



Late Glacial–Holocene record of benthic foraminiferal morphogroups from the eastern Arabian Sea OMZ: Paleoenvironmental implications

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The Arabian Sea is characterized today by a well-developed and perennial oxygen minimum zone (OMZ) at mid-water depths. The Indian margin where the OMZ impinges provides sediment records ideal to study past changes in the OMZ intensity and its vertical extent in response to the changes of monsoon-driven primary productivity and intermediate water ventilation. Benthic foraminifera, depending upon their adaptation capabilities to variation in sea floor environment and microhabitat preferences, develop various functional morphologies that can be potentially used in paleoenvironmental reconstruction. In this study, we analysed benthic foraminiferal morphogroups in assemblage records of the last 30 ka in a sediment core collected from the lower OMZ of the Indian margin (off Goa). In total, nine morphogroups within two broadly classified epifaunal and infaunal microhabitat categories are identified. The abundance of morphogroups varies significantly during the late Glacial, Deglacial and Holocene. It appears that monsoon wind driven organic matter flux, and water column ventilation governing the OMZ intensity and sea-bottom oxygen condition, have profound influence on structuring the benthic foraminiferal morphogroups. We found a few morphogroups showing major changes in their abundances during the periods corresponding to the northern hemisphere climatic events. Benthic foraminifera with planoconvex tests are abundant during the cold Heinrich events, when the sea bottom was oxygenated due to a better ventilated, weak OMZ; whereas, those having tapered/cylindrical tests dominate during the last glacial maximum and the Holocene between 5 and 8 ka BP, when the OMZ was intensified and poorly ventilated, leading to oxygen-depleted benthic environment. Characteristically, increased abundance of taxa with milioline tests during the Heinrich 1 further suggests enhanced ventilation attributed probably to the influence of oxygen-rich Antarctic Intermediate Water (AAIW).

Keywords. Paleontology; benthic foraminifera; oxygen minimum zone; Arabian Sea.

1. Introduction

Seasonally reversing monsoon winds produce seasonal and spatial patterns in the Arabian Sea surface circulation, hydrography and biological productivity. A strong oxygen minimum zone

(OMZ) currently exists in the Arabian Sea at intermediate water depths between 150 and 1250 m due to a combination of high primary productivity induced large flux of organic matter and poor ventilation of thermocline waters (Wyrski 1973; Olson *et al.* 1993). In recent years, the

temporal variability in the Arabian Sea OMZ on longer to shorter time scales has been a subject of intense research, because of its implications on past changes of biogeochemical cycles and nutrient inventory contributing to global climate change.

The benthic environment within the OMZ, as witnessed today in the Arabian Sea is typified by low-oxygen level and high organic matter content (Paropkari *et al.* 1993; Calvert *et al.* 1995). Benthic foraminifera have the potential to serve as indicators of the OMZ intensity, as many of the taxa are considered to be sensitive to changes in ocean-floor oxygen condition. Studies on modern benthic foraminifera indicate that among the various abiotic and biotic factors, trophic (organic carbon flux) and oxygen conditions are the main parameters governing the benthic foraminiferal population, particularly in areas of oxygen depletion and high primary production such as the Arabian Sea margins within the OMZ (e.g., Sen Gupta and Machain-Castillo 1993; Bernhard *et al.* 1997; Loubere 1997; Jammink *et al.* 1998; den Dulk *et al.* 1998, 2000; Schulte *et al.* 1999; Murray 2000; Bharti and Singh 2013). It is difficult to distinguish the relative effectiveness of these two parameters controlling the distribution of the benthic foraminifera, as both the factors are generally coupled. Variation in benthic foraminiferal assemblage in terms of species diversity and abundance of sensitive species are frequently used as indicators for paleoceanographic reconstruction. Several studies have suggested a high potential of morphologies of foraminiferal tests in paleoenvironmental reconstructions (e.g., Chamney 1976; Corliss 1985; Bernhard 1986; Nigam *et al.* 2007) in areas where ocean bottom is characterized by high carbon flux and oxygen-poor conditions. The adapted morphogroups developed in response to the environmental stress are expected to be unaltered in both the living and fossil assemblages, as test morphologies are generally not obscured by taphonomic processes (Bernhard 1986), except for a few regions affected by strong bottom water currents. Thus, morphogroup analysis of benthic foraminiferal fossil assemblages can provide valuable information about changes in past ocean-bottom environments.

In recent years, a few studies have been carried out to investigate the Quaternary history of the deep water circulation and the OMZ intensity in the Arabian Sea, based primarily on the species abundance variation in benthic foraminiferal assemblages (Hermelin *et al.* 1995; von Rad *et al.*

1999; den Dulk *et al.* 1998, 2000; Schmiedl and Leuschner 2005). These studies were mainly focused on the western and northern regions of the Arabian Sea.

The aim of this work is to use benthic foraminiferal morphogroups to decipher history of past changes in benthic environment of the eastern Arabian Sea margin within the oxygen minimum zone. In this effort, we have made use of existing knowledge on modern foraminiferal ecology, morphology and microhabitat preferences.

2. Study area

Surface ocean circulation along the west coast of India is driven by seasonal monsoon winds (Warren 1964; Wyrtki 1973). During the summer monsoon (June–September), winds blow from the southwest towards Asia, the South Equatorial Current (SEC) intensifies, northern branch of which forms the Somali Current as a part of anticyclonic southwest monsoon circulation (Schott and McCreary 2001). In this season, the West Indian Coastal Current (WICC) flows southward along the eastern margin of the Arabian Sea (Shetye *et al.* 1990; Shetye 1998) and finally joins the eastward flowing Southwest Monsoon Current (SMC) in the southeastern Arabian Sea (Shenoi *et al.* 1999; Schott and McCreary 2001; Shankar *et al.* 2002). The strongly stratified water mass forms in summer due to high precipitation and runoff from the Western Ghats (Joseph and Freeland 2005). Weak upwelling occurs along the southwest coast of India (south of 10°N) during this season (Sharma 1966; Wyrtki 1973; Naidu *et al.* 1999). During winter monsoon (December–March), the wind pattern reverses and a cyclonic circulation develops causing weak, sporadic upwelling along the coasts off Pakistan and India (Colborn 1975; Zhang 1985; Bauer *et al.* 1991). The cool dry air brought by northeasterly winds in winter intensifies evaporation, leading to surface cooling and vertical mixing in the eastern Arabian Sea (north of 10°N) (Banse and Mc Clain 1986; Madhupratap *et al.* 1996; Kumar *et al.* 2000). In this season, the WICC reverses and the Northeast Monsoon Current (NMC) transport waters from the Bay of Bengal (BOB) into the southeastern Arabian Sea up to 13°N (Sarma 2002; Shankar *et al.* 2016).

