Journal of the Palaeontological Society of India
Volume 62(1), June 30, 2017: 51-58

ISSN 0552-9360

RESPONSE OF CASSIDULINIDS TO THE OXYGEN MINIMUM ZONE INTENSITY FLUCTUATIONS DURING THE LAST 70 KYR IN THE EASTERN ARABIAN SEA, OFF GOA

SHIVRANJAN KR. BHARTI*

DEPARTMENT OF GEOLOGY, BANARAS HINDU UNIVERSITY, VARANASI- 221005, INDIA
*PRESENT ADDRESS: PALAEOTOLOGY DIV, NCEGR, GEOLOGICAL SURVEY OF INDIA, CHQ, 15 A&B KYD STREET, KOLKATA-16, W.B., INDIA
E-MAIL: bhartisrgsi@gmail.com

ABSTRACT:

In order to study the response of benthic foraminifera, a closely spaced samples of a 9.65m long sediment core which was retrieved from 1230m water depth off Goa, were analysed both qualitatively and quantitatively. The down-core abundance pattern of cassidulinids shows millennial-scale variation almost paralleling the organic-carbon-concentration (%C_{org}) sediment record. The cassidulinid population appears to be controlled by both bottom oxygen condition and primary productivity. This study deciphers that the intervals during 15 – 17 kyr BP, 23 – 24 kyr BP, 28 – 29.5 kyr BP, 38 – 39 kyr BP, 45 – 46 kyr BP and 60 – 61 kyr BP were the periods of cassidulinid minima related to the weak Oxygen Minimum Zone (OMZ) intensity and low surface primary productivity in the eastern Arabian Sea. These events of abundance minima of cassidulinds correspond with the time equivalents of north Atlantic Heinrich Events.

Keywords: Benthic foraminifera, cassidulinids, OMZ, Arabian Sea

INTRODUCTION

The Arabian Sea is characterised by a strong OMZ attributed to high biological productivity and poor ventilation of thermocline (Wyrtki, 1973). Previous studies reveal past changes in productivity, ventilation of intermediate waters and depths of local overturning resulted in a significant variation in the OMZ intensity (Altabet *et al*., 1995; Schultz *et al*., 1998; Reichart *et al*., 1998; 2002; Schulte *et al*., 1999 and Singh *et al*., 2006). Benthic foraminifera are reliable indicators of OMZ intensity, as many of the taxa are considered to be sensitive to the changes in both the dissolved oxygen concentrations and C_{org} flux together determining the strength of the OMZ (Kaiho, 1994; Cannariato and Kennett, 1999). The benthic environment within the OMZ, as witnessed in the Arabian Sea is typified by low oxygen content and high organic matter content, which is reflected in associated benthic foraminiferal assemblages (Hermelin, 1992 and Hermelin and Schmmild, 1990). The examined core-site is situated near base of the present OMZ (1230 m). Thus, the temporal variation in benthic foraminiferal assemblages in the core can be used to interpret fluctuations in the OMZ strength of central part of the western Indian margin during the late Quaternary. Palaeoenvironmental interpretations were derived from qualitative and quantitative analyses of benthic foraminiferal assemblages of closely spaced samples of dated sediment core (MD76-131) from the central part of the upper continental slope of India.

This paper focuses on 70 kyr record of cassidulinids along with the brief note on their taxonomy and known ecology. Modern ecological data revealed that cassidulinids are very sensitive to the bottom water oxygen conditions and organic carbon content (Corliss and Chen, 1988; Kaiho, 1994; Kaiho, 1999). In the examined core, cassidulinids show remarkable robust positive correlation with the %C_{org} content record from the same core (Singh *et al*., 2011). Hence, with the aid of geochemical tracer (%C_{org}), the present study endeavours to know the response of cassidulinids to the OMZ intensity fluctuations for the last 70 kyr in the eastern Arabian Sea.

OCEANOGRAPHIC SETTING

Surface circulation and hydrography of the Arabian Sea is mainly controlled by the seasonal reversal of monsoon driven winds. During the summer monsoon, the West Indian Coastal Current (WICC) flows southwards and joins eastward flowing Southwest Monsoon Current (SMC). In winter monsoon season, the surface water currents reverse, flowing anti-clockwise. The WICC also reverses and the Northeast Monsoon Current (NMC) transports water from the Bay of Bengal into the eastern Arabian Sea. During summer monsoon season, a low salinity plume in the offshore region south of 20° N is created by the excess of precipitation over evaporation and heavy runoff from the Western Ghats (Naqvi *et al.,* 2003). During winter monsoon, the WICC reverses and the Northeast Monsoon Current (NMC) transports waters from the Bay of Bengal (BOB) into the eastern Arabian Sea. The influence of BOB low salinity water in the eastern Arabian Sea is most prevalent up to 13° N (Sarma, 2002). The strong north-easterly winds in winter causes upwelling (though weak) and vertical mixing offshore India north of 15° N (Bauer *et al*., 1991; Madhupratap *et al*., 1996). Additionally in areas offshore India and Pakistan, a deep mixing across the thermocline results in high surface productivity (Madhupratap *et al*., 1996). High biological productivity results in severe oxygen depletion in intermediate waters at 150-1250 m water depth (Olson *et. al*., 1993; Wyrtki, 1973).

MATERIAL AND METHODS

A 9.65 m long piston core (MD76-131) was raised from central part of the western Indian margin at 1230 m water depth (off Goa: Lat.-15° 31.8' N; Long.-72° 34.1' E) by R / V Marion Dufresne in 1976 (Figure 1). The core site is situated well above the Calcite Compensation Depth (c.2400 m, Belyaeva and Burmistrova, 1984). The sediment core in general is characterised by dark coloured indistinctly laminated sediments with intermittently light coloured homogenous facies. The

