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Diachronism in Late Neogene-Quaternary planktic foraminiferal events in Northern and Eastern Indian Ocean: Palaeoceanographic implications

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The First and Last occurrences of planktic foraminiferal species in deep sea cores provide useful biostratigraphic datum planes in the Neogene. We examined the Late Neogene-Quaternary planktic foraminiferal biostratigraphies from DSDP holes 219 and 214 (Northern Indian Ocean) and ODP Hole 763A from the Eastern Indian Ocean. Graphic Correlation amongst these three deep sea cores from Northern and Eastern Indian oceans and subsequent integration with magnetostratigraphy resulted in assessing twenty-five Late Neogene- Quaternary planktic foraminiferal events for their usefulness in biostratigraphic correlation. A Composite Standard Reference Section was developed for the Indian Ocean, representing maximum stratigraphic ranges. Numerical age estimates were made for all the planktic foraminiferal events at the three holes. This resulted in a quantitative assessment of the extent of diachronism. We found that out of twenty-five events, six are synchronous, while nine events are synchronous between any two holes and diachronous at the third hole. Ten events were found to be diachronous. Maximum diachronous events showed the extent of diachronism between 0.4 to 1.2 Ma. The maximum extent of diachronism observed was 2.5 Ma. We divided the events into three categories, which include synchronous, fairly synchronous and diachronous events designated respectively as IO-Cat-1, IO-Cat-2, and IO-Cat-3. The primary cause of diachronsim was found to be water mass preferences of individual species. This study provides the first detailed numerical age estimates, the extent of diachronsim, and its palaeoceanographic implications from the Indian Ocean.

Keywords: Graphic Correlation, diachronism, planktic foraminifera, Indian Ocean, Late Neogene, Quaternary, Palaeoceanography