The water masses in the eastern Arabian Sea are a combination of locally and externally generated water masses (Schott and McCreary 2001). The

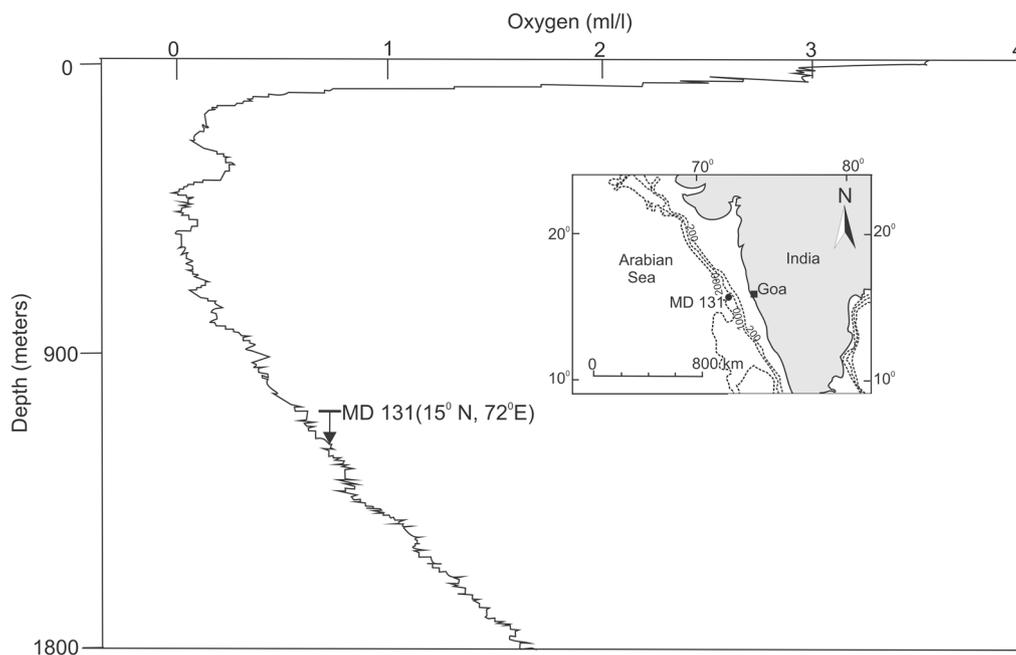


Figure 1. Locations of the sediment core MD 131 (water depth 1230 m) (inset) and a vertical profile of oxygen level measured at 11.30°N , 73.30°E , depicting approx. oxygen conditions at the core site.

high-salinity water (Arabian Sea Water: ASW) is generated in the northern Arabian Sea in winter and spreads southward to the equator with its core at a depth of about 200 m (Kumar and Prasad 1999; Schott and McCreary 2001). The two high-salinity water masses originating in the Persian Gulf (Persian Gulf Water: PGW) and the Red Sea (Red Sea Water: RSW) flow into the Arabian Sea in the southeasterly direction at about 300 and 500 m depth, respectively (Schott and McCreary 2001). However, the influence of Arabian Sea Water (ASW) and Persian Gulf Water (PGW) in the eastern Arabian Sea is less evident (Rameshbabu *et al.* 1980). A low-salinity, oxygen-rich Antarctic Intermediate Water (AAIW) is present in the southern and southeastern Arabian Sea south of 12°N (Wyrтки 1971; Sastry and D'Souza 1972; Swallow 1984; Olson *et al.* 1993; You 1998; Fine *et al.* 2008). A pronounced oxygen minimum zone (OMZ) exists between 150 and 1250 m water depths because of high biological productivity, high O_2 consumptions and poor ventilation (Wyrтки 1973; Swallow 1984; Caille *et al.* 2015).

3. Methods

A 9.65 m long piston core (MD 131) was raised from the central part of the Indian margin (off

Goa) at 1230 m water depth (figure 1). The core site ($15^{\circ}31.8'\text{N}$; $72^{\circ}34.1'\text{E}$) is situated at lower boundary of the present day OMZ. The core provides uninterrupted sedimentary sequence of hemi-pelagic mud, free of turbiditic (or mass flow) deposition and reworking, which is characterized by dark coloured indistinctly laminated sediments with intermittently light coloured homogeneous facies. The sediment core was sampled at 1–2 cm intervals. In this study, we used samples up to 3.7 m core depth at 2–4 cm intervals. The age model is based on 7 AMS ^{14}C dates (Ivanochko *et al.* 2005; Singh *et al.* 2011); and the studied section spans 5–30 kyr. In total, 134 samples were analyzed for benthic foraminifera. For separation of benthic foraminifera tests, approximately 5 g of dried sediment of each sample was washed through wet sieving over a $63\ \mu\text{m}$ screen. Dry residue larger than $63\ \mu\text{m}$ was sieved again over a $125\ \mu\text{m}$ screen. The $>125\ \mu\text{m}$ size fraction was taken for this study. This size fraction is widely used for benthic foraminiferal studies in different areas of world oceans including low-oxygen settings. It is possible that some small sized foraminifera may be abundant in finer fraction ($63\text{--}125\ \mu\text{m}$). However, the faunal composition, species relative abundances and diversity do not change much, while adding the finer fraction to the coarse size fraction ($>125\ \mu\text{m}$) and most of the

species found in small size fraction also occurred in coarse fraction. Schumacher *et al.* (2007) and Caulle *et al.* (2014) have already demonstrated that adding the small size fraction (63–125 μm) did not lead to a major change in bathymetric trends in foraminiferal diversity and composition. Furthermore, several studies from the Arabian Sea OMZ regions suggest that benthic assemblages of coarse fraction accurately reflect environmental change (e.g., von Rad *et al.* 1999; den Dulk *et al.* 2000; Caulle *et al.* 2015). The major advantage of selecting $>125\ \mu\text{m}$ size fraction is that, for future studies our faunal data would be comparable to the benthic foraminiferal records from other Arabian Sea OMZ regions, which are mainly based on >125 or $>150\ \mu\text{m}$ size fractions. For qualitative and quantitative benthic foraminiferal analyses, the processed samples were split into sub-samples using

Otto-Splitter to obtain suitable aliquots having about 200–300 specimens. Those samples having less frequent occurrence of benthics were completely used for the separation of tests, even though certain samples contain <100 specimens. Five samples containing <40 specimens are not considered for data analysis and interpretation (Wollenburg *et al.* 2007). Presently, the core site is situated well above the foraminiferal lysocline (c. 3300 m; Belyaeva and Burmistrova 1984), and thus dissolution of calcitic foraminiferal tests was expected to be negligible. All specimens were identified under a stereozoom microscope and classified following taxonomic criteria of Loeblich and Tappan (1987, 1992) and Sen Gupta (2002). Benthic foraminifera are again classified into morphogroups as defined by Phleger (1951), Bernhard (1986), Corliss and Chen (1988), Corliss and Fois (1990)

Table 1. Morphogroup classification of benthic foraminifera from the examined core MD 131 as defined by Phleger (1951), Bernhard (1986), Corliss and Chen (1988), Corliss and Fois (1990) and Živković and Babić (2003).