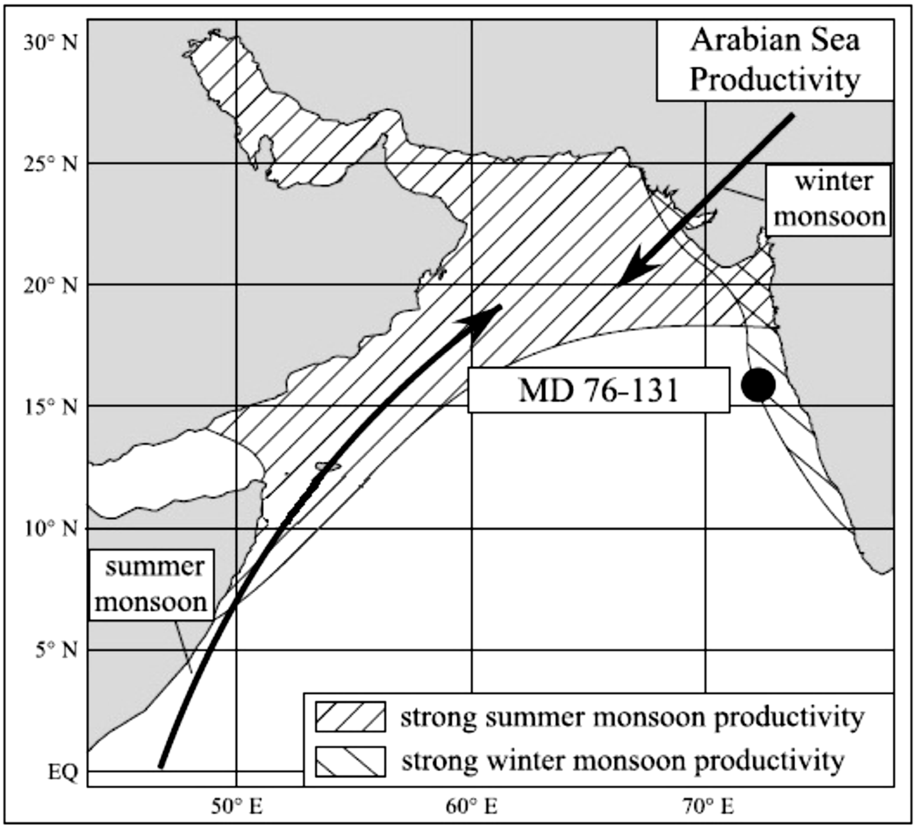

Fig. 1. Map showing the location of Core MD 76-131 off Goa (15º31.8'N, 72º34.1'E) and areas predominantly reflecting summer and winter monsoon-driven upwelling are hatched (Singh *et al.*, 2011). Thick line with arrowhead shows direction of atmospheric circulation during the summer and winter seasons.

narrow homogenous intervals are lithologically in sharp contact with the laminated strata. The core provides an uninterrupted sedimentary sequence (commonly hemi – pelagic mud), free of turbiditic (or mass flow) deposition and reworking. The core was sampled at 1 to 2cm intervals. Samples ranging from 2 to 4cm intervals were used for this study. In total 332 samples were analysed for various micropaleontological parameters. The examined core MD 76–131 spans 5–70 ka and the age model is based on AMS ^{14}C ages in the upper 360 cm (roughly 40 ka) and for intervals beyond the radiocarbon dating window chronostratigraphic control is achieved by tuning $\delta^{15}N$ record with (GISP2) [Ivanochko *et al*., 2005].

For separation of foraminifers' tests, sediment samples were processed following the conventional micropaleontological techniques. About 5g of dried sediment of each sample was soaked in 5% Hydrogen Peroxide solution for twelve hours and boiled a little before wet screening. Samples were washed through wet sieving over a 63µm screen. Dry residue coarser than 63µm was sieved again over a 125µm screen. Following previous benthic foraminiferal studies in the Indo – Pacific Ocean (Herguera and Berger, 1991; Miao and Thunell, 1996; Naidu and Malmgren, 1995; Rathburn and Miao, 1995; den Dulk *et al*., 1998, 2000; Almogi- Labin *et al*., 2000), the coarse fraction (>125µm) was used in the present study. The specimens were identified and counted under a stereozoom binocular microscope (Wild M3Z). Scanning electron micrographs of foraminiferal species were obtained at SEM-EDX, Lab., NCEGR, Kolkata, GSI. The species recovered are lodged in the Micropaleontology laboratory, Department of Geology, Banaras Hindu University, Varanasi. Systematic classification of benthic foraminifera is based on Loeblich and Tappan (1992) and Sen Gupta (2002), with morphological criteria taken from Loeblich and Tappan (1987).

RESULTS

The benthic foraminiferal assemblages of core MD76-131 are mainly composed of buliminids, cassidulinids, uvigerinids, cibicidids, miliolids and fursenkoinids and other taxa (in decreasing order of relative abundance). The percentage abundance of total cassidulinids varies between 0.8% - 40%. Species of the cassidulinids population are *Cassidulina carinata* Silvestri, *C. crassa* d'Orbigny, *Globocassidulina oblonga* (Reuss) and, *G. subglobosa* (Brady). Systematic descriptions of all four species are provided and illustrated by scanning electron micrographs in figure 3. Remarks on observed morphological features and known ecology are briefly presented.

SYSTEMATIC PALAEONTOLOGY

Class **Foraminifera** D'Orbigny, 1826
Order **Buliminida** Fursenko, 1958
Superfamily **Cassidulinacea** d'Orbigny, 1839
Family **Cassidulinidae** d'Orbigny, 1839
Subfamily **Cassidulininae** d'Orbigny, 1839
Genus ***Cassidulina*** d'Orbigny, 1826
(Type species *Cassidulina laevigata* d'Orbigny, 1826)

