

Benthic Foraminifera as Proxy for Oxygen-depleted Conditions Off the Central West Coast of India

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Abstract: In order to study the response of benthic foraminifera, especially the rectilinear bi- and tri-serial benthic foraminifera (RBF) to oxygen-depleted conditions from the Arabian Sea off central west coast of India, 103 surface sediment samples collected from a water depth of 15 m to 3300 m were studied for the benthic foraminiferal content. A total of 383 recent benthic foraminiferal species were identified. Out of the total 383 benthic foraminiferal species identified in the study area, 65 species belong to 18 rectilinear bi- and tri-serial benthic foraminifer genera. The RBF abundance remains consistently high (>40%) between 90 m to ~1200 m water depth. The intermediate depth zone of increased abundance of RBFs coincides with the prominent intermediate water oxygen minimum zone of the Arabian Sea (upper boundary ~100 m and lower boundary ~1000 to 1250 m). The other significant abundance (>40%) of rectilinear benthic foraminiferal forms is reported from the water depth range of ~50 to ~60 m with the maximum abundance reaching upto ~78% at the water depth of 56 m. This zone has also been reported to be affected by seasonal severe oxygen-depleted conditions. Therefore, we propose that the increased abundance of RBF may be used as an indicator of oxygen-depleted conditions in the Arabian Sea. This benthic foraminiferal response to oxygen-depleted conditions, especially from the shallow water depths is significant as it can be applied to document the geologic extent of shallow water oxygen-depleted conditions that have been suggested as a consequence of spurt in the anthropogenic activities in the coastal regions.

Keywords: Oxygen Minima Zone, Rectilinear benthic foraminifera, Deep and shallow water OMZ, Central west coast of India.

INTRODUCTION

Severe oxygen depleted conditions have been reported from several shallow and deep-water regions of world oceans (Wyrki, 1962; Sen Gupta et al. 1980; Turner and Rabalais, 1994; Diaz and Rosenberg, 1995; Osterman, 2003). Prominent intermediate as well as shallow water hypoxic conditions have also been reported from the region off central west coast of India (Sen Gupta and Naqvi, 1984; Naqvi et al. 2000). The intermediate depth of low oxygenated waters (<0.5 ml/l) extend from ~100 m to a depth of ~1000 to ~1250 m (Stackelberg, 1972; Sen Gupta et al. 1976; Sen Gupta et al. 1980; Naqvi, 1994; Levin et al. 2000). The coastal hypoxic conditions have significant economic implications, as these lead to reduction in fish catch and enhanced emission of greenhouse gases (Rabalais and Turner, 2001). Since the origin/intensification of coastal hypoxic zones have been attributed to spurt in the anthropogenic activities (Malakoff, 1998; Naqvi et al.

2000), understanding the geographical and geologic extent of shallow water hypoxic zones is important (Blackwelder et al. 1996). To achieve this objective one needs to have site specific proxies.

Foraminifera are one of the efficient proxies that have been used to trace the geologic extent of both coastal and deep water hypoxic zones (Sen Gupta et al. 1996; Bernhard et al. 1997; Dulk et al. 1998; Schulz et al. 1996; Dickens and Owen, 1999; Gooday et al. 2000; den Dulk et al. 2000; Platon et al. 2005). However, the response of foraminifera to hypoxia in different parts of the world oceans (Fig.1) appears to be region specific, with different foraminiferal assemblages being dominant in different hypoxic zones (Sen Gupta and Machain-Castillo, 1993). Numerous reports indicate that *Bolivina*, *Fursenkoiina*, *Uvigerina*, *Bulimina*, *Buliminella*, *Stainforthia*, *Brizalina* and *Loxostomum*, all belonging to rectilinear morphogroup, are the most abundant genera reported in hypoxic regions worldwide (Kaiho, 1994;

