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Deep-sea benthic foraminiferal changes in the eastern Indian Ocean (ODP Hole 757B): Their links to deep Indonesian (Pacific) flow and high latitude glaciation during the Neogene

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This study analyses 26.5 Ma record of deep-sea benthic foraminifera from 194 samples from Ocean Drilling Program Hole 757B (latitude 17°01.458' S, longitude 88°10.899' E, water depth of 1652.1 m) located on the Ninetyeast Ridge, southeastern Indian Ocean below equatorial divergence zone. The data document important changes in benthic foraminiferal population at Hole 757B since the late Oligocene. The well-oxygenated, oligotrophic species including Cibicides cicatricosus, C. pseudoungerianus *and* Oridorsalis umbonatus *were dominant during the late Oligocene to the early Miocene. These species began to decline as site 757 moved northward into the influence of the Indonesian Throughflow (ITF) beneath surface and subsurface water masses from the Pacific Ocean.* Cibicides cicatricosus *and* C. pseudoungerianus *disappeared in the late Miocene (10-8 Ma) at Hole 757B. The lower bathyal to abyssal species* Nuttallides umbonifera *shows a major increase at ~11.5 Ma coinciding with a significant increase in Neodymium (Nd) isotope values, indicating substantial transport of deep Pacific water to the Indian Ocean through the Indonesian seaway.* Nuttallides umbonifera *decreases drastically during 3-2.8 Ma, though the Nd isotope values do not show a decrease. We relate this change to a low sample resolution in the latter study. This event coincides with the final closure of the Indonesian seaway and a switch in shallow ITF source from warm, saline South Pacific to cool, fresh North Pacific thermocline water, which triggered global cooling and major expansion of Northern Hemisphere glaciation.*

Introduction

The opening and closing of the seaways and high latitude glaciation drive important changes in thermocline and thermohaline circulation of ocean basins, impacting surface and deep-sea biota as well as regional and global climates. For example, closure of the Indonesian seaway during the early Pliocene (4-3 Ma) triggered important climatic changes including cooling of the global thermocline, major expansion of Northern Hemisphere ice sheets, and African aridification (Cane and Molnar, 2001; Karas et al., 2009). Likewise, a major increase in the Antarctic glaciation during the middle Miocene impacted deep-sea biota (e.g., Gupta et al., 2004). The Indonesian seas provide a passage for substantial transport of Pacific Ocean waters into the Indian Ocean called as the Indonesian Throughflow (ITF) (Gordon, 1986; Wyrtki, 1987). The ITF transfers water from the Pacific Ocean to the Indian Ocean in the thermocline layer, which influences heat and freshwater budgets of the two oceans (Gordon and Fine 1996; Godfrey, 1996).

The constriction of the Indonesian seaway due to northward movement of New Guinea in the early Pliocene changed the source of ITF, leading to aridification of east Africa and major expansion of the Northern Hemisphere glaciation (NHG) (Cane and Molnar, 2001). The constriction of the seaway obstructed the deeper connection between the two ocean basins, leading to significant reduction of transport of intermediate to deep Pacific waters to the Indian Ocean. While seasonal as well as geological variability in ITF (thermocline water) has been analyzed in greater detail in numerous recent studies (e.g. Gordon and Fine, 1996; Cane and Molnar, 2001, Gordon et al., 2003; Karas et al., 2009) little is known about the lower bathyal (intermediate) to abyssal (deep) flow from the Pacific to the Indian Ocean during the Neogene. The only study from this region by Martin and Scher (2006) suggests an extensive transport of intermediate water through the Indonesian seaway from 10 to 5.5 Ma and stepwise reduction from 5.5 to 3.4 Ma using Neodymium (Nd) isotope data of fish teeth from Hole 757B. Though this study provides useful information on the intermediate to deep water flow from the Pacific to the Indian Ocean, the study is at very low sample resolution which may have failed to capture exact timing of the events related to ITF

variability. The present study is aimed at understanding deep-sea paleoceanographic changes in the eastern Indian Ocean and their link with Pacific deep water flow as well as high latitude glaciation by analyzing conventional proxies – deep-sea benthic foraminifera, from Ocean Drilling Program (ODP) Hole 757B at higher resolution (Annexure I) combined with Nd isotope data of Martin and Scher (2006).

Site Location and Oceanographic Settings of Hole 757B

Hole 757B is located on the Ninetyeast Ridge, eastern Indian Ocean, at a latitude of 17°01.458' S, longitude of 88°10.899' E, and water depth of 1652.1 m in the southeastern Indian Ocean below equatorial divergence zone on the northern edge of the subtropical gyre and somewhat south of the South Equatorial Current or main ITF path (Fig. 1).

