Deep-sea paleoceanography of the Maldives Islands (ODP Hole 716A), equatorial Indian Ocean during MIS 12–6

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Deep-sea benthic foraminifera, planktic foraminifer *Globigerina bulloides* and pteropods have been quantitatively analysed in 451 samples from Ocean Drilling Program (ODP) Hole 716A, to understand both surface and deep-sea paleoceanographic changes in the equatorial Indian Ocean basin during the late Quaternary (~444–151 Kyrs). Benthic foraminifera were analysed from >125 μm size fraction whereas *Globigerina bulloides* and pteropods were analysed from >150 μm size fraction. Factor analysis of most dominant benthic foraminiferal species over the studied time span made it possible to identify three biofacies characterizing distinct deep-sea environmental settings at Hole 716A. The environmental interpretation of each species is based on the ecology of recent deep-sea benthic foraminifera. The faunal record indicates fluctuating deep-sea conditions including changes in surface productivity, organic food supply and deep-sea oxygenation linked to changing wind intensities. These changes are pronounced on glacial-interglacial time scales driven by summer monsoon winds.

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1. Introduction

Deep-sea benthic foraminifera have widely been used in palaeoceanographic reconstructions throughout the world ocean including the Arabian Sea owing to availability of knowledge on modern ecology of benthic foraminifera (Gupta 1994 1997; Jannink *et al.* 1998; Dickens and Owen 1999; Gupta and Thomas 1999; Kouwenhoven *et al.* 1999; Russo *et al.* 2002; Nagendra *et al.* 2004; Schumacher *et al.* 2007; Rai and Maurya 2007). Benthic foraminifera show a great deal of variation in their diversity as well as abundances (Singh and Gupta 2005; Schumacher *et al.* 2007; Wollenburg *et al.* 2007). Benthic foraminifera are applied as proxies to understand deep-sea oxygenation and organic flux to the sea floor (Sen Gupta and Machain-Castillo 1993; Jannink *et al.* 1998; Gupta and Thomas 1999; van der Zwaan *et al.* 1999). Planktic foraminifera, on the other hand, help understand changes in sea-surface palaeoceanography through time slices. For instance, high populations of sub-polar species *Globigerina bulloides* have often been linked to intense wind-induced upwelling in the tropics (Prell *et al.* 1992; Gupta *et al.* 2003). Several workers have described a strong positive correlation between primary productivity and pteropod production in the open ocean (Deuser 1986; Almogi-Labin *et al.* 1998). Pteropods are marine holoplanktic micro-gastropods having aragonitic shells and adapted to pelagic mode of life. These are common members of calcareous zooplankton communities in the upper ocean (Almogi-Labin *et al.* 1998). The preservation state of pteropod shells reflects changes in the aragonite saturation condition of seawater (Haddad and Droxler 1996). Moreover the regional climatic influence on deep-water chemistry and changes in deep-water circulation occurring on glacial/interglacial and stadial/interstadial time scales can affect pteropod preservation in the Indian Ocean (Klöcker *et al.* 2006).

The present study focuses on understanding deep-sea palaeoceanographic evolution of Hole 716A, Maldives Islands, equatorial Indian Ocean during the late Quaternary (~444 to 151 Kyrs) using census data of deep-sea benthic foraminifera combined with relative abundances of planktic foraminifer species *Globigerina bulloides* and pteropods.

Keywords. Benthic foraminifera; deep-sea paleoceanography; *Globigerina bulloides*; Hole 716A; pteropods

An attempt has also been made to understand whether deep-sea changes at Hole 716A were driven by monsoonal winds on glacial-interglacial time scales or changes in solar insolation. Known ecological preferences of benthic foraminifera from different ocean basins have been used to understand palaeoceanographic changes in the equatorial Indian Ocean.

2. Location and oceanographic setting

Ocean Drilling Program (ODP) Hole 716A is located on the broad central plateau of the Maldives Ridge (04°56.0' N; 73°17.0' E) at a water depth of 533.3 m (figure 1), southeastern Arabian Sea, equatorial Indian Ocean. The hole lies on a flat terrain on a broad, shallow basin, and contains a virtually complete Cenozoic sedimentary record while remaining distant from any terrigeneous influence throughout its development (Purdy and Bertram 1993). Hole 716A is located just above the Arabian Sea oxygen minimum zone (OMZ) having a well preserved sedimentary record, and is suitable for both benthic and planktic foraminiferal and pteropod studies (figure 2). The modern day dissolved oxygen content at Hole 716A is little less than 2 ml/L (figure 2).

In the Maldives region, the winds are stronger from May-September or October and primary productivity reaches its maximum in September, i.e. at the end of the southwest monsoon, but is moderate compared to high-productivity areas of the Arabian Sea (Schulte *et al.* 1999). Hole 716A lies under the direct influence of Southwest Monsoon Current that drives upwelling and productivity changes in the Maldives region (Schulte *et al.* 1999; figure 1). However, the upwelled water is overlain by a thin low-salinity layer (5-10 m thick), which results from local precipitation (Schulte *et al.* 1999). The effect of upwelling, therefore, is small though the thermocline is shallow. A deepening of the mixed layer is observed during the northeast monsoon, but without an increase in primary productivity owing to the inflow of low salinity surface waters from the Bay of Bengal (Schulte *et al.* 1999). The climatological map (SeaWiFS chlorophyll) of the Indian Ocean shows high surface primary production

