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ORIGINAL PAPER

A highly diverse living benthic foraminiferal assemblage in the oxygen deficient zone of the southeastern Arabian Sea

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Abstract
The exchange of seawater between the Arabian Sea and the Bay of Bengal, creates a strong seasonality in the southeastern Arabian Sea, including the oxygen deficient zone (ODZ) at intermediate depth. Here, we assess the effect of this strong seasonality on benthic foraminifera living within ODZ of the southeastern Arabian Sea. We delineate five benthic foraminiferal assemblages characterizing different dissolved oxygen levels. A distinct depth zonation in living benthic foraminiferal species is observed within the southeastern Arabian Sea ODZ. *Cassidulina laevigata, Cassidulina carinata* and *Eponides umbonatus* dominate shallow depth, hypersaline, oxygen rich, warm water environment with low organic matter (%C_{org}) availability. The upper slope intense suboxic zone with moderate %C_{org} abundance, is characterized by *Bolivina seminuda, Hopkinsinella glabra* and *Eubuliminella exilis*. A similar suboxic zone, but with high %C_{org} concentration on the middle slope, is represented by *Rotaliatinopsis semiinvoluta, Hopkinsinella glabra* and *Epistominella exigua*. The lower slope (∼ 1000–1500 m) assemblage is dominated by rectilinear species, namely *Bulimina arabiensis, Bulimina elegans* and *Bolivina earlandi* and represents a comparatively higher dissolved oxygen environment (1–2 mL/L) with high organic carbon at deeper water depths. *Bolivina earlandi, Bulimina aculeata* and *Globocassidulina subglobosa* dominate deep-water benthic foraminifera population, where bottom water is oxygen rich (> 2 mL/L) with plenty of organic matter and the lowest bottom water temperature and salinity. The living benthic foraminiferal abundance as well as diversity increases manifold within the southeastern Arabian Sea ODZ and may be attributed to the strong seasonality. The depth habitat of the dominant living benthic foraminifera has also been reported.

Keywords Benthic foraminifera · Oxygen depleted zone · Indian Ocean · Diversity · Species · Mannar · Gulf · Organic carbon

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Introduction

The eukaryotic life on Earth developed only after the great oxygenation event. But, the first billion years of eukaryotic life on earth was under severely oxygen depleted conditions, not comparable to today, suggesting sustenance under oxygen deficient environment (Zimorski et al. 2019). However, a majority of the extant marine organisms are critically influenced by the dissolved oxygen and food (Wishner et al. 2018; Laffoley and Baxter 2019). The restricted circulation and water column stratification leading to limited replenishment, coupled with high marine primary productivity results in excessive utilization of the available oxygen and thus creates oxygen deficient zones (ODZ) (Naqvi et al. 2009). Post-industrialization global warming is creating life threatening challenges for the terrestrial as well as marine biospheres. In the ocean ecosystem, increasing sea surface temperature (SST) is suggested as the leading factor for the decrease in dissolved oxygen and thus the expanding ODZs (Moffitt et al. 2015). Anthropogenic activities have contributed towards the expansion of ODZs (Breitburg et al. 2018), by facilitating oxygen loss from warm waters and increased nutrient load (Bouwman et al. 2005) supporting primary productivity (Reed and Harrison 2016). The decreased dissolved oxygen in the sea surface water increases the mortality of planktic fauna (Takarina et al. 2017) and causes vertical compression of benthic habitat (Stramma et al. 2010; McCormick and Levin 2017). The decreased dissolved oxygen also alters marine elemental cycling (Naqvi et al. 2010; Li et al. 2017). Therefore, it is important to understand the dynamics of ODZs. The record of spatio-temporal variability of ODZs helps in understanding its dynamics.

Biologically productive regions like the eastern Pacific Ocean (off Peru and off California margin), continental margin off Western Africa and the Arabian Sea are the key zones to understand the oceanographic processes depleting the dissolved oxygen at certain depth in the ocean (Laffoley and Baxter 2019). In the Arabian Sea, a strong coastal upwelling induced primary productivity, sluggish circulation coupled with water column stratification, creates an intense perennial ODZ at intermediate depths. The well-defined ODZ in the Arabian Sea is the deepest ODZ (150–1500 m) in the world ocean (Naqvi et al. 2009). Additionally, a seasonal hypoxic zone also develops on the continental shelf (Naqvi et al. 2006). The intense ODZs of the Arabian Sea include the region off Oman, off Pakistan and off the southern tip of India. A low dissolved oxygen zone has also been reported from the western Bay of Bengal (Bristow et al. 2017). Interestingly, the Bay of Bengal ODZ is not as intense as that in the Arabian Sea. The influx of Arabian Sea high salinity water is suggested to sustain the dissolved oxygen in the Bay of Bengal (Jain et al. 2017). The water between the Arabian Sea and the Bay of Bengal is exchanged through the region off the southern tip of India, creating a strong seasonal contrast in the ambient parameters, including a low dissolved oxygen zone in this region. Therefore, the south-eastern Arabian Sea, can provide insight into the effect of the change in cross basin exchange of seawater in modulating ODZ in both the Arabian Sea and Bay of Bengal.

The low dissolved oxygen affects living benthic fauna, in the region, where it impinges on bottom sediments (Levin 2003; Levin et al. 2000). Benthic foraminifera (marine unicellular protists) are very sensitive to change in the ambient dissolved oxygen (Kaiho 1994; Kaminski et al. 1995; Jorissen et al. 1995; Gooday et al. 2000; Kurbjeweit et al. 2000; Singh et al. 2006; Filipsson and Nordberg 2004, 2010; Bhaumik and Gupta 2005; Nigam et al. 2007; Filipsson et al. 2011; Kaminski 2012; Mackensen et al. 1985; Caulle et al. 2015; Manasa et al. 2016; Singh et al. 2018). Thus, benthic foraminifera have been extensively used to reconstruct the past ODZ strength in the world ocean (Reichart et al.

1998; Den Dulk et al. 2000; Aksu et al. 2002; Nigam et al. 2009; Singh et al. 2015; Naik et al. 2017). Benthic foraminifera include a few thousands of species worldwide, with unique microhabitat preference (Lei et al. 2017, 2019). Different species thrive in different ODZ regions in the world ocean. Therefore, it is imperative to document the unique benthic foraminiferal assemblage and/or species characteristic of the different ODZs.

From the Arabian Sea, living benthic foraminifera have been documented from ODZ off Pakistan margin (Caulle et al. 2014; Enge et al. 2014; Erbacher and Nelskamp 2006; Gooday et al. 2009; Jannink et al. 1998; Larkin and Gooday 2008; Schumacher et al. 2007), off Oman (Hermelin and Shimmield 1990; Gooday et al. 2000) and off the Indian margin (Caulle et al. 2015). So far, there is no such detailed study documenting living benthic foraminifera from the ODZ off the eastern and western margin of India. Additionally, a majority of paleo-ODZ studies relied on the application of benthic foraminifera identified in the top one or two cm of the sediments recovered from the modern ODZ. However, benthic foraminifera frequently migrate up or down in the sediments (Mackensen and Douglas 1989), especially in response to the changing ambient dissolved oxygen. Therefore, the living benthic foraminifera in a substantial section of the top sediments must be documented for more precise identification of assemblage characteristic of the ambient ODZ. Here we assess the influence of strong seasonality on benthic foraminifera living in the top 5 cm of the sediments within the ODZ of the southeastern Arabian Sea.

Study area and physiographic setting

The study area, Gulf of Mannar (the southeastern Arabian Sea), is at the intersection of the eastern Arabian Sea and western Bay of Bengal. The area is influenced by the Indian monsoon and seasonally reversing winds (Vinayachandran and Yamagata 1998). The seasonal winds strongly modulate the coastal currents. During the southwest monsoon, west India coastal current brings higher salinity water from the Arabian Sea into the bay. The low salinity water from the Bay of Bengal is transported to the eastern Arabian Sea by the equatorward east India coastal current, during the northeast monsoon season (Shankar et al. 2002). The strong monsoon wind causes upwelling/vertical mixing, resulting into higher primary productivity throughout the year (Jyothibabu et al. 2014). The marine primary productivity, however, remains higher during the southwest monsoon because of much stronger wind strength, in comparison to the northeast monsoon winds. Thus, plenty of food is available for planktic as well as benthic fauna. The higher primary productivity also generates secondary biological mass (Jagadeesan et al. 2013). The organisms feeding on the settling organic matter consume oxygen from the water column. This creates perennial ODZ in the intermediated depths. The bottom water dissolved oxygen varied between 0.48 and 3.48 mL/L (21–155 μM) (Fig. 1) with the lowest value at 510 m. These seasonally reversing winds are also responsible for the changes in the physico-chemical properties of ambient seawater. Due to the upwelling of cold water (< 26 °C), the ocean surface temperature decreases to its lowest value during the south-west monsoon. Whereas, during the pre-monsoon, the warmest SST is ~ 29.0 °C, due to the Indo-Pacific Warm Pool (IPWP) effect (Boyer et al. 2013). Bottom water temperature varies between 2.06 and 25.96 °C with lower value towards deeper depth (Fig. 1). The movement of both the high and low salinity water through the region imparts a distinct seasonality, with higher sea surface salinity (~ 35 psu) during summer and lower values during winter (~ 33 psu). Bottom water salinity also varies seasonally, although the amplitude of variation was much

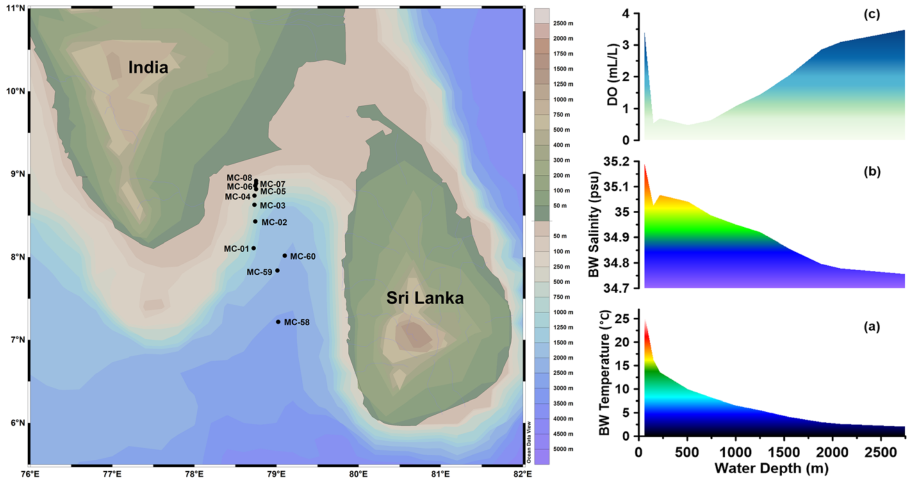

Fig. 1 The multi-core sample locations in the Gulf of Mannar, southeastern Arabian Sea (left panel) and the bottom water **a** temperature (°C), **b** salinity (psu) and **c** dissolved oxygen (mL/L) (right panel). The colored contours represent bathymetry

reduced (34.75–35.19 psu; Fig. 1) and increased with depth. The inner shelf region off Kanyakumari is characterized by a relict carbonate platform (Rao et al. 2003).

Materials and method

From the Gulf of Mannar, 11 multi-core samples were collected during the 4th cruise of RV *Sindhu Sadhana* (SSD004), just after the southwest monsoon (October 2014) (Fig. 1). The samples were collected by using an Ocean Scientific International Limited Maxi Multi-corer having 600 mm long core tubes of 110 mm outer diameter and 100 mm internal diameter. The samples also contained overlying water at sediment–water interface. The overlying water was used to measure the ambient seawater parameters. The sediment cores were carefully sub-sampled at one-centimeter interval and top five samples (0–5 cm) from all 11 multicore stations, were used for this study. One half of each section was stained with ethanol rose-Bengal solution (2 g of rose-Bengal dissolved in 1 L of 70% ethanol). The stained sediment samples were stored at 4 °C. After 4–6 weeks, the samples were freeze-dried and wet sieved by using a 63 µm sieve (Jorissen et al. 1992; Singh et al. 2018; Suokhrie et al. 2020). The coarse fraction was stored in plastic vials. A representative aliquot of the coarse fraction was weighed to pick 300 specimens by using Olympus SZX 12 stereo-zoom microscope. A few samples did not contain 300 living specimens. In such samples, 0.5 g coarse fraction was taken to pick all available living benthic foraminifera. Only the specimens with stained proloculus were considered as living and in case of any uncertainty, a drop of water was applied to ensure the efficiency of stain. All the picked specimens were identified up to the species level. The species were identified by comparing the morphology (shell material; number, shape and arrangement of chambers; ornamentation; type and position of aperture; sutures; periphery; and others) of the specimens found in the south-eastern Arabian Sea with the previously published plates. The identification was further confirmed by checking the type-specimen description in the Ellis and Messina Catalogue of Foraminifera (Ellis and Messina 1940–2019). Among all the living benthic foraminifera, only those species with ≥ 3% relative abundance, were used for the detailed statistical analysis. Multi variate statistical package (MVSP) was run between ambient parameters and species abundance, and is discussed. The ambient parameters were compared with foraminifera in both the core-top section as well as the 0–5 cm section, to understand species' living depth habitat/vertical movement and their ecological preferences.

For the total inorganic carbon (TIC), organic carbon (%C_{org}) and total nitrogen measurements, a small amount (~ 5 g) of the freeze-dried sediment was finely powdered. TIC was measured by using a Coulometer (model CM 5015 CO2) and Total Carbon (C) and (N) was measured by using CNS element analyzer (model FLASH 2000 Thermo Scientific). From the repeat runs of certified reference material (Soil 1 and TWTUC) after every five samples during the total carbon and inorganic carbon analysis, respectively, the error in total carbon is estimated as < 1.9% and in inorganic carbon, the error is < 0.9%, of the reported value. The organic carbon (%C_{org}) was estimated by subtracting inorganic carbon from the total carbon. The physico-chemical parameters of the seawater at the sediment–water interface were downloaded from the World Ocean Atlas (WOA 13) (Boyer et al. 2013). The statistical software, MultiVariate Statistical Package (MVSP) and Statistica-8 was used to understand the relationship between benthic foraminiferal species and ambient ecological parameters along with their significance level.

Results

The multicore samples cover the region from the very shallow-continental shelf to deep continental slope. The sediments were mainly clayey-mud except at station MC07 and MC08, where it was mainly coarse sand. The main source of clay in this region is input from the Bay of Bengal water as it brings a lots of clay as a result of higher monsoon sediment influx. The abundance of illite and chlorite in the clay fraction in the south-eastern Arabian Sea was attributed to the transport from the Bay of Bengal (Chauhan and Gujar 1996). Additionally, the aeolian transport of clay from the Arabia and Somalia, to the southeastern Arabian Sea was suggested from the presence of palygorskite in the clay fraction (Chauhan 1996). The coarse sand on the continental shelf is derived from the broad carbonate shelf. This heterogeneity in sediment type also influences the living habitat of benthic fauna in the region.