Hole 757B is currently bathed by Indian Deep Water (IDW) – a water mass with a potential temperature of 1.25-4°C, a salinity maximum of ~34.7-34.8 and oxygen of ~ 4.7 ml/L (Tomczak and Godfrey, 2003). This water mass occupies 500 to 3800 m water depths with a core at ~2400 m (Tomczak and Godfrey, 2003). GEOSECS data (1983) indicate that the water above Hole 757B has a temperature of 3.1°C, PO_4 content of 0.055 ml/L, NO_3 content of 0.78 ml/L, dissolve oxygen (DO) concentration of ~ 3.20 ml/L. At present, the
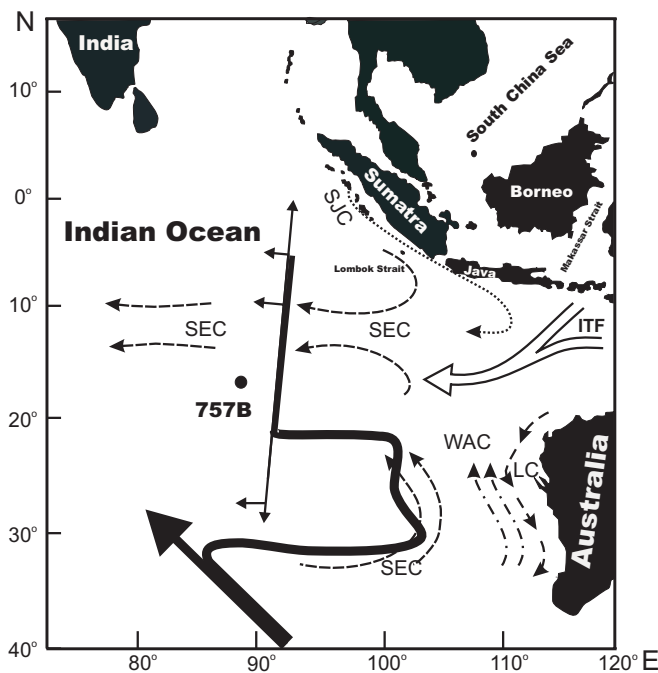

Figure 1. Location of Ocean Drilling Program Hole 757B with surface and deep water currents. The black solid arrow marks the routes of Antarctic Bottom Water in the eastern Indian Ocean (Warren and Johnson, 2002). The hollow, large arrow shows the path of deep Pacific waters through the Indonesian seaway during late Miocene to Pliocene. The broken arrows are surface currents. ITF = Indonesian Throughflow, LC = Leeuwin Current, SJW = South Java Current, SEC = South Equatorial Current, WAC = West Australian Current.

IDW originates as North Atlantic Deep Water (NADW) which is pushed into the Indian Ocean with the Antarctic Circumpolar Water (CPW) (Tomczak and Godfrey, 2003). The water mass below 4000 m is mainly Antarctic Bottom Water (AABW) that flows in the area of Hole 757B through gaps in the Broken Ridge (Warren and Johnson, 2002) (Fig. 1). The IDW mixes with AABW below 2500 m and looses its identity. The surface water mass above Hole 757B is modulated by the low salinity waters of ITF and Sumatra-Java Current (Fig. 1). The heat and water exchange between the Indian and Pacific Oceans takes place through the ITF, which increases the surface temperature in the eastern Indian Ocean (Gordon et al., 2003).

Hole 757B was located at 45° S at a water depth of 1500 m in the early Eocene (~50 Ma), and at 29° S in a temperate region near the subtropical convergence zone at a water depth of 1500 m across the Oligocene-Miocene boundary (~23.5 Ma) (Peirce et al., 1989). This site shifted to 21° S at ~10 Ma and to 18°30' S at ~5 Ma (Peirce et al., 1989). Thus paleolatitude study suggests that Site 757 was close to the present day location by ~10 Ma (Peirce et al., 1989) under the influence of the Indian monsoon that began to intensify around that time (Kroon et al., 1991). The deep water mass in the vicinity of Hole 757B may have been of Pacific origin during the Miocene to the early Pliocene because the deep Indonesian passage was open during that time.

Indonesian Seaway and the Indonesian Throughflow

Transport of water from the Pacific Ocean to the Indian Ocean through the Indonesian seaway is accomplished mainly in the thermocline layer which is drawn from the North Pacific (Gordon and Fine, 1996). Whereas the surface and thermocline components of the ITF move towards the Indian Ocean without significant impedance by topography, below thermocline depths numerous sills separating the basins of the Indonesian seas impede throughflow. The lower thermocline and deeper water is more saline and of South Pacific origin (Gordon and Fine, 1996). The deepest link between the Indian Ocean and Indonesian seas and bulk of transport of Indonesian Sea water occurs in the vicinity of Timor involving an array of passages along the Timor Passage and across the Outer Banda Arc (Gordon et al., 2003). Fieux et al. (1996) suggested a sill depth near Timor at 1200-1300 m, whereas Van Anken et al. (1988) found a sill near 1450 m. The cooler, more saline and better oxygenated deep water in Timor Passage below 1500 m is derived from the Indian Ocean (Fieux et al., 1996). Exchange between Banda and Timor Seas is blocked below 1450 m.

