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Pliocene Indonesian Throughflow change and planktic foraminiferal diversity in the eastern subtropical Indian Ocean

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The opening and closing of seaways due to plate tectonic movement strongly influenced the past oceanic circulation patterns which have their influence on the past climate and faunal record. The considerable restructuring of one such seaway, Indonesian seaway, took place during Pliocene (4–3 Ma). This would have changed the source of Indonesian Throughflow (ITF) from warm and saline south Pacific waters to the north Pacific cool and relatively fresh waters. In the present study, three indices of diversity (Shannon-Wiener Index; $H(S)$, equitability; E' and alpha index; α) at ODP sites 762B and 763A in the eastern subtropical Indian Ocean are calculated to better understand the role of ITF on Pliocene surface hydrography and planktic foraminiferal diversity. A major interval of early Pliocene demonstrates more diverse fauna and low abundance of fertile taxa along with increased planktic Mg/Ca ratios. Strong influence of warm ITF waters due to broad and open seaway until the end of early Pliocene, increased the sea surface temperature (SST) and depth of thermocline in the Leeuwin current area of eastern subtropical Indian Ocean. This would have been responsible for more vertical niche partitioning of surface water and thus, higher planktic foraminiferal diversity. The significant decline in faunal diversity between critical interval of ~3.5 and 3 Ma (beginning of Late Pliocene) is suggested to be the response of fall in SST and increase in surface water productivity possibly due to relatively less influence of ITF waters in the eastern Indian Ocean as a consequence of significant constriction of Indonesian Seaway.

Keywords: Diversity, Indian Ocean, Indonesian Throughflow, Pliocene, planktic foraminifera.

THE climatic systems during most of the Cenozoic are significantly influenced by opening and closing of various seaways due to the drifting of continents[1]. Significant changes in the circulation during the Pliocene as a result of several tectonic rearrangements in the tropics are believed to be the major causal mechanism for plunging the world into an ice age with well-known northern

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Hemisphere Glaciations[2,3]. The interval of this climate shift was also accompanied by the Indonesian seaway constriction between 4 and 3 Ma resulting in a switch in the source of throughflow from warm, saline south Pacific to cooler and fresher north Pacific waters as reflected by a fall of SST in the eastern subtropical Indian Ocean[4,5].

A part of Indonesian Throughflow (ITF) water joins the westward flowing South Equatorial Current (SEC), and another part flows southward along the west coast-off Australia as Leeuwin Current (LC), which is dominantly responsible for the poleward heat transport in Indian Ocean[6]. The LC transports warm, less saline tropical waters from ITF region to southward in the eastern subtropical Indian Ocean off western Australia and restrains the upwelling in spite of predominant equator ward winds[7,8]. Beneath the LC more saline waters are transported northward by the cold Western Australian Current (WAC). The seasonal cycle of southeastward flowing South Java Current (SJC) may also influence the water mass balance in this region. The main objective of the present study is to better understand the influence of changing climatic conditions due to switch of ITF waters on the planktic foraminiferal diversity in the eastern subtropical Indian Ocean during the Pliocene.

The present study is based on the planktic foraminiferal data spanning the time interval of last 6.5 Ma from ODP sites 762B (19°53.24′S, 112°15.24′E, 1360.0 m water depth) and 763A (20°35.20′S, 112°12.50′E, 1367.5 m water depth) in the eastern subtropical Indian Ocean under the influence of the present day Leeuwin Current (LC) (Figure 1)[9]. A total of 156 core samples (76 samples at site 762B from 108.9 m and 80 samples at site 763A from 109.4 m thick sequence) have been analysed to generate the faunal census data. Approximately 10 cm^3 of each sample was treated with a mixture of one part of dilute (5%) hydrogen peroxide (H_2O_2) solution and three part of water until the complete disintegration of clays. It was then wet-sieved using Tyler sieves over 63 μm and 149 μm size fraction. The concentration of H_2O_2 solution is too weak (<2%) for any kind of destruction of the calcareous test of planktic foraminifera. After drying, the washed sample of >149 μm size fraction was divided with the help of a microsplitter into a portion expected to have nearly 300 specimens of planktic foraminifera. The study produced census data from the split samples by picking and mounting all the planktic foraminifera on faunal assemblage slides. The planktic foraminiferal census data was utilized to calculate three different diversity parameters in terms of Shannon–Wiener Index [$H(S)$], equitability (E') and alpha index (α).