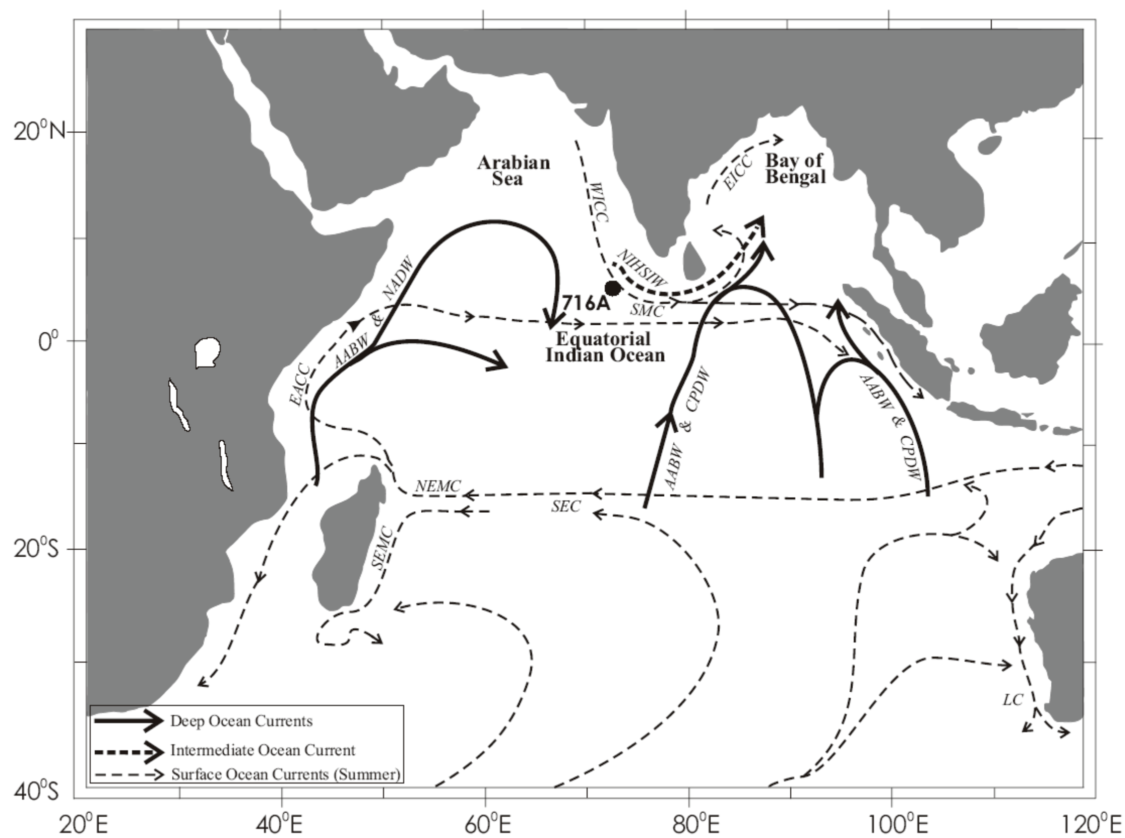

Figure 1. Location of ODP Hole 716A, Maldives Ridge, equatorial Indian Ocean with regard to present-day ocean currents (redrawn after Schott and McCreary 2001 and Kawagata *et al.* 2006). AABW, Antarctic Bottom Water; NADW, North Atlantic Deep Water; CPDW, Circumpolar Deep Water; NIHSIW, North Indian High Salinity Intermediate Water; SMC, Southwest Monsoon Current; WICC, West Indian Coast Current; EICC, East Indian Coast Current; EACC, East African Coast Current; LC, Leeuwin Current; NEMC and SEMC, Northeast and Southeast Madagascar Current; SEC, South Equatorial Current.

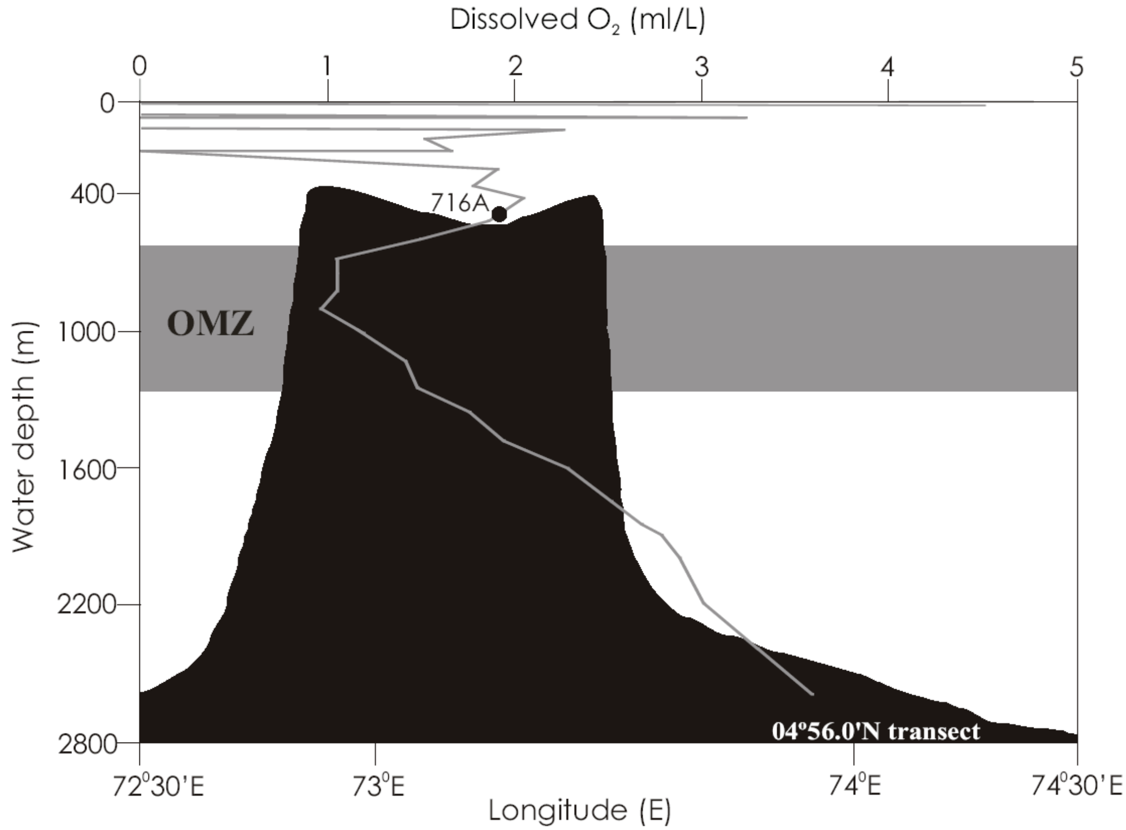

Figure 2. Vertical profile of dissolved oxygen content along East-West transect at 04°56' N (based on the data from GEOSECS 1983). OMZ, Oxygen Minimum Zone; grey shade indicates location of Arabian Sea oxygen minimum zone (OMZ).

during southwest monsoon season (August) (Wiggert *et al.* 2006). Thus in the present day ocean, the upwelling and productivity changes in the Maldives region could be related to summer monsoon variability, though Beaufort *et al.* (1997) linked these changes to eastward equatorial jets.

3. Materials and methods

Four hundred fifty one core samples of 10 cm^3 volume were analyzed from Hole 716A from ~300 Kyr old sediment sequence, rich in foraminifera, nannofossils and pteropods ranging from 443826 yrs BP to 151460 yrs BP. Each sample was sliced at a contiguous 1 cm interval. Samples were soaked in water with baking soda for 8–12 h, and washed with a jet of water over a 63 μm size sieve. The washed samples were dried in an electric oven at ~60°C and transferred into labelled glass vials. Hard sediment samples were treated with 5-10 drops of 2% hydrogen peroxide. Benthic foraminifera were examined from an aliquot of ~300 specimens of each sample from >125 μm size fraction. This size fraction is in compatibility with numerous recent findings from the Indian and the Atlantic Oceans (Schmiedl and Mackensen 1997; Gupta and Thomas 2003). Individuals of each species were identified, counted and their percentages calculated. The percentages of *G. bulloides* and pteropods were calculated from an aliquot of ~300 specimens from >150 μm size fraction from each sample. Fast Fourier Transform (FFT) was carried out to remove noise from the data for better interpretation.

Factor analysis was run on 13 most dominant species and species groups of benthic foraminifera to identify biofacies. Factor analysis enabled the selection of two factors that account for ~60% of the total variance (table 1). Three biofacies were extracted based on species with highest negative or positive factor scores (figures 3-6) and their environments were interpreted (table 2). Biofacies were named after the most dominant species. Band pass Fast Fourier Transformation (FFT) filtering was performed on 65°N July insolation, *G. bulloides*, pteropods and selected benthic foraminifera at 3.3–6.6 × 10^{-5} Hz frequency limits to understand a phase relation between different proxies (figure 7).