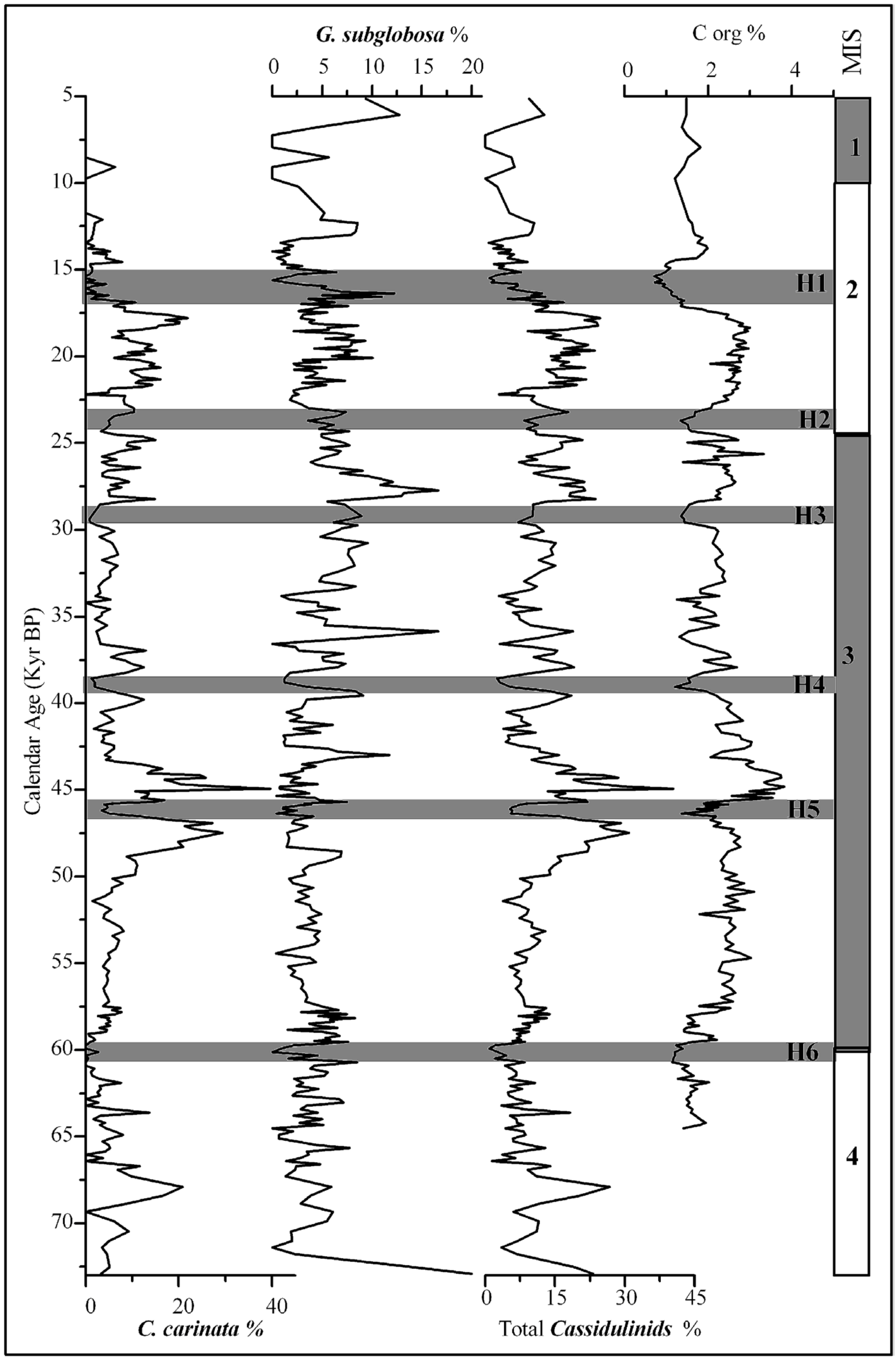

Fig. 2. Down core variation patterns of relative abundance of organic carbon concentration, *Cassidulina carinata, Globocassidulina subglobosa*, total Cassidulinids and %C_{org} (from Singh *et al.*, 2011) for core MD 76-131.

Cassidulina carinata Silvestri
(Figs 3. 1a-c.)

Cassidulina laevigata d'Orbigny var. *carinata* Silvesri ; 1896, v. 12, p. 104, pl. 2, figs. 10a-c.

Cassidulina carinata Barker, 1960, no. 9, p. 110, pl. 54, figs. 2-3.- Eade, 1967, v. 1, no. 4, p. 429, figs. 2, no. 5-9. - Srinivasan and Azmi, 1976, p. 346, list. - Wang et al., 1985, p. 336, pl. 4, fig. 17.

Cassidulina carinata Silvestri; Rodrigues *et. al.*, 1980, p. 54, pl. 5,figs. 3,6,9. - Van Marle, 1986, p. 141, pl. 2, figs. 4-5.

Remarks: Recorded specimens of *C. carinata* resembles most closely with forms described as *C. delicata* Cushman from the late Tertiary of East Borneo (Le Roy, 1941a), *C. cushmani* from late Tertiary of Java (Boomgaart, 1949), *C. laevigata* d' Orbigny from the Late Miocene of New Guinea (Belford, 1966) and *C. neocarinata* Thalmann from Tertiary of New Zealand (Hornibrook, 1961). Phleger *et al.* (1953) stated that *C. carinata* might be differentiated from *C. neocarinata* in having a broader apertural face and tooth, and a less compresssed, more coarsely perforate test. *C. carinata* differs from the typical *C. laevigata* d' Orbigny by its characteristic peripheral keel. According to Hageman (1979) *C. carinata* is an open marine mud-dweller. Guichard (1997) reported this as a shallow infaunal species. Gupta and Thomas (1999) suggested its association with high nutrient condition.

This species in the present day ocean is a phytodetritus feeder (Fontanier *et al.* 2003) and known from well-ventilated areas (Hayward *et al.,* 2002). *C. carinata* is found to be one of the predominate taxa of the foraminiferal population in core MD76-131, with its maximum abundance reaching up to 30%.

Cassidulina crassa d'Orbigny
(Fig. 3.2)

Cassidulina crassa d'Orbigny, 1839b, p. 56, pl. 7, figs. 18-20. -Brady, 1884, no. 9, p. 429, pl. 54, figs. 4-5. -Cushman, 1925, p. 54, pl. 8, figs. 37-39. - Barker, 1960, no. 9, p. 110, pl. 54, figs. 4-5. - Belford, 1966, no. 79, p. 151, pl. 26, figs. 5-9. - Boltovskoy, 1976,v.26, p.154, pl. 2, fig. 19.

Remarks : Belford (1966) observed a trifid aperture in his specimens of *C. crassa*, and therefore placed them in the genus *Globocassidulina*. In our specimens, though the aperture is often triangular in the central part, it is not trifid, but comparable with the *Cassidulina* type of aperture. Therefore, this species is retained in the genus *Cassidulina*. This is known to prefer shallow infaunal microhabitat (de Stigter *et al*., 1998). den Dulk *et al*. (2000) recorded this taxon in sediment cores within the OMZ of northern Arabian Sea. In the examined core it shows extremely rare occurrence.