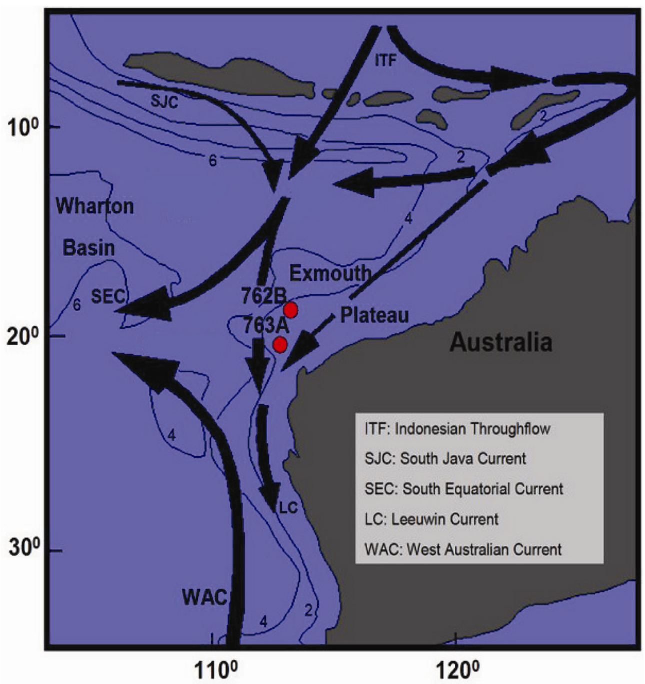

Figure 1. Location of ODP sites 762B and 763A in the eastern Indian Ocean with major surface and subsurface currents affecting the region. Depth contours are in kilometers (from Rai and Singh[17]).

$H(S)$ takes into account both the total number of species and their relative abundance to provide better understanding about species richness and evenness in distribution. The equation given by Buzas and Gibson[10] has been utilized to estimate equitability (E'). The α-index was initially explained by Fisher *et al.*[11] to calculate the species richness. The value of α-index usually helps to explain the change in pattern of foraminiferal species richness[12]. We calculated α-index following Williams[13].

The mathematical expressions for these indices are: Shannon–Wiener diversity index [$H(S)$]

$$H(S) = -\sum_{i=1}^{S} pi \ln pi,$$

where S shows the total number of the planktic foraminiferal species in the given sample and pi shows the fraction of the ith species in the sample. More diverse fauna is represented by higher values of $H(S)$ in the sample which also shows more even distribution of species in population. Thus, the value of $H(S)$ helps to know the number of species and about how among all the species of a community the abundance of different species is distributed.

Equitability (E')

$$E' = e^{H(S)}/S,$$

where S shows the total number of species present in the sample and e represents the base of natural (Naperian) logarithms. E' explains the relation between dominant and rare species of total population in better ways. The values of equitability varies between 0 and 1, where 1 represents complete evenness.

Alpha index (α)

$$S = \alpha \log (1 + [N/\alpha]),$$

where N is the number of individuals and α is a constant that can also be utilized as an index of diversity[11].

The sum of percentages of *Globigerina bulloides*, *Globigerina falconensis*, *Globigerinita glutinata* and *Neogloboquadrina dutertrei* is considered as 'fertile' taxa which respond strongly to the increase in surface water productivity[14–16]. The relative abundance of fertile planktic foraminifera was also compared with foraminiferal diversity. We also used the published *Globigerinoides sacculifer* Mg/Ca record of ODP site 763A from Karas *et al.*[5]. In this study, we followed the age-depth model by Rai and Singh[17] for ODP site 762B and planktic foraminiferal biochronology for ODP site 763A developed by Sinha and Singh[18]. Time-series plots of various diversity measurements [$H(s)$, E' and α] are shown in Figures 2 and 3.

The three different foraminiferal diversity indices [$H(s)$, E' and α] show closely similar pattern of variation during past ~6.5 Ma at both the sites examined (Figures 2 and 3). In general, values of various diversity indices

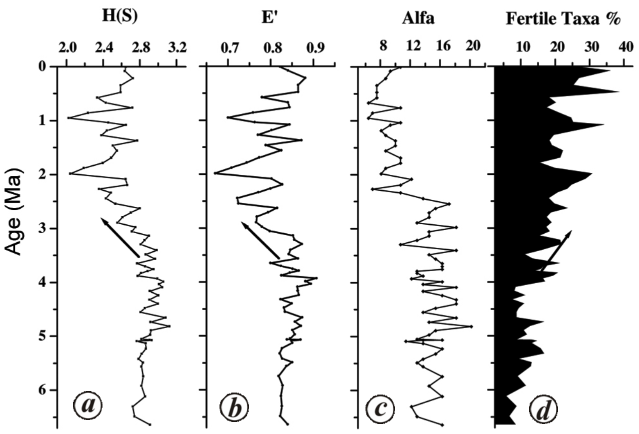

Figure 2. Time series plots of the values of (***a***) Shannon–Wiener index, $H(S)$; (***b***) equitability, E'; (***c***) alpha index, α; (***d***) percentage of fertile planktic foraminiferal taxa at ODP site 762B.

