

Species diversity variations in Neogene deep-sea benthic foraminifera at ODP Hole 730A, western Arabian Sea

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Deep-sea benthic foraminifera are an important and widely used marine proxy to understand paleoceanographic and paleoclimatic changes on regional and global scales, owing to their sensitivity to oceanic and climatic turnovers. Some species of benthic foraminifera are sensitive to changes in water mass properties whereas others are sensitive to organic fluxes and deep-sea oxygenation. Benthic faunal diversity has been found closely linked to food web, bottom water oxygen levels, and substrate and water mass stability. The present study is aimed at analyzing species diversity trends in benthic foraminifera and their linkages with Indian monsoon variability during the Neogene. Species diversity of benthic foraminifera is examined in terms of number of species (S), information function (H), equitability (E) and Sanders' rarefied values, which were combined with relative abundances of high and low productivity benthic foraminifera at Ocean Drilling Program Hole 730A, Oman margin, western Arabian Sea. The Oman margin offers the best opportunity to understand monsoon-driven changes in benthic diversity since summer monsoon winds have greater impact on the study area. The species diversity was higher during the early Miocene Climatic Optimum (~17.2–16.4 Ma) followed by a decrease during 16.4–13 Ma coinciding with a major increase in Antarctic ice volume and increased formation of Antarctic Bottom Water. All the diversity parameters show an increase during 13–11.6 Ma, a gradual decrease during 11.6–9 Ma and then an increase with a maximum at 7 Ma. Thereafter the values show little change until 1.2 Ma when all the parameters abruptly decrease. The benthic foraminiferal populations and diversity at Hole 730A were mainly driven by the Indian monsoon, and polar waters might have played a minor or no role since early Neogene period as the Arabian Sea is an enclosed basin.

1. Introduction

Paleoclimate studies provide useful information for understanding land–ocean–atmospheric interactions over different time scales. The present day climatic regimes resulted from changes in polar ice volume including waning and waxing of polar ice sheets since the late Oligocene (Kennett and Barker 1990; Zachos *et al.* 2001). The plate tectonic evolution of the Indian subcontinent (e.g., uplift of the Himalaya–Tibetan plateau complex)

and opening and closing of the seaways (e.g., opening of the Drake Passage and closing of the Panamanian, Tethyan, and Indonesian seaways) also had significant impact on the global climate system (Kennett *et al.* 1974; Molnar *et al.* 1993; Haug and Tiedemann 1998; Lawver and Gahagan 1998; Barker and Thomas 2004; Hamon *et al.* 2013). The major expansion of the East Antarctic Ice Sheet (EAIS) began in the earliest Oligocene which was permanently established in the middle Miocene (Kennett and Barker 1990; Zachos *et al.* 2001). The

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increased Antarctic ice volume during this time intensified thermal gradients between the tropics and the poles that increased the seasonality of surface ocean productivity and deep water oxygenation in all the ocean basins (Kennett and Barker 1990; Ehrmann and Mackensen 1992; Zachos *et al.* 2001; Barker and Thomas 2004; Gupta *et al.* 2004). The increase in Antarctic ice volume in the middle Miocene intensified the production and circulation of the Antarctic Bottom Water (AABW) (Kennett and Barker 1990). These changes in ocean surface productivity, deep-sea circulation, and oxygenation brought pronounced changes in marine fauna in the Indian Ocean (Gupta *et al.* 2004).