Ecological parameters

The seawater temperature at the sediment–water interface varied between 2.06 and 25.96 °C. The salinity varied between 34.75 and 35.19 psu and both decreased with increasing depth. Bottom water dissolved oxygen varied between 0.48–3.48 mL/L (21–155 μM) and ODZ (< 2.00 mL/L or < 90 μM) lies between 152 and 1550 m water depth. The organic carbon concentration varied from 1.52% to 6.86% in core-tops (0-1 cm). In the top 5 cm sediment section, %C_{org} varied between 1.57 and 6.37%. Organic carbon increased from shallow to deeper depths with slight decrease after MC01 (1550 m) (Fig. 2). C_{org}/TN varied between 8.84–16.43 in the core-top and 6.64–15.19 in the 0–5 cm section. In the 0–5 cm section, C_{org}/TN was lower at intermediate depths as compared to the shallower and deeper depths. Such a trend was not observed in core-top section (Fig. 3).

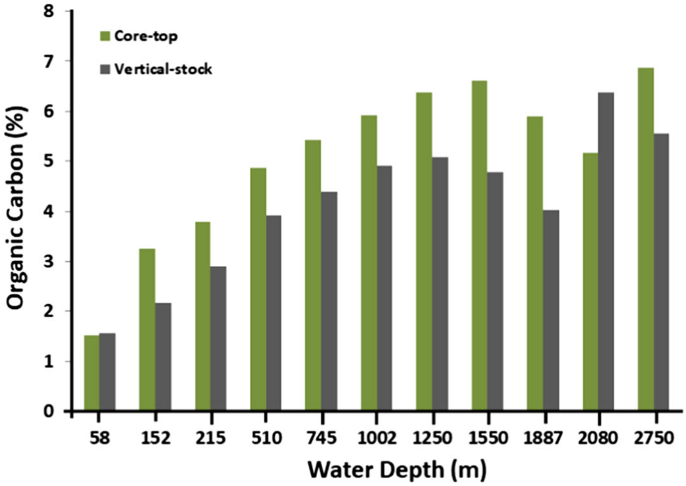

Fig. 2 The organic carbon variation with depth in the core-top (0–1 cm) and 0–5 cm section in the Gulf of Mannar, southeaeast Arabian Sea

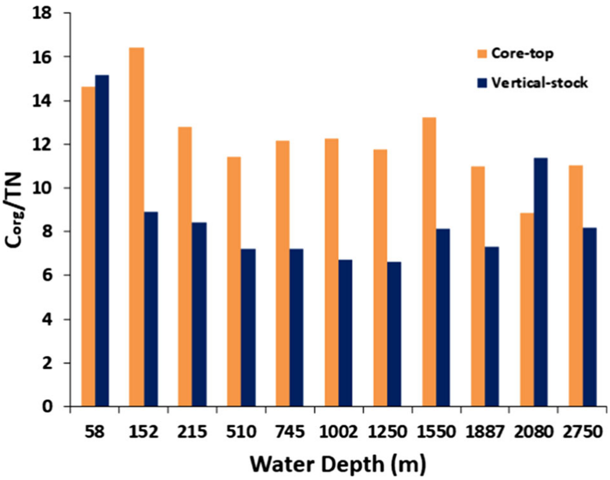

Fig. 3 C_{org}/Total Nitrogen (%TN) variation with depth in core-top (0–1 cm) and 0–5 cm section in the Gulf of Mannar, southeaeast Arabian Sea

Faunal abundance

The living benthic foraminiferal abundance varied between 14 and 3216 specimen/g sediment in the core-top section (Singh et al. 2018) (Fig. 4a). The abundance decreased to 8–48 specimen/g sediment in the combined top 5 cm section of the sediment (Fig. 4b). The reduced abundance in the 0–5 cm section was mainly due to the rare presence of living benthic foraminifera in deeper sections (2–3 cm, 3–4 cm and 4–5 cm). We found the highest abundance of living benthic foraminifera at 215 m (MC06) and the minimum was at 1887 m (MC60) in the core-top sections. The same is also true for the 0–5 cm section

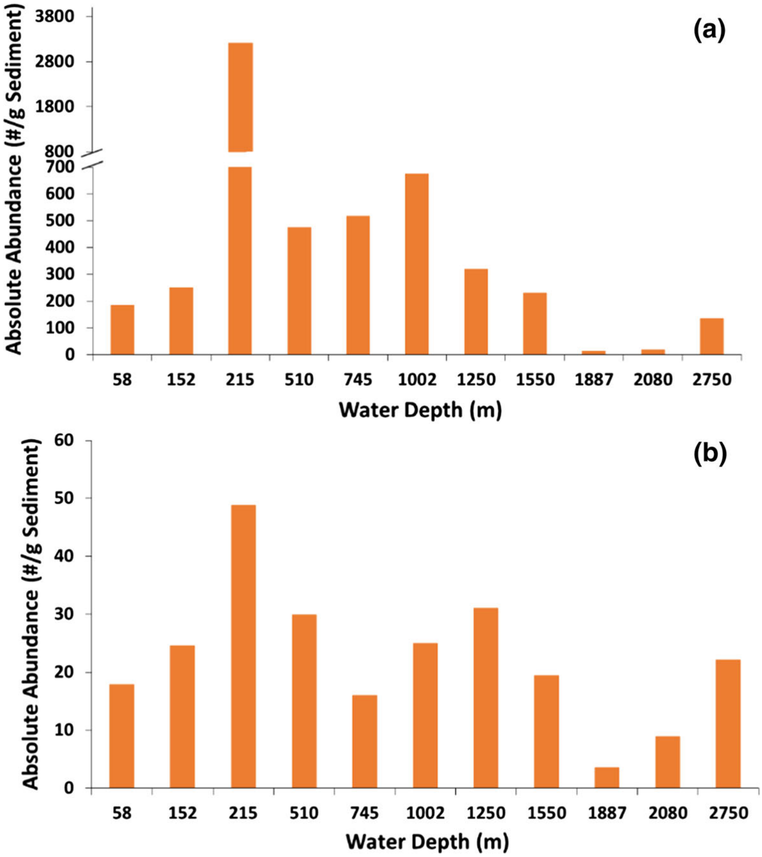

Fig. 4 The absolute abundance of living benthic foraminifera (#/g Sediment) in the **a** core-top (0–1 cm) and **b** 0–5 cm section in the Gulf of Mannar, southeaeast Arabian Sea

(Fig. 4a, b). In the core-top sections, the absolute abundance increased many folds at intermediate water depth stations (MC03, 04, 05, 06), as compared to shallower/deeper non ODZ depths. Such an abundance trend was, however, not as prominent in the 0–5 cm section.

A total of 4427 living benthic foraminifera were picked and identified up to species level. We found 112 living benthic foraminifera in the south-eastern Arabian Sea (Table 1). In terms of the species composition at the shallowest station (MC08; 58 m), *Cassidulina laevigata* (45%), *Eponides umbonatus* (20%) and *Cassidulina carinata* (11%) were the top three contributors in the core-top as well as the 0–5 cm section. The relative abundance of these species was, however, lower in the 0–5 cm section [*Cassidulina laevigata* (35%), *Eponides umbonatus* (15%) *Cassidulina carinata* (9%)] (Fig. 5). In the core-top section of station MC07 and MC06, with the lowest dissolved oxygen, *Bolivina seminuda* dominates the assemblage with 31% and 49% relative abundance, respectively. Besides this, the abundant presence of *Bulimina elegans*, *Bolivina dilatata* and *Hopkinsinella glabra*, represents the low dissolved oxygen assemblage in this region. *Bolivina seminuda* dominates the 0–5 cm section also, with 40% abundance at MC07 and 57% at MC06 (Fig. 5). At MC05 and MC04, *Rotaliatinopsis semiinvoluta* (23% and 25% respectively) was the

Table 1 The check-list of the living benthic foraminifera reported from the southeastern Arabian Sea

Species	Original description	Identification source
Adercotryma glomeratum	*Lituola glomerata* Brady, 1878	Zheng and Fu 2001, Pl. 44, Fig. 8
Ammodiscus gullmarensis	*Ammodiscus gullmarensis* Höglund, 1948	Lei and Li, 2016, Pg. 9, Fig. 5
Ammoglobigerina globigeriniformis	*Lituola nautiloidea* var. *globigeriniformis* Parker & Jones, 1865	Zheng and Fu, 2001, Pl. 61, Figs. 1–3
Anturina haynesi	*Anturina haynesi* Jones, 1984	Loeblich and Tappan, 1988, Pl. 462, Fig. 1
Baggina diversa	*Baggina diversa* McCulloch, 1981	McCulloch, 1981, Pl. 51, Fig. 12, 13
Bolivina acaulis	*Bolivina acaulis* Egger, 1893	Ellis and Messina Foraminifera Catalogue, Fig. 73620
Bolivina advena	*Bolivina advena* Cushman, 1925	Ellis and Messina Foraminifera Catalogue, Fig. 1545
Bolivina aff. *mera*	*Bolivina plicatella* var. *mera* Cushman & Ponton, 1932	Ellis and Messina Foraminifera Catalogue, Fig. 1867
Bolivina churchi	*Bolivina churchi* Kleinpell & Tipton, 1980	Ellis and Messina Foraminifera Catalogue, Fig. 65532
Bolivina compacta	*Bolivina robusta* var. *compacta* Sidebottom, 1905	Ellis and Messina Foraminifera Catalogue, Fig. 1912
Bolivina cuneatum	*Bolivina (Loxostoma) cuneatum* Hofker, 1951	Ellis and Messina Foraminifera Catalogue, Fig. 41079
Bolivina currai	*Bolivina currai* Sellier de Civrieux, 1976	Ellis and Messina Foraminifera Catalogue, Fig. 68144
Bolivina dilatata	*Bolivina dilatata* Reuss, 1850	Ellis and Messina Foraminifera Catalogue, Fig. 1664
Bolivina earlandi	*Bolivina earlandi* Parr, 1950	Ellis and Messina Foraminifera Catalogue, Fig. 38250
Bolivina jacksonensis	*Bolivina jacksonensis* Cushman & Applin, 1926	Ellis and Messina Foraminifera Catalogue, Fig. 1750
Bolivina lowmani	*Bolivina lowmani* Sellier, 1976	Ellis and Messina Foraminifera Catalogue, Fig. 68151
Bolivina robusta	*Bulimina (Bolivina) robusta* Brady, 1881	Barker, 1960, Pl. 53, Figs. 7–9
Bolivina seminuda	*Bolivina seminuda* Cushman, 1911	Ellis and Messina Foraminifera Catalogue, Fig. 1932
Bolivina spinescens	*Bolivina spinescens* Cushman, 1911	Ellis and Messina Foraminifera Catalogue, Fig. 1950
Bolivina striatula	*Bolivina striatula* Cushman, 1922	Ellis and Messina Foraminifera Catalogue, Fig. 1957
Bolivina subspathulata	*Bolivina subspathulata* Boomgaart, 1949	Ellis and Messina Foraminifera Catalogue, Fig. 37544
Bolivina victoriana	*Bolivina victoriana* Cushman, 1936	Ellis and Messina Foraminifera Catalogue, Fig. 2029
Bolivina zanzibarica	*Bolivina zanzibarica* Cushman, 1936	Ellis and Messina Foraminifera Catalogue, Fig. 2033
Buccella differens	*Buccella differens* McCulloch, 1981	McCulloch, 1981, Pl. 58, Fig. 8
Bulimina aculeata	*Bulimina aculeata* d'Orbigny, 1826	Barkar, 1960, Pl. 51, Figs. 7–9

Table 1 continued

Species	Original description	Identification source
Bulimina alazanensis	*Bulimina alazanensis* Cushman, 1927	Ellis and Messina Foraminifera Catalogue, Fig. 2156
Bulimina arabiensis	*Bulimina arabiensis* Bharti & Singh, 2013	Bharti and Singh, 2013, Fig. 3
Bulimina elegans	*Bulimina elegans* d'Orbigny, 1826	Ellis and Messina Foraminifera Catalogue, Fig. 2243
Bulimina marginata	*Bulimina marginata* d'Orbigny, 1826	Ellis and Messina Foraminifera Catalogue, Fig. 2317
Bulimina marginospinata	*Bulimina marginospinata* Cushman & Parker, 1938	Ellis and Messina Foraminifera Catalogue, Fig. 2322
Bulimina pseudoaffinis	*Bulimina psuedoaffinis* Kleinpell, 1938	Martin, 1952, Pl. 23, Fig. 4
Bulimina pupoides	*Bulimina pupoides* d'Orbigny, 1846	Ellis and Messina Foraminifera Catalogue, Fig. 76935
Bulimina spinosa	*Bulimina spinosa* Seguenza, 1862	Ellis and Messina Foraminifera Catalogue, Fig. 2462
Bulimina striata	*Bulimina striata* d'Orbigny in Guérin-Méneville, 1832	Ellis and Messina Foraminifera Catalogue, Fig. 24405
Cancris cf. *penangensis*	*Cancris* cf. *penangensis* McCulloch, 1977	McCulloch, 1977, Pg. 344, Pl. 135, Fig. 110
Cancris sagra	*Rotalina (Rotalina) sagra* d'Orbigny, 1839	Loeblich and Tappan, 1988, Pl. 591, Fig. 4
Cancris sp.	*Cancris* sp.	Loeblich and Tappan, 1988, Pl. 591
Cassidulina aff. *minuta*	*Cassidulina* aff. *minuta* Cushman, 1933	Ellis and Messina Foraminifera Catalogue, Fig. 2803
Cassidulina angulosa	*Cassidulina angulosa* Cushman, 1933	Ellis and Messina Foraminifera Catalogue, Fig. 2724
Cassidulina carinata	*Cassidulina laevigata* var. *carinata* Silvestri, 1896	Ellis and Messina Foraminifera Catalogue, Fig. 2786
Cassidulina laevigata	*Cassidulina laevigata* d'Orbigny, 1826	Ellis and Messina Foraminifera Catalogue, Fig. 2782
Cassidulinoides waltoni	*Cassidulionoides waltoni* Uchio 1960	McCulloch, 1977, Pl. 166, Figs. 8, 12
Cibicidoides mundula	*Truncatulina mundula* Brady, Parker & Jones, 1888	Loeblich and Tappan, 1955, Pl. 4, Fig. 4
Cibicidoides wuellerstorfi	*Anomalina wuellerstorfi* Schwager, 1866	Jones, 1994, Pl. 93, Fig. 9
Crespinella umbonifera	*Operculina umbonifera* Howchin & Parr, 1938	Loeblich and Tappan, 1988, Pl. 632, Figs. 9–13
Eggerelloides scaber	*Bulimina scabra* Williamson, 1858	Mendes et al., 2013, Pl. 1, Fig. 1
Epistominella exigua	*Pulvinulina exigua* Brady, 1884	Barker, 1960, Pl. 107, Figs. 13, 14
Epistominella pulchella	*Epistominella pulchella* Husezima & Maruhasi, 1944	Ellis and Messina Foraminifera Catalogue, Fig. 39933
Epistominella sp.	*Epistominella* sp.	Loeblich and Tappan, 1988, Pl. 627
Epistominella umbonifera	*Pulvinulinella umbonifera* Cushman, 1933	Ellis and Messina Foraminifera Catalogue, Fig. 18042