Genus ***Globocassidulina*** Voloshinova 1960
Type species *Cassidulina globosa* Hantken, 1876

Globocassidulina oblonga (Reuss)
(Fig 3.7)

Cassidulina oblonga Reuss; 1850, v. 1, p. 376, pl. 18, figs. 5, 6. - Boltovskoy, 1978a, v. 26, p.152, pl. II, fig.31.

Globocassidulina oblonga; Belford, 1966, no. 79, p. 150, pl. 26, figs. 1-4, text-figs. 17(17, 18). - Srinivasan and Azmi, 1976, p. 348, list.

Globocassidulina oblonga (Reuss); Van Marle, 1986, p. 143, pl. 5, fig. 21.

Remarks: In most of our specimens, the last chamber is elongated. Brady (1884) and Marks (1951) based on observed variation in external features, placed *oblonga* in the synonymy of *C. crassa* d' Orbigny. However, Cushman (1925) and Nørvang (1958) considered the two species as valid ones. *Globocassidulina oblonga* has been reported from abysso-bathyal depths in Indian Ocean (Gupta, 1994; Rai and Srinivasan, 1994; Rai and Singh, 2004). In the present investigation it shows sporadic occurrence, but at times its abundance increases with maximum about 8%.

Globocassidulina subglobosa (Brady)
(Fig 3.8)

Cassidulina subglobosa; Brady, 1884, no. 9, p. 430, pl. 54, figs. 17a-c.- Barker , 1960 no. 9, p. 112, pl. 54, figs. 17a-c. - Boltovskoy, 1978a, v. 26, p.155, pl. II, fig. 34.

Globocassidulina subglobosa; Belford, 1966, no. 79, p. 149, pl. 25, figs.11-16, text-figs. 17 : 1-6, text-figs. 18 : 1-4. - Srinivasan and Azmi, 1976, p. 348, list.- Corliss,1979a, v. 25, no. 1, p. 8, pl. 3, figs. 12-13.

Globocassidulina subglobosa (Brady); Kurihara and Kennett, 1981, In: Kennett *et al*. (Eds.), Int. Repts of DSDP 90: 2, p. 1073, pl. 5, figs.4-8. - Boresma, 1984b, p. 1286, pl. 8, fig. 5.

Remarks: Examined species of *G. subglobosa* is characterised by enrolled biserial test and elongate slit-like aperture extending up rather across the apertural face.

G. subglobosa is a cosmopolitan species distributed in different water masses of wide bathymetric range and associated with warm AABW having temperature between 0.6°C to 0.8°C in the southwest India Ocean (Corliss, 1979b, 1983). This species is an indicator for NADW in the North Atlantic (Streeter, 1973; Lohmann, 1978; Schnitker, 1979; Hermelin, 1986). The predominance of this species in the MOW (Meditrranean Outflow Water) has also been recorded by Murray (1991). *G. subglobosa* is one of the most characteristic species of the Indian Deep Water (IDW) which is known to be largely of the Atlantic origin (Lohman, 1978; Corliss, 1979a, 1979b, 1983; Peterson, 1984). *G. subglobosa* is a phytodetritus feeder (Gooday, 1994) and an infaunal taxon (Corliss, 1985, 1991; Corliss and Chen, 1988). *G. subglobosa* is considered to thrive in sediment with high organic carbon content and can tolerate low dissolved oxygen concentration (Miller & Lohmann, 1982; Corliss and Chen, 1988). In the South China Sea, the Sulu Sea and the northern Arabian Sea *G. subglobosa* is reported within the OMZ where the organic carbon content of the sediment is highest and the oxygen penetration depth is shallowest (Miao and Thunell, 1993; den Dulk *et al*., 2000). However, in the Pacific Ocean, *G. subglobosa* is considered to be related to the environment with low surface productivity and thereby low flux of organic matter to the sea floor (Loubere and Banonis, 1987; Burke *et al*., 1993). *G. subglobosa* is an important species of benthic assemblages of the core MD76-131 and its abundance increases with maximum of about 13.6%.

Down – core variation pattern

Temporal variation pattern of total cassidulinids shows significant fluctuation on millennial to centennial scales with prominent increase in abundance during 18 – 22 kyr BP, 27 – 28 kyr BP, 44 – 45 kyr BP, 47 – 48 kyr BP and 67 – 68 kyr BP. The Holocene Period is characterized by the low abundance except at ~ 6 kyr BP with a moderate increase. A considerable decrease in abundance is observed between 15 – 17 kyr BP, 23 – 24 kyr BP, 28 – 29.5 kyr BP, 38 – 39 kyr BP, 45.5 – 46.5 kyr BP and 60 – 61 kyr BP (Figure 2)

DISCUSSION

Cassidulinids are characterized by the lenticular to flattened and ovoid test, prefer infaunal habitat, moderate to high organic carbon content and tolerate low oxygen environment (Corliss and Chen, 1988; Corliss and Fois, 1990; Kaiho, 1999). Out of four species, *C. carinata* and *G. subglobosa* are the major constituents of the cassidulinid population in the examined core samples. Abundance profile of *C. carinata,* a shallow infauna (Guichard, 1997), associated with high nutrient condition (Gupta and Thomas, 1999), follows the pattern of the total cassidulinid down-core pattern. The abundance record of *G. subglobosa* also follows the pattern of cassidulinid profile at least between 5 to 40 kyr BP and the abundance has been low from 40 to 70 kyr BP (lower part of the Marine Isotope Stage 3). Large specimens (> 350μm) of *Globocassidulina* are considered to be related to the oxic environment (Kaiho, 1994). Probably, the water mass characteristics might have influenced the abundance pattern of *G. subglobosa* in the lower part of the core.

