194/bg-6-1273-2009, 2009.

Mojtahid, M., Jorissen, F., Lansard, B., Fontanier, C., Bombled, B., and Rabouille, C.: Spatial distribution of live benthic foraminifera in the Rhône prodelta: Faunal response to a continental–marine organic matter gradient, *Mar. Micropaleontol.*, 70, 177–200, doi:10.1016/j.marmicro.2008.12.006, 2009.

20 Mojtahid, M., Griveaud, C., Fontanier, C., Anschutz, P., and Jorissen, F. J.: Live benthic foraminiferal faunas along a bathymetrical transect (140–4800 m) in the Bay of Biscay (NE Atlantic), *Revue de Micropaléontologie*, 53, 139–162, doi:10.1016/j.revmic.2010.01.002, 2010.

Moodley, L., van der Zwaan, G. J., Herman, P. M. J., Kempers, L., and van Breugel, P.: Differential response of benthic meiofauna to anoxia with special reference to Foraminifera (Protista: Sarcodina), *Mar. Ecol.-Prog. Ser.*, 158, 151–163, 1997.

25 Morigi, C., Jorissen, F. J., Gervais, A., Guichard, S., and Borsetti, A. M.: Benthic foraminiferal faunas in surface sediments off NW Africa: Relationship with the organic flux to the ocean floor, *J. Foramin. Res.*, 31, 350–368, 2001.

30 Mullineaux, L. S. and Lohmann, G. P.: Late Quaternary Stagnations and recirculation of the eastern Mediterranean: Changes in the deep water recorded by fossil benthic foraminifera, *J. Foramin. Res.*, 11, 20–39, 1981.

Murray, J. W., Weston, J. F., Haddon, C. A., and Powell, A. D. J.: Miocene to recent bottom water masses of the north-east Atlantic: An analysis of benthic foraminifera, in: *North Atlantic*

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Palaeoceanography, edited by: Summerhayes C. P. and Shackleton, N. J., 21, 219–230, London, special Publication of the Geological Society, 1986.

Naidu, P. D. and Malmgren, B. A.: Do benthic foraminifer records represent a productivity index in oxygen minimum zone areas? An evaluation from the Oman Margin, Arabian Sea, Mar. Micropaleontol., 26, 49–55, 1995.

Nair, R. R., Ittekkot, V., Manganini, S. J., Ramaswamy, V., Haake, B., Degens, E. T., Desai, B. N., and Honjo, S.: Increased particle flux to the deep ocean related to monsoons, Nature, 338, 749–751, 1989.

Neira, C., Sellanes, J., Levin, L. A., and Arntz, W. E.: Meiofaunal distributions on the Peru margin:: relationship to oxygen and organic matter availability, Deep Sea Res. Pt. I, 48, 2453–2472, doi:10.1016/S0967-0637(01)00018-8, 2001.

Nolet, G. J. and Corliss, B. H.: Benthic foraminiferal evidence for reduced deep-water circulation during sapropel deposition in the eastern Mediterranean, Mar. Geol., 94, 109–130, 1990.

Ohga, T. and Kitazato, H.: Seasonal changes in bathyal foraminiferal populations in response to the flux of organic matter (Sagami Bay, Japan), Terra Nova, 9, 33–37, 1997.

Olson, D. B., Hitchcock, G. L., Fine, R. A., and Warren, B. A.: Maintenance of the low-oxygen layer in the central Arabian Sea, Deep-Sea Res. Pt. II, 40, 673–685, 1993.

Paulmier, A. and Ruiz-Pino, D.: Oxygen minimum zones (OMZs) in the modern ocean, Prog. Oceanogr., 80, 113–128, doi:10.1016/j.pocean.2008.08.001, 2009.

Peterson, L. C.: Recent abyssal benthic foraminiferal biofacies of the eastern Equatorial Indian Ocean, Mar. Micropaleontol., 8, 479–519, 1984.

Phipps, M. D.: Les foraminifères benthiques de la marge portugaise: Impact des apports organiques sur la densité, la biodiversité et la composition des faunes, Ph.D. thesis, University of Angers, France, 2012a.

Phipps, M., Jorissen, F., Pusceddu, A., Bianchelli, S., and Stigter, H. D.: Live Benthic Foraminiferal Faunas Along a Bathymetrical Transect (282–4987 M) on the Portuguese Margin (ne Atlantic), J. Foramin. Res., 42, 66–81, doi:10.2113/gsjfr.42.1.66, 2012.

Piña-Ochoa, E., Høglund, S., Geslin, E., Cedhagen, T., Revsbech, N. P., Nielsen, L. P., Schweizer, M., Jorissen, F., Rysgaard, S., and Risgaard-Petersen, N.: Widespread occurrence of nitrate storage and denitrification among Foraminifera and Gromiida, P. Natl. Acad. Sci. USA, 107, 1148–1153, doi:10.1073/pnas.0908440107, 2009.