Table 1 continued

Species	Original description	Identification source
Eponides umbonatus	*Rotalina umbonata* Reuss, 1851	Barker, 1960, Pl. 105, Fig. 2
Eubuliminella exilis	*Bulimina elegans* var. *exilis* Brady, 1884	Jones, 1994**,** Pl.50, Figs. 5, 6
Fissurina caudimarginata	*Fissurina aligeria* subsp. *caudimarginata* McCulloch, 1977	McCulloch, 1977, Pl. 58, Fig. 28
Fissurina crassiporosa	*Fissurina crassiporosa* McCulloch, 1977	McCulloch, 1977, Pl.56, Fig. 22
Fursenkoina cornuta	*Virgulina cornuta* Cushman, 1913	Matoba, 1982, Pl. 2, Fig. 8
Fursenkoina obliqua	*Fursenkoina obliqua* Saidova 1975	Ellis and Messina Foraminifera Catalogue, Fig. 80524
Globobulimina pacifica	*Globobulimina pacifica* (Cushman, 1927)	Barker, 1960, Pl. 50, Figs. 7–10
Globocassidulina porrecta	*Cassidulina crassa* var. *porrecta* Heron-Allen & Earland, 1932	Ellis and Messina Foraminifera Catalogue, Fig. 2754
Globocassidulina subglobosa	*Cassidulina subglobosa* Brady, 1881	Loeblich and Tappan 1988, Pl. 557, Figs. 18–23
Gyroidina cf. *guadalupensis*	*Gyroidina cf. guadalupensis* McCulloch, 1977	McCulloch, 1977, P1. 140, Figs. 8, 12
Gyroidina io	*Gyroidina io* Resig, 1958	Ellis and Messina Foraminifera Catalogue, Fig. 47407
Gyroidina pilasensis	*Gyroidina pilasensis* McCulloch, 1977	McCulloch, 1977, P1. 140, Figs. 1, 2
Gyroidina quinqueloba	*Gyroidina quinqueloba* Uchio, 1960	Ellis and Messina Foraminifera Catalogue, Fig. 54104
Gyroidina tenera	*Truncatulina tenera* Brady, 1884	McCulloch, 1977, P1. 141, Fig. 13
Hansenisca soldanii	*Gyroidina soldanii (*d'Orbigny, 1826)	Ellis and Messina Foraminifera Catalogue, Fig. 9058
Hanzawaia concentrica	*Cibicides concentricus* Cushman, 1918	Ellis and Messina Foraminifera Catalogue, Fig. 22756
Haplophragmoides evolutum	*Haplophragmoides columbiense* var. *evolutum* Cushman & Mcculloch, 1939	Ellis and Messina Foraminifera Catalogue, Fig. 77360
Hoeglundina heterolucida	*Hoeglundina heterolucida* McCulloch, 1981	McCulloch, 1981, Pl. 57, Fig. 7
Hopkinsina atlantica	*Hopkinsina pacifica* var. *atlantica* Cushman, 1944	Ellis and Messina Foraminifera Catalogue, Fig. 32481
Hopkinsinella glabra	*Uvigerina auberiana* var. *glabra* Millett, 1903	Ellis and Messina Foraminifera Catalogue, Fig. 23035
Hyalinea balthica	*Nautilus balthicus* Schröter, 1783	Ellis and Messina Foraminifera Catalogue, Fig. 37878
Hyalinonetrion elongata	*Miliola elongata* Ehrenberg, 1844	Loeblich and Tappan, 1988, Pl. 455, Figs. 6–8
Lagena oceanica	*Lagena oceanica* Albani 1974	Ellis and Messina Foraminifera Catalogue, Fig. 61865
Lagenammina longicollis	*Lagenammina longicolli* Wiesner, 1931	Zheng and Fu, 2001, Pl. 6, Fig. 11
Lagenosolenia eucerviculata	*Lagenosolenia eucerviculata* McCulloch, 1977	McCulloch, 1977, Pl. 60, Figs. 5–7

Table 1 continued

Species	Original description	Identification source
Lenticulina tortugaensis	*Robulus tortugaensis* McCulloch, 1981	McCulloch, 1981, Pl. 27, Fig. 1
Melonis chathamensis	*Melonis chathamensis* McCulloch, 1977	McCulloch, 1977, Pl.180, Fig. 5
Melonis pompilioides	*Nautilus pompilioides* Fichtel & Moll, 1798	Khare, 1992, Pg. 171, Pl. 16, Fig. 1
Melonis sp.	*Melonis* sp.	Loeblich and Tappan, 1988, Pl. 696
Neouvigerina ampullacea	*Uvigerina asperula* var. *ampullacea* Brady, 1884	Ellis and Messina Foraminifera Catalogue, Fig. 23031
Neouvigerina porrecta	*Uvigerina porrecta* Brady, 1879	Ellis and Messina Foraminifera Catalogue, Fig. 23214
Nonion glabrella	*Nonion glabrella* Cushman, 1930	Ellis and Messina Foraminifera Catalogue, Fig. 13968
Nonion granosum	*Nonionina granosa* d'Orbigny, 1846	Cushman, 1939, Pl. 2, Fig. 17
Nonion sp.	*Nonion* sp.	Loeblich and Tappan, 1988, Pl. 690
Nonionella limbato-striata	*Nonionella limbato-striata* Cushman, 1931	Ellis and Messina Foraminifera Catalogue, Fig. 14046
Nonionella simplex	*Ziesenhenneia simplex* McCulloch, 1977	McCulloch, 1977, Pl. 160, Figs. 12, 14
Nonionellina labradorica	*Nonionina labradorica* Dawson, 1860	Loeblich and Tappan, 1988, Pl. 689, Figs. 8–17
Oridorsalis umbonatus	*Rotalina umbonata* Reuss, 1851	Jones, 1994, Pl. 95, P1. 11
Osangularia bengalensis	*Anomalina bengalensis* Schwager, 1866	Loeblich and Tappan, 1988, Pl. 708, Figs. 1–5
Portatrochammina eltaninae	*Portatrochammina eltaninae* Echols, 1971	Loeblich and Tappan, 1988, Pl. 129, Figs. 4–6
Pseudoeponides equatoriana	*Rotalia equatoriana* LeRoy, 1941	Bhatia and Kumar, 1976, Pl. 2, Fig. 8
Pullenia bulloides	*Nonionina bulloides* d'Orbigny, 1846	Barker, 1960, Pl. 84, Figs. 12, 13
Pullenia salisburyi	*Pullenia salisburyi* Stewart & Stewart, 1930	Yassini and Jones, 1995, Pg. 249, Figs. 936–939
Pullenia sp.	*Pullenia* sp.	Loeblich and Tappan, 1988, Pl. 696
Pyropiloides elongatus	*Pyropiloides elongatus* Zheng, 1979	Loeblich and Tappan, 1988, Pl. 689, Figs. 8–17
Reophax rostrata	*Reophax rostrata* Höglund, 1947	Zheng and Fu, 2001, Pl. 22, Figs. 1–7
Rosalina columbiensis	*Discorbis columbiensis* Cushman, 1925	Ellis and Messina Foraminifera Catalogue, Fig. 59055
Rotaliatinopsis semiinvoluta	*Pulleniatina semiinvoluta* Germeraad, 1946	Loeblich and Tappan, 1988, Pl. 714, Figs. 7–11
Rotalidium annectens	*Rotalia beccarii* var. *annectens* Parker & Jones, 1865	Khare, 1992, Pg. 181–182, P1. 17, Fig. 51
Rotorbinella bikiniensis	*Rotorbinella bikinensis* McCulloch, 1977	McCulloch, 1977, Pl. 115, Figs. 14–15

Table 1 continued

Species	Original description	Identification source
Rutherfordoides rotundiformis	*Rutherfordoides rotundiformis* McCulloch, 1977	McCulloch, 1977, Pl. 105, Figs. 6–10
Saccammina huanghaiensis	*Saccammina huanghaiensis* Zheng & Fu, 2001	Zheng and Fu, 2001, Pl. 5, Figs. 22- 25
Saccorhiza ramosa	*Hyperammina ramosa* Brady, 1879	Zheng and Fu, 2001, Pl. 9, Figs. 9–12
Trochammina conica	*Trochammina conica* Earland, 1934	Zheng and Fu, 2001, Pl. 115, Fig. 7
Uvigerina aff. *longa*	*Uvigerina longa* Cushman & Bermúdez, 1937	Ellis and Messina Foraminifera Catalogue, Fig. 23159
Uvigerina aff. *mediterranea*	*Uvigerina mediterranea* Hofker, 1932	Ellis and Messina Foraminifera Catalogue, Fig. 29802
Uvigerina auberiana	*Uvigerina auberiana* d'Orbigny, 1839	Ellis and Messina Foraminifera Catalogue, Fig. 23033
Uvigerina canariensis	*Uvigerina canariensis* d'Orbigny, 1839	Ellis and Messina Foraminifera Catalogue, Fig. 23067
Uvigerina multicostata	*Uvigerina multicostata* Leroy, 1939	Ellis and Messina Foraminifera Catalogue, Fig. 31290
Uvigerina peregrina	*Uvigerina peregrina* Cushman, 1923	Ellis and Messina Foraminifera Catalogue, Fig. 23190
Valvulineria hamanakoensis	*Anomalina hamanakoensis* Ishiwada, 1958	Matoba, 1970, Pl. 4, Figs. 12, 13
Valvulineria minuta	*Valvulineria minuta* Parker, 1954	Ellis and Messina Foraminifera Catalogue, Fig. 43951

The details of the type species are also included. For the references cited in this table, please refer the previous literature

dominant species along with *Bolivina currai* (5% and 13%, respectively) and *Epistominella exigua* (5% and 13% respectively), whereas *Hopkinsinella glabra* (19% and 6%, respectively) and *Rotaliatinopsis semiinvoluta* (13% and 14% respectively) were abundant in the 0–5 cm section. *Bolivina currai* was also present at MC07 (12%) in the core-top (Fig. 5). At MC03, *Epistominella exigua* (39%) *Bolivina dilatata* (14%) and *Bolivina currai* (10%) were dominant in both the core-top as well as the 0–5 cm section with 26%, 10% and 6% abundance, respectively. At MC02, *Bolivina dilatata* (18%), *Bolivina churchi* (13%) and *Pullenia salisburyi* (6%) were abundant in the core-top and *Bolivina dilatata* (15%), *Bolivina churchi* (12%) and *Bulimina arabiensis* (6%) were abundant in the 0–5 cm section (Fig. 5). At MC01, *Uvigerina peregrina*, *Rotorbinella bikinensis* and *Pseudoeponides equatoriana* were the most dominant species in the core-top, whereas *Bolivina earlandi*, *Bulimina arabiensis* and *Uvigerina peregrina* were abundant in the 0–5 cm section. At the deeper stations (MC60, 59 and 58), *Bulimina aculeata*, *Globocassidulina subglobosa*, *Pseudoeponides equatoriana* were abundant in the core-top section, whereas 0–5 cm section was dominated by *Bolivina earlandi, Bulimina aculeata* and *Pseudoeponides equatoriana* (Fig. 5).

The depth habitat of the dominant species in the south-eastern Arabian Sea was defined from its vertical distribution (Fig. 5, Table 2). Amongst the dominant living benthic foraminifera in the south-eastern Arabian Sea, 17 (*Baggina diversa, Bulimina*

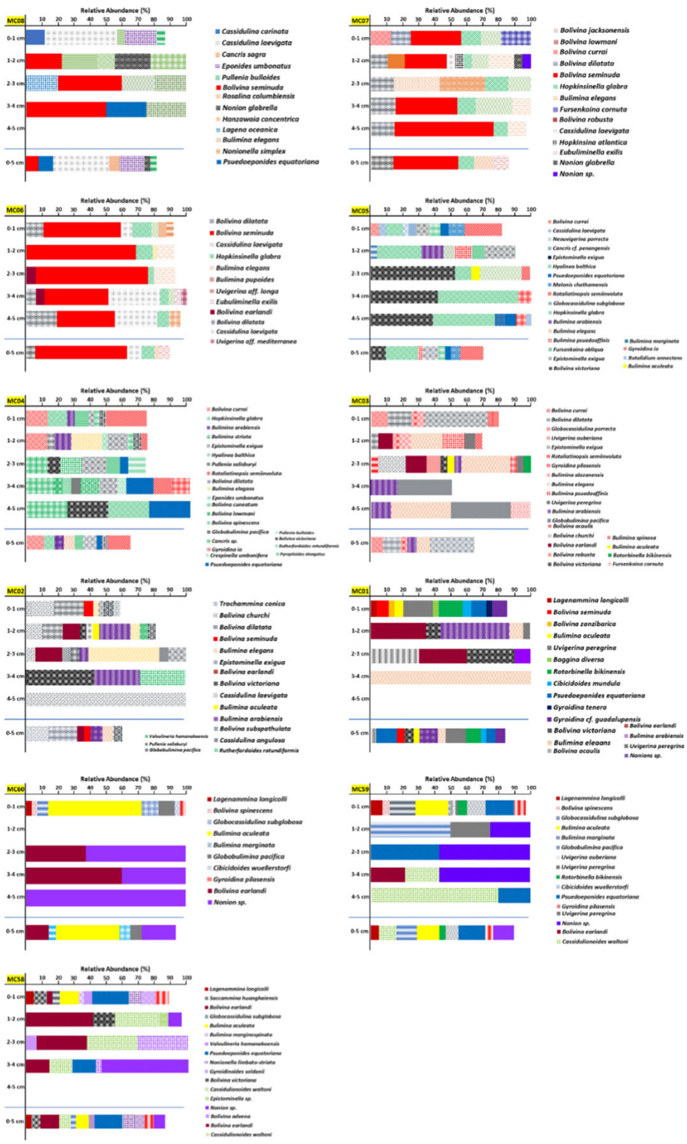

Fig. 5 The relative abundance of benthic foraminifera species in each section up to 5 cm depth as well as in the 0–5 cm section. The species having > 3% relative abundance are illustrated in the graph

marginospinata, Bulimina pupoides, Bulimina striata, Cancris cf. penangensis, Cassidulina carinata, Cibicidoides mundula, Cibicidoides wuellerstorfi, Eponides umbonatus, Gyroidina cf. guadalupensis, Gyroidina tenera, Gyroidinoides soldanii, Lagenammina longicolli, Melonis chathamensis, Neouvigerina porrecta, Saccammina huanghaiensis, Trochammina conica) were strictly epifaunal (found only in the top 0–1 cm section). Only one species (*Bolivina acaulis*) was shallow-infaunal (found in 1–3 cm section of the sediments). The depth habitat of a majority (23) of the species (*Bolivina churchi, Bolivina currai, Bolivina dilatata, Bolivina earlandi, Bolivina seminuda, Bulimina aculeata,*

Table 2 Depth habitat of the dominant living benthic foraminifera in the south-eastern Arabian Sea