The volume and composition of ITF waters have varied through time. An open connection between the Pacific and Indian Oceans existed through Tethys prior to the Miocene (Martine and Scher, 2006).The destruction of the Tethys led to the progressive restriction of the seaway from the early to the late Miocene. The deep pathways between the Pacific and Indian Oceans largely closed in the latest Miocene at ~6 Ma (Nishimura and Suparka, 1997), and the Indonesian seaway finally constricted in the early Pliocene 4-3 Ma that led to a switch in the source of thermocline water from the South Pacific to the North Pacific Ocean (Cane and Molnar, 2001). The closing of deep connections between the Pacific and Indian Oceans may have driven significant changes in the thermohaline circulation and deep-

sea biota of the eastern Indian Ocean, as well as regional climatic shifts.

Materials and Methods

We analyzed 194 samples of 10 cc volume spanning the past 26.5 Ma after processing with the standard methods as given in Gupta and Thomas (1999). Core samples were soaked in clean water with half spoon of baking soda for 8-12 hours. Wet samples were washed over a 63 μm size sieve, dried in an electric oven at ~50°C temperature and transferred into labeled glass vials. Processed dry samples were split into suitable aliquots to obtain ~300 specimens of benthic foraminifera from >125 μm size fraction. This size fraction allows a comparison with numerous studies on deep-sea benthic foraminifera and water masses carried out on sediments from different ocean basins. Specimens of benthic foraminifera were identified up to species level, counted and their percentages were calculated. Dominant species with at least 10% or more population in any given sample are plotted combined with published Nd isotope data of fish teeth from Hole 757B (Martin and Scher, 2006) in Figs. 2-3. Preservation of benthic foraminifera was good throughout the studied interval. Interpolated ages for each sample are based on nannofossil datums of Peirce et al. (1989) and updated to Berggren et al. (1995). The average time resolution per sample is ~137 Kyr based on interpolated ages.

Deep-sea Benthic Foraminifera and their Environments

Benthic foraminifera are an important constituent of deep-sea environments living at all depths up to carbonate compensation depth and at all latitudes from tropics to poles. Because of their good fossilization potential, benthic foraminifera are reliable proxy to understand nature of deep water masses in the geologic past. Numerous studies provide an insight into the factors controlling the distribution of benthic foraminifera (Herb, 1971; Streeter, 1973; Schnitker, 1974; Lohmann, 1978; Corliss, 1979; Thomas, 1992; Hermelin and Shimmield, 1995; Gupta, 1994; Smart and Murray, 1994; Gupta and Thomas, 1999, 2003). Some studies suggest that distribution patterns of benthic foraminifera are closely related to organic carbon flux or organic carbon content of sediments (Miller and Lohmann, 1982; Altenbach and Sarnthein, 1989; Gooday, 1988, 1993; Schmiedl et al., 1997; De Stigter et al., 1998). Other studies emphasize on sensitivity of benthic foraminifera to oxygen levels of the bottom water and pore water oxygenation (Corliss, 1985; Sen Gupta and Machain-Castillo, 1993; Gooday, 1994; Loubere, 1996; Jannink et al., 1998). Benthic foraminifera occupy perched epibenthic to deep infaunal microhabitats and utilize diverse trophic mechanisms (De Stigter et al., 1998; Corliss, 1985). Their good fossilization potential and often considerable population make them useful tool in paleoceanographic and paleoclimatic studies.

The environmental preference of *Cibicides cicatricosus* is not well constrained. This species has been found associated with various biofacies indicative of different environmental condition in the southeastern Indian Ocean (Singh and Gupta, 2004). The species has numerous large size pores on its spiral side which suggest preference of this species to more oxygenated condition.

Cibicides pseudoungerianus, a species closely resembling *C. ungerianus*, is known to be intolerant to low-oxygen conditions (Barmawidjaja et al., 1992; den Dulk, 2000) and is typical of upper bathyal depths (700 and 2000 m) where water temperature is higher than 2.5-3°C and carbon flux >2.5 g C m^{-2} year^{-1} (Altenbach et al., 1999; Murgese and De Deckker, 2005). According to Barbieri (1998), it is typical of neritic to bathyal depths while Spencer (1996) correlated it with bathyal settings. This species is inferred to indicate high oxygen and low organic carbon condition.

Cibicides wuellerstorfi has been considered as a raised epibenthic species that prefers to live in high energy environments (Lutze and Thiel, 1989; Mackensen et al., 1995). In the Arctic Basin and in the Norwegian-Greenland Sea, the high abundance of this species has been suggested to reflect scarcity of food particles in the sediment (Linke and Lutze, 1993). As a suspension feeder and elevated epibiont, *C. wuellerstorfi* can survive on low organic carbon levels and can withstand strong bottom currents (Linke and Lutze, 1993). Loubere and Fariduddin (1999) considered it an indicator of high seasonal food supply under oligotrophic conditions. In the Indian Ocean, *C. wuellerstorfi* and *N. umbonifera* have been found associated with AABW (Corliss, 1979, 1983; Bremer and Lohmann, 1982), whereas in the Atlantic and Southern Oceans, *C. wuellerstorfi* has been associated with young, well-oxygenated water masses like NADW (Mackensen et al., 1995; Schmiedl and Mackensen, 1997; Gooday, 2003). Thus, *C. wuellerstorfi* can endure low organic carbon levels and strong bottom currents as a suspension feeder and an elevated epibiont (Linke and Lutze, 1993). Gupta (1997) relates this species with the oxygenated, strong bottom currents and strongly pulsed food supply in the Indian Ocean.