We calculated species diversity using the number of species (*S*), Information Function (*H*), Equitability (*E*) and Sanders' rarefaction number (figure 8). The Information

Table 1. Varimax rotated factor scores of most dominant benthic foraminifera from 444-151 Kyr interval at Hole 716A. Factors 1 and 2 were considered in identifying benthic foraminiferal biofacies

Species/species group	Factor 1	Factor 2	Factor 3	Factor 4
Bolivinids	0.00663	0.04037	–0.46936	–0.14692
Bolivinita sp.	**0.65098**	0.00348	0.43092	–0.12550
Bulimina aculeata	**0.77177**	**–0.31896**	–0.07833	0.28291
Buliminids	**0.70112**	**–0.37982**	–0.31078	0.25017
Cibicides bradyi	**0.11892**	0.15387	0.75055	–0.14248
Cibicides wuellerstorfi	**–0.23000**	**–0.24553**	0.67931	–0.09410
Cymbaloporetta squammosa	**0.71922**	0.45473	0.25182	–0.06528
Reussella simplex	**0.11463**	0.76128	0.02202	–0.10022
Sphaeroidina bulloides	**–0.63904**	–0.14043	–0.30626	0.24655
Textularia sagittula	0.00814	**–0.61657**	–0.38323	–0.45665
Uvigerina peregrina	**–0.26963**	**–0.38738**	–0.18915	0.38094
Uvigerina porrecta	**–0.15761**	0.74594	–0.10112	–0.19681
Uvigerina proboscidea	–0.02690	**–0.17219**	–0.00535	0.80710
Variance %	32.36	27.89	23.31	16.43

Factors scores in bold were used in defining benthic foraminiferal biofacies.

Function takes into account both number of species and the abundance of individuals of each species, thus H is a measure of both species richness and evenness. Equitability is a measure of equality of species proportions and gives an idea of the number of equally distributed species required to give a particular value of *H*. The Information Function (*H*) was calculated using the Shannon-Wiener Diversity index (Shannon and Wiener 1949) given by the formula:

$$H = -\sum_{i=1}^{S} p_i \ln p_i,$$

where S is the number of species in a given sample, p_i is the proportion of the ith species in the sample and ln is the natural logarithm. To calculate Equitability (E), we used the mathematical expression given by Buzas and Gibson (1969) as:

$$E = e^H / S.$$

Sanders' values were calculated by rarefying against 100 individuals (Sanders, 1968). This procedure allows one to compare samples of differing sizes directly.

The chronology for the studied interval of Hole 716A, is based on linear interpolation between two nannofossil datums: FAD of *Emiliania huxleyi* and LAD of *Pseudoemiliania lacunosa* (Backman *et al.* 1988) and a CALIB 5.0.2 (Stuiver *et al.* 2006) calibrated AMS ^{14}C date of 30536.65 calendar years before the present (cal yrs BP) from depth of 1.07 meters below sea floor (mbsf). The ages of the faunal datums were updated to the time scale of Berggren *et al.* (1995). The interpolated ages were tuned with SPECMAP stacked age model (Imbrie *et al.* 1984) by wiggle matching between the isotope data (unpublished) from Hole 716A and SPECMAP record. The average age interval per sample (1 cm) is 877 yrs (ranging from 472 to 1305 yrs).

4. Important foraminiferal fauna and their ecological preferences

The most dominant benthic foraminiferal species recorded from Hole 716A are *Bulimina aculeata*, *Bolivinita* sp., *Cibicides wuellerstorfi*, *C. bradyi*, *Cymbaloporetta squammosa*, *Reussella simplex*, *Sphaeroidina bulloides*, *Textularia sagittula*, *Uvigerina proboscidea*, *U. peregrina*, *U. porrecta*, and the dominant groups are Buliminids and Bolivinids. These species characterize various biofacies and have been used to understand deep-sea palaeoceanographic changes at Hole 716A (figures 3–6). The cumulative percentages of benthic foraminifera belonging to different biofacies have been combined with upwelling indicator planktic foraminifer *Globigerina bulloides* and pteropods to understand wind-induced changes in surface productivity and resultant organic flux to the sea floor (figure 3). Following are the inferred microhabitats of each species and/or group of species:

No well established record is available about the ecological preferences of *Cymbaloporetta squammosa*. Though, *C. squammosa* along with *Cibicides refulgens*, *Ehrenbergina carinata, Bolivina pusilla, Astrononion umbilicatulum* and *Quinqueloculina weaveri* suggest high flux of organic matter (Gupta and Satapathy 2000). The raw-percent and 5 point FFT time series of *C. squammosa* show a parallelism with *Bolivinita* sp. and *Bulimina aculeata* which have a well established microhabitat of low to intermediate

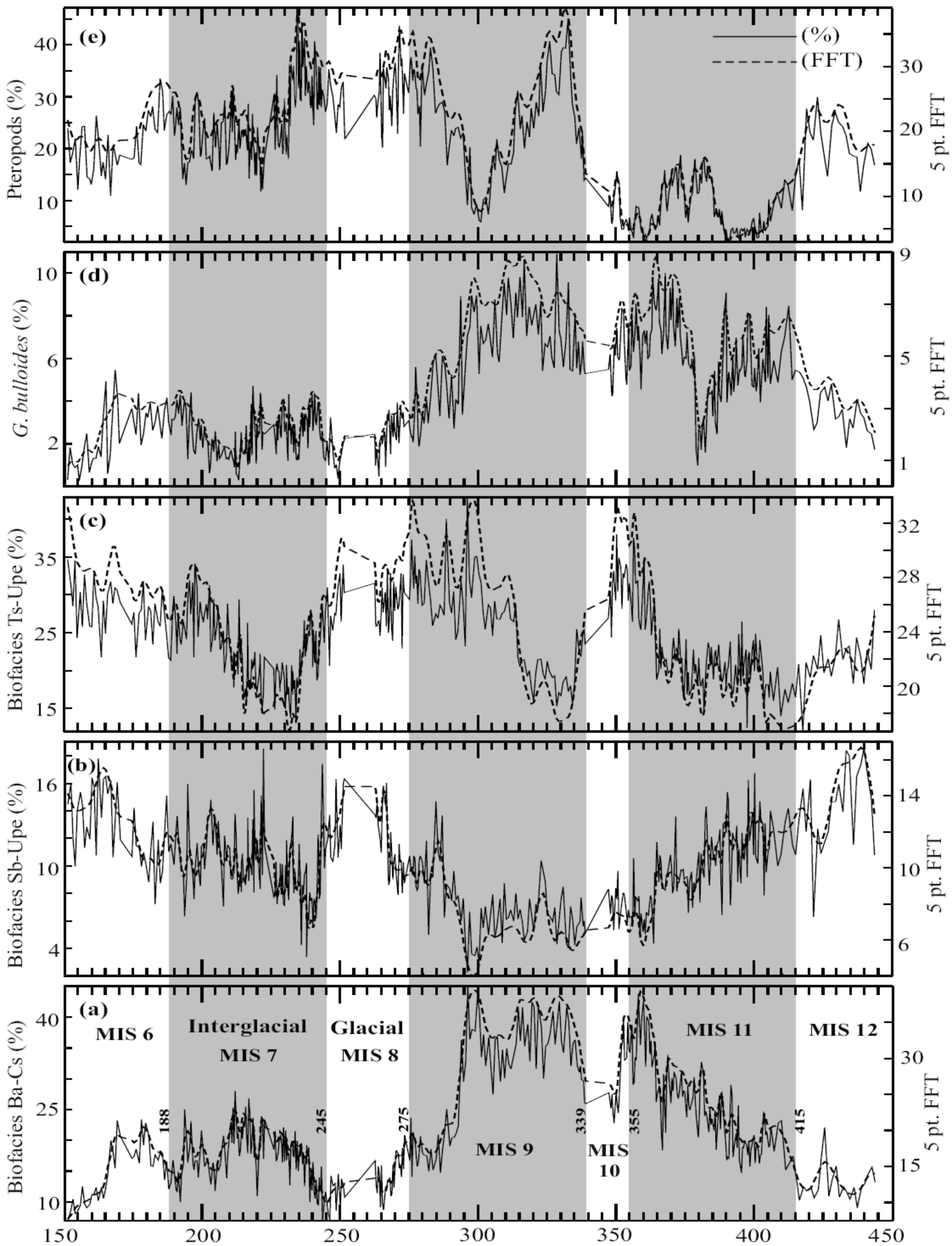

Figure 3. Percent and Fast Fourier Transform (FFT) time series of **(a)** cumulative percentages of species of biofacies Ba-Cs **(b)** biofacies Sb-Upe, **(c)** biofacies Ts-Upe, **(d)** *Globigerina bulloides*, and **(e)** pteropods from Hole 716A. Grey bars indicate interglacial periods (Imbrie *et al.* 1984); MIS, Mar. Isotope Stage.

oxygen and sustained flux of organic matter from high surface productivity (figure 3).