Species	Living habitat		
	Epifaunal (0–1 cm)	Shallow-infaunal (1–3 cm)	Deep-infaunal (3–5 cm)
Baggina diversa	■		
Bolivina acaulis		■	
Bolivina churchi	■	■	
Bolivina currai	■	■	
Bolivina dilatata	■	■	
Bolivina earlandi	■	■	
Bolivina seminuda	■	■	
Bolivina victoriana	■	■	■
Bulimina aculeata	■	■	
Bulimina arabiensis	■	■	■
Bulimina elegans	■	■	■
Bulimina marginata		■	■
Bulimina marginospinata	■		
Bulimina pseudoaffinis	■	■	
Bulimina pupoides	■		
Bulimina striata	■		
Cancris cf. *penangensis*	■		
Cancris sagra	■	■	
Cassidulina carinata	■		
Cassidulina laevigata	■	■	■
Cassidulionoides waltoni	■	■	
Cibicidoides mundula	■		
Cibicidoides wuellerstorfi	■		
Epistominella exigua	■	■	■
Eponides umbonatus	■		
Eubuliminella exilis		■	■
Fursenkoina cornuta	■		■
Globobulimina pacifica		■	■
Globocassidulina porrecta	■	■	
Globocassidulina subglobosa	■	■	
Gyroidina cf. *guadalupensis*	■		
Gyroidina pilasensis	■	■	
Gyroidina tenera	■		
Gyroidinoides soldanii	■		
Hopkinsinella glabra	■	■	■
Hyalinea balthica	■	■	
Lagenammina longicolli	■		
Melonis chathamensis	■		
Neouvigerina porrecta	■		
Nonion glabrella	■	■	
Nonion sp.		■	■
Nonionella limbato-striata	■	■	
Psuedoeponides equatoriana	■	■	■
Pullenia bulloides	■	■	
Pullenia salisburyi	■	■	
Rotaliatinopsis semiinvoluta	■	■	
Rotorbinella bikinensis	■	■	
Saccammina huanghaiensis	■		
Trochammina conica	■		
Uvigerina aff. *longa*	■	■	
Uvigerina auberiana	■	■	
Uvigerina peregrina	■	■	
Valvulineria hamanakoensis	■	■	

The epifaunal forms were found in the top 0–1 cm, shallow-infaunal in top 1–3 cm and deep-infaunal in 3–5 cm of the sediments

Bulimina psuedoaffinis, Cancris sagra, Cassidulionoides waltoni, Globocassidulina porrecta, Globocassidulina subglobosa, Gyroidina pilasensis, Hyalinea balthica, Nonion glabrella, Nonionella limbato-striata, Pullenia bulloides, Pullenia salisburyi, Rotaliatinopsis semiinvoluta, Rotorbinella bikinensis, Uvigerina aff. longa, Uvigerina auberiana, Uvigerina peregrina, Valvulineria hamanakoensis) varied from epifaunal to shallow-infaunal. Only four species, namely *Bulimina marginata, Eubuliminella exilis, Globobulimina pacifica*, and *Nonion* sp., were shallow to deep-infaunal (living at 1–5 cm depth) in the south-eastern Arabian Sea. A few species (*Bolivina victoriana, Bulimina arabiensis, Bulimina elegans, Cassidulina laevigata, Epistominella exigua, Hopkinsinella glabra, Psuedoeponides equatoriana*) were found in all top 5 cm sections of the sediments, suggesting a variable depth habitat from epifaunal to deep-infaunal. Interestingly, one species, namely *Fursenkoina cornuta* was found in epifaunal and deep-infaunal habitats and not within shallow-infaunal depths. The ecological preferences in the core-top and 0–5 cm section are discussed separately.

Biodiversity index

From the surface distribution of living benthic foraminifera, Margalef index (d) for richness, Pielou index (J) for evenness and Shannon index (H) for diversity was calculated by using PRIMER software. The species richness, diversity and evenness were high at the intermediate depths, within the ODZ. In the core-top section, Margalef index varied from 1.5 to 6.1 with the maximum value at MC02 (1250 m) and minimum at MC07 (152 m) (Fig. 6). Pielou index varied between 0.88–0.97 with the maximum value at MC01 (1550 m) and the minimum at MC06 (215 m). Shannon index (H) varied between 1.77 and 2.98, with the maximum value at MC02 (1250 m) and the minimum at MC07 (152 m). The same pattern is also observed in the 0–5 cm section also with higher d, J and H index at the intermediate depths (Fig. 6).

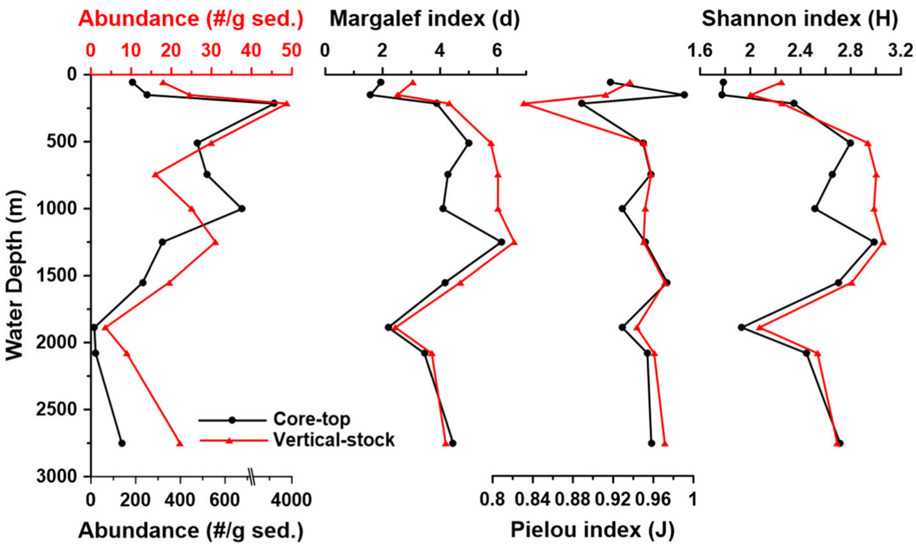

Fig. 6 Biodiversity indices [Margalef index (d) for richness, Pielou index (J) for evenness and Shannon index (H) for diversity] of the living benthic foraminifera in the core-top (0–1 cm) and 0–5 cm section

Ecological preferences of living benthic foraminifera in core-top section

Total 49 species had ≥ 3% abundance in the core-top samples (0–1 cm). In the Canonical Correspondence Analysis (CCA), total 14 species had a negative relationship and 11 were positively correlated with the bottom water dissolved oxygen (Figs. 7, 8a). The relationship of benthic foraminifera species with the organic matter was also evaluated, as ODZ and $\%C_{org}$ are closely linked. A total of 13 species were positively correlated with $\%C_{org}$ and 7 were negatively correlated (Fig. 8b). With the bottom water temperature, salinity and $\%C_{org}$/TN, the relationship, however, was opposite to that with $\%C_{org}$. Considering the large number of species with positive/negative correlation, we evaluated the significance level of the relationship between species abundance and ecological parameters (p-value < 0.05). From the p-value, we observed that only *Lagenammina longicolli* and *Gyroidina pilasensis* had significantly positive relationship and *Bolivina currai* and *Hopkinsinella glabra* had negative relationship with dissolved oxygen (Table 3). It is interesting to mention that none of the species had a significantly positive correlation with organic carbon. This is likely because $\%C_{org}$ is in excess and not limiting in the Gulf of Mannar. However, *Cassidulina carinata*, *Cassidulina laevigata, Cancris sagra* and *Eponides umbonatus* were negatively correlated with $\%C_{org}$ (Table 3). *Lagenammina longicolli*, *Bolivina spinescens, Globocassidulina subglobosa, Cibicidoides wuellerstorfi* and *Gyroidina pilasensis* were negatively correlated with $\%C_{org}$/TN, whereas *Fursenkoina cornuta* and *Bulimina elegans* were positively correlated. Beside this, species like *Cassidulina carinata*, *Cassidulina laevigata, Cancris sagra* and *Eponides umbonatus* showed a significant positive correlation with bottom water temperature and *Gyroidina pilasensis* was negatively correlated. In case of bottom water salinity, only *Bolivina seminuda* showed a significant positive correlation, while *Bulimina striata*, *Hyalinea balthica* and *Rotaliatinopsis semiinvoluta* showed a significant negative correlation with ambient salinity (Fig. 7; Table 3).

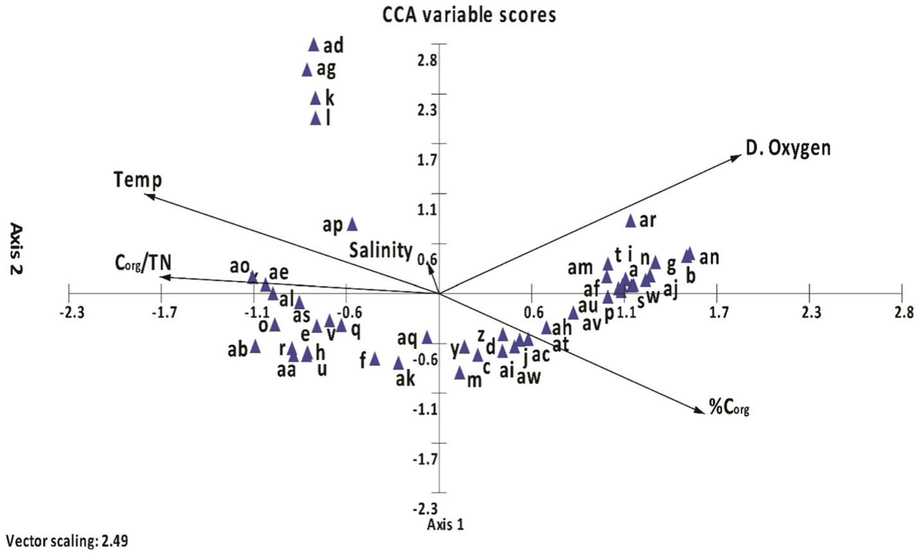

Fig. 7 Canonical correspondence analysis plot between the relative abundance of species in the core-top section and ambient ecological parameters. See Table 3 for abbreviation details

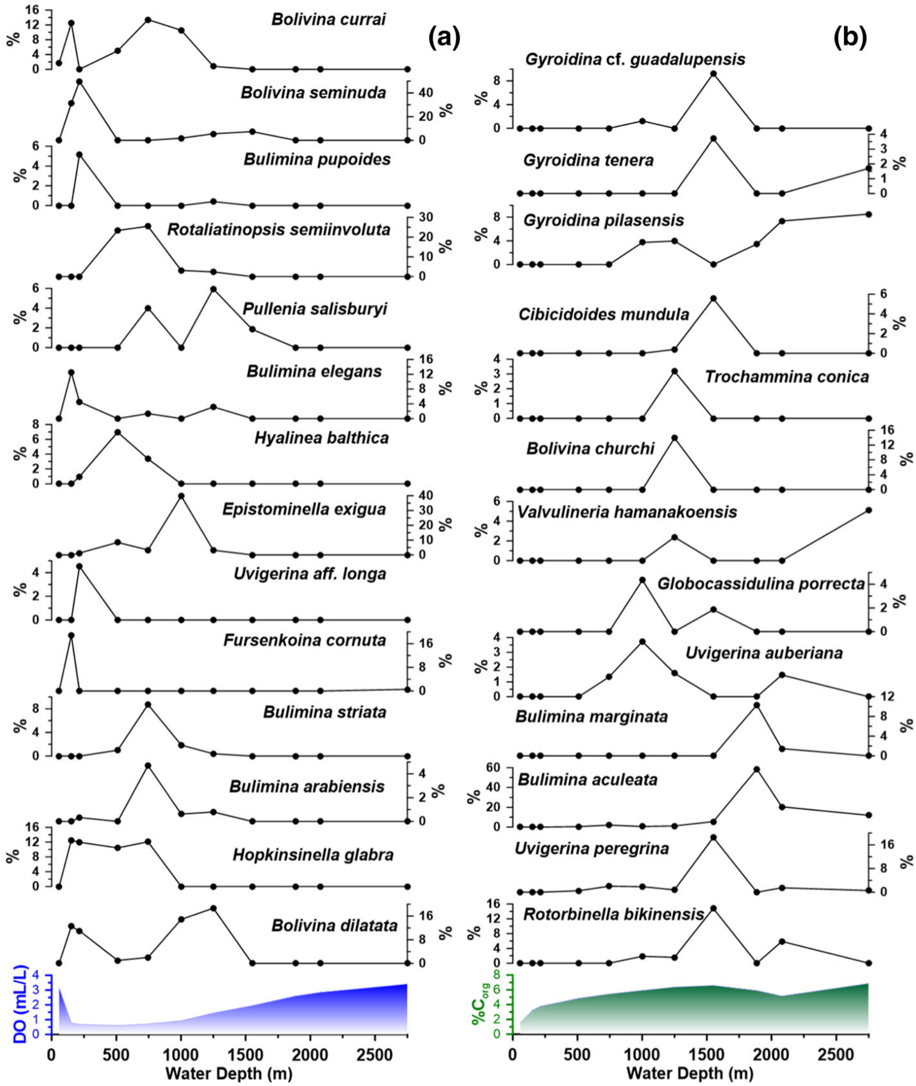

Fig. 8 The **a** relative abundance (%) of benthic foraminifera showing negative relationship with bottom water dissolved oxygen, and **b** positive relationship with organic carbon (%C_{org}), in the core-top sections

Living benthic foraminifera in 0–5 cm section and their ecological preferences

Total 43 species had ≥ 3% relative abundance in the top 5 cm section. Amongst all the abundant species, 10 showed positive and 12 species showed negative correlation with bottom water dissolved oxygen in the CCA plot (Figs. 9, 10a). *Lagenammina longicolli* was significantly positively correlated, whereas *Hopkinsinella glabra* and *Bulimina elegans* were significantly negatively correlated with dissolved oxygen. Beside this, 14 species showed a positive and 6 species showed a negative relationship with %C_{org} in sediments (Fig. 10b). *Lagenammina longicolli*, *Cassidulinoides waltoni, Psuedoeponides*

Table 3 The species with significant correlation with the ecological parameter (p =/≤ 0.05) in the core-top section (0–1 cm)