ARTICLE HISTORY

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INTRODUCTION

The biotic world of planktic organisms, their evolution, speciation and extinctions through geological time recorded in the different parts of the world oceans, also appear to be linked due to the spatial and temporal connectivity of the oceans. This global connectivity has necessitated developing a robust time framework for the deep sea cores recovered from different parts of the world. The availability of a time framework for every deep sea core is an essential prerequisite for reliable stratigraphic correlation and understanding the temporal and spatial connectivity in the geological past, including the cause and effect relationships (Sinha and Singh, 2008). The problems in correlating the palaeoceanographic events from distant parts arise once we venture into older sediments, beyond the scope of radiocarbon dating, where biostratigraphy remains the only method for developing a time framework. Planktic foraminifera have extensively been used for biostratigraphic correlation over long distances in the world oceans owing to their rapid evolution, pelagic habitat and worldwide distribution. With time, the traditional methods of stratigraphic correlation utilizing biostratigraphic zones were gradually replaced by correlation employing biohorizons (Hedberg, 1976). Such biohorizons, when established as being synchronous using integration with other known synchronous events, like magnetostratigraphy or chemostratigraphy, become "chronohorizons" (Spencer-Cervato *et al*., 1994). The planktic foraminiferal Zonal boundaries are based on the First Occurrences (FOs) and Last Occurrences (LOs) of individual species, which were thought to be synchronous (Spencer-Cervato *et al*., 1994). Long-distance biostratigraphic correlation utilizing planktic foraminiferal Zones faced problems due to cross latitudinal and inter-ocean diachronism in planktic foraminiferal events (FOs and LOs). Employing one set of Zones, e.g., Bolli (1957a,b 1966), Banner and Blow (1965), and Blow (1969) to areas outside tropics ran into difficulties because the stratigraphic ranges of the zonal marker species either represented local ranges or the species themselves were absent due to latitudinal provincialism and ecological preferences. Such challenges led to the establishment of separate Zonal schemes for temperate regions (Jenkins, 1967, 1971). Complications came in zonal correlations even within the same latitudinal range in the Atlantic, Pacific, and Indian oceans because of the development of biogeographic provincialities in planktic foraminifera. Such problems due to the biogeographic provinciality delimited the use of Zonal schemes of Jenkins (1967) and Kennett (1973) outside the South Pacific. For the North Atlantic, Poore and Berggren (1975) developed an amended version of the Neogene Zonal Scheme of Kennett (1973). Later Poore (1979) developed a separate zonal scheme for the North Atlantic region. Some zonal schemes were also developed for transitional (mid-latitude) areas (Kennett, 1973). Species specifically inhabiting transitional areas were very few, probably indicating that almost all the evolution was largely centered in either tropical or temperate regions (Kennett and Srinivasan, 1983). Only other zonal scheme for transitional regions was established by Berggreen (1977) for the South Atlantic based on the changing sequence of *Globorotalia*. Separate zonal schemes based on dissolution-resistant Planktic foraminiferal species were erected by Jenkins and Orr (1971, 1972). The planktic foraminiferal zones have been amended from time to time and many syntheses were presented (Srinivasan and Kennett, 1981a, 1981b; Berggren *et al*., 1985a, 1985b; Berggren *et al*., 1995a, 1995b; Sinha and Singh, 2008; Wade *et al*., 2011, Kaushik *et al*., 2020). With growing knowledge about diachronism, the need to assess each planktic foraminiferal event (FO and LO) became imperative. Several workers successfully integrated planktic foraminiferal biostratigraphy with stable isotope stratigraphy, magnetostratigraphy, and astronomically tuned time scale. With the advancements in stratigraphic correlation using stable isotopes and magnetostratigraphy, diachronism became the rule rather than the exception. It is still hard to believe the origin of the old notion that species should appear and become extinct simultaneously throughout the world. All the known and proposed mechanisms for speciation do not presume such priory knowledge about the synchronous appearance and extinction of fossil events worldwide. Biostratigraphy integrated with magnetostratigraphy led to the determination of numerical ages of planktic foraminiferal events. Such studies allowed quantitative estimation of the extent of the diachrony of the planktic foraminiferal events amongst regions, latitudes and oceans (Berggren, 1973, 1992; Berggren *et al*. 1985a, 1985b, 1995a, 1995b; Chaison and Pearson, 1997; Weaver and Raymo, 1989; Srinivasan and Sinha, 1992; Sinha and Singh, 2008; Wade *et al*., 2011, Kaushik *et al*., 2020). Application of Shaw's graphic correlation method (Shaw, 1964) further strengthened our understanding of the diachronism in planktic foraminiferal events, the seat of evolution, migration, etc. Though a number of studies indicated that the observed diachronism shown by planktic foraminifera during Cenozoic was more due to latitudinal provincialism, the fundamental question that has largely remained unanswered to date is about the various causative factors behind the observed diachronism. A presumption is generally made that the ancestors and decedents of the species comprising the lineage belong to the same water mass and have the same ecological preferences. Some studies indicated a gradual shift of the species' habitat from mid-latitudes to lower latitudes before becoming extinct (Jenkins, 1992). If the species' first appearance in a stratigraphic section is evolutionary, it is presumed that the appearance represents a reliable datum. There are instances when the ancestor of a particular species is not found in the stratigraphic section or found in sporadic quantity, then the species is said to have migrated from its native water mass at a later date due to relocation of the habitat itself and the appearance is understood to be migratory in nature. This is one way of interpreting diachronism. Srinivasan and Sinha (1991, 1992) documented diachronism in Late Neogene Planktic foraminiferal events in a North-South transect from the equator to cool subtropical water mass in the Southwest Pacific ocean. Their studies were based on a detailed biostratigraphic investigation of Deep Sea Drilling Project (DSDP) holes drilled during Leg-90. These authors convincingly showed that the first appearance of a species away from its native water mass is stratigraphically younger and thus diachronous. This study demonstrated cross latitudinal diachronism in planktic foraminiferal species. Other relevant contemporary studies on Southwest Pacific were made by Dowsett (1988, 1989a, 1989b) in a series of papers, who also demonstrated cross latitudinal diachronism in Southwest Pacific Late Neogene planktic foraminiferal events. While Srinivasan and Sinha (1991, 1992) demonstrated the diachronism mostly in First Occurrence events, Dowsett's work mainly was based on Last Occurrence events. However, both the studies convincingly demonstrated that the diachronism in the late Neogene planktic foraminiferal events was due to the influence of water mass and latitudinal provincialism.