The microhabitat preference of *Bolivinita* sp. is not well understood, but numerous species of *Bolivinita* have been

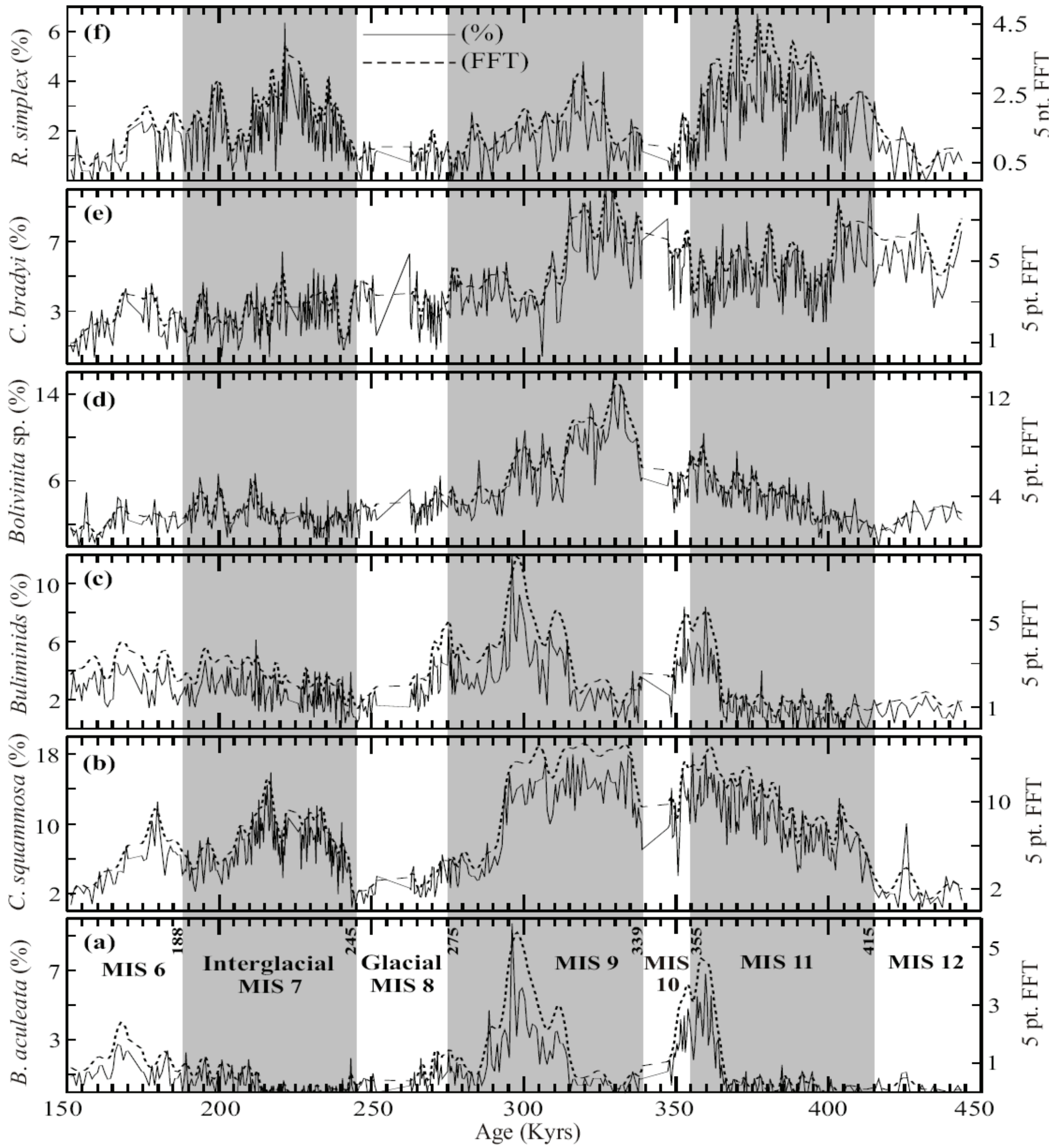

Figure 4. Percent and Fast Fourier Transform (FFT) time series of different species of biofacies Ba-Cs.

found proliferating in areas of sustained flux of organic matter under high productivity belts (Thomas *et al.* 1995; Gupta 1997). This species has tentatively been put under genus *Bolivinita* and will be assigned a species status after a detailed taxonomic study. Bolivinids, in general, have a preference for low oxygen and high food environments (Gupta and Satapathy 2000; Gooday 2003). They flourish in relatively warm water of the OMZ. Species of *Bolivina* are rare and observed at a wide range of depths throughout the Indian Ocean (Gupta 1994). High abundances of Bolivinids in the Bay of Biscay (Poag and Low 1985) and the North Central Indian Ocean (Boersma and Mikkelsen 1990) during the Neogene have been attributed to increased primary productivity, increased organic flux and development of an OMZ. In the Atlantic Ocean, Bolivinid peaks during the early Miocene have been inferred to reflect sluggish bottom-water circulation, either regionally or globally, with reduced oxygen levels of the bottom water (Smart and Murray 1994). *Bolivina pygmaea* is found in the Arabian Sea at the depth range of 200-600 m where the oxygen content of the deep water is very low and organic carbon content is high (Hermelin and Shimmield 1990). *Bolivina pseudopunctata* prefers low to high temperature and lower oxygen conditions. Low-oxygen fauna in the Gulf of