Piña-Ochoa, E., Høglund, S., Geslin, E., Cedhagen, T., Revsbech, N. P., Nielsen, L. P., Schweizer, M., Jorissen, F., Rysgaard, S., and Risgaard-Petersen, N.: Widespread occur-

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- rence of nitrate storage and denitrification among Foraminifera and Gromiida, *P. Natl. Acad. Sci. USA*, 107, 1148–1153, 2010.
- Rao, R. R., Molinari, R. L., and Festa, J. F.: Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean. 1. Description of mean monthly mixed layer depth, and sea-surface temperature, surface current, and surface meteorological fields, *J. Geophys. Res.*, 94, 10801–10815, 1989.
- Reichart, G. J., den Dulk, M., Visser, H. J., van der Weijden, C. H., and Zachariasse, W. J.: A 225 kyr record of dust supply, paleoproductivity and the oxygen minimum zone from the Murray Ridge (northern Arabian Sea), *Palaeogeography, Palaeoclimatology, Palaeoecology*, 134, 149–169, doi:10.1016/S0031-0182(97)00071-0, 1997.
- Reichart, G. J., Lourens, L. J., and Zachariasse, W. J.: Temporal variability in the northern Arabian Sea oxygen minimum zone (OMZ) during the last 225,000 years, *Paleoceanography*, 13, 607–621, doi:10.1029/98PA02203, 1998.
- Risgaard-Petersen, N., Langezaal, A. M., Ingvarsdson, S., Schmid, M. C., Jetten, M. S. M., Op den Camp, H. J. M., Derksen, J. W. M., Piña-Ochoa, E., Eriksson, S. P., Peter Nielsen, L., Peter Revsbech, N., Cedhagen, T., and van der Zwaan, G. J.: Evidence for complete denitrification in a benthic foraminifer, *Nature*, 443, 93–96, doi:10.1038/nature05070, 2006.
- Rixen, T., Haake, B., Ittekkot, V., Guptha, M. V. S., Nair, R. R., and Schlüssel, P.: Coupling between SW monsoon-related surface and deep-ocean processes as discerned from continuous particle flux measurements and correlated satellite data, *J. Geophys. Res.*, 101, 28569–28582, 1996.
- Rixen, T., Ittekkot, V., Haake-Gaye, B., and Schäfer, P.: The influence of the SW monsoon on the deep-sea organic carbon cycle in the Holocene, *Deep-Sea Res. Pt. II*, 47, 2629–2651, 2000.
- Ryther, J. H. and Menzel, D. W.: On the production, composition and distribution of organic matter in the western Arabian Sea, *Deep-Sea Res. Pt. I*, 12, 199–209, 1965.
- Schiebel, R.: Rezente benthische Foraminiferen in Sedimenten des Schelfes und oberen Kontinentalhanges im Golf von Guinea (Westafrika) (Recent benthic foraminifera in sediments of the shelf and upper continental slope from the Gulf of Guinea (West Africa)), *Berichte-Reports Geologisches und Paläontologisches Institut des Universität Kiel*, 59, 1–179, 1992.
- Schmiedl, G.: Rekonstruktion des spätquartären Tiefenwasserzirkulation und Produktivität im östlichen Südatlantik anhand benthischer Foraminiferen (Late Quaternary benthic

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[◀](#)