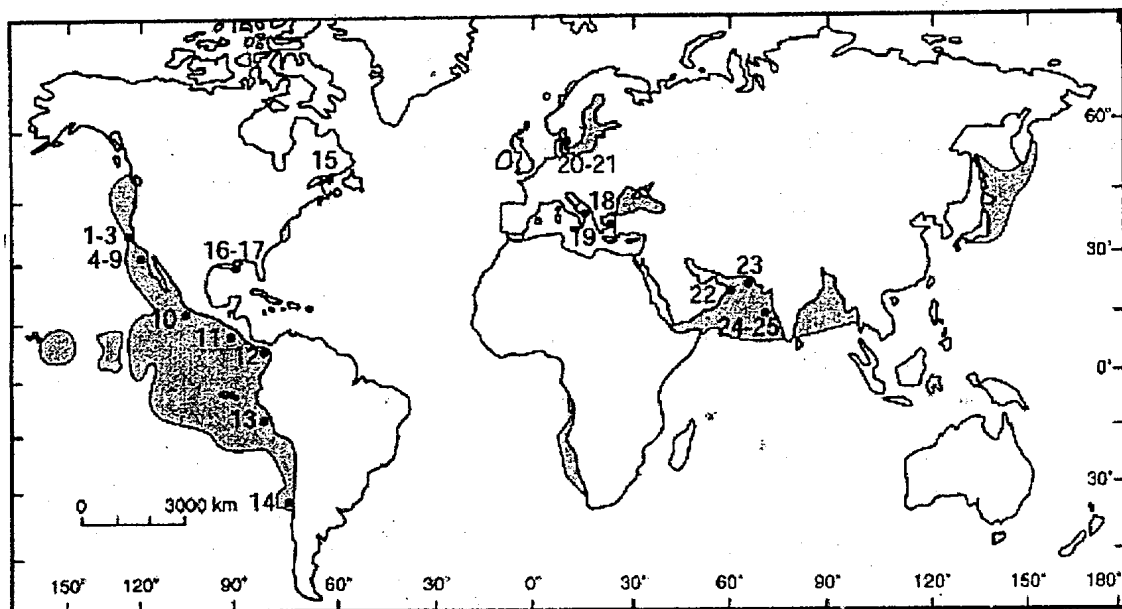


Fig.1. The world locations where the relationship between foraminifera and Oxygen Minima Zone has been studied on the basis of minimum 5 surface sediment samples (modified after Bernhard and Sen Gupta, 1999). **Santa Barbara Basin:** 1. Harman (1964), 2. Phlegar and Soutar (1973), 3. Bernhard et al. (1997); **Off California:** 4. Streeter (1972), 5. Phlegar and Soutar (1973), 6. Blake (1976), 7. Douglas and Heitman (1979), 8. Quinterno and Gardner (1987), 9. Bernhard (1992); **Off Mexico:** 10. Perez-Cruz and Machain-Castillo (1990); **Off El Salvador:** 11. Smith (1964); **Gulf of Panama:** 12. Golik and Phlegar (1977); **Off Peru:** 13. Resig (1981); **Peru-Chile Trench:** 14. Ingle et al. (1980); **Nova Scotia:** 15. Corliss and Emerson (1990); **Gulf of Mexico:** 16. Sen Gupta et al. (1997), 17. Osterman (2003); **Aegean Sea:** 18. Katz and Thunell (1984); **Adriatic Sea:** 19. Jorissen et al. (1992); **Drammensfjord, Norway:** 20. Alve (1995), 21. Bernhard and Alve (1996); **Off Oman:** 22. Gooday et al. (2000); **Off Pakistan:** 23. Jannink et al. (1998); **Off Goa, India:** 24. Mazumder et al. (2003), 25. Present Study.

Bernhard and Sen Gupta, 1999), the collective response of rectilinear benthic foraminifera to hypoxia has remained unresolved.

Though various workers have studied the response of foraminifera to intermediate water hypoxia in the Arabian Sea that comprise ~60% of the global hypoxic shelf and bathyal floor (Helly and Levin, 2004), most of these studies have been carried out from the region off Pakistan and Oman margin (Dulk et al. 2000; Gooday et al. 2000).