Ehrenbergina carinata thrives in high temperature, low oxygen and high nutrient levels (Nomura, 1991; Gupta and Satpathy, 2000). Gupta et al. (2006) suggested that *E. carinata* is indicative of intermediate to high flux of organic matter and low oxygen condition in the central Indian Ocean. At Hole 757B, this relationship does not hold true.

Epistominella exigua is an epibenthic, cosmopolitan, abyssal species, which feeds opportunistically on phytodetritus deposited seasonally on the sea floor (Gooday, 1988; Gooday and Turley, 1990; Smart and Murray, 1994; Thomas et al., 1995). Loubere and Fariduddin (1999) suggested that this species is most abundant at highly seasonal food fluxes that occur more than once a year (e.g., spring and fall blooms). This species reflects intermediate to high flux, high seasonality and well-oxygenated condition in tropical and northeastern Indian Ocean (Gupta and Thomas, 2003; Gupta et al., 2008). Murgese and De Deckker (2005) suggested that this species prefers a cold and well-oxygenated environment, where carbon flux to the sea floor is low. This species is indicative of high oxygen, low organic carbon, and high seasonality condition.

Globocassidulina subglobosa is a cosmopolitan species occurring over a wide range of bathymetry and in association with a number of different water masses. Fariduddin and Loubere (1997) observed this species associated with the NADW in the Atlantic Ocean and categorized it as a low-productivity species. In the South Atlantic, high abundances of *G. subglobosa* occur within the depth range of Circumpolar Deep Water (CDW) and in oligotrophic areas at higher elevations of ridges and submarine hills (Schnitker, 1980; Mackensen et al., 1995). In the South China Sea, *G. subglobosa* was observed tolerating warm waters (Miao and Thunell, 1993). In the southeastern Indian Ocean, *G. subglobosa* has been found associated with the
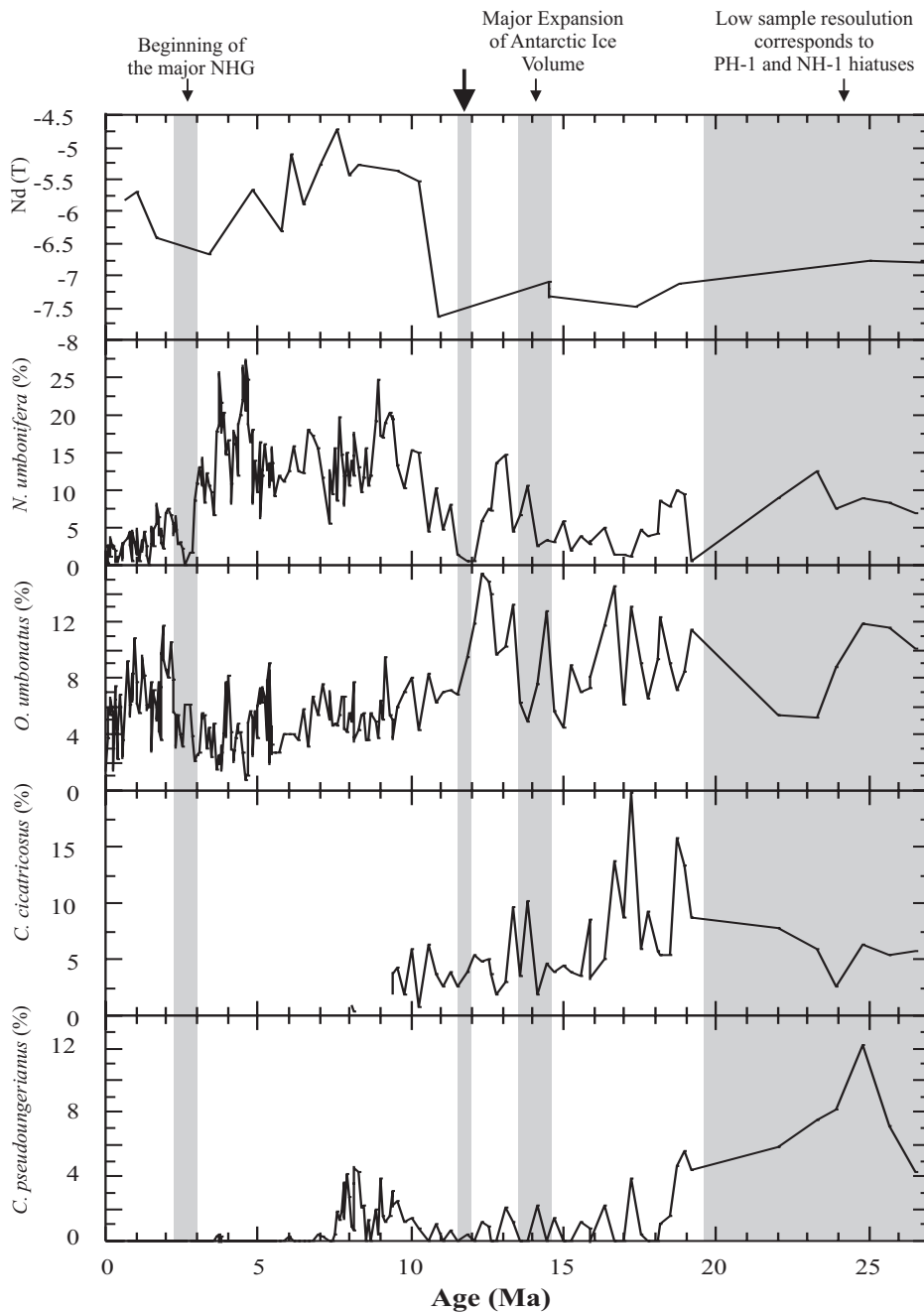
Figure 2. Percent distribution of **Cibicides pseudoungerianus, Cibicides cicatricosus, Oridorsalis umbonatus** *and* **Nuttallides umbonifera** *at Hole 757B combined with Neodymium (Nd) isotope values (Martin and Scher, 2006).* **Nuttallides umbonifera** *and Nd isotope values show a major increase at ~11.5 Ma (thick arrow), during which time* **Oridorsalis umbonatus** *decreased indicating substantial transport of cold, corrosive deep Pacific flow to the Indian Ocean.* **Nuttallides umbonifera** *shows a major decrease whereas* **Oridorsalis umbonatus** *shows an increase during 3-2.8 Ma indicating a substantial reduction or complete shutdown of deep water from the Pacific. We do not see a major change in Nd isotope values during 3-2.8 Ma owing to low sample resolution or constriction of the Indonesian Throughflow.*