The continuous build-up of Antarctic ice sheets strengthened the wind regimes which drove open-ocean and coastal upwelling over large parts of the Indian, Pacific and Atlantic oceans during the middle to late Miocene (Gupta *et al.* 2004). This upwelling-driven productivity led to the formation of a 'biogenic bloom' and expansion of the oxygen minimum zone (OMZ) at intermediate water depths within both the Indian and Pacific oceans during the middle to late Miocene (~15–5 Ma) (Pisias *et al.* 1995; Dickens and Owen 1999; Gupta and Thomas 1999; Hermoyian and Owen 2001). As a result, the deep-sea benthic foraminiferal faunas underwent restructuring and changes in diversity worldwide (e.g., Douglas and Woodruff 1981; Gupta *et al.* 2001, 2013; Singh *et al.* 2012). In the western Arabian Sea, distribution of deep-sea benthic foraminifera, biomass, and diversity differ from other parts of the Indian and other ocean basins since the area is landlocked and is located under the influence of the monsoon regime (Hermelin and Shimmield 1990; Gupta 1994; Kurbjewit *et al.* 2000). Recently, several researchers analyzed changes in water mass circulation, surface productivity, and response of deep-sea biota to these changes in the Arabian Sea during the Neogene (e.g., Boersma and Mikkelsen 1990; Hermelin and Shimmield 1990; Kroon *et al.* 1991; Prell *et al.* 1992; Gupta and Thomas 1999, 2003; Kawagata *et al.* 2006; Smart *et al.* 2007). The variations in deep-sea benthic foraminiferal diversity have been related to the presence of food, heterogeneity of the habitat, deep-ocean circulation, and predation (Buzas and Gibson 1969; Gibson and Buzas 1973; Gooday 1988; Rai and Singh 2001; Singh *et al.* 2012; Gupta *et al.* 2013).

In this study, we examined species diversity trends in late Neogene deep-sea benthic foraminifera at Ocean Drilling Program (ODP) Hole 730A in the western Arabian Sea in order to understand the influence of monsoon driven changes in deep water oxygenation and surface productivity on benthic faunal diversity during the Neogene. An attempt was also made to discriminate between

monsoon driven changes and those induced by pole-induced deep-sea circulation on species diversity.

2. Study area

ODP Hole 730A is located off the continental margin of Oman, western Arabian Sea (water depth – 1065.8 m; latitude 7°43.885'N; longitude 57°41.519'E; figure 1) which, in recent years, has attracted numerous excellent studies to reconstruct Indian monsoon driven deep and surface paleoceanographic changes in the northern Indian Ocean during different time periods. Intense southwest (SW) monsoon winds drive strong upwelling off the coast of Oman, causing enhanced surface biological production and activity during the summer (June–September) season (Wyrтки 1971; Brock *et al.* 1991; Schott and McCreary 2001). On the contrary, during the winter or northeast (NE) monsoon season (November–February), the prevalence of dry and weak northeasterly winds promotes oligotrophic conditions in the Arabian Sea (e.g., Schott and McCreary 2001). Upwelling processes allow deeper-cold-nutrient rich water to shoal and maintain high levels of euphotic activity in the Arabian Sea (Hermelin and Shimmield 1990). This results in a pronounced oxygen minimum zone with oxygen levels below 0.05 ml/l at intermediate water depths between 200 and 1200 m throughout the Arabian Sea (Hermelin and Shimmield 1990). The OMZ controls microbial decay, respiration by biota, and increased preservation of monsoon-driven organic matter and seasonal fluxes to the deep sea sediments (Hermelin and Shimmield 1990; Gupta 1994; Reid 2003).

The Red Sea and Persian Gulf outflows feed a high-salinity, low-oxygen, and nutrient-rich warm water mass (Red Sea–Persian Gulf Intermediate Water or RSPGIW) to intermediate water depths of the northwestern Arabian Sea. It is a major constituent of intermediate water in the Arabian Sea which mixes down at 1000–2000 m water depths (Gupta and Srinivasan 1992; You 1998; Kawagata *et al.* 2006). The intensity of RSPGIW and sinking of Arabian Sea surface water is controlled by NE monsoon winds over the Arabian Sea (Woelk and Quadfasel 1996). Below RSPGIW, lies the North Indian Deep Water (NIDW) at 1500–4000 m water depths (Wyrтки 1973; Tomczak and Godfrey 1994). In the northwestern Indian Ocean, NIDW has high salinity (35.85 psu) with a temperature of 2°C and oxygen of 4.7 ml/l, which is formed by the mixing of saline North Atlantic Deep Water (NADW) (Vincent *et al.* 1974), Antarctic Intermediate Water (AAIW) and well-oxygenated AABW, as well as RSPGIW to the north of the 10°S