[▶](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- foraminiferal assemblages from the eastern South Atlantic Ocean: reconstruction of deep water circulation and productivity changes), *Berichte zur Polarforschung*, 160, 1–207, 1995.
- Schmiedl, G. and Leuschner, D. C.: Oxygenation changes in the deep western Arabian Sea during the last 190,000 years: Productivity versus deepwater circulation, *Paleoceanography*, 20, 1–14, doi:10.1029/2004PA001044, 2005.
- Schmiedl, G. and Mackensen, A.: Late Quaternary paleoproductivity and deep water circulation in the eastern South Atlantic Ocean: Evidence from benthic foraminifera, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 130, 43–80, 1997.
- Schmiedl, G., Mackensen, A., and Müller, P. J.: Recent benthic foraminifera from the eastern South Atlantic Ocean: dependence on food supply and water masses, *Mar. Micropaleontol.*, 32, 249–287, 1997.
- Schönfeld, J.: Taxonomy and Distribution of the *Uvigerina Peregrina* Plexus in the Tropical to Northeastern Atlantic, *J. Foramin. Res.*, 36, 355–367, doi:10.2113/gsjfr.36.4.355, 2006.
- Schumacher, S., Jorissen, F. J., Dissard, D., Larkin, K. E., and Gooday, A. J.: Live (Rose Bengal stained) and dead benthic foraminifera from the oxygen minimum zone of the Pakistan continental margin (Arabian Sea), *Mar. Micropaleontol.*, 62, 45–73, doi:10.1016/j.marmicro.2006.07.004, 2007.
- Shetye, S. R., Gouveia, A. D., and Shenoi, S. S. C.: Circulation and water masses of the Arabian Sea, in: *Biogeochemistry of the Arabian Sea*, edited by: Lal, D., Indian Academy of Sciences, Bagalore, 9–25, 560 080 India, 1994.
- Stubbings, H. C.: The marine deposits of the Arabian Sea. An investigation into their distribution and biology, *Scientific Reports of the John Murray Expedition 1933–34*, 3, 31–158, 1939.
- Swallow, J. C.: Some aspects of the physical oceanography of the Indian Ocean, *Deep-Sea Res.*, 31, 639–650, 1984.
- Timm, S.: Rezente Tiefsee-Benthosforaminiferen aus Oberflächensedimenten des Golfes von Guinea (Westafrika) – Taxonomie, Verbreitung, Ökologie und Korngrößenfraktion, *Berichte – Reports, Geologisches und Paläontologisches Institut des Universität Kiel*, 59, 1–192, 1992.
- Van der Weijden, C. H., Reichart, G. J., and Visser, H. J: Enhanced perservation of organic matter in sediments deposited within the oxygen minimum zone in the northeastern Arabian Sea, *Deep-Sea Res.*, 46, 807–830, 1999.
- Van der Zwaan, G. J., Jorissen, F. J., Verhallen, P. J. J. M., and von Daniels, C. H.: *Uvigerina* from the Eastern Atlantic, North Sea Basin, Paratethys and Mediterranean, in: *Atlantic-European Oligocene to Recent Uvigerina*, edited by: Van der Zwaan, G. J., Jorissen, F. J.,

Verhallen, P. J. J. M., and von Daniels, C. H., Utrecht Micropaleontological Bulletins, 35, 7–19, 1986.

Van Leeuwen, R. J. W.: Sea-floor distribution and Late Quaternary faunal patterns of planktonic and benthic foraminifers in the Angola Basin, Utrecht Micropaleontological Bulletins, 38, 755–776, 1989.

Walton, W. R.: Techniques for recognition of living foraminifera, Contribution Cushman Foundation of Foraminiferal Research, 3, 56–60, 1952.

Weston, J. F.: Distribution and ecology of Recent Deep Sea benthic foraminifera in the North-east Atlantic Ocean, Ph.D thesis, University of Exeter, England, 1982.

Wyrтки, K.: Physical oceanography of the Indian Ocean, in: the Biology of the Indian Ocean, edited by: Zeitschel, B., Springer, Berlin, 18–36, 1973.

Zobel, B.: Biostratigraphische Untersuchungen an Sedimenten des indisch-pakistanischen Kontinentalrandes (Arabisches Meer), "Meteor" Forsch.-Ergebnisse, C(12), 9–73, 1973.

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



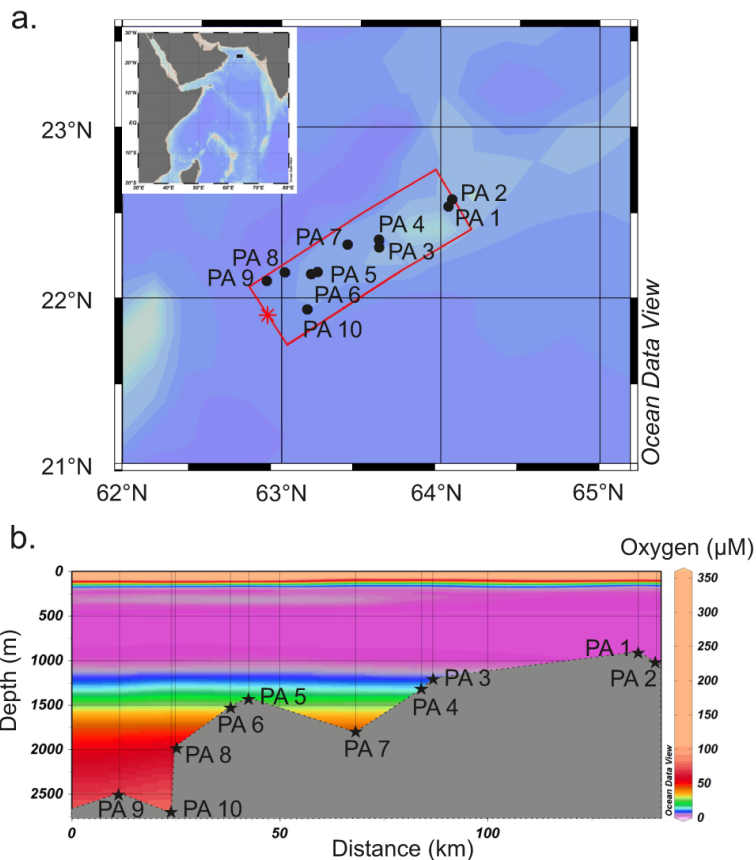
[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Fig. 1. (a) Study area and stations location on the Murray ridge, northern Arabian Sea. The red square correspond to the bathymetric – oxygen transect in **(b)**. **(b)** Water depths of the studied stations and their location within the bottom water oxygenation transect (CTD oxygen values from this study). The seafloor line was extrapolated between stations.