where strong bottom currents are likely to occur (Schmiedl et al., 1997). Singh and Gupta (2004) suggested that this species reflects well-oxygenated deep waters having strongly pulsed food supply and good carbonate preservation in commonly oligotrophic environments in the southeastern Indian Ocean. At Hole 757B, this species is inferred to indicate high oxygen and low organic carbon water mass similar to CDW or NADW.

The environmental preferences of *Nuttallides umbonifera* have widely been debated. The species has been inferred to be an indicator of AABW (Streeter, 1973; Lohmann, 1978; Mackensen et al., 1995), but this relation is not visible in the southeastern Atlantic Angola Basin (Van Leeuwen, 1989). Bremer and Lohmann (1982) have linked abundant occurrences of this species to the presence of corrosive bottom water or AABW, whilst others have interpreted it as an indicator of low food supply (Gooday, 1994; Loubere and Fariduddin, 1999). Since the AABW is well-oxygenated and occurs at greater depths in the modern oceans, the relatively lesser amount of organic carbon reaching these depths can be easily oxidized, and the CO_2 produced by oxidation causes carbonate corrosiveness (Gupta, 1997). Considering all published studies, we suggest that *N. umbonifera* has a stronger relation with carbonate corrosivity than any other environmental factor.

Oridorsalis umbonatus is a long ranging species, which lives in a variety of environments (Gupta, 1990; Miao and Thunell, 1993; Schmiedl and Mackensen, 1997; Gupta and Thomas, 1999). It is an important cosmopolitan taxon of lower bathyal and abyssal faunas associated with AABW in the Indian Ocean (Corliss, 1979; Gupta, 1994), in the Atlantic (Streeter and Schackleton, 1979) and in the Antarctic (Uchio, 1960). In the Sulu Sea, this species reflects low organic carbon and higher carbonate saturation levels of the bottom waters, having a positive relation with carbonate saturation levels (Miao

AABW (Corliss, 1979). This species has also been suggested to feed on phytodetritus (Gooday, 1994) and a pulsed food supply to the seafloor in the northeastern Indian Ocean (Gupta and Thomas, 2003). Ohkushi et al. (2000) suggested that *Globocassidulina* lives in areas with enhanced, continuous food supply. This taxon is often found abundant in the sediments receiving lower organic matter in the regions