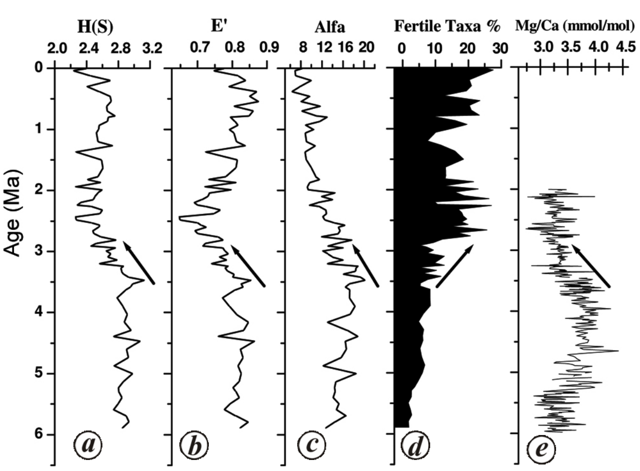

Figure 3. Time series plots of (***a***) Shannon–Wiener Index, $H(S)$; (***b***) equitability, E'; (***c***), alpha index, α; (***d***) percentage of fertile planktic foraminiferal taxa; (***e***) *Globigerinoides sacculifer* Mg/Ca records (Karas *et al.*[5]) at ODP site 763A.

remain persistently high during ~6.5–3.5 Ma at both sites (Figures 2 and 3). These species diversity indices show distinct decrease in their values at the beginning of late Pliocene between 3.5 and 3 Ma. Within this critical time interval of 3.5–3 Ma percentage of fertile planktic foraminiferal taxa started increasing significantly at both sites. At site 763A Karas *et al.*[5] also recorded noticeable decrease in the planktic Mg/Ca record at ~3.5 Ma which remained low during rest of the younger section (Figure 3). The Pleistocene period (last ~2 Ma) is marked with relatively low H(S) and α values whereas E' shows moderately higher values at both the sites. The relative abundance of fertile planktic taxa also remains high during most of the Pleistocene with some marked fluctuations.

Diversity of planktic foraminifera has been used in several quantitative paleoecologic interpretations (e.g. Ottens[19]). Earlier, Stehli[20] and Balsam and Flessa[21] suggested that diversity of planktic foraminifera is influenced by sea surface temperature and surface ocean circulation systems. In general, diversity of many marine organisms increases from high to low latitudes. Rutherford *et al.*[22] have noted that the planktic foraminiferal diversity is related to the structure of the upper-water column (the thermocline depth) rather than to sea-surface temperature (SST). The thermal structure of the near-surface ocean is responsible for the availability of niches for floating plankton, and may thus control their diversity[22,23]. However, increase in SST towards the equator is accompanied by a proportional increase in surface-water stratification. A thermocline with a gradual temperature change and a deep base may provide more niches per unit surface area than a thermocline with quick temperature change and a shallow base. The value of species diversity reaches to the minimum at high latitudes because of the near absence of thermocline and minute vertical partitioning of niches. The broad, permanent thermocline due to higher SST at middle latitudes is responsible for considerably high species diversity. In addition, planktic foraminiferal diversity can also be associated with surface water productivity[24]. The value of $H(S)$ of the Arabian Sea planktic foraminifera in the upwelling regions remains relatively low than in the non-upwelling regions[19].

The faunal diversity record during early Pliocene until ~3.5 Ma shows long-term increased values which correspond with low abundance of fertile planktic foraminiferal taxa indicating more oligotrophic condition. The higher values of planktic foraminiferal Mg/Ca ratio at ODP site 763A[5] during most of the early Pliocene reflect increased SST in the region. The ITF was mainly fed from warm south Pacific waters possibly due to better open Indonesian seaway during early Pliocene[4,25,26]. Most of the early Pliocene (before ~3.5 Ma) is suggested to reflect considerably higher SST with deeper thermocline due to which winds were unable to upwell deep, cold and nutrient-rich water to the surface[27]. Sinha and Singh[28] also noted increasing abundance of oligotrophic planktic foraminifers and low abundance of thermocline dweller species during most of the early Pliocene suggesting stratified warm and oligotrophic surface water due to strong Leeuwin Current in the eastern Indian Ocean. Thus, we propose that better surface–water stratification due to deep thermocline provides sufficient space for more niche partitioning which results in more diverse planktic foraminiferal fauna.