Except for a brief mention in reports by Zobel (1973) and abundance of *Bulimina costata* from oxygen minimum zone (OMZ) off central west coast of India (Mazumder et al. 2003), no attempt has yet been made to study the relationship, if any, between distribution of benthic foraminifera and dissolved oxygen concentration, from the region off central west coast of India (Fig. 1).

The objective of the present study is to understand the effect of oxygen-depleted conditions on the spatial distribution of benthic foraminifera, especially the rectilinear benthic foraminifera, in the Arabian Sea, off central west coast of India.

Oxygen Minimum Zone: A Prologue

The solubility of oxygen decreases with decreasing salinity and increases with the decrease in temperature. The amount of dissolved oxygen in seawater (including values of supersaturation) varies between 0.0 and 8.5 ml/l, the usual range being 1.0-6.0 ml/l (Tait, 1981). Based on dissolved oxygen concentration, Tyson and Pearson (1991) proposed classification of aquatic environments and corresponding biofacies into four zones: (a) oxic (aerobic biofacies, with 8.0-2.0 ml/l O₂), (b) dysoxic (dysaerobic, 2.0-0.2 ml/l O₂), (c) suboxic (quasi anaerobic, 0.2-0.0 ml/l O₂), and (d) anoxic (anaerobic, 0.0 ml/l O₂). The more general physiological or ecological term "hypoxia" indicates a degree of oxygen depletion that would induce a severe stress on marine organisms, without necessarily implying a specific threshold value (Tyson and Pearson, 1991). The zone in the oceans, where concentration of dissolved oxygen is least, due to excessive use of available oxygen by organisms (for respiration) and organic matter (to degrade itself) but limited supply, resulting from reduced circulation of water, is referred as Oxygen Minimum Zone (OMZ) (Sen

Gupta and Machain-Castillo, 1993). The OMZ is caused by biochemical processes resulting in consumption of oxygen, whereas its position and distribution is governed by circulation (Wyrki, 1962). The OMZ has a geographical importance because of the formation of organic-rich sediments under reduced oxidation condition (Kennett, 1982). Although bottom water oxygenation is not directly influenced by organic input, the oxygenation of interstitial waters and the primary redox fronts do change in response to the variations in the organic matter flux (Fontanier et al. 2002).

The major regions exhibiting hypoxia irrespective of sampling depth are the Baltic Sea, Black Sea, Gulf of Aden, Arabian Sea, Bay of Bengal, Philippine region, northwest Pacific margin, eastern Pacific, Norwegian region and southwest African region (Kamykowski and Zentara, 1990). The majority of the marine records of hypoxia from world oceans are from depths above 1500 m.

MATERIALS AND METHODS

During the cruises of *RV Gaveshani* (G-18) and *ORV Sagar Kanya* (SK-117), 103 sediment samples were collected from the region off central west coast of India, off Goa, (Vijaydurg to Bhatkal) from water depth of 15 m to 3300 m (Fig. 2). Fifty one samples were collected by La Fond Dietz snapper and 52 samples by spade corer (Table 1). Each top (0-2 cm) sediment sample was processed through 63 μ m sieve after treating with sodium hexa-

mataphosphate and hydrogen peroxide to remove the clayey particles and organic matter, respectively. The plus 63 μ m fraction was used for picking of total (non-stained) foraminifera. Around 300 to 500 specimens of both benthic and planktic foraminifera each were picked and identified up to species level. Presence of few agglutinated forms in most of the samples indicates that the surface sediments were well recovered. Since it has been noted from previous reports that rectilinear benthic foraminifera (RBF) are essential components of oxygen-depleted environments, a special emphasis has been given to this group. The percentage of RBF within the total benthic foraminifera is plotted against the depth. In order to reduce the minor variations in depth distribution of RBF, a five-point moving average has also been plotted (Fig.3).

In order to establish a relationship, if any, between foraminifera and concentration of dissolved oxygen in seawater, the RBF percentage along the aforesaid transects were plotted against dissolved oxygen concentration at similar depths (Fig.4). Oxygen concentration values have been tabulated from a previously published report (Sen Gupta et al. 1980) for two transects along 15°23'N and 14°55'N latitudes, and shown as AB and CD in Fig.2.