The examined core comes from the base of the OMZ, and thus very sensitive to the changes in their intensity. OMZ can be formed either by lethargic circulation of oxygen-poor source

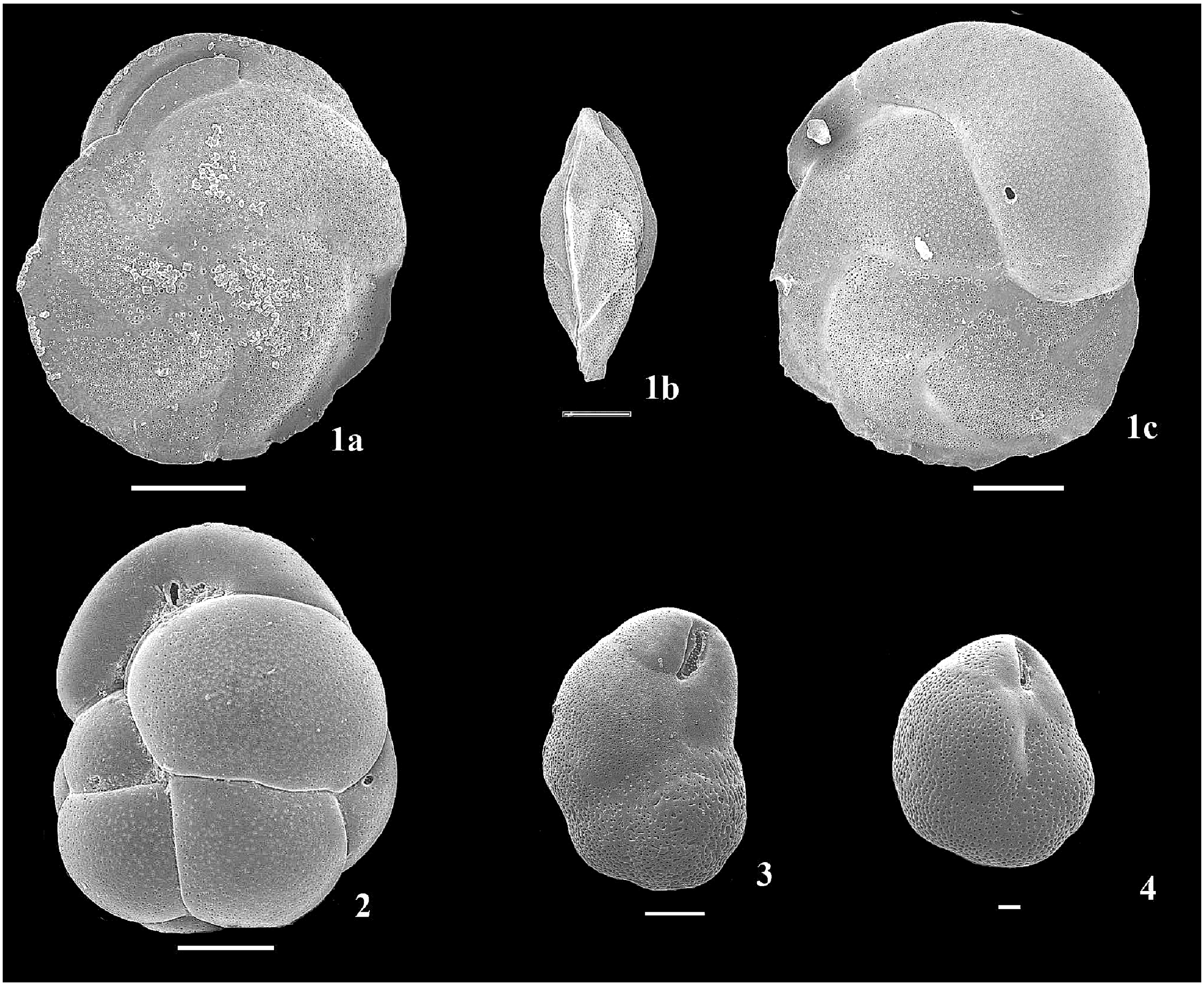

Fig. 3.1. ***Cassidulina carinata*** Silvestri 1a. Apertural view; X 190, 1b. Side view; X 220, 1c. Backside view; X150; 2. ***Cassidulina crassa*** d'Orbigny; Apertural view, X330; 3. ***Globocassidulina oblonga*** (Ruess); X 258; 4. ***Globocassidulina subglobosa*** Brady; X319

waters or by high primary production by photosynthesis or upwelling, in the latter case the decay of sinking organic matter consumes such a great amount of oxygen that the intermediate water depths contain substantially less oxygen than water above or below. Thus, the intensity of the OMZ is closely coupled with the primary productivity induced organic carbon flux. There are various factors for the organic carbon enrichment in the sea floor sediment such as production of organic carbon and its preservation. Paropkari *et al.* (1992) concluded that the intensity of OMZ is primarily controlled the preservation of organic carbon in slope of Oman and the western Indian margin. In the examined core, the total cassidulinid shows almost paralleling the C_{org} content record. The abundance pattern of cassidulinids indicates a prominent increase during 18–22 kyr BP, 27–28 kyr BP, 44 – 45 kyr BP, 47 – 48 kyr BP and 67– 68 kyr BP. These time intervals of abundance maxima of cassidulinids closely correspond to the maxima in $\%C_{org}$ content. During the Holocene Period, the cassidulinid abundance is low except its moderate value at 6 kyr BP. A prominent and rapid decline in abundance of cassidulinids is recorded between 10 and 12, between 15 and 17 kyr BP, between 28 and 29.5 kyr BP, between 38 and 39 kyr BP, between 45.5 and 46.5 and between 60 and 61; and these intervals correspond to the minimum value of $\%C_{org}$ content. The down core variation patterns show the predominance of cassidulinids is an indicative of a strong OMZ, whereas decreased abundance marks a weaker OMZ.

Studies on the C_{org} distribution in the surficial sediments along the western continental margin suggested that primary productivity is the main factor controlling the content of the organic carbon in sediments (Calvert *et al*., 1995). Furthermore, using different proxies of productivity, Singh *et al.* (2011) suggested $\%C_{org}$ as a robust geochemical tracer of primary productivity in the western Indian continental slope. Therefore the construction of $\%C_{org}$ is used in this study area as an indicator of surface primary productivity. Study shows that the abundance of casssidulinid group is strongly dependent on OMZ intensity which is controlled by the sea surface productivity.