Tapered & Cylindrical	Spherical	Biconvex
<i>Bulimina aculeata</i> *	<i>Cassidulina oblonga</i>	<i>Canceris auriculus</i>
<i>Bulimina alazanensis</i> *	<i>Cassidulina subglobosa</i>	<i>Ceratobulimina pacifica</i>
<i>Bulimina costata</i> *	<i>Chilostomella ovoidea</i>	<i>Hoeglundina elegans</i>
<i>Bulimina marginata</i> *	<i>Lagena hispidula</i>	<i>Lenticulina peregrina</i>
<i>Bulimina striata</i> *	<i>Lagena striata</i>	<i>Oridorsalis tenera</i>
<i>Bulimina arabiensis</i> *	<i>Pullenia bulloides</i>	<i>Oridorsalis umbonatus</i>
<i>Buliminella tenuata</i> *	<i>Sphaeroidina bulloides</i>	<i>Osangularia bengalensis</i>
<i>Chilostomella oolina</i>		
<i>Dentalina communis</i>	Planoconvex	Flattened ovoid
<i>Dentalina filiformis</i>	<i>Anomalinooides evolutus</i>	<i>Cassidulina carinata</i>
<i>Ehrenbergina pacifica</i>	<i>Cibicides marialana gigas</i>	<i>Fissurina</i> sp.
<i>Fursenkoina bradyi</i> *	<i>Cibicides mediocris</i>	
<i>Fursenkoina bramletti</i> *	<i>Cibicides refulgens</i>	Flattened-tapered
<i>Fursenkoina cornuta</i> *	<i>Cibicides robertsonianus</i>	<i>Bolivina pseudobeyrichi</i> *
<i>Globobulimina pacifica</i> *	<i>Cibicides wuellerstorfi</i>	<i>Bolivina robusta</i> *
<i>Globobulimina pupoides</i> *	<i>Epistominella rugosa</i>	<i>Bolivina subspinescens</i> *
<i>Globobulimina pyrula</i> *	<i>Gavelinopsis lobatulus</i>	<i>Vaginulina margaritifera</i>
<i>Lagenodosaria scalaris</i>		
<i>Marginulina glabra</i>	Rounded-trochospiral	Milioline
<i>Marginulina tenuis</i>	<i>Gyroidinooides aff. orbicularis</i>	<i>Biloculina lucernula</i>
<i>Robertina oceanica</i>	<i>Gyroidinooides neosoldanii</i>	<i>Biloculina murrhyna</i>
<i>Ruakituria magdalidiforme</i>		<i>Nummuloculina irregularis</i>
<i>Uvigerina porrecta</i> *	Rounded - planispiral	<i>Pyrgo depressa</i>
<i>Uvigerina hispida</i> *	<i>Hyalinea balthica</i>	<i>Quinqueloculina lamarckiana</i>
<i>Uvigerina-interrupta-costata</i> *	<i>Melonis barleeaanum</i>	<i>Quinqueloculina aff. lamarckiana</i>
<i>Uvigerina peregrina</i> *	<i>Nonionella miocenica</i>	<i>Quinqueloculina oblonga</i>
<i>Uvigerina proboscidea</i> *	<i>Pullenia quadriloba</i>	<i>Quinqueloculina seminulum</i>
	<i>Pullenia subcarinata</i>	<i>Sigmoilina tenuis</i>
	<i>Robulus nikobarensis</i>	<i>Sigmoilopsis schlumbergeri</i>
	<i>Spirophthalmidium acutumargo</i>	<i>Spiroloculina rotunda</i>

*Species referred as rectilinear forms by Nigam *et al.* (2007).

and Živković and Babić (2003) using morphological characteristics of tests (table 1). Based on the census data, the relative abundance (%) of each species and morphogroup category was calculated. We have compared benthic foraminiferal morphogroup records with the published proxy records of primary productivity (C_{org} %, Singh *et al.* 2011) and OMZ intensity, oxygen concentration (aragonite%, Naidu *et al.* 2014). The methodologies of estimation of C_{org} and aragonite contents along with robustness of these proxies for productivity and OMZ reconstructions are discussed in Singh *et al.* (2011) and Naidu *et al.* (2014), respectively.

4. Results

4.1 Benthic foraminiferal assemblage records

A total of 89 species belonging to 51 genera and 34 families of benthic foraminifera are reported. Calcareous benthic foraminifera form the bulk of the foraminiferal population (>90%). Agglutinated taxa represented by 11 species of 7 genera and 4 families constitute rest of the benthic foraminiferal assemblage. The calcareous benthic foraminiferal assemblages are composed mainly of buliminid, uvigerinid, bolivinid, cibicidid, miliolid, cassidulinid groups; and *Pullenia* and *Gyroidinoides* species (figure 2). Other quantitatively important taxa are *Fursenkoina*, *Oridorsalis* and *Chilostomella* species, *Osangularia bengalensis*, *Sphaeroidina bulloides*, *Hoeglundina elegans* and *Melonis barleeanum*. Although, benthic foraminiferal abundance records reveal broad changes in the composition of assemblages during the late Glacial, Deglacial and the Holocene periods; prominent changes at millennial scale are noticed during certain intervals corresponding to northern hemispheric climatic events (figure 2). The buliminids account for an average of 28% of the benthic population in the examined core. The percentage abundance of this group varies between its minimum 5% and maximum 73%. The main constituent taxa of the buliminid assemblage are *B. costata*, *B. aculeata* and *B. alazanensis*. Temporal variation in relative abundance of the total buliminids reveals prominent increases between 18 and 23 ka BP (maximum at ~22.5 ka BP), 13 and 14 ka BP and 5 and 8 ka BP. The abundance of buliminids significantly declined during 15–17.5 ka BP, and 23.5–24.5 ka BP. Cassidulinids is the next