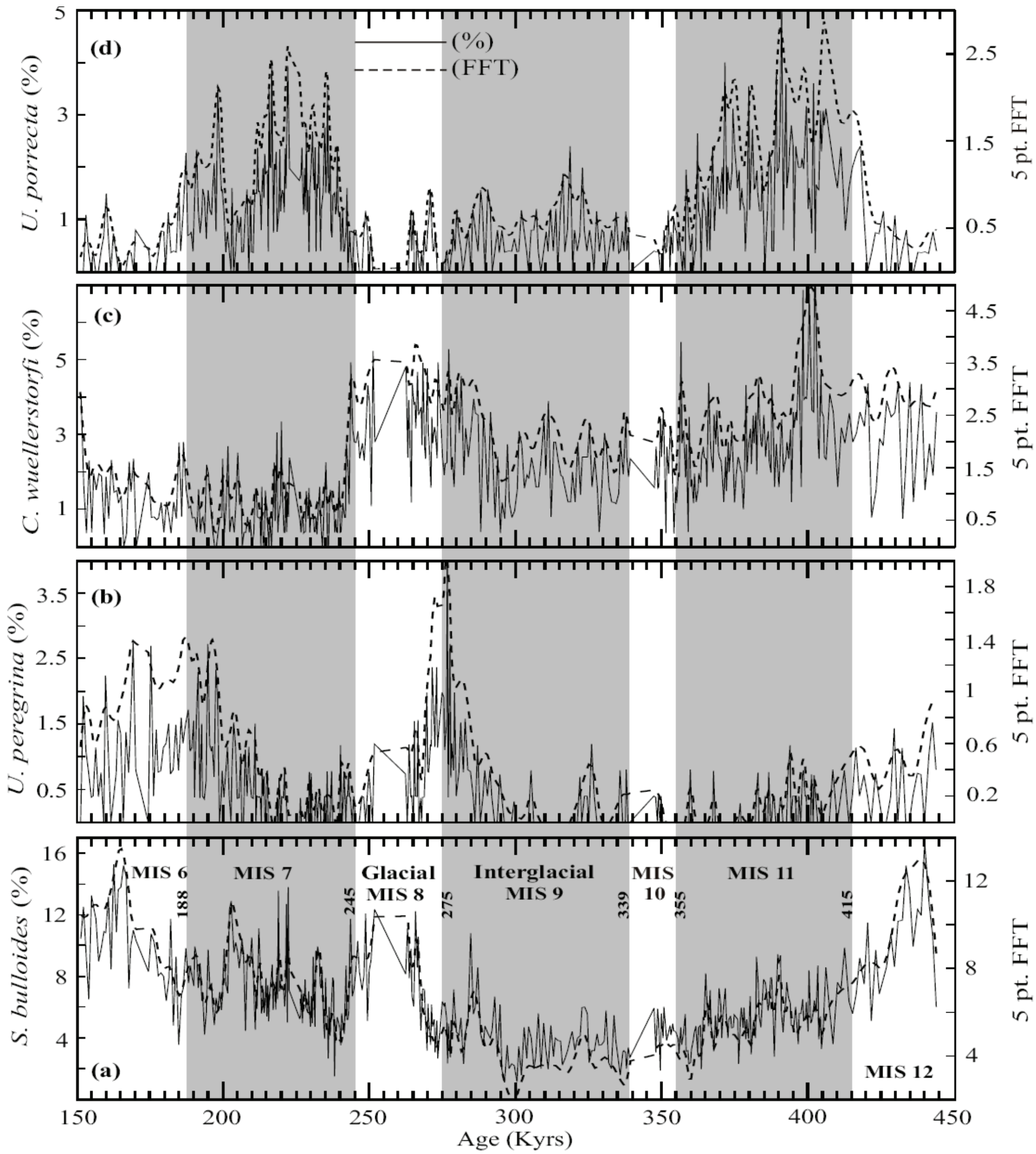

Figure 5. Percent and Fast Fourier Transform (FFT) time series of different species of biofacies Sb-Upe.

Mexico is represented by the shallow, deltaic assemblage of *Bolivina barbata, Bulimina marginata* and *Bolivina alata,* present in the discharge area of the Mississippi River, which is a zone of high productivity (Sen Gupta and Machain-Castillo 1993).

Bulimina aculeata is suited to higher nutrient, and intermediate temperature and oxygen conditions. This species strongly dominates benthic foraminiferal assemblage at bathyal depths just below the OMZ (Hermelin and Shimmield 1990). This species shows good correlation with relatively high organic carbon in the eastern Mediterranean (Olausson 1960). In the South Atlantic, South China Sea, and Arabian Sea, the species is confined to depths between 1500 and 2500 m and is controlled by productivity and organic carbon flux (Miao and Thunell 1993). In the Gulf of Aden, *B. aculeata* shows higher abundances under present-day high productivity region and during interglacial stages, making it an indirect indicator of the extent of the southwest Indian Monsoon (Almogi-Labin *et al.* 2000). *Buliminids*, in general, are suited to high organic carbon flux and intermediate to low oxygen level as evident from several species under this group. *Bulimina marginata* are known to tolerate dysoxia (Sen Gupta and Machain-Castillo 1993). Van der Zwaan and Jorissen (1991) identified it as an opportunistic species since

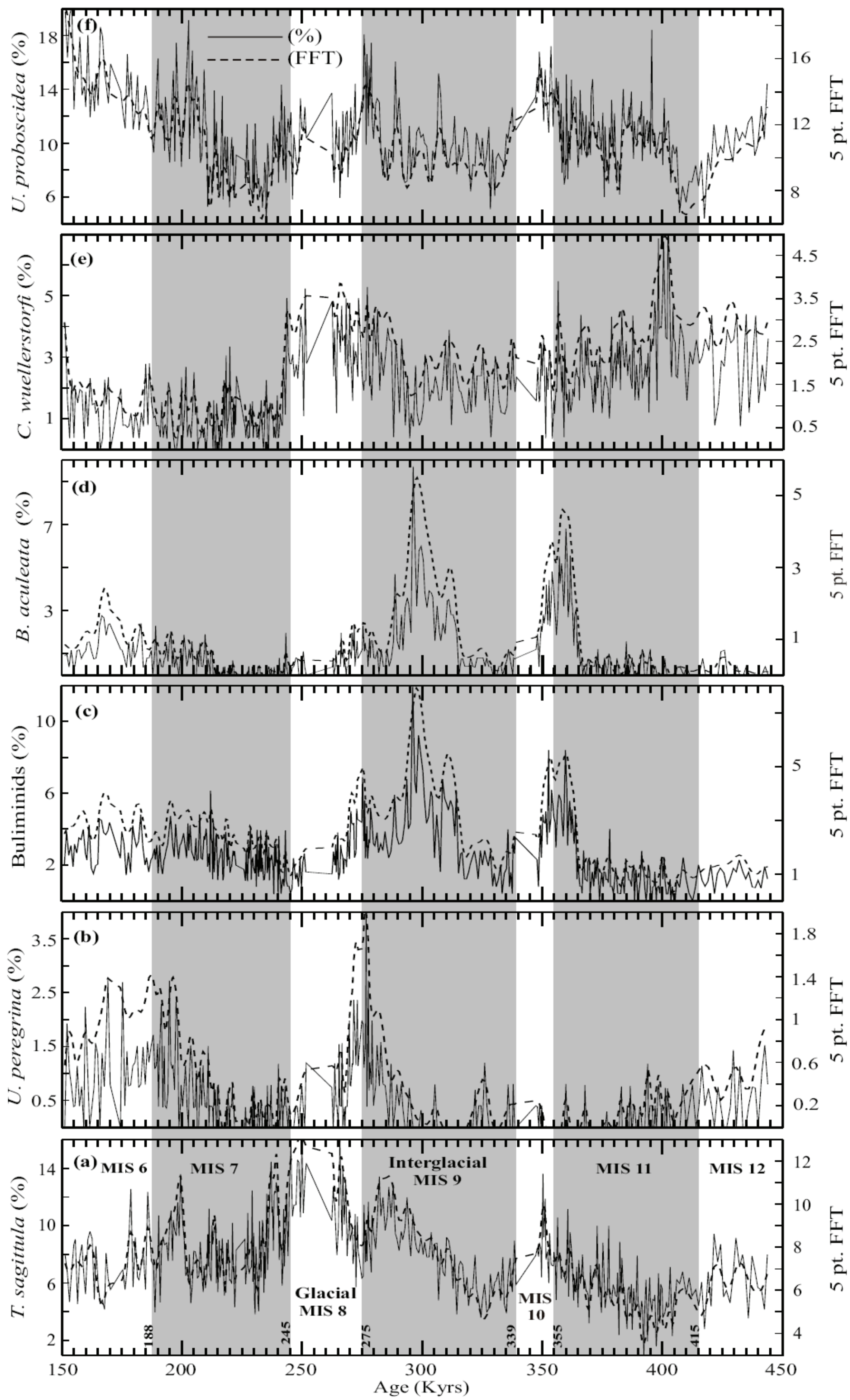

Figure 6. Percent and Fast Fourier Transform (FFT) time series of different species of biofacies Ts-Upe.