RESULTS

A total of 383 benthic foraminifer species were identified. Though foraminifera from the shelf region off central west coast of India were previously documented (Nigam and Khare, 1999), this is the first comprehensive report from the slope and deeper waters of the Arabian Sea. Out of the total 383 benthic foraminiferal species identified in the study area, 65 species belong to 18 genera of rectilinear bi- and tri-serial benthic foraminifera, namely *Bolivina* (18 species), *Bolivinella* (1 species), *Brizalina* (3 species), *Bulimina* (7 species), *Buliminella* (1 species), *Fursenkoina* (5 species), *Hopkinsinella* (1 species), *Loxostomina* (1 species), *Neouvigerina* (2 species), *Pleurostomella* (1 species), *Reussella* (2 species), *Sagrinella* (2 species), *Sigmavirgulina* (1 species), *Siphouvigerina* (1 species), *Stainforthia* (1 species), *Trifarina* (2 species), *Uvigerina* (15 species), and *Virgulinitella* (1 species).

The surface distribution of rectilinear benthic foraminifera (RBF) shows wide variation in the study area. Maximum abundance (78.2%) of RBF is reported at SC-06 (water depth 56 m) while the RBFs are absent at SC 14 station (water depth 18 m) (Table 1). The plot of relative abundance of RBF shows significantly increased abundance between ~90-1200 m water depth. The five-point running average (Fig.3) shows that the RBF abundance reaches 40%

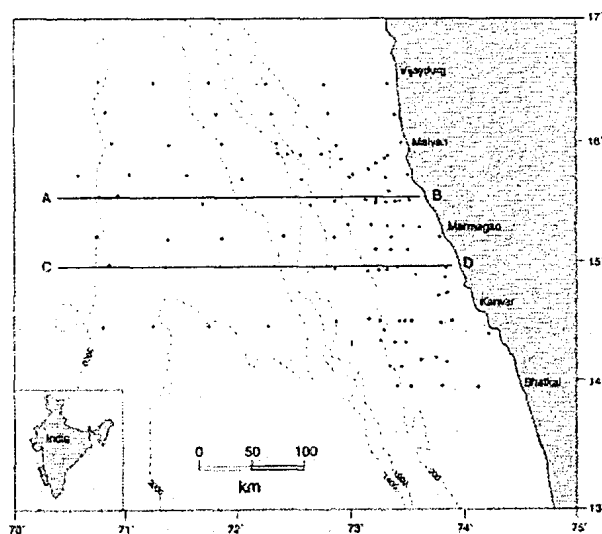


Fig.2. Location map of the study area (line AB and CD are two transects along 15°23'N and 14°55'N latitudes, respectively, as given in Sen Gupta et al. 1980).

Table 1. Details of the samples used in previous study and abundance of rectilinear benthic foraminifera in the samples analyzed

Sample No.	Water Depth (m)	RBF (%)
18/1	54	11.07
18/2	68	49.83
18/3	78	56.41
18/4	88	47.75
18/5	100	46.03
18/7	220	60.57
18/9	990	58.33
18/10	1050	70.00
18/11	1330	58.54
18/13	115	61.27
18/16	62	44.37
18/17	61	39.81
18/19	57	34.15
18/20	58	52.03
18/21	64	14.94
18/22	80	38.20
18/24	115	65.06
18/26	332	71.13
18/27	126	69.36
18/30	80	27.78
18/31	65	30.14
18/32	56	53.11
18/33	51	49.70
18/36	75	36.01
18/38	93	48.80
18/39	111	52.63
18/42	112	58.06
18/43	99	58.40
18/46	61	40.46
18/47	54	51.08
18/48	48	57.25
18/49	58	35.41
18/55	206	63.61
18/56	210	53.38
18/57	140	73.08
18/58	105	51.74
18/59	96	44.78
18/60	82	29.96
18/63	46	36.29
18/68	110	64.54
18/69	146	67.17
18/70	218	60.94
18/71	210	44.27
18/72	109	59.30
18/73	83	42.55
18/75	71	14.68
18/76	61	25.87
18/79	52	39.93
18/82	66	7.97
18/85	117	58.44
18/86	176	69.63
SK 117 SC-01	3140	2.60
SK 117 SC-02	2775	2.70
SK 117 SC-03	2170	14.20
SK 117 SC-04	1000	51.10
SK 117 SC-05	86	44.40
SK 117 SC-06	56	78.20
SK 117 SC-07	2850	5.90
SK 117 SC-08	2180	9.30