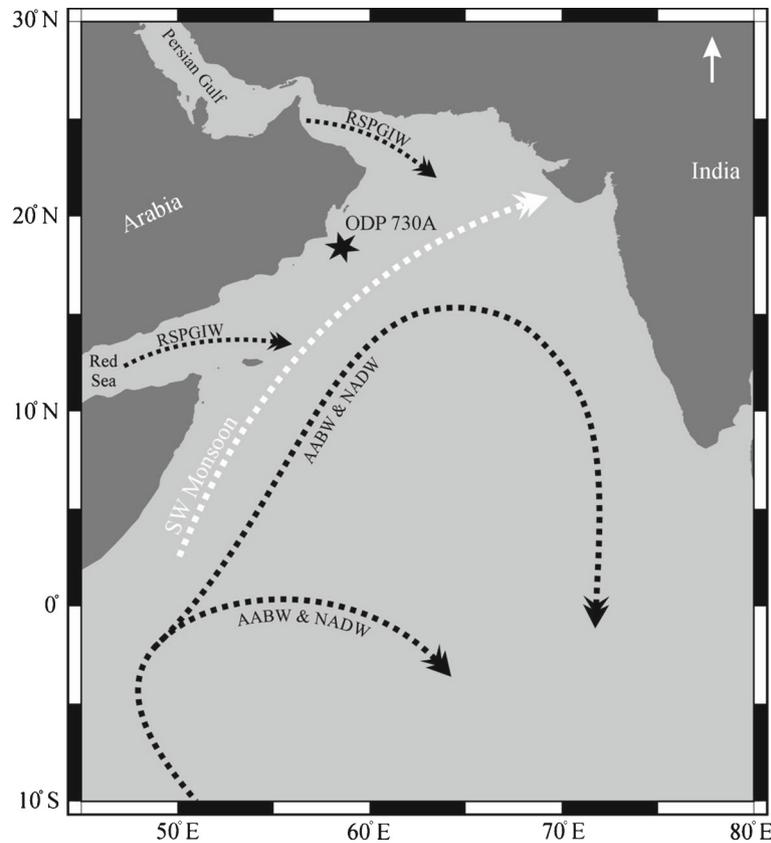


Figure 1. Location map of ODP Hole 730A, Oman margin, western Arabian Sea. Also shown are present day intermediate and bottom water flows (Kawagata *et al.* 2006) and direction of the southwest monsoon current (Findlater 1971). (AABW=Antarctic Bottom Water; NADW=North Atlantic Deep Water; RSPGIW=Red Sea–Persian Gulf Intermediate Water).

Hydrochemical Front (Wyrтки 1971; Tchernia 1980). Wyrтки (1988) and Reid (2003) referred to this water mass as Lower Circumpolar Deep Water (LCDW), which is a carbonate undersaturated, oxygen-rich water mass flowing as a western boundary current from the southern Indian Ocean towards the north through the western Indian basins at >3800 m water depths.

3. Materials and methods

We examined 200 core samples of 10 cc volume from ODP Hole 730A covering a sediment thickness of 403 m below sea floor (mbsf), which were processed using the standard procedures as described in Gupta and Thomas (1999). The average age per sample is ~85,000 years based on planktic foraminiferal and calcareous nannofossil datums (Prell *et al.* 1989), which were updated to Berggren *et al.* (1995). Sample processing was carried out in the Paleoceanography and Paleoclimatology Laboratory, Department of Geology & Geophysics, IIT, Kharagpur. Each sample was soaked in water with a few drops of diluted Hydrogen Peroxide [H_2O_2 (15%)] and half a spoon of baking soda for

approximately 8–10 hours. The soaked samples were washed over a 63 μm size sieve using a jet of clean tap water, dried in an electric oven at $\sim 50^\circ\text{C}$, and dry samples were transferred to labelled glass vials. After each wash the sieve was stained with methylene blue to identify contaminated specimens from the previous sample.

Each sample was dry-sieved over 125 μm size sieve and split into suitable aliquots to obtain ~ 300 individuals of benthic foraminifera under the microscopic. Each sample was thinly scattered on a black picking tray ruled with gridlines under the microscope. The specimens were identified and counted to calculate percentages. The greater than 125 μm size fraction was studied under the microscope for better comparison with the recent studies on benthic foraminifera from other ocean basins.