important component of the benthic assemblage in the core and *Cassidulina carinata* and *C. subglobosa* are the major constituents of the cassidulinid population. Temporal variation pattern of total cassidulinids shows significant variation down-core, with prominent increase in abundance during 27–28 ka BP, 17.5–22 ka BP and 5–6 ka BP (figure 2). A considerable decrease in abundance is noticed between 28 and 29 ka BP, 22.5 and 25 ka BP and 15 and 17 ka BP. Cibicidid population in benthic foraminiferal assemblages is represented by *Cibicides marialana gigas*, *C. mediocris*, *C. refulgens*, *C. robertsonianus* and *C. wuellerstorfi*. The abundance of total cibicidids in the core varies between its maximum 22% and minimum 0%. The abundance pattern of this group is opposite to that of the buliminids and shows its abundance maxima during 15–17 ka BP and 25–27 ka BP (figure 2). Between 21 and 23 ka BP, this group is characteristically extremely low in its abundance. The miliolids in the examined core are represented mainly by *Quinqueloculina*, *Pyrgo* and *Biloculina*. Miliolids constitute bulk of the porcelaneous tests of benthic population. This group shows remarkable variation in its abundance down-core with maximum during 14.5–17 ka BP and a significant increase between 25 and 30 ka BP (figure 2). The main constituent taxa of uvigerinid population in benthic assemblages are *U. interrupta-costata*, *U. peregrina*, *U. hispida* and *U. proboscidea*. The relative abundance of total uvigerinids in the core varies between 0% and 23%, with high abundances during 29–30, 23.5–25.5, 20.5–21.5, 12–13.5 ka BP and maximum at around 6 ka BP. The periods between 14 and 17.5 ka BP, 22 and 23 ka BP and 26 and 29 ka BP are characterized by a significant decline in its abundance. *Bolivina robusta* is the only quantitatively significant species of bolivinid population in the examined core. The bolivinid group shows its maximum abundance between 8 and 12 ka BP. Between 17.5 and 30 ka BP, bolivinids are either absent or present with very low abundance. The constituent species of *Pullenia* are *P. bulloides*, *P. quadriloba* and *P. subcarinata*. The abundance record of *Pullenia* spp. reveals rapid fluctuations down-core on century to millennial scales (figure 2). The prominent increase in abundance occurred between 18 and 22 ka BP; however, *Pullenia* spp. abundance was conspicuously low during 15–17 and 23–24.5 ka BP (figure 2). It is interesting to record that since 13 ka BP, pullenids are absent except for a few specimens present in core-top samples. The *Gyroidinoides* population is composed of two

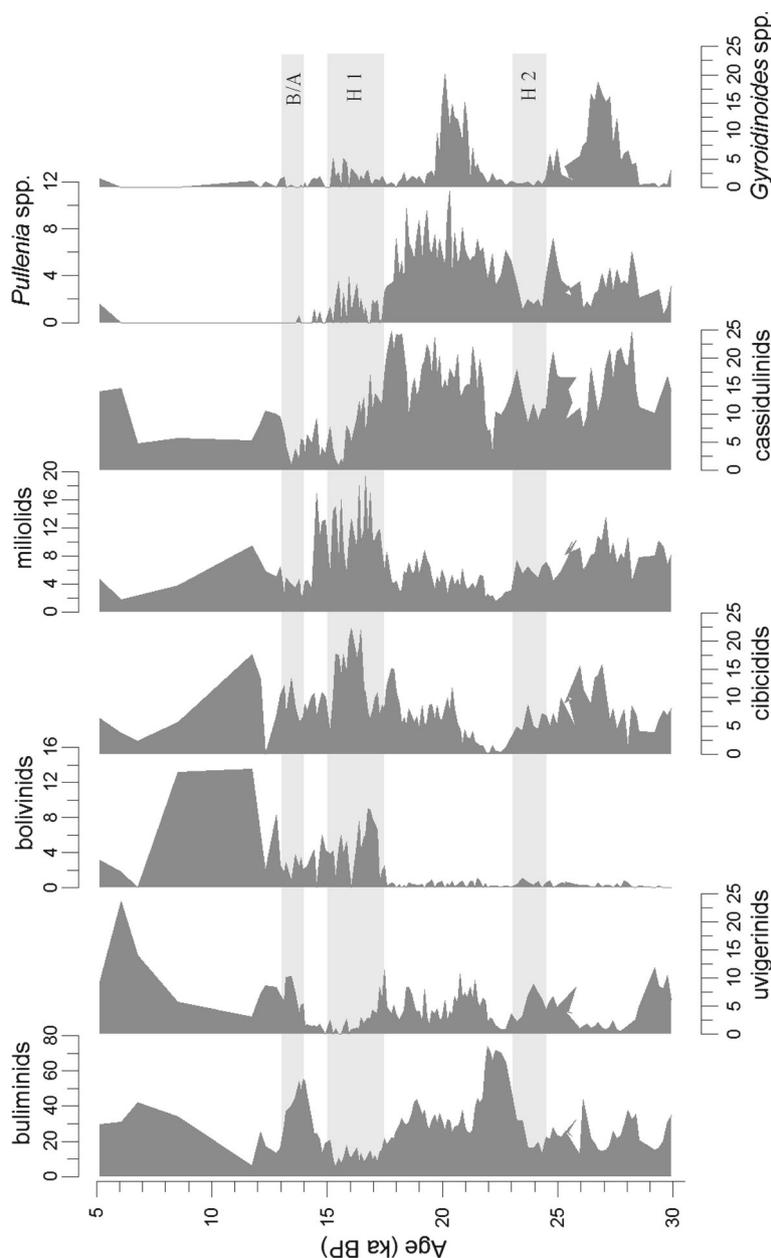


Figure 2. Temporal variations in relative abundances of quantitatively important benthic foraminiferal groups in cores MD 131 (B/A: Bølling/Allerød; H1, H2: Heinrich events).

species, *G. aff. orbicularis* and *G. neosoldenii*. The abundance of *Gyroidinoides* spp. has been very low all through, except for two brief intervals (20–21, 26.5–27.5 ka BP) (figure 2). The abundance pattern of buliminids is opposite to those of cibicidids and miliolids. In general, high abundances of buliminids, cassidulinids and *Pullenia* spp. together are recorded during the late Glacial period with maxima between 18 and 23 ka BP, as compared to the Deglacial and Holocene periods. The intervals of prominent decline in abundances of these

groups and increased abundances of cibicidids and miliolids broadly correspond to the north Atlantic cold Heinrich events. A brief interval of high abundance of buliminids during 13–14 ka BP corresponds to the warm Bølling/Allerød event.

Increased abundance of buliminids, cassidulinids, uvigerinids, bolivinids, fursenkoinids, *Gyroidinoides* and *Pullenia* species are generally explained by high rate of organic matter deposition to the sea floor, resulting from high surface primary productivity (Corliss and Fois 1990; Rathburn and

Corliss 1994; Jorissen *et al.* 1995; den Dulk *et al.* 2000). Majority of the constituent species of these groups and genera are also known to be limited to the low-oxygen environment. It has been suggested, however, that certain taxa change their microhabitat preferences in response to varying bottom water oxygen concentrations, thus experiencing a wide range of oxygen limit (e.g., Barmawidjaja *et al.* 1992). High abundances of cibicidids and miliolids in sediment cores of the northern Arabian Sea OMZ have been attributed to the low organic flux coupled with an oxic benthic environment (e.g., den Dulk *et al.* 2000). Previous studies also suggested an association of *Hoeglundina elegans*, *Sphaeroidina bulloides*, *Melonis barleeanum* and *Oridorsalis* species in mesotrophic to eutrophic environments to moderately oxygen depleted condition, whereas *Chilostomella* species to the highly oxygen deficient condition (Linke and Lutze 1993; Kaiho 1994; Gooday 1994; Kuhnt *et al.* 1999; Gooday *et al.* 2000). *Osangularia* species is known to prefer low-oxygen bottom condition (Jannink *et al.* 1998).