Table 2. Benthic foraminiferal biofacies with their respective factor scores and preferred environments based on modern day ecological preferences of different species (please see text)

Biofacies	Varimax rotated factor scores	Environment
Ba – Cs	Factor 1 (+ve)	High flux of organic matter from high surface productivity, low oxygen content
Bulimina aculeate (P)	0.77177	
Cymbaloporetta squammosa (S)	0.71922	
Buliminids	0.70112	
Bolivinita sp.	0.65098	
Cibicides bradyi	0.11892	
Reussella simplex	0.11463	
Sb – Upe	Factor 1 (-ve)	Low organic carbon content, better oxygenation
Sphaeroidina bulloides (P)	–0.63904	
Uvigerina peregrina (S)	–0.26963	
Cibicides wuellerstorfi	–0.23000	
Uvigerina porrecta	–0.15761	
Ts – Upe	Factor 2 (-ve)	Intermediate to high, but variable flux of organic matter, variable oxygenation
Textularia sagittula (P)	–0.61657	
Uvigerina peregrina (S)	–0.38738	
Buliminids	–0.37982	
Bulimina aculeata	–0.31896	
Cibicides wuellerstorfi	–0.24553	
Uvigerina proboscidea	–0.17219	

P, primary species; S, secondary species.

it is notably tolerant of the oxygen stress and seems to utilize the nutrient increase.

Cibicides bradyi has both epifaunal and infaunal occurrences (Barmawidjaja *et al.* 1992). This species was found associated with *Stilostomella abyssorum*, *Melonis pompilioides*, *Pleurostomella brevis* and *Pleurostomella obtusa* by Gupta and Thomas (2003), indicating moderate to high organic flux and intermediate seasonality in the Indian Ocean.

Cibicides wuellerstorfi can endure low organic carbon levels and strong bottom currents as a suspension feeder and elevated epibiont (Linke and Lutze 1993). In the Atlantic and Southern Oceans, *C. wuellerstorfi* is associated with young, well oxygenated water masses like North Atlantic Deep Water (NADW) (Gooday 1993; Schmiedl and Mackensen 1997) whereas in the Indian Ocean, *Cibicides wuellerstorfi* has been associated with the presence of AABW (Corliss 1983). Loubere and Fariduddin (1999) suggested it as an indicator of high seasonal food supply under oligotrophic conditions, whereas Gupta (1997) relates this species with the oxygenated, strong bottom currents with strongly pulsed food supply in the Indian Ocean.

Reussella simplex is a relatively shallow water species (van Marle 1991), exclusively tropical and cosmopolitan in nature (Montaggioni and Vénec-Peyré 1993). Reussella simplex is found in oxygen minimum zone of central west coast of India (Mazumder *et al.* 2003). Moreover, from the strikingly similar trends (figure 3) with *C. squammosa* and *U. porrecta*, it can be assumed that *R. simplex* proliferates under high productivity and low to intermediate oxygen condition of the water column.

Sphaeroidina bulloides thrives in well-oxygenated water and is intolerant to oxygen depletion (Barmawidjaja *et al.* 1992). In the Southern Atlantic, dominance of *S. bulloides* is generally considered as typical to that of high productivity areas (Gooday 2003) and may be influenced by coastal upwelling (Schiebel 1992). However, Loubere and Fariduddin (1999) found this taxon dominant on continental slopes under low seasonality. In the Indian Ocean, association of *S. bulloides* with *Cibicides wuellerstorfi*, and *Anomalina globulosa* indicates cool, active currents, low to intermediate organic flux, high seasonality and high oxygenation (Gupta and Thomas 2003).

The environmental preference of *Textularia sagittula* is not well-known. Though, tapered elongate forms such as *Textularia* are regarded as "deep infauna". Unpublished record indicates that association of *T. sagittula* with *Uvigerina proboscidea* suggests intermediate to high surface food flux and better deep-sea oxygenation (De 2008).

Uvigerina peregrina prefers a microhabitat characterized by high concentrations of bacteria, exoenzymes and meiofauna, and is typical of sediments enriched in organic carbon and depleted in oxygen, common in areas below upwelling productivity (Altenbach and Sarnthein 1989). It is found in the OMZ in the northwestern Arabian Sea where surface productivity is highest and oxygen is minimum. However, Jannink *et al.* (1998) argued that *U. peregrina* tolerates somewhat lower food levels and/or more degraded organic matter, having no relation with oxygen deficiency. This species has been found colonizing bacterial mats in the Gulf of Mexico (Sen Gupta *et al.* 1997) and northeast

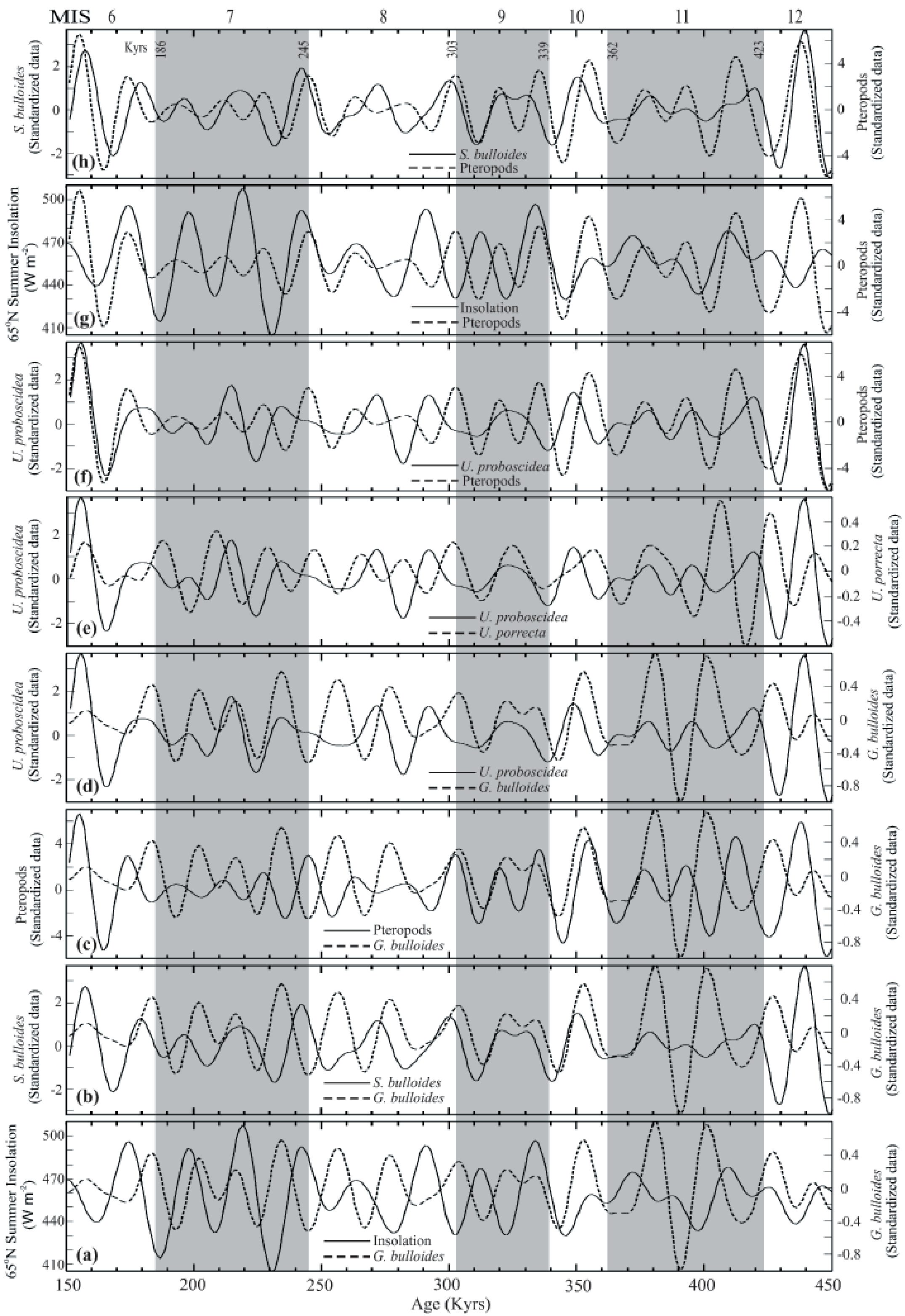

Figure 7. Band pass filtered (3.3-6.6 x 10^{-5} Hz frequency) time series of important species of benthic foraminifera, planktic foraminifer *Globigerina bulloides*, pteropods and 65°N July insolation (panels a-h). Most of the species of benthic foraminifera show a good (but not one to one) correlation between them over the studied interval.