We have plotted percentages of most dominant and environmentally sensitive benthic foraminiferal species including *Uvigerina proboscidea*, *Epistominella exigua*, *Cibicides wuellerstorfi*, *Nuttallides umbonifera* and OMZ taxa (comprising *Bolivina seminuda*, *Bulimina aculeata*, *Bulimina exilis*, *Chilostomella ovoidea*, and *Uvigerina peregrina*) (Sen Gupta and Bernhard 1999) with diversity parameters and global oxygen and carbon isotope

curves (Zachos *et al.* 2001). The numerical ages are based on foraminiferal and nannofossil datums (Prell *et al.* 1989) and updated to the age model of Berggren *et al.* (1995). Species diversity was studied in terms of SHE analysis, where S represents the number of species, H is the information function and E is the equitability. 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 i th species in the sample and \ln is the natural logarithm. To calculate the equitability, the mathematical expression given by Buzas and Gibson (1969) was used:

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

Sanders' rarefaction number was also calculated for each sample by rarefying against 100 individuals (Sanders 1968). Sanders' values are commonly used in the ecological studies of deep-sea fauna (e.g., Rex *et al.* 1997).

The combined plots of species diversity and high seasonality species *Epistominella exigua* and *Cibicides wuellerstorfi*, OMZ species and dissolution resistant species *Nuttallides umbonifera* are shown in figure 2 to understand influence of monsoon seasonality and deep-sea circulation on benthic fauna (figure 2). To strengthen our understanding of species diversity and monsoon relationships, we also correlated Sanders' values with productivity indicator taxon *Uvigerina proboscidea* during selected time intervals using linear correlation method (figure 4).

Uvigerina proboscidea flourishes in high productivity zones of the Indian Ocean irrespective of oxygen content of deep waters (Gupta and Srinivasan 1992; Gupta and Thomas 1999; Almogi-Labin *et al.* 2000; Singh and Gupta 2004). High relative abundances of *Uvigerina proboscidea* indicate a year-round, sustained and high flux of organic matter from the sea surface to the ocean floor during intervals of high surface productivity (Gupta and Srinivasan 1992; Gupta and Thomas 1999; De and Gupta 2010). Gupta and Srinivasan (1992) observed a relationship between higher abundances of *Uvigerina proboscidea* and increased upwelling due to intensification of trade winds in the open eastern Indian Ocean.

Epistominella exigua is a cosmopolitan species which feeds opportunistically on phytodetritus deposited seasonally on the sea floor and linked with elevated oxygen level (Gooday 1993;

Smart *et al.* 1994; Schmiedl *et al.* 1997; Jannink *et al.* 1998; Kurbjeweit *et al.* 2000). This species has been used as a proxy for pulsed organic inputs to the sea floor and relative changes in productivity (Smart *et al.* 1994; Saraswat *et al.* 2005). *Cibicides wuellerstorfi* has been suggested as an epibenthic foraminifer that prefers to live on raised objects above the sediment–water interface in high energy environments (Lutze and Thiel 1989; Linke and Lutze 1993; Mackensen *et al.* 1995). This species is a suspension feeder occurring in regions of low food supply and low organic carbon flux (Linke and Lutze 1993). The numerical dominance of *C. wuellerstorfi* in the Arctic Basin and the Norwegian–Greenland Sea has been inferred to reflect scarcity of food particles in the sediment (Lutze and Thiel 1989; Linke and Lutze 1993). On the Ontong Java Plateau this species occurs abundantly in post-glacial environments typified by low productivity (Burke *et al.* 1993). *Cibicides wuellerstorfi* is associated with AABW (Corliss 1979, 1983). *Nuttallides umbonifera*, though found in several habitats, has mostly been found associated with corrosive bottom waters in the Atlantic Ocean (Bremer and Lohmann 1982). This species has been defined as an opportunist (Corliss 1983; De and Gupta 2010).