Species	Abbr.	DO	C_{org}	Species	Abbr.	DO	C_{org}
Lagenammina longicolli	a	**.6904** **p = .019**	.4306 p = .186	*Uvigerina peregrina*	z	.0357 p = .917	.3747 p = .256
Saccammina huanghaiensis	b	.5665 p = .069	.3719 p = .260	*Uvigerina* aff. *longa*	aa	− .3179 p = .341	− .2602 p = .440
Trochammina conica	c	− .0874 p = .798	.2687 p = .424	*Fursenkoina cornuta*	ab	− .2759 p = .412	− .3597 p = .277
Bolivina churchi	d	− .0874 p = .798	.2687 p = .424	*Baggina diversa*	ac	.0642 p = .851	.3144 p = .346
Bolivina currai	e	**− .6320** **p = .037**	− .1626 p = .633	*Cancris sagra*	ad	.4312 p = .186	**− .7223** **p = .012**
Bolivina dilatata	f	− .5591 p = .074	.0106 p = .975	*Cancris* cf. *penangensis*	ae	− .4322 p = .184	− .0167 p = .961
Bolivina earlandi	g	.4792 p = .136	.3447 p = .299	*Valvulineria hamanakoensis*	af	.4399 p = .176	.4648 p = .150
Bolivina seminuda	h	− .4648 p = .150	− .3730 p = .259	*Eponides umbonatus*	ag	.3908 p = .235	**− .7306** **p = .011**
Bolivina spinescens	i	.4807 p = .134	.1654 p = .627	*Rotorbinella bikinensis*	ah	.1546 p = .650	.3661 p = .268
Bolivina zanzibarica	j	.0642 p = .851	.3144 p = .346	*Cibicidoides mundula*	ai	.0583 p = .865	.3352 p = .314
Cassidulina carinata	k	.3701 p = .263	**− .7346** **p = .010**	*Cibicidoides wuellerstorfi*	aj	.4997 p = .118	.1729 p = .611
Cassidulina laevigata	l	.3406 p = .305	**− .7636** **p = .006**	*Epistominella exigua*	ak	− .3713 p = .261	.1896 p = .577
Globocassidulina porrecta	m	− .2108 p = .534	.2955 p = .378	*Hyalinea balthica*	al	− .5113 p = .108	− .0373 p = .913
Globocassidulina subglobosa	n	.5556 p = .076	.1777 p = .601	*Psuedoeponides equatoriana*	am	.5932 p = .054	.4287 p = .188
Hopkinsinella glabra	o	**− .7507** **p = .008**	− .3667 p = .267	*Nonionella limbato-striata*	an	.5070 p = .111	.3677 p = .266
Bulimina aculeata	p	.4719 p = .143	.2919 p = .384	*Melonis chathamensis*	ao	− .3451 p = .299	− .0398 p = .908
Bulimina arabiensis	q	− .3875 p = .239	.1290 p = .705	*Pullenia bulloidea*	ap	.0406 p = .906	− .4072 p = .214
Bulimina elegans	r	− .4545 p = .160	− .3819 p = .246	*Pullenia salisburyi*	aq	− .2427 p = .472	.3646 p = .270
Bulimina marginata	s	.3105 p = .353	.1738 p = .609	*Gyroidinoides soldani*	ar	.5881 p = .057	.2333 p = .490
Bulimina marginospinata	t	.4309 p = .186	.3407 p = .305	*Rotaliatinopsis semiinvoluta*	as	− .5277 p = .095	.0682 p = .842
Bulimina pupoides	u	− .3261 p = .328	− .2407 p = .476	*Gyroidina quinqueloba*	at	.0642 p = .851	.3144 p = .346

Table 3 continued

Species	Abbr.	DO	C_{org}	Species	Abbr.	DO	C_{org}
Bulimina striata	v	− .4126 p = .207	.1228 p = .719	*Gyroidina pilasensis*	au	**.6074** **p = .047**	.5275 p = .095
Globobulimina pacifica	w	.4228 p = .195	.2551 p = .449	*Gyroidina tenera*	av	.2812 p = .402	.4570 p = .158
Neouvigerina porrecta	x	− .3451 p = .299	− .0398 p = .908	*Gyroidina* cf. *guadalupensis*	aw	.0311 p = .928	.3395 p = .307
Uvigerina auberiana	y	− .2480 p = .462	.3047 p = .362				

The numbers marked in bold, indicate the significant correlation

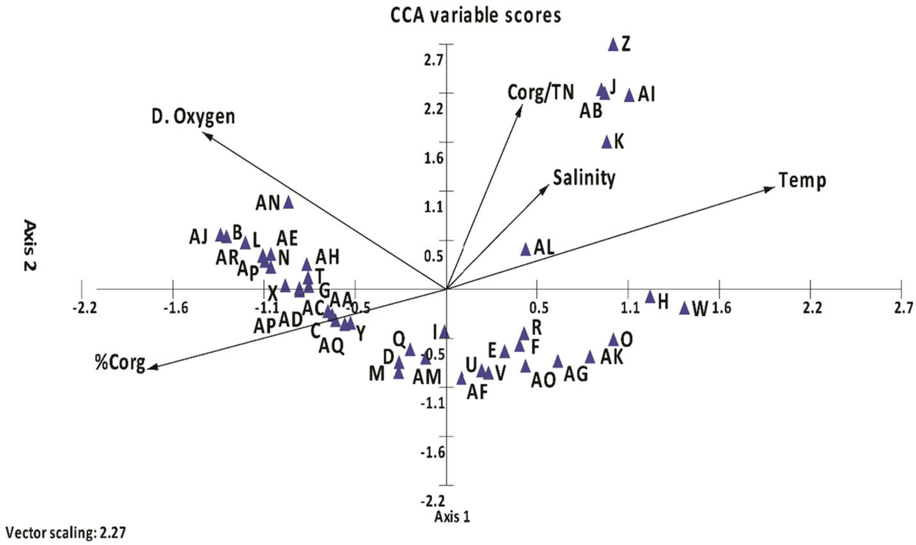

Fig. 9 Canonical correspondence analysis plot between the relative abundance of species in the top 5 cm section and ambient ecological parameters. See Table 4 for abbreviation details

equatoriana, Gyroidina pilasensis showed a positive correlation, whereas *Cassidulina laevigata* and *Nonion glabrella* were negatively correlated with %C_{org}. *Cassidulina carinata*, *Cassidulina laevigata, Cancris sagra, Eponides umbonatus, Nonion glabrella* were significantly positively correlated with %C_{org}/TN and none of the species were significantly negatively correlated. *Bolivina seminuda, Cassidulina carinata, Cassidulina laevigata, Eubuliminella exilis, Cancris sagra, Eponides umbonatus, Nonion glabrella* were significantly positively correlated, whereas *Gyroidina pilasensis* showed a significant negative relationship with bottom water temperature (Fig. 9; Table 4). *Bolivina seminuda*, *Eubuliminella exilis* showed a significant positive and *Bolivina currai*, *Bulimina psuedoaffinis*, *Bulimina striata*, *Hyalinea balthica*, *Rotaliatinopsis semiinvoluta* showed a significant negative correlation with bottom water salinity (Fig. 10; Table 4).

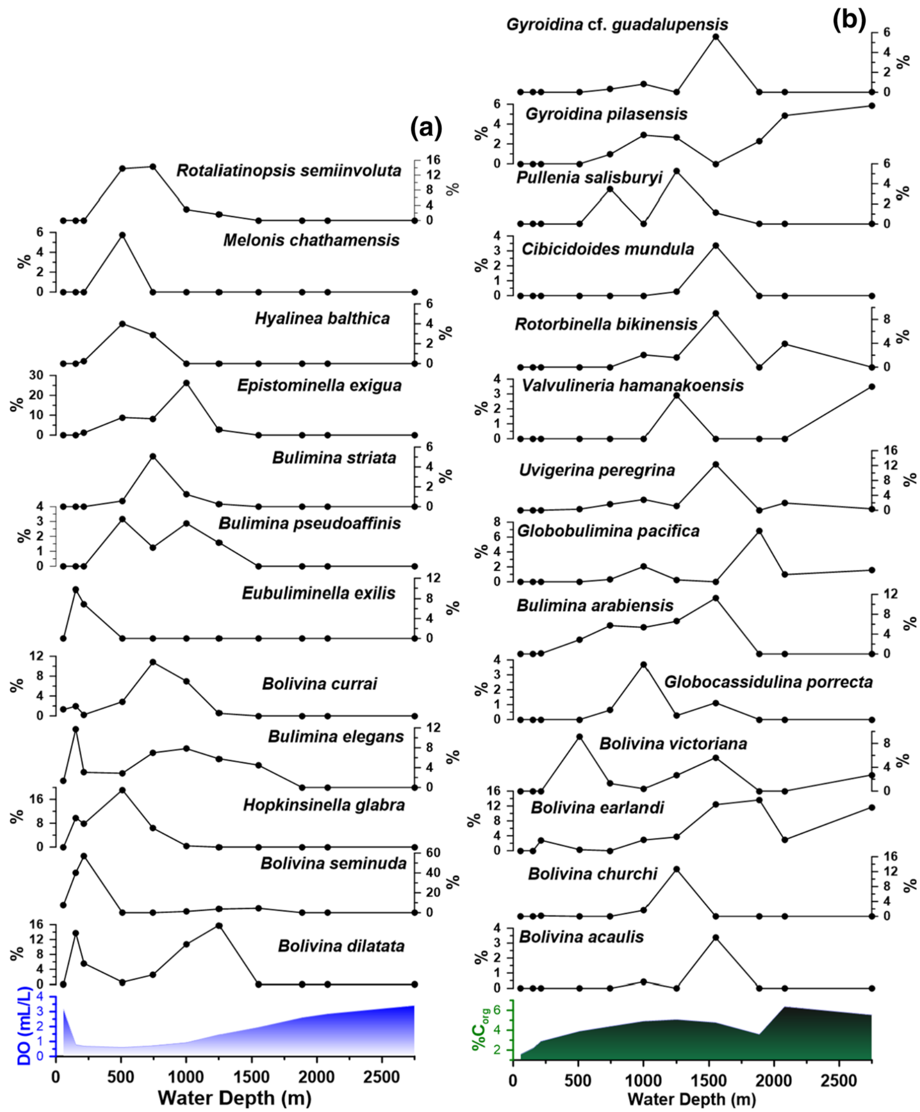

Fig. 10 The **a** relative abundance (%) of benthic foraminifera showing negative relationship with bottom water dissolved oxygen, and **b** positive relationship with organic carbon (%C_{org}) in the top 5 cm section

Benthic foraminifera within ODZ (core-top, 0–1 cm)

A total 14 species (*Bolivina dilatata, Hopkinsinella glabra, Bulimina arabiensis, Bulimina striata*, *Fursenkoina cornuta*, *Uvigerina* aff. *longa, Epistominella exigua, Hyalinea balthica, Bulimina elgans, Pullenia salisburyi, Rotaliatinopsis semiinvoluta, Bolivina seminuda, Bolivina currai and Bulimina pupoides*) (Fig. 8a) were negatively correlated with bottom water dissolved oxygen. Out of these, two species, namely *Bolivina currai* and *Hopkinsinella glabra* showed a significant negative correlation with dissolved oxygen, based on p-value. These species were abundant at ODZ depths, especially lower to mid-

Table 4 The species with significant correlation with the ecological parameter (p =/≤ 0.05) in the 0–5 cm section

Species	Abbr.	DO	C_{org}	Species	Abbr.	DO	C_{org}
Lagenammina longicolli	A	**.6987** **p = .017**	**.6717** **p = .024**	*Eubuliminella exilis*	W	− .4419 p = .174	− .5622 p = .072
Saccammina huanghaiensis	B	.5646 p = .070	.4051 p = .216	*Globobulimina pacifica*	X	.3366 p = .312	.1820 p = .592
Bolivina acaulis	C	.0341 p = .921	.1666 p = .624	*Uvigerina peregrina*	Y	.0205 p = .952	.3085 p = .356
Bolivina churchi	D	− .1246 p = .715	.2332 p = .490	*Cancris sagra*	Z	.4312 p = .186	− .5902 p = .056
Bolivina currai	E	− .5327 p = .092	.0035 p = .992	*Valvulineria hamanakoensis*	AA	.3529 p = .287	.4019 p = .220
Bolivina dilatata	F	− .5329 p = .091	− .1222 p = .720	*Eponides umbonatus*	AB	.3780 p = .252	− .5973 p = .052
Bolivina earlandi	G	.5225 p = .099	.3998 p = .223	*Rotorbinella bikinensis*	AC	.1338 p = .695	.4291 p = .188
Bolivina seminuda	H	− .4157 p = .203	− .5821 p = .060	*Cibicidoides mundula*	AD	.0577 p = .866	.1618 p = .635
Bolivina victoriana	I	− .2181 p = .520	.1894 p = .577	*Cibicidoides wuellerstorfi*	AE	.5016 p = .116	.5720 p = .066
Cassidulina carinata	J	.3923 p = .233	− .5953 p = .053	*Epistominella exigua*	AF	− .4791 p = .136	.1798 p = .597
Cassidulina laevigata	K	.2972 p = .375	**− .6709** **p = .024**	*Hyalinea balthica*	AG	− .5055 p = .113	− .0300 p = .930
Cassidulionoides waltoni	L	.5943 p = .054	**.6304** **p = .038**	*Psuedoeponides equatoriana*	AH	.5997 p = .051	**.6626** **p = .026**
Globocassidulina porrecta	M	− .2883 p = .390	.2434 p = .471	*Nonion glabrella*	AI	.3557 p = .283	**− .6995** **p = .017**
Globocassidulina subglobosa	N	.5209 p = .100	.5612 p = .072	*Nonionella limbato-striata*	AJ	.5070 p = .111	.3193 p = .338
Hopkinsinella glabra	O	**− .6748** **p = .023**	− .3525 p = .288	*Melonis chathamensis*	AK	− .3451 p = .299	− .0560 p = .870
Bulimina aculeata	P	.4672 p = .147	.2462 p = .466	*Pullenia bulloides*	AL	.0068 p = .984	− .3943 p = .230
Bulimina arabiensis	Q	− .3128 p = .349	.3214 p = .335	*Pullenia salisburyi*	AM	− .2478 p = .463	.2471 p = .464
Bulimina elegans	R	**− .7251** **p = .012**	− .2766 p = .410	*Gyroidinoides soldanii*	AN	.5964 p = .053	.1960 p = .563
Bulimina marginata	T	.2367 p = .483	.0334 p = .922	*Rotaliatinopsis semiinvoluta*	AO	− .5462 p = .082	.0461 p = .893
Bulimina psuedoaffinis	U	− .5720 p = .066	.1795 p = .597	*Gyroidina pilasensis*	AP	.5636 p = .071	**.7685** **p = .006**
Bulimina striata	V	− .4190 p = .200	.1026 p = .764	*Gyroidina* cf. *guadalupensis*	AQ	.0104 p = .976	.1747 p = .607
				Nonion sp.	AR	.5708 p = .067	.3432 p = .302

The numbers marked in bold, indicate the significant correlation

ODZ depths. These highly abundant benthic foraminifera species of ODZ, belong to the angular asymmetrical morpho-group, a widely accepted morphological adaptation in the ODZ conditions. Surprisingly, a few rounded symmetrical forms like *Epistominella exigua*, *Hyalinea balthica*, as well as the rounded symmetrical forms with comparatively bigger aperture, like *Rotaliatinopsis semiinvoluta* and *Pullenia salisburyi*, are also abundant in the ODZ. These findings suggest that except angular asymmetrical forms, the rounded forms with bigger aperture can also adapt and thrive well in the ODZ.

Benthic foraminifera within ODZ (0–5 cm section)

In the top 5 cm section, 12 species (*Bolivina dilatata, Hopkinsinella glabra, Bulimina striata, Epistominella exigua, Hyalinea balthica, Bulimina elegans, Bulimina pseudoaffinis, Rotaliatinopsis semiinvoluta, Bolivina seminuda, Bolivina currai, Melonis chathamensis* and *Eubuliminella exilis*) (Fig. 10a) were negatively correlated with bottom water dissolved oxygen. *Hopkinsinella glabra* and *Bulimina elegans* were significantly negatively correlated with the ambient dissolved oxygen. Interestingly, it is evident that the species that showed affinity for intense ODZ condition in the core-top section, does not necessarily show a similar preference in 0–5 cm section. The difference in the representative species in the core-top and 0–5 cm section suggests vertical migration of species is important phenomena in the ODZ and the species representing vertical movement, should be carefully considered for paleo-reconstruction.