Table 1. Contd....

Sample No.	Water Depth (m)	RBF (%)
SK 117 SC-09	2050	13.90
SK 117 SC-10	2020	17.30
SK 117 SC-11	380	53.00
SK 117 SC-12	70	24.70
SK 117 SC-13	21	4.60
SK 117 SC-14	18	0.00
SK 117 SC-15	80	34.10
SK 117 SC-16	780	38.00
SK 117 SC-17	1900	10.20
SK 117 SC-18	1950	8.20
SK 117 SC-19	2300	12.80
SK 117 SC-20	2750	2.80
SK 117 SC-21	2750	5.30
SK 117 SC-22	2040	11.60
SK 117 SC-23	1900	12.00
SK 117 SC-24	2050	16.50
SK 117 SC-25	1470	18.00
SK 117 SC-26	240	70.10
SK 117 SC-27	62	8.60
SK 117 SC-28	15	13.90
SK 117 SC-29	18	3.60
SK 117 SC-30	90	34.30
SK 117 SC-31	1130	29.20
SK 117 SC-32	1650	9.70
SK 117 SC-33	2200	19.40
SK 117 SC-34	2600	8.10
SK 117 SC-35	3300	2.70
SK 117 SC-36	2850	5.80
SK 117 SC-37	2420	13.50
SK 117 SC-38	1920	25.70
SK 117 SC-39	1040	47.90
SK 117 SC-40	100	55.00
SK 117 SC-41	20	49.20
SK 117 SC-42	28	5.10
SK 117 SC-43	75	22.90
SK 117 SC-44	325	13.00
SK 117 SC-45	1650	35.30
SK 117 SC-46	2350	16.80
SK 117 SC-47	3000	8.40
SK 117 SC-48	3000	3.70
SK 117 SC-49	1680	28.50
SK 117 SC-50	294	28.60
SK 117 SC-51	80	51.00
SK 117 SC-52	19	24.70

at 90 m water depth and remains consistently high (except for decreased abundance in two samples at ~300 m water depth) till ~1200 m water depth, with the maximum abundance reaching up to 73.0% at the water depth of 140 m. Except the high abundance of RBFs between ~90-1200 m water depth region, increased RBF abundance (>40%) is also observed within the water depth range of 50 to 60 m (Fig.3). In this comparatively shallow water zone maximum RBF abundance reaches up to ~78% (SC-06, water depth 56 m). The plot of RBF abundance