Bolivina seminuda is a shallow infaunal species, which has been recorded in high abundance within the central part of the OMZ. This species has better adaptation to live in disoxic environments (Glock *et al.* 2011). The abundances of *Bulimina exilis* are found in the fine fraction (63–150 μ m) of samples from the OMZ at the end of the summer in Pakistan Margin (Jannink *et al.* 1998). *Bulimina aculeata*, an intermediate to deep infaunal species, has been reported at lower bathyal depths and below lower boundary of OMZ in the Arabian Sea (Hermelin and Shimmiel 1990; Miao and Thunell 1993; Jannink *et al.* 1998). This species dominates high-productivity, interglacial intervals in the Arabian Sea (Almogi-Labin *et al.* 2000). The deep infaunal *Chilostomella ovoidea* has found in OMZ with assemblage of *Uvigerina peregrina* in the northwestern Arabian Sea. This species has a close relationship with the oxygen content of the overlying water masses (Hermelin and Shimmiel 1990). All these low oxygen tolerant species have been reported in OMZ environment from different oceans (Sen Gupta and Bernhard 1999).

4. Results and discussion

Deep-sea benthic foraminifera capture signatures of export flux to the deep sea resulting from monsoon-induced changes in the surface and deep-water column of the Arabian Sea (Hermelin 1992;

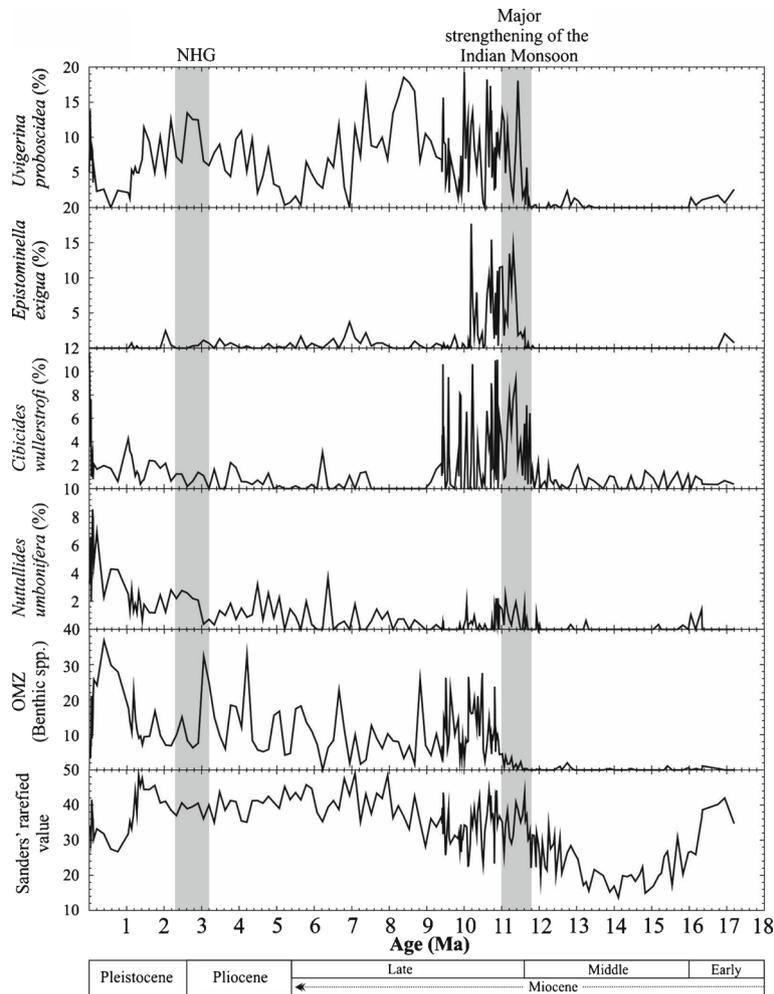


Figure 2. Relative abundances of benthic foraminiferal species *Epistominella exigua*, *Cibicides wuellerstorfi*, *Nuttallides umbonifera* and OMZ taxa (comprising *Bolivina seminuda*, *Bulimina aculeata*, *Bulimina exilis*, *Chilostomella ovoidea* and *Uvigerina peregrina*) combined with Sanders' rarefied values and *Uvigerina proboscidea* percentages.