The changed tectonic setting of the Indonesian gateway at the beginning of late Pliocene (3.5–3 Ma)[4,26,29] evidently reduced the Leeuwin Current due to decrease in ITF waters[6]. The considerable decline in the planktic Mg/Ca record at ODP site 763A during ~3.5–3 Ma (Figure 3) shows significant drop in surface temperature of LC area in the eastern subtropical Indian Ocean while in the tropical Indian Ocean SST remained constant[5]. This indicates that the reduction in ITF was due to tectonic restriction of the Indonesian seaway and not just cooling as the causal factor. The fall in surface temperature may be responsible for shoaling of thermocline depth which reduced the available space for the vertical niche partitioning. Karas *et al.*[30] also suggest that tectonically driven changes during this critical interval strengthen the global climate change by further shoaling of thermocline in different oceans. We observed higher percentages of fertile planktic foraminiferal taxa at the beginning of late Pliocene (Figures 2 and 3) indicating increased surface water productivity. Rai and Singh[17] also recorded increased abundances of high productivity benthic foraminiferal species, *Uvigerina proboscidea* and total infaunal taxa which correspond with the distinct decline in planktic foraminiferal diversity [*H*(*S*)] at ODP site 762B (Figure 4) signifying the growth of prominent upwelling and enhanced surface productivity. Rai and Singh[17] explained that shoaling of thermocline was responsible for stronger offshore equator ward winds and intense offshore Ekman transport which resulted in upwelling of cold, nutrient-rich deep water and higher surface water productivity at the western coast off Australia in the eastern Indian Ocean.

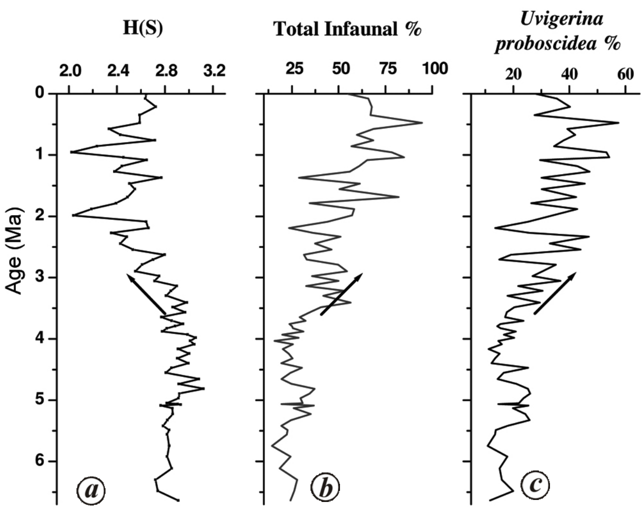

Figure 4. Time series plots of the values of (***a***) Shannon–Wiener Index, *H*(*S*) (present work); (***b***) percentage of total benthic infaunal taxa; and (***c***) percentage of benthic foraminifer, *Uvigerina proboscidea* at ODP site 762B.

The less stratified cold surface water due to shoaling of thermocline and increase in upwelling led surface water productivity is responsible for distinct decline in planktic foraminiferal diversity. We therefore considered the reduction in ITF during 3.5–3 Ma due to significant constriction of Indonesian seaway as a main causate for decline in the species diversity of planktic foraminifera of eastern subtropical Indian Ocean.

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Anthropogenic drivers shift diatom dominance–diversity relationships and transparent exopolymeric particles production in River Ganga: implication for natural cleaning of river water

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We studied the relationships among diatom biodiversity, transparent exopolymeric particles (TEP) and water quality at the confluences of four tributaries of River Ganga (Yamuna, Assi, Varuna and Gomti) during low flow. Diatom abundance changed with concurrent shifts in water chemistry with dominance–diversity curves markedly skewed from a log-normal pattern. Canonical correspondence analysis segregated chloride-loving and calcifilous species from N- and P-favoured taxa. Despite pollution-induced reduction of diatom diversity, TEP production continued to rise plausibly due to dominance transference of TEP producers. However, with further increase in nutrient pollution, TEP declined. Since TEP enhances sedimentation removal of carbon, nutrients and heavy metals, the present study confirms one of the fundamental mechanisms that underline the self-purification capacity of River Ganga and has relevance from a biodiversity/river conservation perspective.

Keywords: Anthropogenic drivers, carbon sequestration, diatoms, transparent exopolymeric particles.

THE relative positions of species along environmental gradients reflect affinities to resources and modifying influences of stressors and disturbances. Ecosystems with high species diversity are relatively efficient in buffering ecological impacts of, for instance, nutrient pollution[1]. Diatom communities, a diverse group of benthic protists in aquatic ecosystems, are modulated by nutrients as well as ionic composition, pH, light and temperature[2–4]. At the same time, diatoms with unique cell-wall composition and potential to produce transparent exopolymeric particles (TEP) help regulating carbon sequestration and removal of nutrients and heavy metals[5].

The role of biodiversity in improving ecosystem stability and recovery is now well-established[6,7], but the

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