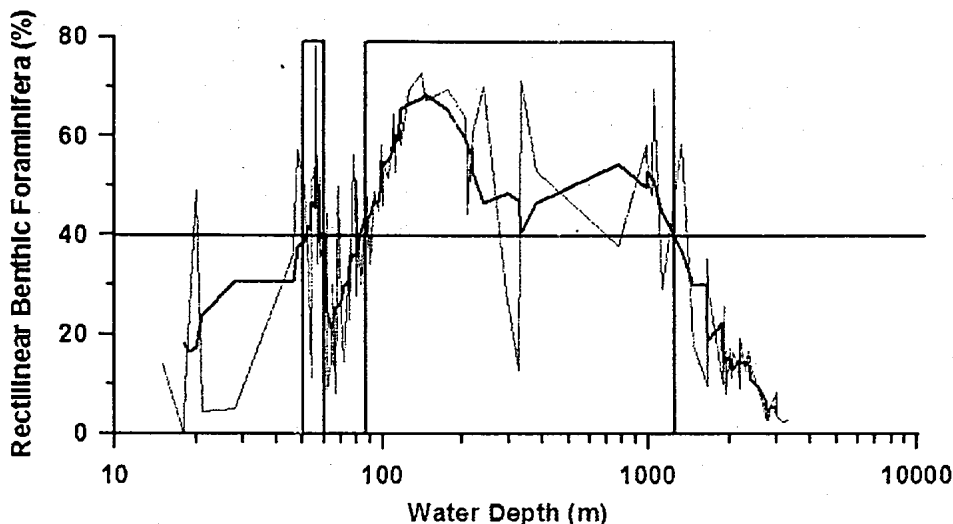


Fig.3. Distribution of rectilinear benthic foraminifera against the water depth in the study area. Thick line is the five-point average, while the horizontal line shows the >40% rectilinear benthic foraminiferal abundance. The water depth is plotted as log-scale. The rectangles mark the increased abundance of RBF in both shallow (~50-60 m) and shallow to intermediate water depth (~90-1100 m) regions.

and seawater oxygen concentration along two transects shows an inverse relationship (Fig. 4).

DISCUSSION

Figure 1 shows the parts of the world oceans where a relationship between foraminifera in surface sediments (only those papers are included wherein minimum 5 surface samples have been analyzed) and OMZ has been studied. It indicates that not much attention has been paid to the foraminiferal distribution in the OMZ of Arabian Sea.

Benthic foraminifera have widely been reported to be affected by the presence of oxygen minimum conditions that lead to variation in foraminiferal assemblages (see, Bernhard and Sen Gupta, 1999, for review). However, there is no general agreement on relationship of total benthic foraminifera and oxygen depleted environment. Bernhard (1992) observed a negative correlation between foraminiferal abundance and bottom-water oxygen concentration, whereas, Phlegar and Soutar (1973) reported that oxygen is not a limiting ecological factor for benthic foraminifera in the low-oxygen environments of Baja California. This view is also supported by a number of experimental studies (Bernhard and Alve, 1996; Moodley et al. 1998).

In all these reports RBF constitute one of the abundant foraminiferal assemblages in the OMZ of the world oceans including the OMZ of northern and northwestern Arabian Sea and also the presence of *Bulimina costata* as an indicator

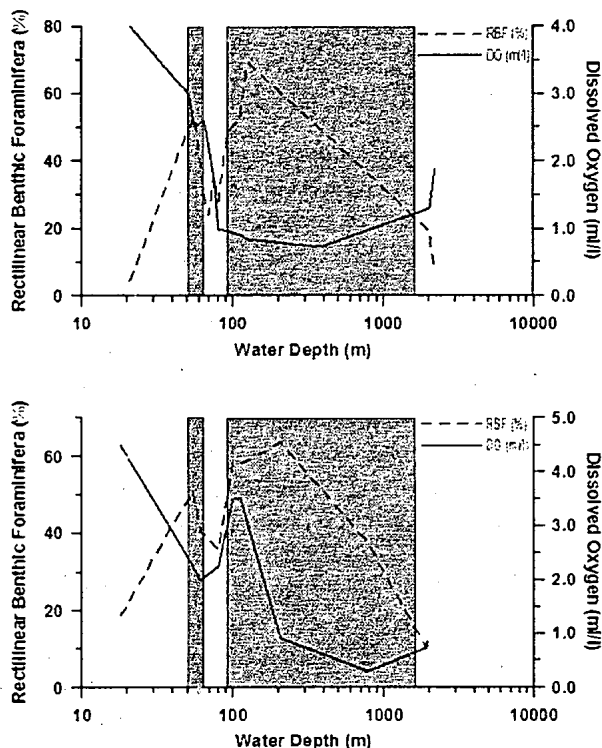


Fig.4. Comparison of the dissolved oxygen concentration and percentage of rectilinear benthic foraminifera against water depth along two transects (shown in Fig.2); broken lines show the percentage of rectilinear form and black lines show the concentration of oxygen (shaded areas show the higher concentration of oxygen and lower percentage of rectilinear form).

fauna for OMZ of eastern Arabian Sea (Mazumder et al. 2003). Hence, in the present study, an attempt was made to document the relationship of RBF (rather than any individual genus or species) with low oxygen concentration. The increased abundance of RBF in the oxygen-depleted zone in the study area may arise because of high tolerance level of certain species to low-oxygen conditions, increased availability of organic matter and decreased predation/ bioturbation (Jannink et al. 1998).