Gupta and Thomas 1999). The Arabian Sea has more distinct deep-sea benthic foraminiferal regimes as compared to the southeastern Indian Ocean because of the latter's configuration and presence of a pronounced OMZ at depths ranging from ~200 to 1200 m which is caused by high organic flux from monsoon-induced high surface productivity and increased oxygen consumption by the deep-sea biota (Hermelin and Shimmield 1990; Den Dulk *et al.* 2000; Mazumder *et al.* 2003; Nigam *et al.* 2007; De and Gupta 2010).

At Hole 730A, the number of species (S), information function (H), equitability (E) and Sanders' rarefied values of benthic foraminifera show significant fluctuations (figure 3). A comparison of these values with previous studies in the eastern and western Indian Ocean is more reasonable because we have used the $>125 \mu\text{m}$ size fraction. The SHE and Sanders' rarefied values increase from 17.2 to 16.4 Ma coinciding with the late Early

Miocene Climatic Optimum (EMCO). The values decrease during ~16.4 to 13 Ma when East Antarctic ice sheets (EAIS) underwent major expansion. All SHE parameters show a general increase with a fluctuating trend from ~13 to 11.6 Ma; thereafter the values show a decrease from 11.6 to 9 Ma and then an increase with a peak at 7 Ma. The diversity values remain more or less constant since 7 Ma with secular variations until the mid-Pleistocene transition (Raymo *et al.* 1997) when all the parameters showed an abrupt decrease at ~1.2 Ma (figure 3). There was no visible change in benthic faunal diversity at Hole 730A, western Arabian Sea during major expansion of the Northern Hemisphere Glaciation (NHG) in the late Pliocene (figure 3), although a major change has been observed in benthic fauna in the eastern Indian Ocean (Gupta and Thomas 2003). We relate this contrasting trend in benthic fauna and diversity to distinct water mass and climate regimes in the two regions.