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

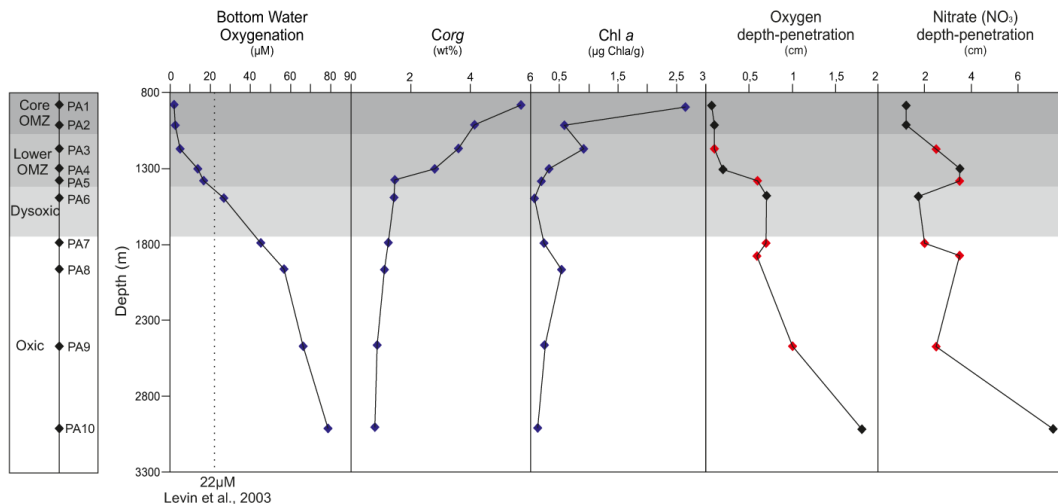


Fig. 2. Environmental parameters: bottom-water oxygenation, organic carbon (C_{org} ; 0–1 cm), chlorophyll *a* (Chl *a*, 0–1 cm), oxygen and nitrate penetration-depths. In red: the results from this study; In blue: The results published in Koho et al. (2013); in black: The results published in Kraal et al. (2012).

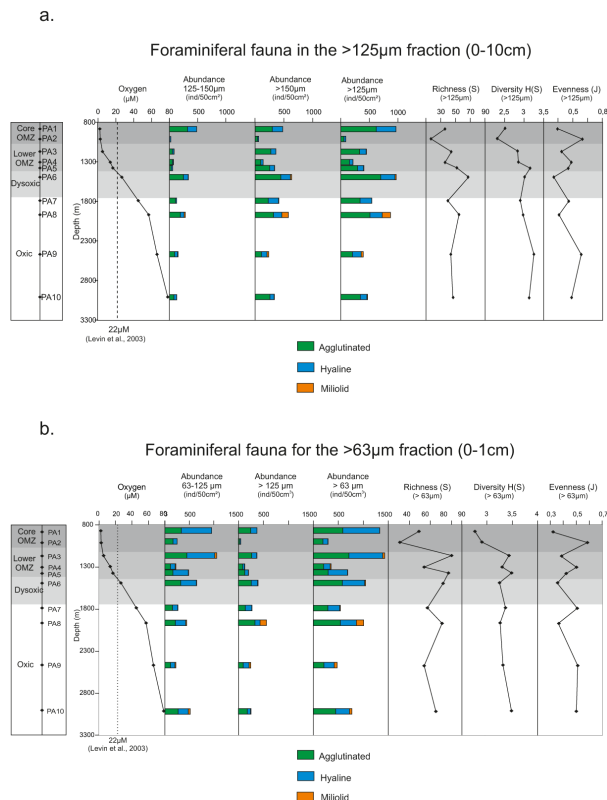


Fig. 3. (a) Live (Rose Bengal stained) foraminiferal abundances (individuals/50 cm²) in the 125–150 μ m, > 150 μ m and > 125 μ m fraction for the entire core (0–10 cm) and foraminiferal biodiversity indices (in the > 125 μ m fraction) along the sampling transect. (b) Live foraminiferal abundances (individuals/50 cm²) in the 63–125 μ m, > 125 μ m, > 63 μ m fractions for the first cm (0–1 cm) of the sediment and foraminiferal biodiversity indices (in the > 63 μ m fraction) along the sampling transect.

BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

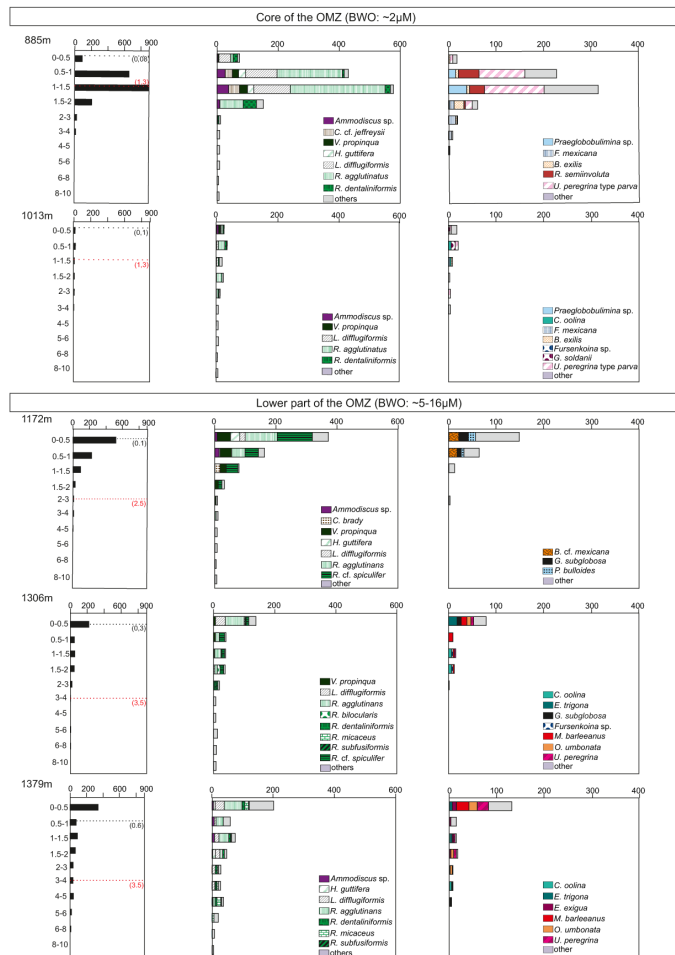


Fig. 4. (Caption on p. 42.)

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
◀ ▶
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



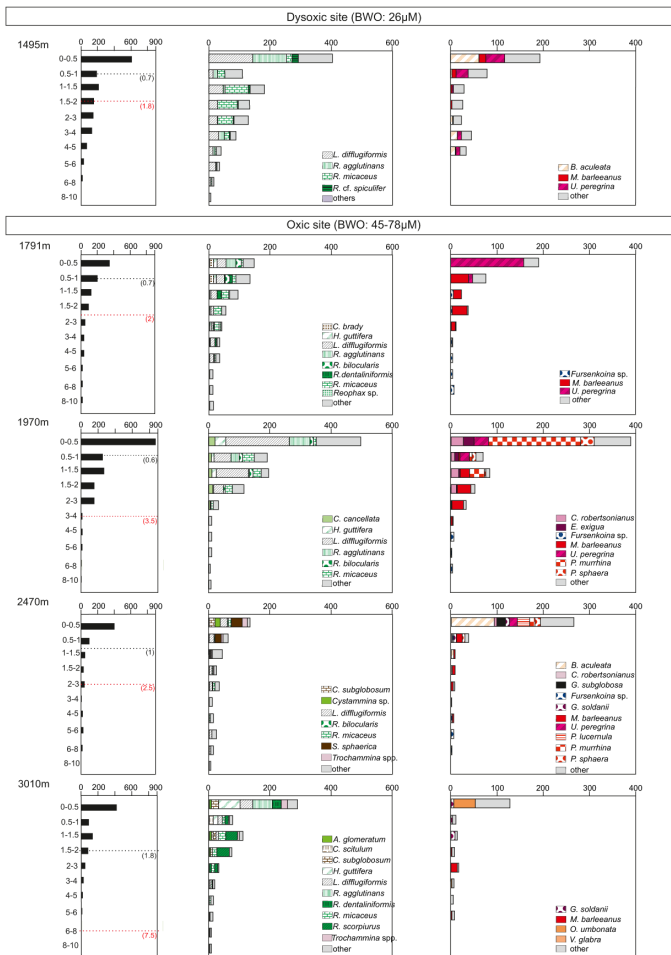


Fig. 4. (Caption on next page.)