Several high resolution studies of the late Quaternary records suggest that the monsoonal circulation, productivity and the OMZ intensity are closely related to each other and related to the global climate events (Behl and Kennett, 1996; Reichart *et al*., 1998, Schulz *et al*., 1998; Von Rad *et al*., 1999; Singh *et al*., 2006). The cassidulinids abundance fluctuations from the examined core-site indicate that the OMZ in the eastern Arabian Sea was weakest or even disappeared at three times in the last 70 kyr BP and these time intervals appear to correspond to the north Atlantic cold events - the Younger Dryas, the Heinrich 1 and Heinrich 6. The intensity of the OMZ during other north Atlantic cold events (H2, H3, H4 and H5) and stadials of the D-O cycles also appears to have been weaker, but not that of the large magnitude. During the peak glacial time (17-22.5 kyr BP) the OMZ was well developed. The faunal data further reveal that the OMZ intensity was stronger in the warm interstadial periods. Thus, it is very well reflected from the faunal record that the OMZ strength in the eastern Arabian Sea has varied in the past on millennial scale. The variability pattern of the OMZ intensity inferred in this investigation has a close similarity with the pattern of past changes in OMZ conditions in the northeastern Arabian Sea (Von Rad *et al*., 1999).

In the recent study, it has been found that in the Eastern Arabian Sea, $\%C_{org}$ content in the sediment is mainly controlled by winter monsoon-driven primary productivity (Singh *et al*., 2011). Consequently, the predominance of the cassidulinids in examined benthic assemblages is related to the winter monsoon-driven high surface primary productivity and relatively low oxygen conditions. The minor differences in down-core variation patterns among the cassidulinid taxa suggest that although cassidulinid population is mainly controlled by C_{org} content and OMZ intensity, the distribution pattern of individual taxa of cassidulinid is controlled by the combination of factors mainly bottom oxygen concentration, organic carbon flux, salinity, temperature, competition and predation.

CONCLUSIONS

The high-resolution abundance record of cassidulinids for the last 70 kyr BP retrieved from 9.65 m long sediment core off Goa shows marked fluctuating trends at millennial scale. In the present study, a faunal and geochemical proxy comparison shows a robust positive correlation between cassidulinids and $\%C_{org}$ content. Study reveals that in the examined core site cassidulinid population is controlled by organic carbon content and tolerant to the low oxygen environment. The organic carbon enrichment in the sediment is controlled by winter monsoon induced primary productivity and preservation under strong OMZ. The time intervals between 15 – 17 kyr BP, 23 – 24 kyr BP, 28 – 29.5 kyr BP, 38 – 39 kyr BP, 45.5 – 46.5 kyr BP and 60 – 61 kyr BP were the period of low abundance of cassidulininds which correspond to the weak OMZ. Present study also reveals that the strength of the OMZ of the eastern Arabian Sea oscillated in concert with the northern Hemisphere climate events (H1-H6).

ACKNOWLEDGMENTS

Prof. A. D. Singh is specially thanked for his constant support and guidance during the course of investigation. Thanks to Prof. M. S. Srinivasan for valuable help in the identification of foraminifers. I acknowledge Raja Ganeshram for providing samples. The research was supported by the Department of Science and Technology (Project No. SR/S4/ES-30/2002), Govt. of India, New Delhi.

REFERENCES

Almogi-Labin, A., Schmiedl, G., Hemleben, C. H., Siman-Tov, R., Segl, M. and Meischner, D. 2000. The influence of the NE winter monsoon on productivity changes in the Gulf of Aden, NW Arabian Sea, during the last 530 ka as recorded by foraminifera. *Marine Micropaleontology*, **40**: 295–319.

Altabet, M. A., Francois, D., Murray, W. and Prell, W. L. 1995, Climate-related variations in denitrification in the Arabian Sea from $^{15}N/^{14}N$ ratios. *Nature*, **373**: 506-509.

Bauer, S., Hitchcock, G. L. and Olsen, D. B. 1991. Influence of monsoonally – forced Ekman dynamics upon surface layer depth and plankton biomass distribution in the Arabian Sea. *Deep Sea Research*, **38**: 531-553.

Behl R. J., Kennett, J. P. 1996. Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr. *Nature,* **379**: 243–246, doi:10.1038/379243a0

Belford, D. J. 1966. Miocene and Pliocene smaller foraminifera from Papua and New Guinea, Dept. of Natural Development, Bureau of Mineral Resource, *Geology and Geophysics*. **79**: 1-305.

Belyaeva, N. V. and Burmistrova, I. I. 1984, Foraminiferal lysocline and critical levels of carbonate sedimentation in the Indian Ocean, *Litologiya i Poleznye Iskopaemye*, **6**: 57–66. (in Russian)

Boomgaart, L. 1949. *Smaller Foraminifera from Bodjonegoro (Java)*. Sappemeer: Smit & Dontje, 175.

Brady, H. B. 1884. *Report on foraminifera dredged by H.M.S. Challenger during the year 1873-1876*. Reports of Scientific results of the exploration Voyage of H.M.S. Challenger. **9**:1-814.

Burke, S. C., Berger, W. H., Coulbourn, W. T. and Vincent, E. 1993. Benthic foraminifera in box core ERDC 112, Ontong Java Plateau. *Journal of Foraminiferal Research,* **23**: 19-39.

Calvert, S. E., Pedersen, T. F., Naidu, P. D. and von Stackelberg, U. 1995. On the organic carbon maximum on the continental slope of the eastern Arabian Sea. *Journal of Marine Research*, **53**: 269-296.

Cannariato, K. G. and Kennett, J. P. 1999. Climatically related millennial-scale fluctuations in strength of California margin oxygen minimum zone during the past 60 k.y. *Geology*, **27**: 975–978.

Corliss, B. H. 1979a. Recent deep-sea benthic foraminiferal distribution in the southeast Indian Ocean: inferred bottom water routes and ecological implications, *Marine Geology*, **31**: 115-138.

Corliss, B. H. 1979b. Taxonomy of recent deep-sea benthonic foraminifera from the southeast Indian Ocean. *Micropaleontology*, **25**(1): 1-19, pls. 1-5.