Discussion

Benthic foraminifera are relatively abundant in the ODZ. We also found higher abundance of benthic foraminifera in the intermediate depths where organic matter was more abundant, and dissolved oxygen was deficient. The quality and quantity of organic matter in the sediments is considered as one of the major factors modulating abundance and diversity of living benthic foraminifera (Jorissen et al. 1995, 2007; Jannink et al. 1998; Schumacher et al. 2007). Benthic foraminifera thrive well in high $\%C_{org}$ environments (Bhaumik et al. 2014; Den Dulk et al. 2000; Gooday and Turley 1990; Jorissen et al. 1992, 1995; Kaminski et al. 1995; McCorkle et al. 1997; Nomaki et al. 2008). The high $\%C_{org}$ sediments are often oxygen deficient. In the Gulf of Mannar, the sediments have excess organic matter. The excess organic matter facilitates such high abundance of living benthic foraminifera, despite of the low dissolved oxygen. The low dissolved oxygen in organic matter rich sediments, however, allows only a few selected benthic foraminiferal species to thrive (Sen Gupta and Machain-Castillo 1993; Van Der Zwaan et al. 1999). Interestingly, this low dissolved oxygen severely affects the predators, thus imparting a positive influence on the survival and growth of benthic fauna in C_{org} rich sediments (Jorissen et al. 1995). As evident, the higher $\%C_{org}$ at the intermediate depths of the southeastern Arabian Sea also facilitates prolific abundance of benthic foraminifera. Although in core-top sections, we did not find any species with significant positive correlation with $\%C_{org}$, in 0–5 cm section *Lagenammina longicolli*, *Cassidulina laevigata, Pseudoeponides equatoriana, Gyroidina pilasensis* showed a significant positive correlation with $\%C_{org}$. Our findings are partially in-line with previous reports from the eastern Arabian Sea where bottom water dissolved oxygen was reported as the prime factor controlling the species composition (Caulle et al. 2015).

In the Gulf of Mannar, *Bolivina seminuda*, *Bolivina dilatata*, *Eubuliminella exilis, Bulimina elegans, Bulimina aculeata and Hopkinsinella glabra* are highly abundant in waters with low dissolved oxygen. Several attempts have been made to identify the key benthic foraminiferal species from the world ocean ODZ, including parts of the Arabian Sea (Hermelin and Shimmield 1990; Jannink et al. 1998; Gooday et al. 2000, 2009; Schumacher et al. 2007; Larkin and Gooday 2008; Enge et al. 2014; Erbacher and Nelskamp 2006; Jannink et al. 1998; Caulle et al. 2014, 2015; Mazumder and Nigam 2014). Earlier, several of these species, including *Bolivina seminuda, Bolivina dilatata* and *Eubuliminella exilis* were reported to be abundant in the upper part of ODZ in the northeastern Arabian Sea (Jannink et al. 1998; Erbacher and Nelskamp 2006; Schumacher et al. 2007; Larkin and Gooday 2008; Gooday et al. 2009; Caulle et al. 2014; Enge et al. 2014). We report a difference in the depth preference of these species in the ODZ of the southeastern Arabian Sea. *Bolivina dilatata* was abundant throughout the ODZ and *Bulimina elegans* as well as *Hopkinsinella glabra* were abundant in the middle and lower part of the ODZ in the southeastern Arabian Sea, with much higher abundance at deeper ODZ depths. We report that *Bulimina currai*, *Bulimina elegans* and *Hopkinsinella glabra* are the most significant species to reconstruct past ODZ from the southeastern Arabian Sea. Besides this, out of the several other dominant species within and below the ODZ of the northern Arabian Sea (*Rotaliatinopsis semiinvoluta*, *Uvigerina peregrina*, *Bulimina aculeata* and *Epistominella exigua*) (Schumacher et al. 2007; Caulle et al. 2014), we only found *Rotaliatinopsis semiinvoluta* and *Epistominella exigua* being negatively correlated with dissolved oxygen in the southeastern Arabian Sea. *Bolivina*, *Bulimina* and *Uvigerina* were also reported to be abundant genera in the eastern Arabian Sea ODZ (Mazumder and Nigam 2014).

Recently, a detailed description of living benthic foraminifera from the continental shelf to slope and further deeper region of the central-western Bay of Bengal ODZ was published (Suokhrie et al. 2020). The central-western Bay of Bengal receives a huge riverine influx. We compared the living benthic foraminifera dominant in the southeastern Arabian Sea ODZ with that from the central-western Bay of Bengal ODZ. Amongst the fourteen species abundant in the surface sediments and the top 5 cm section of the southeastern Arabian Sea ODZ, only three (*Eubuliminella exilis, Hopkinsinella glabra, Rotaliatinopsis semiinvoluta*) were also found in the central Bay of Bengal ODZ (Suokhrie et al. 2020). Incidentally, two of these species, namely *Eubuliminella exilis* and *Rotaliatinopsis semiinvoluta* are abundant in the ODZ of the central-western Bay of Bengal, northern Arabian Sea as well as the southeastern Arabian Sea.

Within the ODZs, denitrification also strongly modulates living benthic foraminifera. The denitrification has been widely reported from the northern Arabian Sea ODZ (Naqvi et al. 2006). The prevalence of denitrification leads to a unique assemblage, as a few benthic foraminifera (*Globobulimina pseudospinescens*, *Nonionella* cf. *stella* and *Stainforthia*, *Bolivina seminuda, B. plicata, B. subaenariensis, B. argentea, Buliminella tenuata, Virgulinella fragilis, Globobulimina turgida*) are capable of denitrification (Risgaard-Petersen et al. 2006; Piña-Ochoa et al. 2010; Bernhard et al. 2012a, b; Glock et al. 2013). Although, several species abundant in the southeastern Arabian Sea ODZ (*Bolivina seminuda, Bolivina dilatata, Eubuliminella exilis, Rotaliatinopsis semiinvoluta* and *Epistominella exigua*), are also present in the northern Arabian Sea, only a few of them (*Bolivina seminuda*) have so far been reported to denitrify. The denitrification has not been reported from the southeastern Arabian Sea, so far (S.W.A. Naqvi, personal communication). Despite of the no report of denitrification from the southeastern Arabian Sea, the presence of several common species in the southeastern and northern Arabian Sea, especially of a species (*B. seminuda*) reported to denitrify, is intriguing. However, a point to be kept in mind here, is that the species reported to denitrify can also respire with oxygen, suggesting that denitrification is an auxiliary metabolism and such foraminifera are facultative anaerobes (Piña-Ochoa et al. 2010). Therefore, it is likely that the abundance of *B. seminuda* at a few depths of the southeastern Arabian Sea ODZ, is not associated with denitrification. Detailed studies on water column and surface sediments of the south-eastern Arabian Sea, during different seasons, will help to confirm the presence of denitrification and its influence on living benthic foraminifera in the southeastern Arabian Sea.

Depth zonation of living benthic foraminifera within the ODZ

A clear demarcation is observed in the depth preference of living benthic foraminifera, within the southeastern Arabian Sea ODZ. *Bolivina seminuda*, *Bolivina dilatata, Eubuliminella exilis, Bulimina elegans* and *Hopkinsinella glabra* were the most abundant at shallow ODZ depth (Station MC06 and MC07). Earlier, *Bolivina dilatata* and *Eubuliminella exilis* were reported to be the most abundant species in the upper part of ODZ ($\sim$ 500 m water depth and 0.1 mL/L dissolved oxygen) from the northeastern Arabian Sea (Jannink et al. 1998; Caulle et al. 2014). The shallow ODZ stations in the southeastern Arabian Sea had low dissolved oxygen (0.5–0.7 mL/L; 22–31 µM) and moderate $\%C_{org}$ (2.1–2.8%). *Uvigerina* ex *gr. Uvigerina semiornata* and *Bolivina* aff. *Bolivina dilatata* were reported at similar depth and $\%C_{org}$, in the northeastern Arabian Sea (Schumacher et al. 2007). We do not find *Uvigerina* in abundance at shallow depths; this could be because of the difference in size fraction used for picking living benthic foraminifera in two studies. We used the widely recommended > 63 µm fraction (Murray 2006) to pick living benthic foraminifera from all the sections. However, in the study from the southeastern Arabian Sea, the fractions > 150 µm and 125–150 µm were used to pick living benthic foraminifera, except for the top 1 cm section, for which 63 µm fraction was used (Caulle et al. 2014).

Bolivina dilatata was present throughout the ODZ in the southeastern Arabian Sea, with comparatively higher abundance in lower ODZ depths. *Bolivina dilatata* is one of the dominant benthic foraminifera in the oxygen deficient waters of several regions, including the Adriatic Sea (Barmawidjaja et al. 1992), eastern south Atlantic Ocean (Schmiedl et al. 1997) and the Arabian Sea (Jannink et al. 1998; Caulle et al. 2014, 2015). Jannink et al. (1998) reported it only from the upper ODZ but Caulle et al. (2015) found it in the lower part of the ODZ.

Eubuliminella exilis (also referred as *Bulimina exilis*) was only present at two shallow ODZ stations (MC06 and 07) along the transect. *Eubuliminella exilis* is commonly referred to as the low oxygen high organic matter favoring species (Jannink et al. 1998; Caulle et al. 2014, 2015). In the southeastern Arabian Sea, however, *E. exilis* is mainly associated with low oxygen rather than higher organic matter. *Eubuliminella exilis* prefers unaltered/labile organic matter (Caralp 1989; Jorissen et al. 1998). We do not have qualitative data of organic matter as this could be a limiting factor for *E. exilis* abundance in the southeastern Arabian Sea. *Bulimina elegans,* was found throughout the ODZ which suggests its preference for low dissolved oxygen conditions.

Abundance of *Bolivina seminuda* has previously been reported from the deeper ODZ depths (1000–1500 m) of the northern Arabian Sea (Jannink et al. 1998; Caulle et al. 2014). In the southeastern Arabian Sea transect, we found abundant presence of *Bolivina* *seminuda*, with a very high abundance ($\sim$ 50%) at upper ODZ depths. The abundant presence of *B. seminuda* throughout the Arabian Sea ODZ, indicates its preference for oxygen deficient environment, as well as its capability of denitrification (Piña-Ochoa et al. 2010). *Hopkinsinella glabra* as an indicator of ODZ is the first report from the Indian Ocean. Although *Hopkinsinella glabra* was earlier reported from the northern Indian Ocean (Gandhi et al. 2002), it was not associated with oxygen deficient environment. In the culture experiments, *Hopkinsinella glabra* was reported to prefer fresh food (Ernst et al. 2005). It was also reported as an opportunistic species (Jorissen et al. 1992) which moves upward and is mainly confined to the sediment water interface (Ernst et al. 2006; Langlet et al. 2013).

Based on the distribution of benthic foraminifera in the southeastern Arabian Sea and its ecological preferences, we delineate specific benthic foraminiferal assemblage characteristic of different dissolved oxygen concentration as well as associated parameters. The assemblages are delineated considering the abundance of species in core-top as well as 0–5 cm section (Table 5, Plate 1). Assemblage (Ass.) 1, comprising of *Cassidulina laevigata, Cassidulina carinata* and *Eponides umbonatus* represents a shallow depth oxygen rich warm water environment with low organic matter availability and saltier conditions. Assemblage 2 includes *Bolivina seminuda, Hopkinsinella glabra* and *Eubuliminella exilis* and represents shallow water intense suboxic conditions with moderate organic matter availability. The assemblage 3 represented by *Rotaliatinopsis semiinvoluta, Hopkinsinella glabra* and *Epistominella exigua* indicates similar kind of suboxic environment but with comparatively high %C_{org} and lower bottom water temperature. Assemblage 4 includes *Bulimina arabiensis, Bulimina elegans* and *Bolivina earlandi* and represents comparatively higher dissolved oxygen conditions (1–2 mL/L, 45–90 µM) with high organic carbon at deeper water depths ($\sim$ 1000–1500 m). Assemblage 5 comprising of *Bolivina earlandi, Bulimina aculeata* and *Globocassidulina subglobosa* includes deep-water benthic foraminifera where bottom water is oxygen rich (> 2.0 mL/L or > 90 µM) along with high food availability with the lowest bottom water temperature and salinity.

Living benthic foraminifera at depths deeper than ODZ

All living benthic foraminifera dominant in the ODZ, were completely absent in the 0–5 cm section at depths deeper than ODZ. The sediments at depths deeper than intermediate ODZ, were rich in organic matter with well oxygenated waters, an unusual complex oceanographic condition. *Bulimina aculeata, Bolivina earlandi, Cassidulionoides waltoni, Pseudoeponides equatoriana, Globocassidulina subglobosa* are the most abundant species in the region deeper than the ODZ. These species have earlier been reported from the well oxygenated and low %C_{org} environment. *Bulimina aculeata* and *Globocassidulina subglobosa* are previously reported from the well oxygenated waters of the northern Arabian Sea (Jannink et al. 1998; Caulle et al. 2014). The abundant presence of these species in the organic matter rich sediments of the southeastern Arabian Sea, however, indicates that these species favor higher dissolved oxygen and are not strongly influenced by %C_{org}.