4.2 Benthic foraminiferal morphogroup patterns

The benthic foraminifera based on the distinguishing morphological features (test's shape and coiling) are classified into nine morphogroups (rounded-trochospiral, biconvex, planoconvex, milioline, rounded-planispiral, spherical, flattened ovoid, tapered/cylindrical and flattened-tapered) (table 1). The rounded-trochospiral morphogroup includes species of *Gyroidinoides* and the planoconvex category consists mainly of *Cibicides* species. The biconvex morphogroup is represented mainly by *Oridorsalis* species, *Hoeglundina elegans*, *Ceratobulimina pacifica* and *Osangularia bengalensis*. *Quinqueloculina*, *Biloculina* and *Spiroloculina* species are the important taxa of the milioline category. The rounded-planispiral morphogroup includes mainly *Melonis barleeanum*, *Hyalinea balthica*, *Robulus nikobarensis*, *Pullenia* species (*subcarinata*, *quadriloba*), *Nonionella miocenica* and *Spirothalmidium acutimargo*. The predominant forms under tapered or cylindrical category are *Bulimina*, *Uvigerina*, *Fursenkoina*, *Dentalina* and *Globobulimina* species; and the flattened-tapered morphogroup mainly includes species of *Bolivina* and *Vaginulina*. *Sphaeroidina bulloides*, *Pullenia bulloides*, *Chilostomella ovoidea* and *Cassidulina* species (*oblonga*, *subglobosa*) are kept under the spherical morphogroup. *Cassidulina carinata* is the important constituent species of

flattened ovoid category. SEM illustrations of selected benthic foraminifera representing different morphogroups are provided in figure 3. The average values of percentage abundance of morphogroups in the examined core are most abundant tapered/cylindrical (36.55%) followed by spherical (14.76%), planoconvex (9.67%), biconvex (9.09%), flattened-ovoid (7.61%), milioline (6.87%), rounded-planispiral (4.76%), rounded-trochospiral (3.67%), and flattened-tapered (1.7%) tests. The individual morphogroup abundance record exhibits prominent changes down-core on millennial scale (figure 4). In general, tapered/cylindrical tests together with spherical, flattened-ovoid morphogroups predominate the foraminiferal assemblages during late glacial period between 18 and 22.5 ka BP. There has been an increase in abundance of tapered/cylindrical forms in the Holocene between 5 and 8 ka BP and 13 and 14.5 ka BP. A rapid increase in abundance of spherical tests is noticed for short spells during 12–13 ka BP and 23.5–24.5 ka BP. Flattened-ovoid tests are almost absent in the Holocene assemblages; whereas, rare occurrence of flattened-tapered tests is noticed in late glacial sediment. The period between 15 and 17.5 ka BP is characterized by a major decline in abundances of tapered/cylindrical, spherical and flattened-ovoid tests. These morphogroups except spherical category also show a significant decrease in their abundances between 23 and 24.5 ka BP. The pattern of variation in abundance of planoconvex tests is opposite to the pattern of tapered/cylindrical tests with abundance maxima of former corresponding to the minima of latter and vice-versa. The milioline and biconvex morphogroups both show major reduction in abundances between 18 and 23 ka BP. Maximum abundance of milioline tests is recorded between 14.5 and 17.5 ka BP. High abundance of biconvex tests is noticed between 23.5 and 24.5 ka BP. In general, major variations in assemblage with respect to relative abundances of different morphogroups are recorded between 13 and 14.5, 15 and 17.5, 18 and 22.5, 23 and 24.5, and 25 and 28 ka BP. The benthic foraminifera having planoconvex and milioline morphologies are important constituents of assemblages between 15 and 17.5 ka BP, a period corresponding approximately to the Heinrich 1 event. In core MD 131, these two morphogroups along with biconvex group also show their high occurrences during the period equivalent to the Heinrich 2 event (between 23 and 24.5 ka BP). Between 25 and 28 ka BP, there has been significant increase in abundances