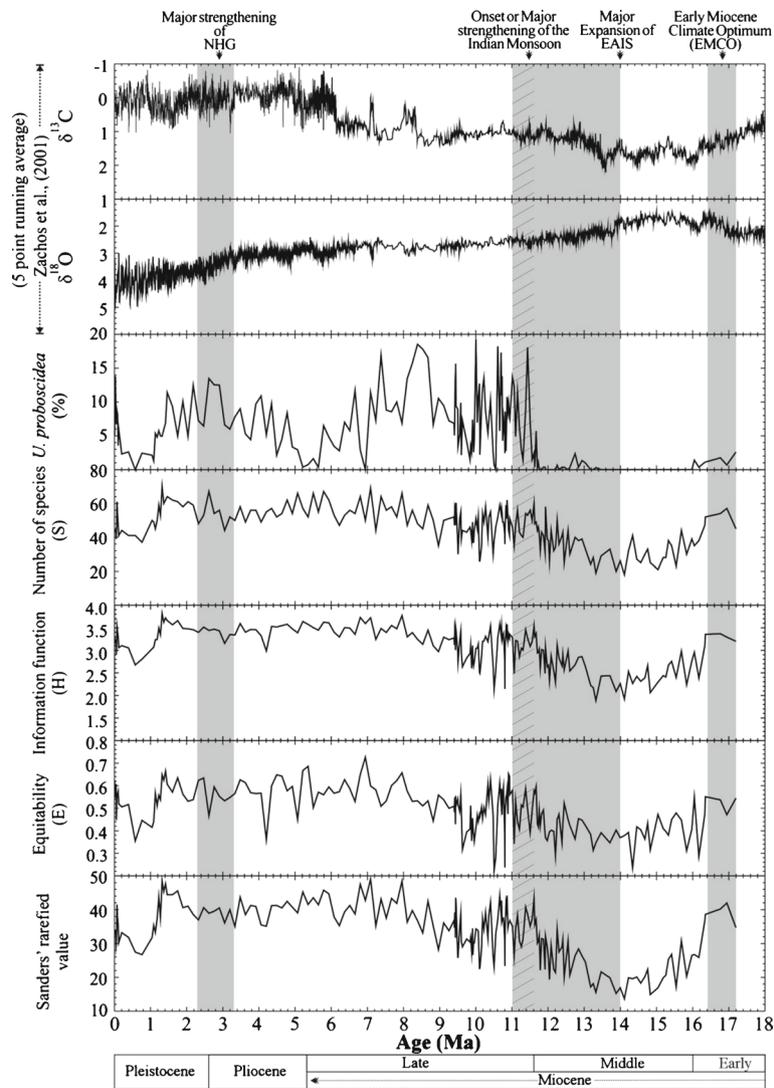


Figure 3. Species diversity parameters including H , S , E and Sanders' rarefied values combined with *Uvigerina proboscidea* percentages at ODP Hole 730A. These values are correlated with global isotope curve (Zachos et al. 2001) to understand if changes in benthic foraminiferal populations at Hole 730A were driven by global oceanic changes or Indian monsoon variability. The grey bars and hature lines coincide with Early Miocene Climate Optimum (EMCO), major expansion of East Antarctic Ice Sheets (EAIS), onset or beginning of Indian monsoon and major strengthening of Northern Hemisphere Glaciation (NHG).

Although, Sanders' values show a broad positive correlation ($R = 0.50$) with productivity indicator *U. proboscidea* during the entire studied interval, the relationship varies in different time segments (figure 4). For example, values of both the proxies show a strong negative correlation ($R = -0.86$) during the late EMCO (17.2–16.4 Ma), but a strong positive correlation ($R = 0.64$) during 16.4–13 Ma coinciding with increased Antarctic ice volume (figure 4b–c). The species diversity values were low in the latter interval as were earlier observed in the eastern Indian Ocean during this time (Gupta et al. 2013). The correlation breaks in the younger interval since 13 Ma where R values remain < 0.4 in all the time slices (figure 4d–f). We link this shift to greater influence of the Indian

monsoon as this interval coincides with the onset of and increased seasonality in the Indian monsoon.

A sudden increase in *Uvigerina proboscidea* percentages at 11.6 Ma at Hole 730A appears to be linked to a significant increase in Indian monsoon intensity that drove increased upwelling and high surface productivity in the Arabian Sea. In the eastern Indian Ocean species, diversity values show a stepwise decrease since the early Miocene following major Antarctic ice volume increase with a rapid decrease in the late Miocene (Gupta et al. 2013). Thomas and Vincent (1987) also observed a decrease in diversity of deep-sea benthic foraminiferal faunas in the Pacific Ocean during this period. The species diversity values in the NW and eastern Indian Ocean show an opposite