Diversity at different depths

The greater diversity within the ODZ of the southeastern Arabian Sea is intriguing. The stressed environments usually support a few opportunistic fauna, thus reducing the

Table 5 Living benthic foraminifera assemblages indicator of different bottom water dissolved oxygen concentration and other associated ecological parameters

	Species composition	Depth (m)	%C_{org}	DO (mL/L)	Temp. (°C)	Salinity (psu)	%C_{org}/TN
Assemblage 1	*Cassidulina laevigata, Cassidulina carinata* and *Eponides umbonatus*	Continental Shelf (58)	1.52–1.57	3.39 (151 µM)	25.96	35.18	14.6–15.1
Assemblage 2	*Bolivina seminuda, Hopkinsinella glabra* and *Eubuliminella exilis*	Upper Continental Slope (152–215)	2.17–3.78	0.53–0.69 (24–31 µM)	13.61–16.28	35.02–35.06	8.4–16.4
Assemblage 3	*Rotaliatinopsis semiinvoluta, Hopkinsinella glabra* and *Epistominella exigua*	Middle Continental Slope (510–745)	3.90–5.43	0.48–0.63 (21–28 µM)	8.26–9.94	34.98–35.04	7.2–12.1
Assemblage 4	*Bulimina arabiensis, Bulimina elegans* and *Bolivina earlandi*	Lower Continental Slope (1002–1550)	4.78–6.60	1.07–2.03 (48–91 µM)	4.09–6.56	34.85–34.95	6.6–13.2
Assemblage 5	*Bolivina earlandi, Bulimina aculeata* and *Globocassidulina subglobosa*	Deeper Region (1887–2750)	4.02–6.86	2.85–3.84 (127–171 µM)	2.06–3.01	34.75–34.79	7.3–11.0

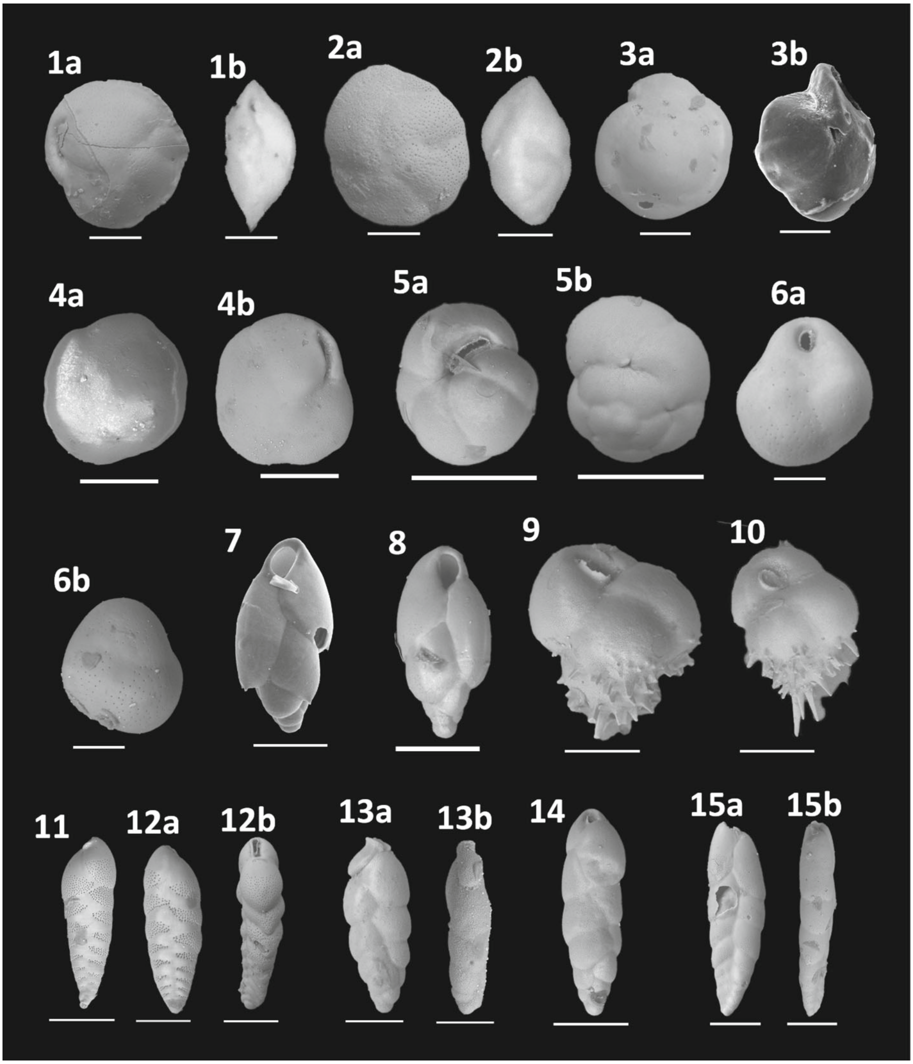

Plate 1 1. *Cassidulina laevigata* (a-side view; b-lateral view), 2. *Cassidulina carinata* (a-side view; b-lateral view, 3. *Eponides umbonatus* (a-side view; b-lateral view, 4. *Epistominella exigua* (a-side view; b-apertural view), 5. *Rotaliatinopsis semiinvoluta* (a-apertural view; b-side view), 6. *Globocassidulina subglobosa* (a-side view; b-lateral view), 7. *Bulimina arabiensis*, 8. *Bulimina elegans*, 9 & 10. *Bulimina aculeata*, 11 & 12. *Bolivina seminuda* (a-side view; b-lateral view), 13. *Hopkinsinella glabra* (a-side view; b-lateral view), 14. *Eubuliminella exilis*, 15. *Bolivina earlandi* (a-side view; b-lateral view). Scale = 100 µm

diversity. The low dissolved oxygen is suggested as a severe stress for benthic foraminifera (Jorissen et al. 1995; Kaminski et al. 1995). Therefore, benthic foraminiferal diversity should decrease within the ODZ. The high diversity in the ODZ, thus suggests a combination of several possibilities. The low diversity on the continental shelf is attributed to the coarse-grained sediments and low $\%C_{org}$. The grain size and $\%C_{org}$ are often linked, as fine-grained sediments provide increased surface area for the organic matter to adhere, thus leading to its better preservation, and vice versa (Burdige 2007). The lack of food availability in coarse grained sediments acts as a deterrent for the proliferation of benthic foraminiferal diversity as well as the population. The coarse-grained texture, also implies high energy conditions, another adverse factor for benthic foraminifera to thrive. The predatory pressure is also comparatively high in the shallow water shelf environment, as macro and mega-benthic population is greater here (Ingole et al. 2010). Thus, the coarse-grained texture, high energy environment coupled with very low %C_{org} reduces the foraminiferal diversity on the continental shelf in the southeastern Arabian Sea.

Although the dissolved oxygen concentration decreases on the slope, the availability of plenty of organic matter, coupled with decreased predatory pressure leads to the proliferation of diverse benthic foraminiferal species within the ODZ (den Dulk et al. 2000; Levin 2003; Enge et al. 2016). The strong seasonality in the southeastern Arabian Sea, leading to a change in the type of organic matter flux to the sediments during different seasons (Jyothibabu et al. 2014), coupled with comparatively higher dissolved oxygen concentration, may also drive the increased diversity. The food preference of living benthic foraminifera vary with species. The availability of different organic matter flux, thus supports various species, increasing the diversity. Additional sampling at the same stations during different seasons, will further confirm the influence of seasonal organic matter flux on benthic foraminifera diversity in the Gulf of Mannar. The decreased diversity at deeper, well oxygenated depths, despite of the availability of plenty of organic matter with fine grained sediments, is attributed to the increased predatory pressure as well as low temperature. Interestingly, the richness and evenness is also higher within the ODZ. The higher richness and evenness suggests abundant presence of several species, again pointing towards the strong seasonality including the availability of different types of food, supporting diverse species. The living benthic foraminiferal diversity indices in the southeastern Arabian Sea are opposite to that of macrobenthic community across a depth transect covering the ODZ in the eastern Arabian Sea (Ingole et al. 2010). The difference in diversity and abundance suggests that the low dissolved oxygen is a severe limiting ecological factor for the macrobenthic community, whereas several benthic foraminifera are well adapted to low dissolved oxygen. The low predatory pressure due to the decreased macrobenthic population (Ingole et al. 2010), allows sustenance of an abundant benthic foraminiferal population (Kaminski et al. 1995).

Comparison of abundance and diversity in the southeastern Arabian Sea with other ODZs

The abundance of living benthic foraminifera increases many folds at ODZ depths in the southeastern Arabian Sea, with an exceptionally high value at MC06 (215 m) in the core-top section. A similar increase in the abundance within ODZ was also reported from other parts of the Arabian Sea, including off Pakistan (Caulle et al. 2014; Schumacher et al. 2007), off Oman (Gooday et al. 2000) and off Mumbai (Caulle et al. 2015) (> 63 µm). This trend of increased abundance within ODZ was not so prominent in other size fractions (> 150 and 63–150 µm). In the top 5 cm section also, the increase in living benthic foraminiferal abundance was not so prominent. A similar abundance pattern with only a marginal increase in benthic foraminiferal abundance in ODZ has also been reported from other parts of the Arabian Sea (Caulle et al. 2014, 2015; Gooday et al. 2000; Schumacher et al. 2007).

Shannon index (H) is often used to represent diversity (number of species present at a station and its relative abundance) (Dubey et al. 2018). In the southeastern Arabian Sea, Shannon index (H) varied between ∼ 1.7 and 3.0. The lower values (∼ 1.7) were at shallow water depths (58 and 152 m) and below ODZ at 1887 m. The lower diversity on the continental shelf is attributed to the coarse-grained texture, very low organic matter and heavy predatory pressure, as well as high energy condition. The low diversity in both the core-top as well as the 0–5 cm section at 1887 m is attributed to the low organic carbon at this station, as compared to other immediate stations. At rest of the stations, Shannon index (H) varies between ∼ 2.0 and 3.0 in both the core-top as well as the 0–5 cm section. A similar range of Shannon index (H) was reported previously from the different parts of the Arabian Sea (Caulle et al. 2014, 2015; Schumacher et al. 2007) except off Oman, where diversity decreased to 0.9 at 412 m with dissolved oxygen concentration being 0.13 mL/L. A comparable low H value (< 1) was also found in Santa Barbara Basin (Bernhard et al. 1997; Gooday et al. 2000) where bottom waters were nearly anoxic. This demonstrates that the extremely low dissolved oxygen or anoxic conditions decrease benthic foraminiferal diversity. As the bottom water dissolved oxygen does not decrease to anoxic levels in the Gulf of Mannar, benthic foraminiferal diversity is not severely affected.

Conclusions

Living (rose -Bengal stained) benthic foraminifera from the southeastern Arabian Sea have been documented. The increased abundance of benthic foraminifera in the core-top (0–1 cm) as well as 0–5 cm section at the intermediate depths, with oxygen deficient waters is attributed to the availability of higher organic matter/food. The species abundance is mainly controlled by the bottom water dissolved oxygen and organic carbon content of the sediments in the region. The abundant presence of *Bolivina currai* and *Hopkinsinella glabra* in the core-top sections is correlated with the dissolved oxygen. However, in the top 5 cm section, *Hopkinsinella glabra* and *Bulimina elegans* are significantly affected by the low dissolved oxygen. The significant negative relationship of *Hopkinsinella glabra* with the ambient dissolved oxygen, in both the top 0–1 cm section as well as the top 5 cm section, suggests it to be a good indicator of low dissolved oxygen environment in the southeastern Arabian Sea. Besides this, we also report five assemblages of living benthic foraminifera representing different bottom water conditions. Assemblage 1, dominated by *Cassidulina laevigata, Cassidulina carinata* and *Eponides umbonatus* indicates shallow depth, hypersaline oxygen rich warm water environment with low organic matter availability. Assemblage 2 includes *Bolivina seminuda, Hopkinsinella glabra* and *Eubuliminella exilis* and represents shallow water intense suboxic condition with moderate organic matter availability. The assemblage 3 includes *Rotaliatinopsis semiinvoluta, Hopkinsinella glabra* and *Epistominella exigua* and indicates similar kind of suboxic environment but with comparatively high $\%C_{org}$ and lower bottom water temperature. Assemblage 4 mainly comprise of rectilinear infaunal species, dominated by *Bulimina arabiensis, Bulimina elegans* and *Bolivina earlandi* and represents comparatively higher dissolved oxygen condition (1–2 mL/L; 45–90 µM) with high organic carbon at deeper water depths (∼ 1000–1500 m). Assemblage 5 comprising of *Bolivina earlandi, Bulimina aculeata* and *Globocassidulina subglobosa* includes deep-water benthic foraminifera where bottom water is oxygen rich (> 2.0 mL/L or > 90 µM) along with high food availability with the lowest bottom water temperature and salinity. These representative benthic foraminiferal assemblages will help in reconstructing paleoceanographic conditions from the southeastern Arabian Sea.

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References

Aksu AE, Hiscott RN, Kaminski MA, Mudie PJ, Gillespie H, Abrajano T, Yasar D (2002) Last Glacial to Holocene paleoceanography of the Black Sea and Marmara Sea: stable isotopic, foraminiferal and coccolith evidence. Mar Geol 190:119–149

Barmawidjaja DM, Jorissen FJ, Puskaric S, van der Zwaan GJ (1992) Microhabitat selection by benthic Foraminifera in the northern Adriatic Sea. J Foramin Res 22:297–317

Bernhard JM, Sen Gupta BK, Borne PF (1997) Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin. J Foramin Res 27:301–310

Bernhard JM, Casciotti KL, McIlvin MR, Beaudoin DJ, Visscher PT, Edgcomb VP (2012a) Potential importance of physiologically diverse benthic foraminifera in sedimentary nitrate storage and respiration. J Geophys Res 117:G03002. https://doi.org/10.1029/2012JG001949

Bernhard JM, Edgcomb VP, Casciotti KL, McIlvin MR, Beaudoin DJ (2012b) Denitrification likely catalyzed by endobionts in an allogromiid foraminifer. ISME J 6:951–960

Bhaumik AK, Gupta AK (2005) Deep-sea benthic foraminifera from gas hydrate-rich zone, Blake Ridge, Northwest Atlantic (ODP Hole 997A). Curr Sci 106:1133–1140

Bhaumik AK, Gupta AK, Clemens SC, Mazumder R (2014) Functional morphology of *Melonis barleeanum* and *Hoeglundina elegans*: a proxy for water-mass characteristics. Curr Sci 88:1969–1973

Bouwman AF, Van Drecht G, Knoop JM, Beusen AHW, Meinardi CR (2005) Exploring changes in river nitrogen export to the world's oceans. Glob Biogeochem Cycl 19:GB1002

Boyer TP, Antonov JI, Baranova OK, Garcia HE, Johnson DR, Mishonov AV et al (2013) World ocean database. https://doi.org/10.7289/v5nz85mt

Breitburg D, Levin LA, Oschlies A, Grégoire M, Chavez FP, Conley DJ, Garçon V, Gilbert D, Gutiérrez D, Isensee K, Jacinto GS, Limburg KE, Montes I, Naqvi SWA, Pitcher GC, Rabalais NN, Roman MR, Rose KA, Seibel BA, Telszewski M, Yasuhara M, Zhang J (2018) Declining oxygen in the global ocean and coastal waters. Science 359:eaam7240

Bristow LA, Callbeck CM, Larsen M, Altabet MA, Dekaezemacker J, Forth M, Gauns M, Glud RN, Kuypers MM, Lavik G, Milucka J (2017) N_2 production rates limited by nitrite availability in the Bay of Bengal oxygen minimum zone. Nat Geosci 10:24

Burdige DJ (2007) Preservation of organic matter in marine sediments: controls, mechanisms, and an imbalance in sediment organic carbon budgets? Chem Rev 107:467–485

Caralp MH (1989) Abundance of *Bulimina exilis* and *Melonis barleeanum*: relationship to the quality of marine organic matter. Geo-Mar Lett 9:37–43

Caulle C, Koho KA, Mojtahid M, Reichart GJ, Jorissen FJ (2014) Live (rose Bengal stained) foraminiferal faunas from the northern Arabian Sea: faunal succession within and below the OMZ. Biogeosciences 11:1155–1175

Caulle C, Mojtahid M, Gooday AJ, Jorissen FJ, Kitazato H (2015) Living (rose-Bengal stained) benthic foraminiferal faunas along a strong bottom-water oxygen gradient on the Indian margin (Arabian Sea). Biogeosciences 12:5005–5019

Chauhan OS (1996) Aeolian deposition of Arabia and Somalia sediments on the southwestern continental margin of India. Curr Sci 71:233–236

Chauhan OS, Gujar AR (1996) Surficial clay mineral distribution on the southwestern continental margin of India: evidence of input from the Bay of Bengal. Cont Shelf Res 16:321–333

Den Dulk M, Reichart GJ, van Heyst S, Zachariasse WJ, Van der Zwaan GJ (2000) Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea. Palaeogeogr Palaeoclimatol Palaeoecol 161:337–359

Dubey R, Saraswat R, Nigam R (2018) Mudbank off Alleppey, India: a bane for foraminifera but not so for carbon burial. Sci Total Environ 634:459–470

Ellis BF, Messina A (1940–2015) Catalogue of foraminifera. Micropaleontology Press, American Museum of Natural History, New York

Enge AJ, Witte U, Kucera M, Heinz P (2014) Uptake of phytodetritus by benthic foraminifera under oxygen depletion at the Indian margin (Arabian Sea). Biogeosciences 11:2017–2026