The significant abundance of RBF (>40%) within both the shallow and deep water oxygen-depleted environments off central west coast of India clearly supports the potential application of the RBF abundance as an index for the oxygen-depleted conditions in the Arabian Sea. *Bolivina-Bulimina* assemblage is dominant among the RBF in the study area. Increased abundance of *Bolivina* has also been reported from the OMZ of the eastern and southeastern Pacific (Smith, 1964; Ingle et al. 1980) as well as from the northwestern Indian Ocean (Hermelin and Shimmield, 1990). The results are further supported by the observation made by Corliss and Emerson (1990) that the infaunal taxa are consistently present within the sediments, thus demonstrating that these taxa are tolerant to a wide range of low-oxygen conditions as determined by pore-water manganese profiles.

The increased (>40%) abundance of benthic foraminifera as observed from the 50-60 m depth zone in the study area is significant in view of the report of Naqvi et al. (2000) who suggested that the presence of coastal hypoxic zone off west coast of India could be linked to increased production of N_2O caused by the addition of anthropogenic nitrate and its subsequent denitrification. Similar hypoxic conditions in coastal areas have also been reported from different parts of the world (Turner and Rabalais, 1994; Diaz and Rosenberg, 1995; Malakoff, 1998; Rabalais, 2000). Increased riverine input of fine-grained sediments rich in organic matter may result in the periodic development of low-oxygen or anoxic conditions in the study area, as also suggested by Murrell and Fleeger (1989) from the Gulf of Mexico, and thus affect benthic foraminiferal distribution. Sen Gupta et al. (1996) also reported the benthic foraminiferal response to the strong spring and summer oxygen depletion in near-shore bottom waters of the Louisiana continental shelf and attributed it to an increase in organic flux from surface to bottom waters near the outflow of Mississippi River (Turner and Rabalais, 1994). Foraminiferal characteristics from coastal hypoxic conditions were also recorded from the Gulf of Mexico

(Osterman, 2003) wherein it was proposed that the 5-30 m thick hypoxic zone was formed seasonally due to spring runoff (Rabalais and Turner, 2001). All these studies support the presence of characteristic foraminiferal assemblage from shallow water oxygen-depleted environment in the present study. Though the distribution of benthic foraminifera is strongly influenced by hydrographic and other conditions (Van der Zwaan and Jorissen, 1991), the higher abundance of rectilinear foraminifera within the water depth of 50-60 m in the present study area clearly indicates the foraminiferal response to low oxygen concentration in coastal waters. It might be a result of either anthropogenic activities or due to natural seasonal influx of west-flowing rivers of Indian coast. These possibilities need to be checked by an intensive study especially through the temporal variation in the abundance of rectilinear benthic foraminifera.

CONCLUSIONS

Based on the benthic foraminiferal study from 103 surface sediment samples collected from central west-coast of India, we conclude that the shallow to intermediate water (90 to 1200 m) OMZ in the Arabian Sea is characterized by increased (>40%) relative abundance of rectilinear bi- and triserial benthic foraminifera. Similarly, the less persistent shallow water (50 to 60 m water depth) oxygen-depleted conditions also result in increased abundance of rectilinear bi- and triserial benthic foraminifera. Thus we propose that the relative abundance of rectilinear benthic foraminifera can be used as an index for delineating oxygen-depleted environments in the Arabian Sea.

It is hoped that the proxy development will help to decipher the extent of oxygen depleted conditions in the past (particularly Holocene) and may even provide the reasons for occurrence of coastal hypoxia in the eastern Arabian Sea.

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