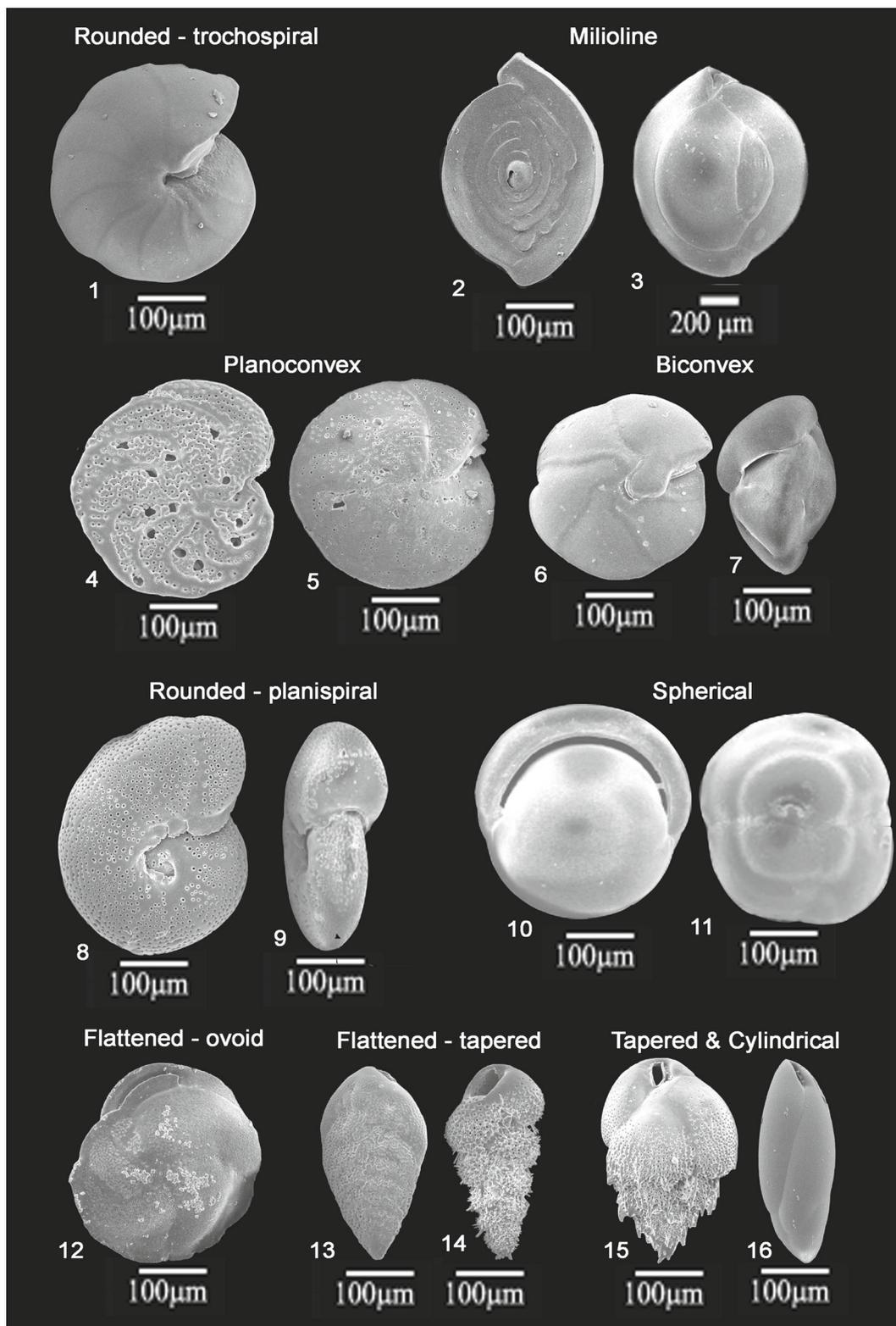


Figure 3. Illustrations of various benthic foraminiferal morphogroup categories. Specimens illustrated are taken from core MD 131. 1. *Gyroidinoides orbicularis* (d'Orbigny), 2. *Spiroloculina rotunda* (d'Orbigny), 3. *Quinqueloculina seminulum* (Linné), 4. *Cibicides wuellerstorfi* (Schwager), 5. *Cibicides marialana gigas* (Keijzar), 6. *Oridorsalis tenera* (Brady), 7. *Oridorsalis umbonatus* (Reuss), 8–9. *Melonis barleeanum* (Williamson), 10. *Pullenia bulloides* (d'Orbigny), 11. *Sphaeroidina bulloides* (d'Orbigny), 12. *Cassidulina carinata* (Silvestri), 13. *Bolivina robusta* (Brady), 14. *Bolivina subspinescens* (Cushman), 15. *Bulimina costata* (d'Orbigny), 16. *Fuesenkoina bramletii* (Galloway and Morrey).

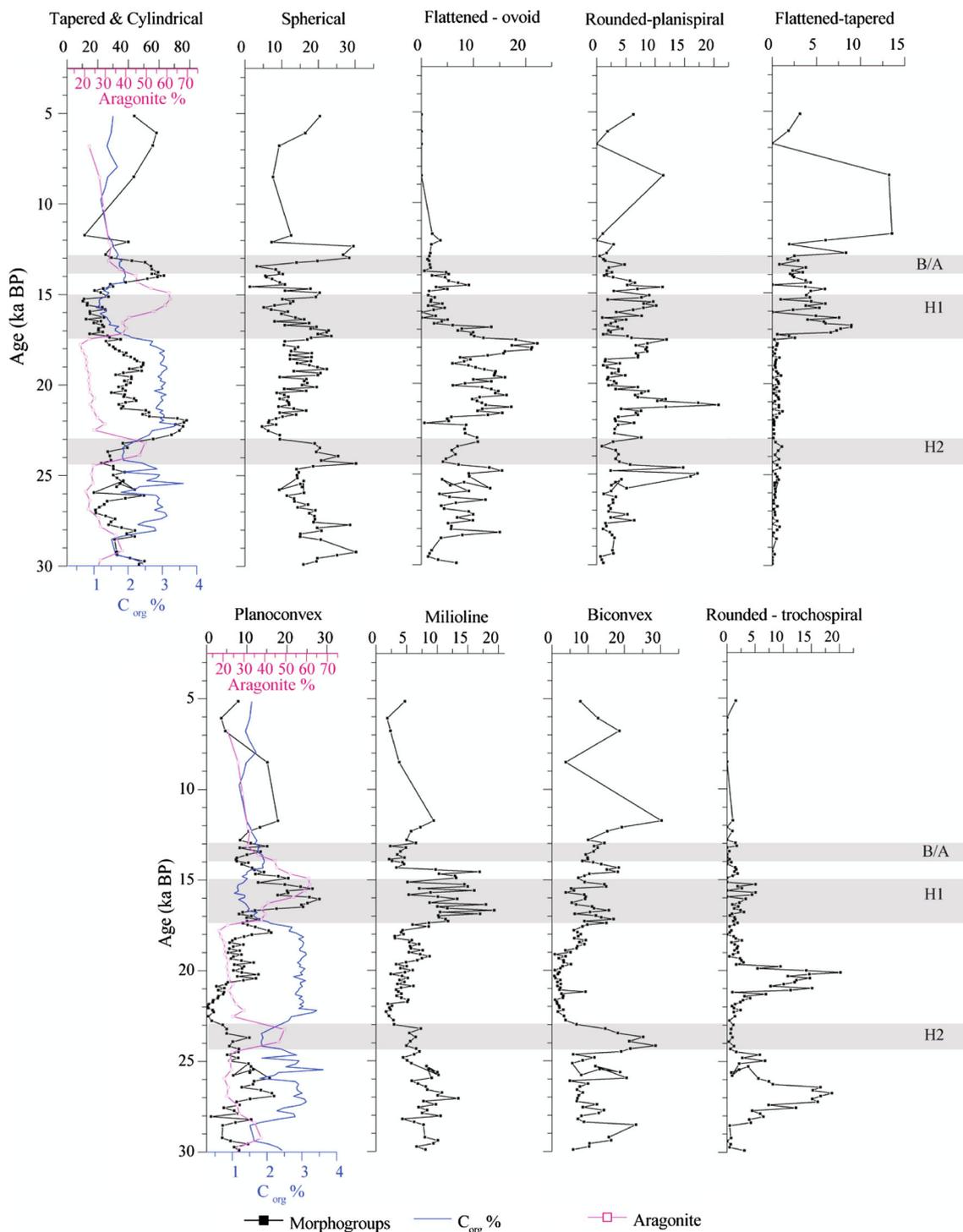


Figure 4. Temporal variation in relative abundances of benthic foraminiferal morphogroups in core MD 131. The morphogroup abundance records are compared with the records of organic $C_{org}\%$ (Singh *et al.* 2011) and aragonite% (Naidu *et al.* 2014). [B/A: Bølling/Allerød; H1, H2: Heinrich events].

of planoconvex, milioline and rounded-trochospiral tests. A peak of abundance of rounded-trochospiral category is also noticed during 20–21 ka BP. The tapered/cylindrical, spherical and flattened-ovoid morphogroups together predominate the benthic

assemblages during the last Glacial maximum between 18 and 22.5 ka BP; whereas, high abundance of tapered/cylindrical tests occurred during the warm Bølling/Allerød event (13–14 ka BP).