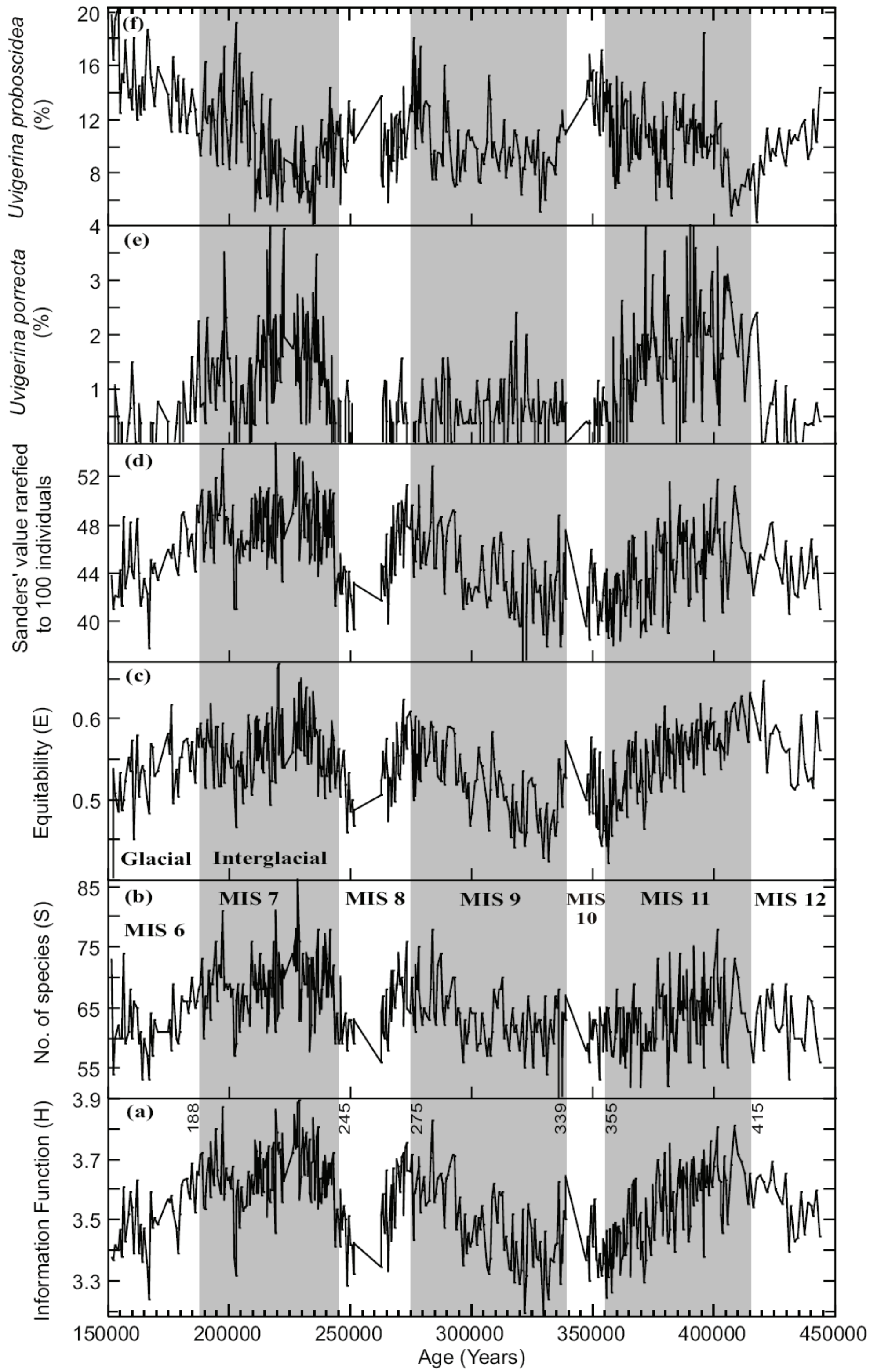

Figure 8. Species diversity in terms of (**a**) Information Function (*H*), (**b**) number of species (*S*), (**c**) Equitability (*E*) and (**d**) Sanders' values rarefied to 100 individuals; percent distribution of (**e**) *Uvigerina porrecta* and (**f**) *Uvigerina proboscidea* from Hole 716A. Grey bars indicate interglacial periods (Imbrie *et al.* 1984); MIS, Mar. Isotope Stage.

Atlantic Ocean (Turley and Dixon 2002) whereas in the Cascadia Margin *U. peregrina* was found attracted to rich bacterial food source at methane seeps (Torres *et al.* 2003). Goldstein and Corliss (1994), however, suggested that *Uvigerina peregrina* prefers to ingest diatom frustules. Recent study from a deeper site (2800 m water depth) from the Bay of Biscay reveals co-occurrence of *U. peregrina* and *B. alazanensis* suggesting high productivity environment (Fontanier *et al.* 2003).

Uvigerina porrecta is a comparatively rare species occurring sporadically in the Indian Ocean (Boltovskoy 1978) and has often been found with an inverse relation with *U. proboscidea*. The test morphology of *U. porrecta* is suggestive of an infaunal microhabitat (Corliss and Chen 1988). This species proliferates in areas typified by sustained flux of organic matter under intermediate to high productivity belts (Barmawidjaja *et al.* 1992; Gupta 1997). *Uvigerina porrecta* prefers low temperature and intermediate oxygen level in the Indian Ocean (De 2008).

Uvigerina proboscidea is found in wider range of temperature and oxygen conditions. It blooms in high productivity regions of the Indian Ocean (Gupta and Srinivasan 1992; Gupta and Thomas 1999; Almogi-Labin *et al.* 2000) particularly when productivity is high throughout the year and seasonality of the food supply is low or absent (Gupta and Thomas 1999; Ohkushi *et al.* 2000). This species is positively correlated with the organic carbon flux and negatively with the dissolved-oxygen concentration in the eastern Indian Ocean as higher primary productivity levels at the sea surface renders organic matter oxidation leaving the water oxygen-depleted at depth (Murgese and De Deckker 2005). Gupta and Thomas (1999), however, inferred *U. proboscidea* as a low seasonality species irrespective of deep-sea oxygenation. Peak abundances *U. proboscidea* are inferred to represent times of high surface productivity related to intense trade winds during the SW Indian monsoon, causing widespread upwelling along equatorial divergence in the Indian Ocean (Gupta and Srinivasan 1992; Gupta and Thomas 1999).