and Thunell, 1993). Mackensen et al. (1995) consider *Oridorsalis* to be living in well-oxygenated, low organic carbon deep-sea conditions, whereas Kaiho (1999) considered *Oridorsalis* to be an indicator of suboxic bottom waters. Rathburn and Corliss (1994) reported it in a transitional infaunal microhabitat, capable of surviving in a food-limited and low oxygen condition.
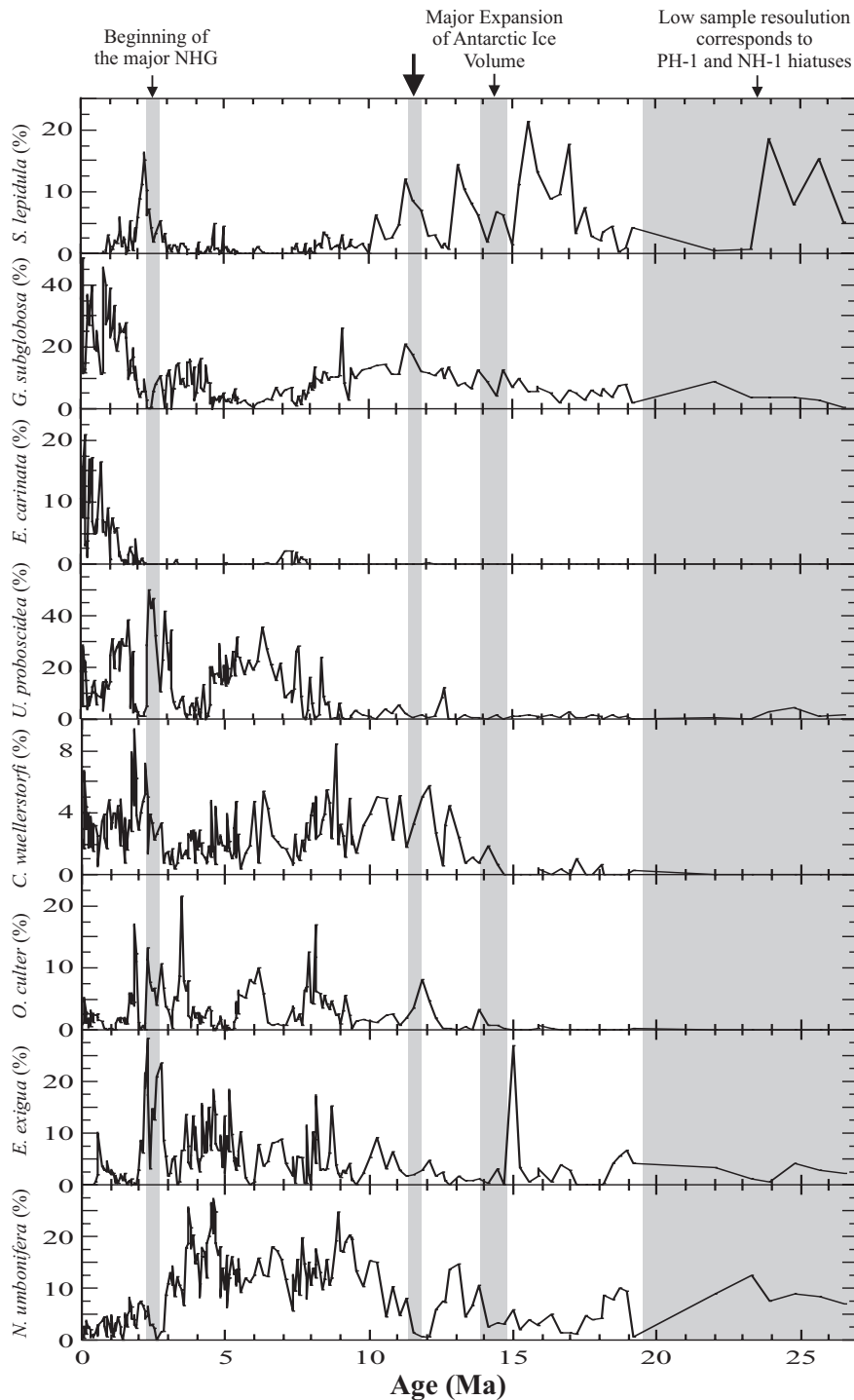
Figure 3. Percent distribution of **Nuttallides umbonifera, Epistominella exigua, Osangularia culter, Cibicides wuellerstorfi, Uvigerina proboscidea, Ehrenbergina carinata, Globocassidulina subglobosa** *and* **Stilostomella lepidula.** *An increase in* **Ehrenbergina carinata** *and* **Globocassidulina subglobosa,** *and major decrease in* **Nuttallides umbonifera** *population during 3-2.8 Ma suggest waned influence of Pacific/Indonesian deep waters and increased influence of the North Atlantic Deep Water, coinciding with major increase of the Northern Hemisphere glaciation.*

(Gupta, 1994). Gupta and Thomas (1999) found assemblages of *Cibicides bradyi* and *Osangularia culter* to be indicative of low oxygen environment with warm water and intermediate to continuous food supply in the Indian Ocean, whereas Singh and Gupta (2004) reported this species from well-oxygenated deep water with low organic flux and high seasonality. This species is inferred to indicate better oxygenation and low organic carbon condition.