5. Discussion

5.1 *Benthic foraminiferal morphogroup as a paleoenvironmental indicator*

Based on the understanding of relationship between modern ecological patterns and faunal distribution, abundances of sensitive species in fossil records are often used for paleoenvironmental reconstructions. The morphologies of fossil benthic foraminifera related to their adaptation capabilities and strategies to changes in ocean bottom environments (e.g., Corliss and Fois 1990), can be potential indicators of paleoenvironments. Recently, Nigam *et al.* (2007) have used the abundance of rectilinear benthic foraminifera as an index for inferring past sea bottom oxygen conditions in the eastern Arabian Sea. Here, we analyzed the time series records of abundance variations of various benthic foraminiferal morphogroups in order to assess their association with past changes in sea floor environment, with assumption that the responses of benthic foraminifera to bottom conditions and the adapted morphologies as preserved in sediment records have not changed from their living counterparts.

The major changes in abundance records of various morphogroups in the studied core show correspondence with millennial scale northern hemisphere climatic cycles recorded in ice-cores and the north Atlantic sedimentary record (figure 4). Benthic foraminifera with planoconvex, and milioline tests are abundant during the periods equivalent to cold Heinrich event 1 (H1) and biconvex tests are high during Heinrich event 2 (H2). During these time intervals, the abundance of tapered/cylindrical and flattened-ovoid tests declined significantly. The period of Heinrich 1 event is also characterized by a significant reduction in abundance of spherical tests. A major increase in tapered/cylindrical tests abundance occurred during the periods of last glacial maximum (LGM) and warm Bølling/Allerød event. Flattened-ovoid and spherical tests also show their high abundances during the LGM. Proxy records of productivity (planktic foraminifera abundance, organic carbon content) and OMZ intensity (pteropod abundance and aragonite content) from the same core (MD 131) demonstrated significant and rapid changes in primary productivity related export flux of organic matter; and water column ventilation during these climatic events attributed to variations in the OMZ intensity and therefore

oxygen condition of benthic environment (Singh *et al.* 2011; Naidu *et al.* 2014). Previous studies carried out elsewhere have shown a good relationship between the morphological features of benthic foraminifera and their microhabitat preferences (e.g., Corliss 1985; Corliss and Emerson 1990), although ecological and microhabitat preference of an individual species may vary in different oceanographic settings (e.g., Barmawidjaja *et al.* 1992; Alve and Bernhard 1995). The benthic foraminiferal microhabitats are classified according to depth at which they live in sediments, viz., epifaunal, shallow infaunal, and intermediate/deep infaunal (Murray 1991; Barmawidjaja *et al.* 1992; Buzas *et al.* 1993; Jannink *et al.* 1998). Foraminifera possessing morphologies featuring high surface area to volume ratio (rounded-trochospiral, biconvex, planoconvex and milioline tests) are suggested to prefer epifaunal habitat; and those having low surface area to volume ratio (flattened, elongated, cylindrical, spherical or rounded-planispiral tests) prefer infaunal microhabitat (e.g., Corliss and Chen 1988).

5.2 *Benthic foraminiferal morphogroup successions*

5.2.1 *Relation to changes in trophic conditions*

We compared our benthic foraminiferal morphogroup records with the $C_{org}\%$ record (Singh *et al.* 2011), a primary productivity proxy (Müller and Suess 1979; Calvert *et al.* 1995), in order to evaluate if there exists a correspondence between temporal variations in morphogroup and bottom trophic condition in the eastern Arabian Sea in the last 30 ka BP. It is observed that except for some brief intervals (e.g., 26–28 ka BP); high abundance of infaunal morphogroups (tapered/cylindrical, flattened-ovoid and spherical) occurs generally in organic carbon rich sediment, whereas, abundance of epifaunal morphogroups (planoconvex, milioline and biconvex) is high in sediment with relatively low organic carbon content (figure 4). However, this relationship is more clearly seen in patterns of tapered/cylindrical and planoconvex which have opposite trends of variations. With the present data set, it is difficult to explain differences in relationship between abundance variation patterns of epifaunal, infaunal morphogroups and C_{org} content during certain intervals such as 26–28 ka BP; for which we require additional geochemical and isotope proxy records. Nevertheless, the organic

carbon flux to ocean bottom appears to be overall an important parameter structuring these benthic foraminiferal morphogroups. Records of other morphogroups (rounded-planispiral, flattened-tapered and rounded-trochospiral) do not exhibit any definite pattern of association with C_{org} , however, the reason for this inconsistency cannot be explained by the available data. It is also possible that the factor other than organic carbon, such as intermediate/deep water ventilation through externally sourced water may have influenced the benthic environment and thus overall response of benthic fauna.

5.2.2 Relation to changes in the oxygen minimum zone intensity

The development of present day OMZ is attributed to the monsoon-induced high surface water productivity related large export flux of organic carbon and its subsequent decay consuming oxygen in the intermediate waters, combined with a poor ventilation of thermocline waters. The paleoceanographic studies reveal that the OMZ intensity, primary productivity and water column ventilation in the Arabian Sea have varied in the past significantly (Altabet *et al.* 1995; Reichert *et al.* 1998; Schulte *et al.* 1999; Ivanochko *et al.* 2005; Klöcker *et al.* 2006). It has been suggested that the intervals of aragonite maxima in sediment records of the Arabian Sea margins were related to the deepening of the ACD due to a weak OMZ (e.g., von Rad *et al.* 1999; Klöcker *et al.* 2006; Singh 2007). Recently, Naidu *et al.* (2014) employing pteropod abundance and aragonite preservation records of the core MD 131, as proxy for the OMZ intensity reconstruction, demonstrated millennial scale changes in the OMZ intensity at the core site in concert with Northern Hemisphere climatic events. The study further revealed that the OMZ was weak during the periods corresponding to the north Atlantic cold Heinrich events (most prominently Heinrich 1 event). We compared records of morphogroup categories with the aragonite % record to evaluate response of various morphogroups to changes in the OMZ intensity (figure 4). We found that the aragonite maxima indicating a weak OMZ during Heinrich events (H1 and H2) correspond to the intervals of major reduction in abundance of tapered/cylindrical tests. On the contrary, the abundance variation pattern of planoconvex tests

almost parallels to the pattern of aragonite%. Therefore, out of nine morphogroups planoconvex (epifaunal) and tapered/cylindrical (infaunal) appear to be more sensitive to the fluctuation in sea bottom oxygen condition associated to the changes in the OMZ intensity (figure 4). The faunal record demonstrates that abundance maxima of planoconvex tests and corresponding low values of tapered/cylindrical tests occur during the Northern Hemisphere cold Heinrich events (H1 and H2) characterized by the low surface productivity, a weak OMZ and oxygenated bottom waters (Singh *et al.* 2006, 2011; Naidu *et al.* 2014). However, tapered/cylindrical benthic forms predominate over the species having planoconvex tests during the last glacial maximum and the Holocene between 5 and 8 ka BP, when productivity was high and the OMZ was intensified resulting to an oxygen-depleted sea-bottom environment. The abundance maximum of milioline tests during the interval corresponding to the cold Heinrich 1 event is suggestive of enhanced oxygenation of benthic environment, probably linked to the intensified inflow of oxygen rich southern-sourced water. Abundant occurrence of miliolids in the northeastern Arabian Sea cores has been suggested to be associated to the condition of a better ventilated OMZ and an oxygenated benthic environment (Jannink *et al.* 1998; den Dulk *et al.* 2000). Several lines of evidence suggest presence of oxygenated southern ocean sourced intermediate waters at the examined core site MD 131 during the Heinrich event 1 (Naidu *et al.* 2014). Hence, we suppose that these benthic foraminiferal morphogroups have potential in deciphering history of the OMZ evolution, at least in the eastern Arabian Sea.