[Title Page](#)

[Abstract](#) [Introduction](#)

[Conclusions](#) [References](#)

[Tables](#) [Figures](#)

[◀](#) [▶](#)

[◀](#) [▶](#)

[Back](#) [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



BGD

10, 15257–15304, 2013

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Fig. 4. Vertical densities (individuals/50 cm³) and abundances (individuals/50 cm³) of the dominant live foraminiferal species (> 2 % for each station) in the > 125 μm fraction. The first panel represents the total foraminiferal densities. The black dotted line refers to the oxygen limit penetration (cm) into the sediment, and the red dotted line to the nitrate depth penetration (cm). The second panel represents the vertical distribution of the dominant agglutinated taxa. The third panel represents the vertical distribution of the dominant hyaline and milioid taxa. Species of same gender were grouped under the same color. Note the different horizontal scale between panels.

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

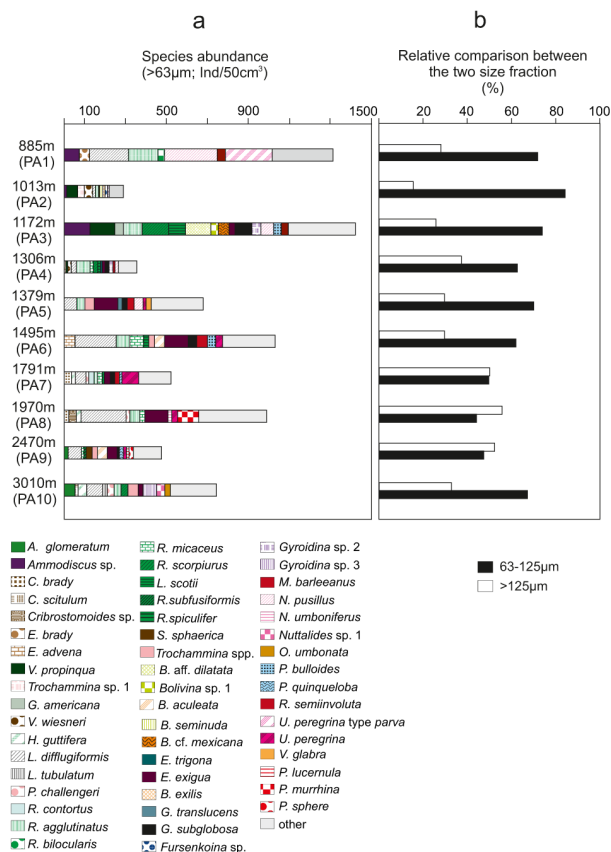


Fig. 5. (a) Species composition and abundance (individuals/50 cm³) in the > 63 µm fraction (sum of > 125 µm and 63–125 µm) for the upper centimeter of the sediment. Species of same gender were grouped under the same color consistent with Fig. 4; **(b)** Relative abundances comparison between the two size fractions (63–125 µm and > 125 µm).



Title Page

Abstract Introduction

Conclusions References

Tables Figures

Navigation: Previous, Next, Home, Search

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

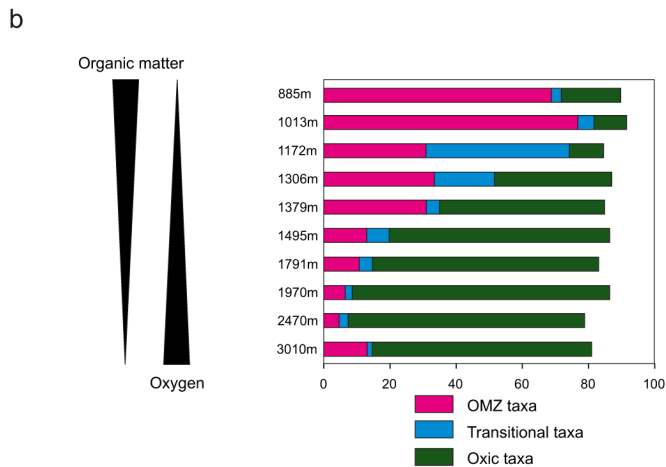
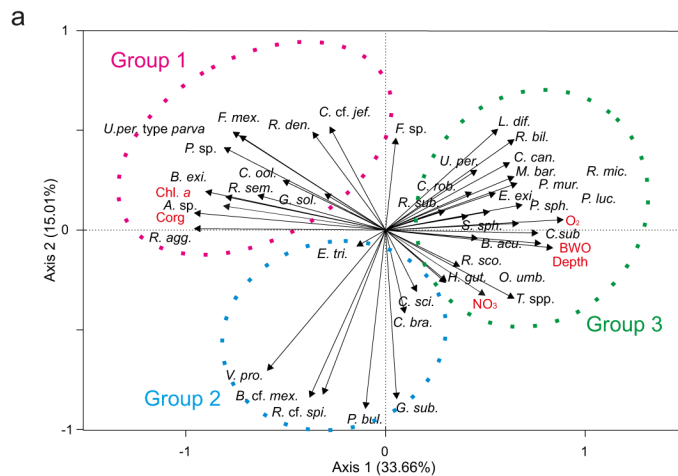


Fig. 6. (Caption on next page.)