Globigerina bulloides is a non-symbiotic, spinose, near surface dwelling planktic foraminifer, living in the upper 100 m (predominant from 50-100 m) in temperate to subpolar water masses (Bé 1977). This species also dominates monsoon-induced upwelling areas in the tropics and prefers a large range of Sea Surface Temperature (SST: 3–28°C, optimum 7–14°C) and salinity (optimum of 34.8 psu; Bé and Tolderlund 1971; Bé and Hutson 1977). *Globigerina bulloides* is not only abundant, but also has a wide geographical and temporal coverage and is among the shallowest-dwelling planktic foraminifera (Mulitza *et al.* 2003). This species has widely been used as a monsoon proxy in the Arabian Sea to understand centennial to millennial scale changes during the late Quaternary and the Holocene (Anderson and Prell 1993; Naidu and Malmgren 1995; Gupta *et al.* 2003).

Pteropod population is influenced by the properties of the water column, and preservation is influenced by the bottom water. Water mass boundaries appear to be fairly efficient barriers to pteropod populations (van der Spoel and Heyman 1983). Owing to their larger size and mass, pteropod tests have a higher settling velocity that promotes deposition close to their habitat (Kalberer *et al.* 1993). Though, the aragonitic shells of pteropods are dissolution prone (Berger 1976). Preservation declines with growing supply of organic carbon, oxygen consumption and greater production of carbon-dioxide. Well-preserved pteropod shells are limited to the marginal seas with anti-estuarine circulation such as the Red Sea and the Mediterranean Sea (e.g. Almogi-Labin *et al.* 1991; Wang *et al.* 1997). In addition, pteropods accumulate in shallow parts of the open ocean and in environments which border carbonate platforms (Droxler *et al.* 1990). In deep ocean, decreasing carbonate saturation results in selective and substantial dissolution of the aragonitic shells (Berner 1997).

5. Results and discussion

Hole 716A lies in an oligotrophic region of the Arabian Sea, which makes it suitable to understand changes in surface productivity and deep-sea oxygenation. In general, the three benthic foraminiferal biofacies show a good correlation with *G. bulloides* and pteropods, marked by important changes at glacial-interglacial time scale during 444–151 Kyrs (figure 3). The high organic carbon, low-oxygen biofacies Ba-Cs shows a strong positive relation with *G. bulloides* populations and a negative relation with pteropods, indicating surface productivity played a major role in shaping the benthic community at Hole 716A. The surface productivity was higher during interglacial stages MIS11 and MIS9 (420–300 Kyr), and moderately high during MIS7 (245–190 Kyr) as supported by high percentages of *G. bulloides*, cumulative percentages of all the species of biofacies Ba-Cs and low populations of pteropods. To understand whether this increase in surface productivity resulted from intense southwest monsoon winds during warm intervals (Schulte *et al.* 1999) or insolation-driven eastward equatorial jets (Beaufort *et al.* 1997), we plotted band pass filtered time series of *G. bulloides* (an upwelling indicator and a proxy for summer monsoon wind intensity) and 65^{o} N July insolation (figure 7). The two time series show an inverse relation during MIS 9 and 8 but a positive relation during other time slices with a phase difference (figure 7). Besides, the amplitude of variability of *G. bulloides* time series was large from 444-345 Kyrs when amplitude of solar variability was smaller. This relationship changes in the younger interval, thus suggesting that the surface productivity changes at

Hole 716A were driven by the summer monsoon winds and not solar insolation. It is generally believed that the summer monsoon intensifies during interglacial periods and weakens during the glacials (Fontugne and Duplessy 1986).

The high oxygen, low-organic carbon biofacies Sb-Upe shows a positive relation with pteropods and an inverse relation with *G. bulloides*. Pteropods show an increase in numbers during phases of weak bioproductivity and higher bottom water oxygenation. Their populations sharply decline during 450–300 Kyr when upwelling-induced surface productivity was high (high *G. bulloides* percentages). The band pass FFT filtered time series of *Sphaeroidina bulloides* (a high oxygen species and dominant component of biofacies Sb-Upe) and pteropods show a strong positive relation indicating that both *S. bulloides* and pteropods prefer to live in better oxygenated, oligotrophic waters (figure 7h). Klöcker *et al.* (2006) suggested that pteropod abundance at Hole 716A corresponds to the 'Indo-Pacific carbonate preservation type' with poor preservation during interglacials and better preservation during glacials. Similar pteropod preservation pattern was reported from core 905 off Somalia, core 137KA off Pakistan margin and core KL15 in the Gulf of Aden which show preservation spikes during stadials (von Rad *et al.* 1999; Almogi-Labin *et al.* 2000; Reichart *et al.* 2002).

The biofacies Ts-Upe shows a variable relation with both *G. bulloides* and pteropods, indicating that the species of this group are opportunistic which can gain even from a variable flux of organic matter. This biofacies shows intermediate to high but variable flux of organic food.

From the above observations, it can be said that the surface and deep conditions at Hole 716A were coupled during the late Quaternary. The species pattern suggests that benthic populations at Hole 716A were influenced by in situ changes in organic food and oxygen levels. The oxygen levels were low during interglacial intervals but not as stressful as in the northwestern Arabian Sea owing to the shallow water depth (533 m) and location of this hole in the southeastern Arabian Sea where modern surface conditions are largely oligotrophic compared to northwestern part of the Arabian Sea (Banse 1987). The band pass FFT time series of dominant benthic foraminifera shows a good correlation between them in the studied interval, indicating their preference to a particular ecological setting.

The species diversity parameters of benthic foraminifera have been plotted in figure 8 (panels a-d). All diversity parameters show strikingly similar trends. It can be noticed that the diversity patterns strictly follow the glacial-interglacial shifts. The species diversity values are high during interglacial intervals when surface productivity was high (low oxygen) and lower during glacials when surface productivity was low. The trends are opposite to those observed by Singh and Gupta (2005) at eastern Indian Ocean ODP Site 757, which may be explained by the fact that the two sites lie in different spheres and at different water depths. It may be argued that benthic foraminiferal species diversified rapidly during interglacial intervals when competition among species was less due to sufficient food supply to the deep-sea. On the other hand, inter-species competition intensified under insufficient organic flux during glacial phases causing species diversity to decline. Gooday (1986) suggested that in low-oxygen environments the predators are scarce and competition is low, leading to high species diversity. In low-oxygen environments, the species can bloom opportunistically because of the high food availability, low competition and absence of predators.

6. Conclusions

Ocean Drilling Program (ODP) Hole 716A witnessed major productivity changes on glacial-interglacial time scales, driven by summer monsoon winds. In general, from 420 to 300 Kyr BP, the surface productivity was higher (high *Globigerina bulloides* and low pteropods). A major decrease in *G. bulloides* population and biofacies Ba-Cs at ~ 300 Kyr BP coinciding with an increase in biofacies Sb-Upe and pteropods, indicates return of more conducive deep-sea conditions due to decrease in surface productivity (oligotrophic conditions) in the Maldivian region. Deep-sea benthic foraminiferal changes at Hole 716A are in contrast to numerous sites in the Indian Ocean, indicating that the deep-sea and surface conditions were typical of Maldivian region during the late Quaternary. Benthic foraminfieral species diversity was higher during interglacial intervals owing to more food availability and low during oligotrophic glacial intervals. This indicates that benthic foraminiferal species availed opportunity to diversify rapidly during interglacial intervals when competition among species was less due to sufficient food supply to the sea floor and absence of predators. On the other hand, inter-species competition intensified under insufficient organic flux and high numbers of predators during glacial phases causing species diversity to decline. The benthic fauna suggest that Hole 716A underwent moderate changes in deep-sea oxygenation during the studied interval.

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