5.3 Bottom water oxygenation

Since the oxygen level of underlying bottom waters is considered as an important parameter governing the microhabitat and related morphological characteristics of benthic foraminifera, we made a broad assessment of past changes in bottom oxygen condition utilizing data available on association of benthic species with sea bottom oxygen level (Appendix). The oxygen sensitive species were grouped into two assemblages broadly associated with (i) oxic environment (O_2 : >0.5 ml/l) and (ii) hypoxic environment (O_2 : <0.5 ml/l). Record of abundance ratio of oxic to hypoxic assemblage in the core MD 131 demonstrates major change

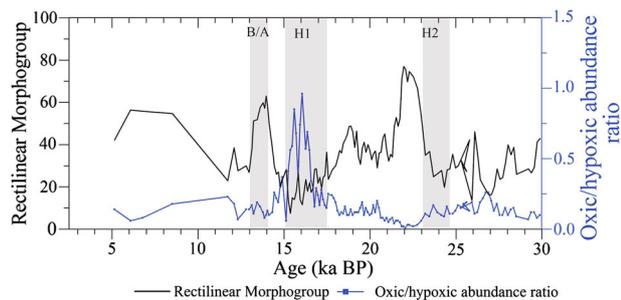


Figure 5. Temporal variation in the oxic/hypoxic benthic foraminiferal abundance ratio; and relative abundance of total rectilinear taxa in core MD 131 [B/A: Bølling/Allerød; H1, H2: Heinrich events].

during Heinrich 1, when oxic taxa dominate the assemblages suggesting high oxygenation of benthic environment (figure 5). It is also evident from the microfaunal that there has been some increase in abundance ratio of oxic/hypoxic taxa for a brief period corresponding to the Heinrich 2 event, but this is not much prominent as compared to the Heinrich 1. Earlier studies suggested low export flux of organic matter associated with weak monsoon circulation, combined with better thermocline ventilation resulting a weakening/breakdown of the OMZ during the Heinrich events, most prominently in Heinrich 1 period (Singh *et al.* 2006; Singh 2007). It appears that in addition to the reduced primary productivity, intermediate water ventilation was relatively more vigorous during the Heinrich 1, probably linked to the intensification of global deep ocean circulation. This supports the earlier inference drawn based on the pteropod data indicating enhanced ventilation during this period due to intensified inflow of oxygen-rich AAIW (Naidu *et al.* 2014). Low values of oxic/hypoxic abundance ratio during the last glacial maximum, the Bølling/Allerød and the Holocene between 5 and 8 ka BP point to low oxygen ocean bottom conditions attributed to the monsoon related high organic carbon export flux coupled with poor water column ventilation and an intensified oxygen minimum zone. Recently, Nigam *et al.* (2007), based on their studies on bathymetric distribution of recent benthic foraminifera in OMZ region off Goa proposed rectilinear forms as proxy for reconstruction of sea bottom oxygen condition. We constructed record of temporal variation in abundance of total rectilinear taxa encountered and compared it with the pattern of our oxic/hypoxic abundance ratio (figure 5). Strikingly, the patterns of variations in both the records match very well with high

values of oxic/hypoxic abundance ratio corresponding to low abundances of rectilinear tests and vice versa.

6. Conclusions

Records of nine morphogroups identified in benthic foraminiferal assemblages of the cores recovered from the lower boundary of the present day OMZ offshore Goa, reveal major changes in their abundances on millennial scale during the last 30 ka. We evaluated the association of foraminiferal morphogroups with monsoon controlled export flux of organic matter and sea bottom oxygen condition related to the OMZ strength. The abundance records of various morphogroups indicate that the patterns of temporal variation in epifaunal planoconvex, milioline and infaunal tapered/cylindrical categories are related to major changes in sea bottom environment (oxygen and trophic conditions) during the Northern Hemisphere climatic events. The abundance maxima of benthic foraminifera with planoconvex tests indicating oxygenated benthic environment are recorded during the periods equivalent to the cold Heinrich events (H1 and H2) particularly during the Heinrich 1. These were the periods when monsoon related surface productivity was low and the OMZ intensity was weak. A significant increase in abundance of milioline tests during Heinrich 1 event further suggests enhanced ventilation of the OMZ and increased oxygenation of bottom water. The dominance of tapered/cylindrical tests in benthic assemblages during the last glacial maximum, the Bølling/Allerød and the Holocene period between 5 and 8 ka is suggestive of oxygen depleted benthic environment associated to the high surface productivity, poor ventilation of the water column and an intensified OMZ.

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Appendix

Constituent species of hypoxic (<0.5 ml/l O₂) and oxic (>0.5 ml/l O₂) benthic foraminiferal assemblages

[Data source of benthic faunal association with oxygen concentrations are from Harman 1964; Smith 1964; Douglas and Heitman 1979; Quinterno and Gardner 1987; Mackensen and Douglas 1989; Corliss and Fois 1990; Bernhard 1992; Kaiho 1994, 1999; Jannink *et al.* 1998; Jorissen *et al.* 2007; Nigam *et al.* 2007; Ohkushi *et al.* 2013; Mazumder and Nigam 2014.]

A1. Hypoxic assemblage

Bulimina spp., *Cassidulina* spp., *Pullenia* spp., *Gyroidinoides* spp., *Uvigerina* spp., *Oridorsalis* spp., *Globobulimina* spp., *Bolivina* spp., *Fissurina* spp., *Fursenkoina* spp., *Dentalina* spp., *Lagena* spp., *Hoeglundina elegans*, *Sphaeroidina bulloides*, *Buliminella tenuata*, *Cibicides refulgens*, *Osangularia bengalensis*, *Lenticulina peregrina*, *Melonis barleeanum*, *Ehrenbergina pacifica*, *Chilostomella oolina*, *Nonionella miocenica*.

A2. Oxic assemblage

Cibicides spp. (excluding *Cibicides refulgens*), *Biloculina* spp., *Quinqueloculina* spp., *Gavelinopsis lobatulus*, *Pyrgo depressa*.

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