Corliss, B. H. 1983. Distribution of Holocene deep-sea benthonic foraminifera in the Southwest Indian Ocean. *Deep-Sea Research,* **30**: 95-117.

Corliss, B. H. 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, **314**: 435-438.

Corliss, B. H. 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Marine Micropaleontology*, **17**: 195-236.

Corliss, B. H. and Chen, C. 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, **16**: 716–719.

Corliss, B. H. and Fois, E. 1990. Morphotype analysis of deep – sea benthic foraminifera from northwest Gulf of Mexico. *Palaios*, **5**(6): 589-605.

Cushman, J. A. 1925. *Foraminifera of tropical central Pacific Bernice*, P. Bishop Museum Bulletin, Tanager Expedition Publication, **27**: 121-144.

De Stigter, H. C., Jorissen, F. J. and Van der Zwaan, G. J. 1998. Bathymetric distribution and microhabitat partitioning of live (Rose Bengal stained) benthic foraminifera along a shelf to bathyal transect in the southern Adriatic Sea. *Journal of Foraminiferal Research*, **28**: 40–65.

den Dulk, M., Reichart, G. J., Heyst S. V., Zacariasse, W. J. and Van der Zwaan, G. J. 2000. Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea. *Palaeogeography Palaeoclimatology, Palaeoecology*, **161**: 337-359.

den Dulk, M., Reichart, G. J., Memn, G. M., Roelofs, E. M. P., Zachariasse, W. J. and Van den Zawaan, G. J. 1998. Benthic foraminiferal response to variations in surface water productivity and oxygenation in the northern Arabian Sea. *Marine Micropaleontology*, **35**: 43-66.

Fontanier, C, Jorissen, F. J., Chaillou, G., David, C. Anschutz, P. and Lafon, V. 2003, Seasonal and interannual variability of benthic foraminiferal faunas at 550m depth in the Bay of Biscay. *Deep Sea Research I*, **50**: 457-494.

Gooday, A. J. 1994. The biology of deep-sea foraminifera: a review of some advances and their applications in paleoceanography. *Palaios*, **9**: 14–31.

Guichard, S. 1997. Thesis Evolution de l'environment dans la zone de l'upwelling maturitanien pendant les derniers 236,000 ans, le temoignage de l'ecosysteme benthique. *Thesis. l'Universite Bordeaux I*, Nº d'ordre:

Gupta, A. K. and Thomas, E. 1999. Latest Miocene- Pleistocene productivity and deep-sea ventilation in the northwestern Indian Ocean (Deep Sea Drilling Project Site 219). *Paleoceanography*, **14**(1): 62-73.

Gupta, A. K. 1994.Taxonomy and bathymetric distribution of Holocene deep-sea benthic foraminifera in the Indian Ocean and the Red Sea. *Micropaleontology*, **40**: 351-367.

Hageman, J. 1979. Benthic foraminiferal assemblages from Plio-Pleistocene open bay to lagoonal sediments of the Western Peloponnesus (Greece). *Utrecht Micropaleontology Bulletin*, **20**: 1-171.

Hayward, B. W., Neil, H., Carter, R., Grenfell, H. R., Hayward, J. J. 2002. Factors influencing the distribution pattern of Recent deep-sea benthic foraminifera, east of New Zealand, Southwest Pacific Ocean. Marine *Micropaleontology*, **46**: 139-176.

Herguera, J. C. and Berger, W. H. 1991. Paleoproductivity from benthic foraminifera abundance: glacial to postglacial change in the west equatorial Pacific. *Geology*, **19**: 1173–1176.

Hermelin, J. O. R. and Shimmield, G. B. 1990. The importance of the Oxygen Minimum Zone and sediment geochemistry in the distribution of Recent benthic foraminifera in the northwest Indian Ocean. *Marine Geology*, **91**: 1-29.

Hermelin, J. O. 1986. Pliocene benthic foraminifera from Black Ridge Plateau: Faunal assemblages and paleocirculation. *Marine Micropaleontology*, **10**: 343-370.

Hermelin, J. O. R. 1992. Variations in the benthic foraminiferal fauna of the Arabian Sea: a response to changes in upwelling intensity? In: Upwelling systems: evolution since the early Miocene, Summerhayes, C.P., Prell, W.L. and Emeis, K.C. (eds.), *Geological Society special Publication*, **64**: 151-166.

Hornibrook, N. De B. 1961. *Tertiary foraminifera from Oamaru district (N.Z.)*, P-1. **8**(3): 530-536.

Kaiho, K. 1994. Benthic foraminiferal dissolved-oxygen index and dissolved oxygen levels in the modern ocean. *Geology*, **22**(8): 719-722.

Kaiho, K. 1999. Effect of organic carbon flux and dissolved oxygen on the benthic foraminiferal oxygen index (BFOI), *Marine Micropaleontology*, **37**: 67–76.

Le Roy, L. W. 1941a. Small foraminifera from the Late Tetiary of Sngkoe Lirang Bay Area, East Bounea, Netherlands, East Indies; *Colorado Sch. Mines Quarterly*, **36**(1): 13-61.

Loeblich, A. R. Jr. and Tappan, H. 1987. *Foraminiferal Genera and their Classification*: Van Nostrand Reinhold Company, New York, **2** : 1182.

Loeblich, A. R. Jr. and Tappan, H. 1992. Present status of foraminiferal classification, p. 93-102. *Studies in Benthic Foraminifera: Proceedings of the Fourth International Symposium on Benthic Foraminifera, Sendai,* 1990 (Eds. Takayanagi, Y., and Saito, T.), Tokai University Press, Tokyo.

Lohmann, G. P. 1978. Abyssal benthonic foraminifera hydrographic indicators in the western South Atlantic Ocean. *Journal of Foraminiferal Research*, **8**: 6-34.

Loubere, P. and Banonis, G. 1987. Benthic foraminiferal assemblage response to the onset of northern hemisphere glaciation: paleoenvironmental changes and species trends in the northeast Atlantic. *Marine Micropaleontology*, **12**:161-181.

Madhupratap, M., Kumar, S. P., Bhattathiri, P. M. A., Kumar, M. D., Raghukumar, S., Nair, K. K. C. and Ramaih, N. 1996. Mechanism of the biological response to winter cooling in the northeastern Arabian Sea, *Nature*, **384**: 549-552.