Stilostomella lepidula is a cosmopolitan taxon, which reflects complicated ecological preferences that are yet to be fully understood. Boersma (1990) suggested that *S. lepidula* prefers to live in sediments that are organic carbon rich and moderately low in oxygen. Gupta and Thomas (2003) found this species associated with intermediate to high flux of organic food and intermediate seasonality. This species became extinct across the mid-Pleistocene Transition, which has further complicated our understanding of its ecological preference (Gupta, 1993; Kawagata et al., 2006, Bhaumik et al., 2008). Kaiho (1999) suggested that species of *Stilostomella* group are good indicator of low oxygen and high organic carbon deep-sea conditions. Thomas et al. (1995) also suggested that this group is abundant in organic rich areas. Bhaumik et al. (2008) linked *S. lepidula* disappearance across the mid-Pleistocene Transition to intense cold intervals with deep-sea strong currents.

Uvigerina proboscidea occupies a shallow infaunal microhabitat in organic carbon rich sediments, independent of oxygenation (e.g., Rathburn and Corliss, 1994) and blooms in high productivity regions (e.g., Gupta, 1997; Jannink et al., 1998; Gupta and Thomas, 1999; Gupta et al., 2004), specifically when productivity is high year-round and seasonality of the food supply is low or absent (Loubere, 1998; Ohkushi et al., 2000). This species is most abundant during the late Neogene at several sites in the Indian Ocean and its peak abundances have been inferred to represent times of high surface productivity related to intensified trade winds during strong southwest Indian monsoon that causes widespread upwelling along equatorial divergence in the Indian Ocean (Gupta and Thomas, 1999; Gupta et al., 2001). Murgese and De Deckker (2005) suggested that the distribution of *U. proboscidea* is mainly limited to low latitudes (north of 25 °S) at depths 700 to 2000 m where carbon flux rate is high (=3.5 g C m^{-2} year^{-1}) owing to higher primary productivity levels at the sea surface, and low oxygen levels (<3 ml/l) due to the organic matter oxidation and the presence of oxygen-depleted Indonesian Intermediate Water and North Indian Intermediate Water. The highest abundance of this

Schmiedl et al. (1997) observed *Osangularia culter* in high oxygen and low food condition in the south Atlantic. However, there is not much known about this species from the Indian Ocean although it has been found associated with *Cibicides wuellerstorfi,* a species preferring pulsed food supply and well-oxygenated conditions

species is between 1700 m and 2300 m in the eastern Indian Ocean (Gupta, 1994).

Results and Discussion

Deep-sea benthic foraminifera show major shifts at Hole 757B, indicating important changes in properties of intermediate to deep waters in the eastern Indian Ocean during the Neogene. Benthic foraminifera underwent first major reorganization during 14.5-11.5 Ma coinciding with major expansion of the Antarctic ice sheets (Savin et al., 1981) and major increase in deep flow from the Pacific through the Indonesian seaway (Martin and Scher, 2006). In general, high oxygen, low-organic carbon species like *Cibicides cicatricosus, Cibicides pseudoungerianus* and *Oridorsalis umbonatus* show higher abundances in the late Oligocene and early Miocene (~26.5-16 Ma) punctuated by intermittently higher occurrences of *Stilostomella lepidula* (Figs. 2 and 3). *Cibicides cicatricosus* and *C. pseudoungerianus* disappeared whereas *Stilostomella lepidula* suffered a major population loss in the early late Miocene during ~ 12-10 Ma, coinciding with a major decrease of *O. umbonatus* population (Fig. 2). *Nuttallides umbonifera* shows first increase at ~14 Ma, and a major stepwise increase during 12-11 Ma (~ 11.5 Ma) during which time *S. lepidula* shows a major decrease (Figs. 2 and 3). *Nuttallides umbonifera* and *S. lepidula*, in general, show opposite trends. *Cibicides wuellerstorfi* shows a major increase ~14 Ma coinciding with major expansion in Antarctic ice volume (Savin et al., 1981), although this species first appeared at Hole 757B in the early Miocene (Fig. 3). *Uvigerina proboscidea* depicts a major increase at ~8 Ma coinciding with major intensification of the Indian monsoon (Kroon et al., 1991) (Fig. 3). Benthic fauna underwent a major reorganization following the NHG. For instance, *Nuttallides umbonifera* shows a stepwise decline beginning at ~3.6 Ma with lowest values during ~3-2.8 Ma, and remained insignificant thereafter. *Oridorsalis umbonatus*, *Globocassidulina subglobosa* and *Ehrenbergina carinata*, on the other hand, show an increase following the NHG (Figs. 2 and 3).

At ~11 Ma, Nd isotopic values increase sharply and remained higher until 5.5 Ma at Site 757 (Fig. 2). The high Nd isotopic values during 11-5.5 Ma have been linked to extensive flow of deep ITF water from the Pacific to the Indian Ocean through the Indonesian seaway and its influence in the area of studied site (Martin and Scher, 2006). This suggests that plate motions had carried the studied site into a region with increased influence of deep ITF and waned influence of southern source water like AABW or Antarctic Intermediate Water (AAIW) at ~11 Ma (Martin and Scher, 2006). The benthic faunal data from Hole 757B, including higher *N. umbonifera, E. exigua* and *O. culter* populations during this time, support observation of Martin and Scher (2006). The cold, corrosive, oligotrophic and better oxygenated deep water from the Pacific Ocean appears to have increased *N. umbonifera* population at 11.5 Ma. We do not expect the role of AABW in modulating *N. umbonifera* population at ~11.5 Ma for following reasons: (1) Hole 757B was quite shallow well above the influence of AABW, (2) paleolatitude of this hole shows its position close to the present day location, (3) the major expansion of Antarctic glaciation and intense production of AABW occurred much before this increase at ~ 14 Ma than the major increase of *N. umbonifera* population at ~11.5 Ma, and (4) the Indonesian seaway was wide open and there was unobstructed transport of

intermediate to deep ITF from the Pacific to the Indian Ocean. However, whether this intermediate to deep Pacific water mass was of southern origin remains speculative.