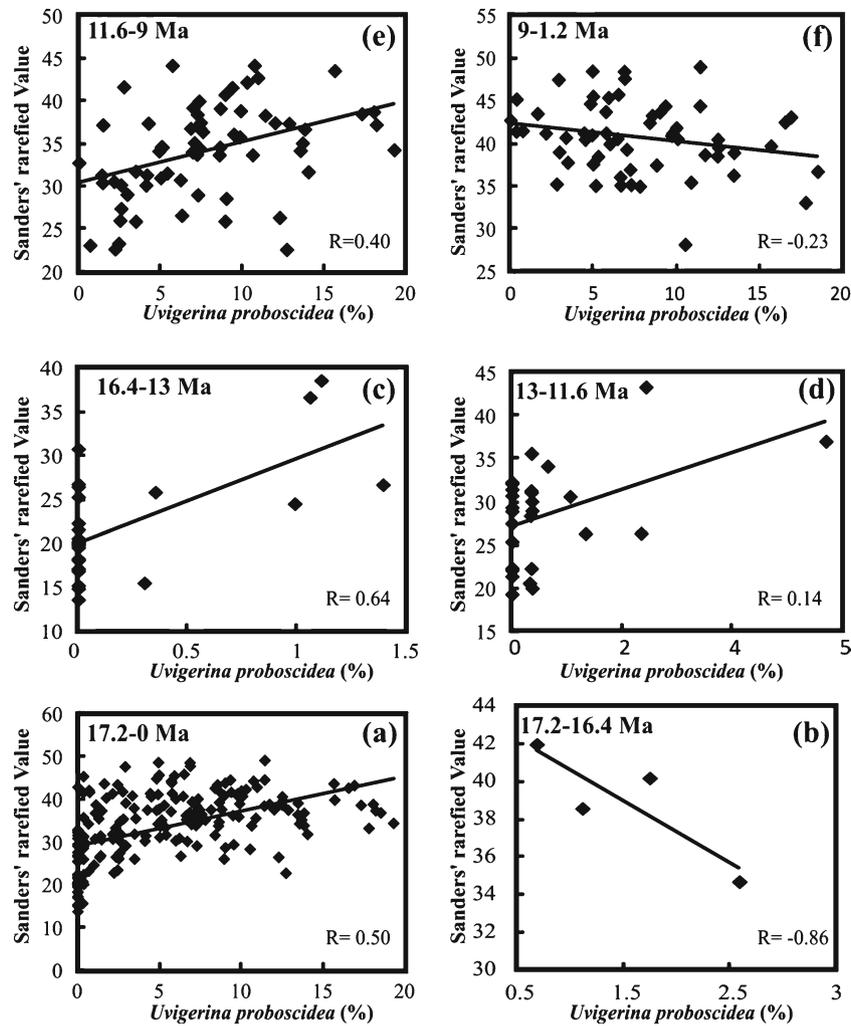


Figure 4. Linear correlation between *Uvigerina proboscidea* and Sanders' rarefied values over the past 17.2 Ma. The value of correlation coefficient (R) is 0.5 for the whole 17.2 Ma period (a), -0.86 for the interval 17.2–16.4 Ma (b), 0.64 for 16.4–13 Ma (c), 0.14 for 13–11.6 Ma (d), 0.4 for 11.6–9 Ma (e), and -0.23 for 9–1.2 Ma interval (f).

trend indicating existence of contrasting climatic regimes in the two regions. The Arabian Sea was dominated by the monsoon regime since 13–12 Ma, whereas eastern Indian Ocean has been under the influence of the Southern Hemisphere climate and ocean circulation since the Oligocene.

The populations of *Epistominella exigua* and *Cibicides wuellerstorfi* increase coevally with *Uvigerina proboscidea* since ~ 12 Ma indicating increased monsoon seasonality resulting in highly variable upwelling in the western Arabian Sea. However, *E. exigua* almost disappears since 10 Ma whereas OMZ species show major and sudden increase at ~ 11 Ma coinciding with increased intensity of the Indian monsoon (figure 2). These faunal trends at Hole 730A suggest strengthening of the Indian monsoon and OMZ since the middle Miocene. The increased abundances of *Nuttallides umbonifera* since ca 11 Ma suggest presence of corrosive deep water in the Arabian Sea.

A major decrease in benthic diversity parameters across the mid-Pleistocene transition could be related to a cold phase during when the Indian monsoon was weaker. The present study suggests that changes in benthic foraminiferal populations and diversity at Hole 730A were mainly driven by the Indian monsoon, and polar waters might have played a minor or no role since this hole has remained at this depth from the early Neogene period (Prell *et al.* 1989). The paleoposition of this hole has also remained the same since the Jurassic, thus making it ideal to study monsoon-induced changes in the western Arabian Sea.

5. Conclusions

Species diversity (S , H , E and Sanders' rarefied values) values of benthic foraminifera at Hole 730A combined with faunal abundances indicate

monsoon wind-induced intense upwelling and thus high surface productivity since ~12 Ma suggesting the onset or major strengthening of the Indian monsoon and wind regimes. A correlation between diversity parameters and *Uvigerina proboscidea* abundances suggests that monsoon-induced productivity played a major role in shaping benthic foraminiferal diversity and abundances in the western Arabian Sea during the Miocene–Pleistocene. Furthermore, benthic foraminiferal trends do not show any significant correlation with global isotope shifts which predate changes at Hole 730A indicating that deep-sea changes in the western Arabian Sea were mainly driven by the Indian monsoon during the study interval. The polar deep waters may not have played a significant role in shaping benthic diversity at Hole 730A. Decrease in diversity parameters since the early Miocene were linked to low food levels as a result of a weak Indian monsoon.

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