Marks, P. Jr. 1951. A revision of the smaller foraminifera from the Miocene of the Vienna Basin. *Contributions from the Cushman Laboratory*, **2**: 33-73.

Miao, Q. and Thunell, R. C. 1996. Late Pleistocene–Holocene distribution of deep-sea benthic foraminifera in the South China and Sulu Sea: paleoceanographic implication, *Journal of Foraminiferal Research*, **26**: 9–23.

Miao, Q. and Thunell, R. C. 1993. Recent deep-sea benthic foraminiferal distributions in the South China and Sulu Seas. *Marine Micropaleontology*, **22**: 1-32.

Miller, K. G. and Lohmann, G. P. 1982. Environmental distribution of recent benthic foraminifera on the northeast United States continental slope. *Geological Society of America Bulletin,* **93**: 200-206.

Murray, J. W. 1991. *Ecology and Palaeoecology of Benthic Foraminifera*, Taylor & Trancis, U.K., 389.

Naqvi, S. W. A., Naik, H., and Narvekar, P. V. 2003, The Arabian Sea, in: Biogeochemistry of Marine Systems, edited by: Black, K. and Shimmield, G., Sheffield Academic Press, Sheffield, 156– 206.

Naidu, P. D. and Malmgren, B. A. 1995. Monsoon upwelling effects on test size of some planktonic foraminiferal species from the Oman Margin, Arabian Sea. *Paleoceanography,* **10**: 117-122.

Nørvang, A. 1958. *Islandiella*, new genus and *Cassidulina* d' Orbigny. *Medd. Dansk. Naturh. Forening*., **120**: 25-41.

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

Paropkari, A. L., Prakash Babu C and Mascarenhas, A. 1992. A critical evaluation of depositional parameters controlling the variability of organic carbon in Arabian Sea sediments. *Marine Geology*, **107**: 213-226

Peterson, L. C. 1984. Recent abyssal benthic foraminiferal biofacies of the eastern equatorial Indian Ocean. *Marine Micropaleontology*, **8**: 479–519.

Phleger, F. B., Parker, F. L. and Peirson, J. F. 1953. North Atlantic depp sea Foraminifera, *Reports of the Swedish Deep-Sea Exped.*1917-1947, Reports **7**(1): 1–122.

Rai, A. K. and Singh, V. B. 2004. Late Neogene deep sea benthic foraminiferal biostratigraphy of ODP site 762B and 763A (Exmouth Plateau), Eastern Indian Ocean, *Journal Geological Society of India*, **63**:415-429.

Rai, A. K. and Srinivasan, M. S. 1994. Pleistocene oceanographic changes indicated by deep sea benthic foraminifera in the Northern Indian Ocean, *Proceedings Indian Acadamy Science (Earth & Planetary Science)*, **103**(4): 499-517.

Rathburn, A. E. and Miao, Q. 1995. The taphonomy of deep-sea benthic foraminifera: comparisons of living and dead assemblages from box core and gravity cores taken in the Sulu Sea. *Marine Micropaleontology,* **25**: 127-149.

Reichart, G. J., Lourns, L. J. and Zachariasse, W. J. 1998. Temporal variability in the northern Arabian Sea Oxygen Minimum Zone (OMZ) during the last 225,000 year, *Paleoceanography*, **13**(6): 607-621.

Reichart, G. J., Schenau, S. J., de Lange, G. J. and Zachariasse,W. J. 2002. Synchroneity of oxygen minimum zone intensity on the Oman and Pakistan Margins at sub-Milankovitch time scales, *Marine Geology*, **185**: 403-415.

Sarma, V. V. S. S. 2002. An evaluation of the physical and biogeochemical processes regulating the perennial suboxic conditions in the water column of the Arabian Sea: *Global Biogeochemical Cycles*, **16**: 11, doi:10.1029/2001GB001461.

Schnitker, D. 1979. The deep waters of the North Atlantic during the past 24,000 years, and re-initiation of the Western Boundary Undercurrent. *Marine Micropaleontology,* **4**: 265-280.

Schulte, S., Rostek, F., E., B., Rullkotter, J. and Marchal, O. 1999. Variations of oxygen minimum and primary productivity recorded in sediments of the Arabian Sea. *Earth and Planetary Science Letters*, **173**: 205-221.

Schulz, H., Von Rad, U. and Erlenkeuser, H. 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years; *Nature*, **393**: 54-57.

Sen Gupta, B. K. 2002. Systematics of modern foraminifera, p. 7-36. In: *Modern Foraminifera* (Ed. Sen Gupta, B. K.): Kluwer Academic Publishers, The Netherlands.

Sen Gupta, B. K. 1988. Water masse relation of the *Cibicides wuellerstorfi* in the eastern Caribbean Sea., *Bulletin de I'Institut de Giologie du Bassin d'Aquitaine, Bordeaux*. **44**: 23-32.

Singh, A. D., Jung, S. J. A., Darling, K., Ganeshram, R., Ivanochko, T. and Kroon, D. 2011, Productivity collapses in the Arabian Sea during glacial cold phases: *Paleoceanography*, **26**: 1–10.

Singh, A. D., Kroon, D. and Ganeshram, R. S. 2006. Millennial scale variations in productivity and OMZ intensity in the eastern Arabian Sea, *Journal Geological Society of India*, **68**: 369-377.

Streeter, S. S. 1973. Bottom water and benthonic foraminifera in the North Atlantic: Glacial- Interglacial contrasts. *Quaternary Research*, **3**: 131-141.

Von Rad, U., Schulz, H., Riech, V., den Dulk, M., Berner, U. and Sirocko, F. 1999. Multiple monsoon – controlled breakdown of oxygen - minimum conditions during the last 30,000 years documented in laminated sediments of Pakistan. *Palaeoceanography Palaeoclimatology Palaeoecology*, **152**: 129-161.

Wyrtki, K. 1973. Physical oceanography of the Indian Ocean. In: *The biology of the Indian Ocean*, (Eds. B. Zeitzschel). Berlin: Springer, p. 18-36.

Manuscript received February 2016

Revised Manuscript accepted December 2016