During 5.5-3.4 Ma, the low Nd isotope values do not match with low *N. umbonifera* percentages at Hole 757B. Rather, *N. umbonifera* continues to show increased abundance until 3.6 Ma and thereafter it sharply declines (Fig. 2). This mismatch between the two records can be explained by low sample resolution in the study of Martin and Scher (2006) or related to the beginning of constriction of the Indonesian seaway. A sharp decrease in *N. umbonifera* percentages during ~3-2.8 Ma suggests substantial reduction or complete shutdown of the Pacific intermediate to deep water flow (deep ITF) to the Indian Ocean through the Indonesian seaway. The reduction of the ITF during 3-2.8 Ma perhaps facilitated increased incursion of NADW in the eastern Indian Ocean, as suggested by increased *C. wuellerstorfi*, *G. subglobosa* and *E. carinata* abundances during this time (Fig. 3).

Conclusions

The Indonesian Throughflow has played an important role in modulating heat and fresh water budget of the Indian and Pacific Oceans that has driven significant regional and global climate variability during the late Neogene. The benthic foraminiferal data from ODP Hole 757B suggest a major increase in transport of intermediate to deep Indonesian Throughflow (ITF) waters (high *Nuttallides umbonifera* and Neodynium isotope values) from the Pacific to the Indian Ocean at ~11.5 Ma. An abrupt decrease in *Nuttallides umbonifera* during 3-2.8 Ma suggests a significant reduction/complete shutdown of intermediate to deep Pacific water to the Indian Ocean, coinciding with the final closure of the Indonesian seaway. During this time *Cibicides wuellerstorfi*, *Ehrenbergina carinata* and *Globocassidulina subglobosa* show a major increase at Hole 757B, suggesting increased influence of the North Atlantic Deep Water in the eastern Indian Ocean.

Acknowledgements

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Annexure 1

List of species used in the present study with their full references

Cibicides cicatricosus = *Anomalina cicatricosa* Schwager, 1866, "Novara" Exped., Geol. Theil., 2: p.260, pl.7, fig. 108

Cibicides pseudoungerianus = *Trucatulina pseudoungerianus* Cushman, 1922, p. 97, pl.20, fig. 9.

Cibicides wuellerstorfi = *Anomalina wuellerstorfi* Schwager, 1866, "Novara" Exped., Geol. Theil., 2(1): p.258, pl.7, fig. 105

Ehrenbergina carinata = *Ehrenbergina carinata* Eade, 1964, New Zealand Jour. Marine and Freshwater Res., 1(4): p. 448, Figs. 8(9), 9(1-4)

Epistominella exigua = *Pulvinulina exigua* Brady, 1884, Rept. Voy. H.M.S. challenger, Zool., no.9, p. 696, pl.103, figs. 13,14

Globocassidulina subglobosa = *Cassidulina subglobosa* Brady, 1884, Rept. Voy. H.M.S. challenger, Zool., no.9, p. 430, pl.54, figs. 17a-c

Nuttallides umbonifera = *Pulvinulinella umbonifera* Cushman, 1933, Contr. Cushman Lab. Foram. Res., 9(4), p. 90, pl.9, fig. A-C

Oridorsalis umbonatus = *Rotalina umbonata* Reuss, 1851, Zeitschr. Deutsh. Geol. Ges., 3: p. 72, pl.5, fig. 32,

Osangularia culter = *Planorbulina culter* Parker and Jones, 1865, Roy. Soc. London, Philos. Trans., 155: p. 421, pl. 19, fig. 1

Stilostomella lepidula = *Nodosaria lepidula* Schwager, 1866, "Novara" Exped., Geol. Theil., 2: p.210, pl.5, fig. 27, 28

Uvigerina proboscidea = *Euvigerina proboscidea* Schwager, 1866, "Novara" Exped., Geol. Theil., 2: p.250, pl.7, fig. 96

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Anil K. Gupta, Professor at the Indian Institute of Technology, Kharagpur, has extensively worked on Neogene foraminifera from Ocean Drilling Program (ODP) cores to understand paleoceanographic and paleoclimatic changes in the Indian Ocean with special reference to the Indian monsoon. Dr. Gupta has innovatively used deep-sea benthic foraminifera as well as planktic foraminifera to understand Indian monsoon variability and its impact on surface and deep ocean.