Enge AJ, Wukovits J, Wanek W, Watzka M, Witte UFM, Hunter WR, Heinz P (2016) Carbon and nitrogen uptake of calcareous benthic foraminifera along a depth-related oxygen gradient in the OMZ of the Arabian Sea. Front Microbiol 7:71

Erbacher J, Nelskamp S (2006) 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 I 53:751–775

Ernst S, Bours R, Duijnstee I, van der Zwaan B (2005) Experimental effects of an organic matter pulse and oxygen depletion on a benthic foraminiferal shelf community. J Foramin Res 35:177–197

Ernst SR, Morvan J, Geslin E, Le Bihan A, Jorissen FJ (2006) Benthic foraminiferal response to experimentally induced Erika oil pollution. Mar Micropaleontol 61:76–93

Filipsson HL, Nordberg K (2004) A 200-year environmental record of a low-oxygen fjord, Sweden, elucidated by benthic foraminifera, sediment characteristics and hydrographic data. J Foramin Res 34:277–293

Filipsson HL, Nordberg K (2010) Variations in organic carbon flux and stagnation periods during the last 2400 years in a Skagerrak fjord basin, inferred from benthic foraminiferal $\delta^{13}C$. Geol Soc Lond Spec Publ 344:261–270

Filipsson HL, Romero OE, Stuut J-BW, Donner B (2011) Relationships between primary productivity and bottom-water oxygenation off northwest Africa during the last deglaciation. J Quat Sci 26:448–456

Gandhi S, Rajamanickam GVM, Nigam R (2002) Taxonomy and distribution of benthic foraminifera from the sediments off Palk Strait, Tamil Nadu, east coast of India. J Palaeontol Soc India 47:47–64

Glock N, Schonfeld J, Eisenhauer A, Hensen C, Mallon J, Sommer S (2013) The role of benthic foraminifera in the benthic nitrogen cycle of the Peruvian oxygen minimum zone. Biogeosciences 10:4767–4783

Gooday AJ, Turley CM (1990) Responses by benthic organisms to inputs of organic material to the ocean floor: a review. Philos Trans R Soc A 331:119–138

Gooday AJ, Bernhard JM, Levin LA, Suhr SB (2000) Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas. Deep-Sea Res II 47:25–54

Gooday AJ, Levin LA, Aranda da Silva A, Bett BJ, Cowie GL, Dissard D, Gage JD, Hughesd DJ, Jeffreys R, Lamontd PA, Larkin KE, Murtya SJ, Schumacherf S, Whitcraft C, Woulds C (2009) Faunal responses to oxygen gradients on the Pakistan margin: a comparison of foraminiferans, macrofauna and megafauna. Deep-Sea Res II 56:488–502

Hermelin JOR, Shimmield GB (1990) 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

Ingole BS, Sautya S, Sivadas S, Singh R, Nanajkar M (2010) Macrofaunal community structure in the western Indian continental margin including the oxygen minimum zone. Mar Ecol 31:148–166

Jagadeesan L, Jyothibabu R, Anjusha A, Mohan AP, Madhu NV, Muraleedharan KR, Sudheesh K (2013) Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India. Prog Oceanogr 110:27–48

Jain V, Shankar D, Vinayachandran PN, Kankonkar A, Chatterjee A, Amol P, Almeida AM, Michael GS, Mukherjee A, Chatterjee M, Fernandes R, Luis R, Kamble A, Hegde AK, Chatterjee S, Das U, Neema CP (2017) Evidence for the existence of Persian Gulf Water and Red Sea Water in the Bay of Bengal. Clim Dyn 48:3207–3226

Jannink NT, Zachariasse WJ, Van Der Zwaan GJ (1998) Living (rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea). Deep-Sea Res I 45:1483–1513

Jorissen FJ, Barmawidjaja DM, Puskaric S, Van Der Zwaan GJ (1992) Vertical distribution of benthic foraminifera in the northern Adriatic Sea: the relation with the organic flux. Mar Micropaleontol 19:131–146

Jorissen FJ, de Stigter HC, Widmark JGV (1995) A conceptual model explaining benthic foraminiferal microhabitats. Mar Micropaleontol 26:3–15

Jorissen FJ, Wittling I, Peypouquet JP, Rabouille C, Relexans JC (1998) Live benthic foraminiferal faunas off CapeBlanc, NW Africa; Community structure and microhabitats. Deep-Sea Res I 45:2157–2188

Jorissen FJ, Fontanier C, Thomas E (2007) Paleoceanographical proxies based on deep-sea benthic foraminiferal assemblage characteristics. In: Hillaire-Marcel C, de Vernal A (eds) Proxies in Late Cenozoic paleoceanography. Elsevier, Amsterdam, pp 263–326

Jyothibabu R, Madhu NV, Jagadeesan L, Anjusha A, Mohan AP, Ullas N, Sudheesh K, Karnan C (2014) Why do satellite imageries show exceptionally high chlorophyll in the Gulf of Mannar and the Palk Bay during the norteast monsoon? Environ Monit Assess 186:7781–7792

Kaiho K (1994) Benthic foraminiferal dissolved oxygen index and dissolved oxygen levels in the modern ocean. Geology 22:719–722

Kaminski MA (2012) Calibration of the benthic foraminiferal oxygen index in the Marmara Sea. Geol Quart 56:757–764

Kaminski MA, Boersma A, Tyszka J, Holbourn AEL (1995) Response of deep-water agglutinated foraminifera to dysoxic conditions in the California borderland basins. In: Proceedings of the fourth international workshop on agglutinated foraminifera. Grzybowski Foundation Special Publication, 3, 131–140

Kurbjeweit F, Schmiedl G, Schiebel R, Hemleben Ch, Pfannkuche O, Wallmann K, SchaKfer P (2000) Distribution, biomass and diversity of benthic foraminifera in relation to sediment geochemistry in the Arabian Sea. Deep-Sea Res II 47:2913–2955

Laffoley D, Baxter JM (2019) Ocean deoxygenation: everyone's problem—causes, impacts, consequences and solutions. Full report. IUCN, Gland, Switzerland, 580pp

Langlet D, Geslin E, Baal C, Metzger E, Lejzerowicz F, Riedel B, Zuschin M, Pawlowski J, Stachowitsch M, Jorissen FJ (2013) Foraminiferal survival after long-term in situ experimentally induced anoxia. Biogeosciences 10:7463–7480

Larkin KE, Gooday AJ (2008) 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 II 56:403–421

Lei Y, Li T, Jian Z, Nigam R (2017) Taxonomy and distribution of benthic foraminifera in an intertidal zone of the Yellow Sea, PR China: correlations with sediment temperature and salinity. Mar Micropaleontol 133:1–20

Lei Y, Li C, Li T, Jian Z (2019) The effect of temperature and food concentration on ingestion rates of *Quinqueloculina seminula* on the diatom *Nitzschia closterium*. J Foramin Res 49:3–10

Levin L (2003) Oxygen minimum zone benthos: adaptation and community response to hypoxia. Oceanogr Mar Biol 41:1–45

Levin LA, Gage JD, Martin C, Lamont PA (2000) Macrobenthic community structure within and beneath the oxygen minimum zone, NW Arabian Sea. Deep-Sea Res II 47:189–226

Li L, Pohl C, Ren JL, Schulz-Bull D, Cao XH, Nausch G, Zhang J (2017) Revisiting the biogeochemistry of arsenic in the Baltic Sea: impact of anthropogenic activity. Sci Total Environ 614:557–568

Mackensen A, Douglas RG (1989) Down-core distribution of live and dead deep-water benthic foraminifera in box cores from the Weddell Sea and the California continental borderland. Deep Sea Res A 36:879–900

Mackensen A, Sejrup HP, Jansen E (1985) The distribution of living benthic foraminifera on the continental slope and rise off southwest Norway. Mar Micropaleontol 9:275–306

Manasa M, Saraswat R, Nigam R (2016) Assessing the suitability of benthic foraminiferal morpho-groups to reconstruct past monsoon from the Bay of Bengal. J Earth Syst Sci 125:571–584

Mazumder A, Nigam R (2014) Bathymetric preference of four major genera of rectilinear benthic foraminifera within oxygen minimum zone in Arabian Sea off central west coast of India. J Earth Syst Sci 123:633–639

McCorkle DC, Corliss BH, Farnham CA (1997) Vertical distributions and stable isotopic compositions of live (stained) benthic foraminifera from the North Carolina and California continental margins. Deep-Sea Res I 44:983–1024

McCormick LR, Levin LA (2017) Physiological and ecological implications of ocean deoxygenation for vision in marine organisms. Philos Trans R Soc A 375:20160322

Moffitt SE, Moffitt RA, Sauthoff W, Davis CV, Hewett K, Hill TM (2015) Paleoceanographic insights on recent oxygen minimum zone expansion: lessons for modern oceanography. PLoS ONE 10:e0115246

Murray JW (2006) Ecology and applications of benthic foraminifera. Cambridge University Press, Cambridge, p 426

Naik DK, Saraswat R, Lea DW, Kurtarkar SR, Mackensen A (2017) Last glacialinterglacial productivity and associated changes in the eastern Arabian Sea. Palaeogeogr Palaeoclimatol Palaeoecol 483:147–156

Naqvi SWA, Naik H, Pratihary A, D'Souza W, Narvekar PV, Jayakumar DA, Devol AH, Yoshinari T, Saino T (2006) Coastal versus open-ocean denitrification in the Arabian Sea. Biogeosciences 3:621–633
Naqvi SWA, Naik H, Narvekar PV (2009) The Arabian Sea. In: Black KD, Shimmield GB (eds) Biogeochemistry of marine systems. Wiley-Blackwell, Hoboken, pp 157–207, ISBN: 978-1-405-14779-8
Naqvi SWA, Bange HW, Farías L, Monteiro PMS, Scranton MI, Zhang J (2010) Marine hypoxia/anoxia as a source of CH_4 and N_2O. Biogeosciences 7:2159–2190
Nigam R, Mazumder A, Henriques P, Saraswat R (2007) Benthic foraminifera as proxy for oxygen depleted conditions off the central west coast of India. J Geol Soc India 70:1047–1054
Nigam R, Prasad V, Mazumder A, Garg R, Saraswat R, Henriques PJ (2009) Late Holocene changes in hypoxia off the west coast of India: micropalaeontological evidences. Curr Sci 96:708–713
Nomaki H, Ogawa NO, Ohkouchi N, Suga H, Toyofuku T, Shimanaga M, Nakatsuka T, Kitazato H (2008) Benthic foraminifera as trophic links between phytodetritus and benthic metazoans: carbon and nitrogen isotopic evidence. Mar Ecol Prog Ser 357:153–164
Piña-Ochoa E, Hogslund S, Geslin E, Cedhagen T, Revsbech NP, Nielsen LP, Schweizer M, Jorissen F, Rysgaard S, Risgaard-Petersen N (2010) Widespread occurrence of nitrate storage and denitrification among Foraminifera and Gromiida. Proc Natl Acad Sci USA 107:1148–1153
Rao VP, Rajagopalan G, Vora KH, Almeida F (2003) Late Quaternary sea level and environmental changes from relic carbonate deposits of the western margin of India. Proc Indian Acad Sci (Earth Planet Sci) 112:1–25
Reed DC, Harrison JA (2016) Linking nutrient loading and oxygen in the coastal ocean: a new global scale model. Glob Biogeochem Cycl 30:447–459
Reichart GJ, Lourens LJ, Zachariasse WJ (1998) Temporal variability in the Northern Arabian Sea oxygen minimum zone (OMZ) during the last 225,000 years. Paleoceanography 13:607–621
Risgaard-Petersen N, Langezaal AM, Ingvardsen S, Schmid MC, Jetten MSM, Op den Camp HJM, Derksen JWM, Pina-Ochoa E, Eriksson SP, Nielsen LP (2006) Evidence for complete denitrification in a benthic foraminifer. Nature 443:93–96
Schmiedl G, Mackensen A, Müller PJ (1997) Recent benthic foraminifera from the eastern South Atlantic Ocean: dependence on food supply and water masses. Mar Micropaleontol 32:249–287
Schumacher S, Jorissen FJ, Dissard D, Larkin KE, Gooday AJ (2007) Live (rose Bengal stained) and dead benthic foraminifera from the oxygen minimum zone of the Pakistan continental margin (Arabian Sea). Mar Micropaleontol 62:45–77
SenGupta BK, Machain-Castillo ML (1993) Benthic foraminifera in oxygen-poor habitats. Mar Micropaleontol 20:183–201
Shankar D, Vinayachandran PN, Unnikrishnan AS (2002) The monsoon currents in the north Indian Ocean. Prog Oceanogr 52:63–120
Singh AD, Kroon D, Ganeshram RS (2006) Millennial scale variations in productivity and OMZ intensity in the eastern Arabian Sea. J Geol Soc India 68:369–377
Singh AD, Rai AK, Verma K, Das S, Bharti SK (2015) Benthic foraminiferal diversity response to the climate induced changes in the eastern Arabian Sea oxygen minimum zone during the last 30 ka BP. Quat Int 374:118–125
Singh DP, Saraswat R, Kaithwar A (2018) Changes in standing stock and vertical distribution of benthic foraminifera along a depth gradient (58–2750 m) in the southeastern Arabian Sea. Mar Biodivers 43:73–88
Stramma L, Schmidt S, Levin LA, Johnson GC (2010) Ocean oxygen minima expansions and their biological impacts. Deep-Sea Res I 57:587–595
Suokhrie T, Saraswat R, Nigam R (2020) Lack of denitrification causes a difference in benthic foraminifera living in the oxygen deficient zone of the Bay of Bengal and the Arabian Sea. Mar Pollut Bull 153:110992
Takarina ND, Wardhana W, Soedjiarti T (2017) Impact of oxygen depletion on planktonic community with emphasis on temperature dynamics at aquaculture scale in Blanakan, West Java. In: Suhendi E, Munawaroh HSH, Hidayat T, Kusumawaty D, Sari IM, Suwarma IR, Nandiyanto ABD, Jupri A, et al (eds) Proceedings of the 3rd international seminar on mathematics, science, and computer science education [020004] (AIP Conference Proceedings, vol. 1848). American Institute of Physics Inc. https://doi.org/10.1063/1.4983932
Van Der Zwaan GJ, Duijnstee IAP, Den Dulk M, Ernst SR, Jannink NT, Kouwenhoven TJ (1999) Benthic foraminifers: proxies or problems? A review of paleocological concepts. Earth-Sci Rev 46:213–236
Vinayachandran PN, Yamagata T (1998) Monsoon response of the sea around Sri Lanka: generation of thermal domes and anticyclonic vortices. J Phys Oceanogr 28:1946–1960

Wishner KF, Seibel BA, Roman C, Deutsch C, Outram D, Shaw CT, Birk MA, Mislan KAS, Adams TJ, Moore D, Riley S (2018) Ocean deoxygenation and zooplankton: very small oxygen differences matter. Sci Adv 4:eaau5180

Zimorski V, Mentel M, Tielens AGM, Martin WF (2019) Energy metabolism in anaerobic eukaryotes and Earth's late oxygenation. Free Radic Biol Med 140:279–294

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