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Fig. 6. (a) PCA plot based on the relative abundances of the dominant species (> 2% in at least one sample) for the entire core (0–10 cm) in the > 125 μm size fraction, together with geochemical data: chlorophyll a (Chl a), organic carbon (C_{org}), bottom-water oxygenation (**BWO**), oxygen depth-penetration (O_2), nitrate depth-penetration (NO_3) and water depths. **(b)** Plot of the percentages of the three defined groups at the different sites. Abbreviation: Group 1: *Ammodiscus* sp. (**A. sp.**), *Bulimina exilis* (**B. exi.**), *Chilostomella oolina* (**C. ool.**), *Cribrostomoides* cf. *jeffreysii* (**C.cf. jef.**), *Fursenkoina Mexicana* (**F. mex.**), *Gyroidina soldani* (**G. sol.**), *Praeglobobulimina* sp. (**P. sp.**), *Reophax agglutinans* (**R. agg.**), *Reophax dentaliniformis* (**R. den.**), *Rotaliatinopsis semiinvoluta* (**R. sem.**), *Uvigerina peregrina* type *parva* (**U. per. type parva**). Group 2: *Bulimina* cf. *mexicana* (**B. cf. mex.**), *Cribrostomoides bradyi* (**C. bra.**), *Cribrostomoides scitulum* (**C. sci.**), *Ehrenbergina trigona* (**E. tri.**), *Globocassidulina subglobosa* (**G. sub.**), *Pullenia bulloides* (**P. bul.**), *Reophax* cf. *spiculifer* (**R. cf. spi.**), *Verneuilinulla propinqua* (**V. pro**). Group 3: *Bulimina aculeata* (**B. acu.**), *Cibidoides robertsonianus* (**C. rob.**), *Cribrostomoides subglobosus* (**C. sub.**), *Cyclamina cancellata* (**C. can.**), *Epistominella exigua* (**E. exi.**), *Hormosina guttifer* (**H. gut.**), *Lagenammia difflugiformis* (**L. dif.**), *Melonis barleeanus* (**M. bar.**), *Oridorsalis umbonata* (**O. umb.**), *Pyrgo lucernula* (**P. luc.**), *Pyrgo murrhina* (**P. mur.**), *Pyrgoella sphaera* (**P. sph.**), *Reophax bilocularis* (**R. bil.**), *Reophax micaceus* (**R. mic.**), *Reophax scorpiurus* (**R. sco.**), *Reophax subsufisiformis* (**R. sub.**), *Saccammina sphaerica* (**S. sph.**), *Trochammina* spp. (**T. spp.**), *Uvigerina peregrina* (**U. per.**).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

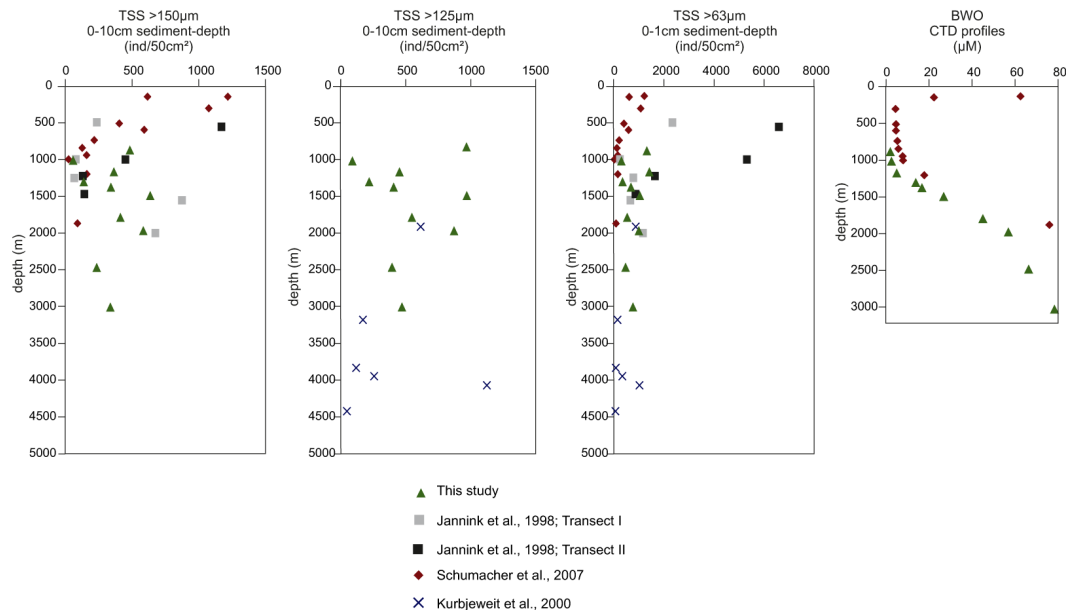


Fig. 7. Foraminiferal abundance (individuals/50 cm³) and BWO comparisons with previous studies from the Arabian Sea (Jannink et al., 1998; Kurbjeweit et al., 2000; Schumacher et al., 2007). Note the scale difference.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



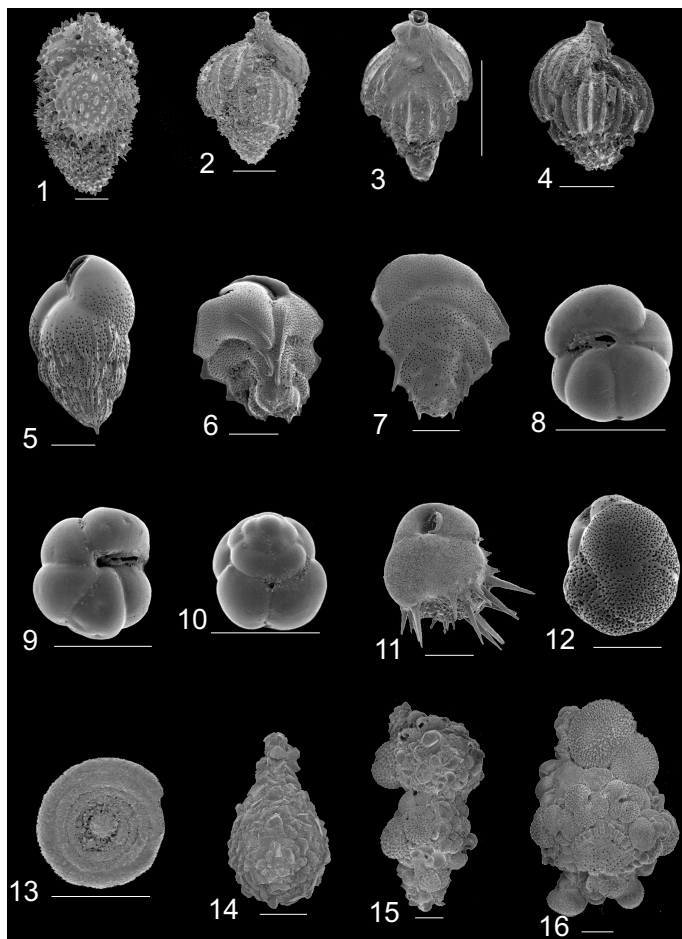


Fig. 8. (Caption on next page.)

Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Live foraminiferal faunas from the northern Arabian Sea

C. Cauille et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 8. SEM pictures of the main foraminiferal taxa. Scale bar = 100 μm . 1: *Uvigerina auberiana* (d'Orbigny 1839), PA8 (1–1.5 cm), > 150 μm . Regrouped with *Uvigerina peregrina* s.s. under *U. peregrina*. 2: *Uvigerina peregrina* s.s (Cushman 1923), PA8 (1–1.5 cm), > 150 μm 3–4: *Uvigerina peregrina* type *parva* (Lutze 1986), PA1 (1–1.5 cm), 3: 63–125 μm , 4: > 150 μm 5: *Praeglobobulimina* sp., PA1 (1–1.5 cm), > 150 μm 6–7: *Ehrenbergina trigona* (Goes 1896), PA4 (0–0.5 cm), > 150 μm 8–10: *Rotaliatinopsis semiinvoluta* (Germeraad 1946), PA1 (1–1.5 cm), 63–125 μm 11: *Bulimina aculeata* (d'Orbigny 1826), PA8 (1–1.5 cm), > 150 μm 12: *Globocassidulina subglobosa* (Brady 1881), PA3 (0–0.5 cm), > 150 μm 13: *Ammodiscus* sp., PA2 (0–0.5 cm), > 150 μm 14: *Lagenammmina difflugiformis* (Brady 1879), PA8 (0–0.5 cm), > 150 μm 15–16: *Reophax agglutinans* (Cushman 1913), PA8 (0–0.5 cm), > 150 μm