The present study encompasses planktic foraminiferal biostratigraphic investigations from northern and eastern Indian oceans and the application of the Graphic Correlation Method to investigate the Late Neogene-Quaternary planktic foraminiferal events and categorize them into synchronous, fairly synchronous and diachronous categories and investigate the probable causes of diachronism. Though on one hand, diachronism is a problem for the biostratigraphers, on the other hand, a large database consisting of diachronous planktic events at a global scale has great potential for a better understanding of evolutionary and ecological processes (Spencer-Cervato *et al*., 1994) behind the diachronism. All events have been assessed for their usefulness in biostratigraphic correlation. An attempt has been made to identify palaeoceanographic factors affecting diachronism

MATERIAL AND METHODS

Biostratigraphic data from Northern and Eastern Indian Ocean.

Though the fundamental questions about the causative factors leading to diachronism need a vast database in space and time (e.g., Spencer Cervato *et al*., 1994), the present work tries to answer the questions in a regional context. Three DSDP/ODP holes were selected for understanding diachrony within Late Neogene Planktic foraminiferal events. The holes are situated along a NW-SE oriented transect from 9^0N (Northern Indian Ocean, DSDP 219) through 11^0S (Northern Indian Ocean, DSDP 214) to the southernmost hole at 20^0S (Eastern Indian Ocean, ODP 763A), covering a spread of 30^0 latitudinal space (Fig.1).

Many workers earlier agreed that one of the causes of observed diachronism in planktic foraminiferal events may be the author's taxonomic bias (Spencer–Cervato *et al*., 1994). In the present study, all the biostratigraphies have been based on the taxonomic concept of Kennett and Srinivasan (1983). The biostratigraphy of the DSDP Hole 214 is taken from Srinivasan and Chaturvedi (1984), Srinivasan and Sinha (1992); for DSDP Hole 219 from Srinivasan and Singh (1992), Srinivasan and Sinha (1992); and for ODP Hole 763A from Sinha and Singh (2008). Detail planktic foraminiferal biostratigraphy, zones and sequential order of planktic foraminiferal events are available with taxonomic consistency from all three holes.

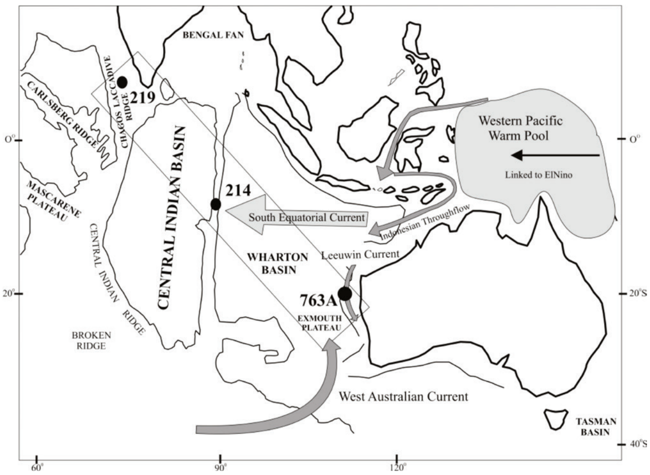


Fig. 1. Location of the DSDP and ODP holes examined for documenting diachronism in Late Neogene-Quaternary Planktic foraminiferal events in Northern and Eastern Indian Oceans. The holes form a latitudinal transect from 9^0N to 20^0S and a longitudinal transect from 72^0E to 112^0E.

Table-1. Depth in meters below the seafloor of each Late Neogene-Quaternary Planktic foraminiferal events at DSDP holes 219, 214 (Northern Indian Ocean) and ODP Hole 763A (Eastern Indian Ocean). NR= Not recorded

Planktic foraminiferal Events	**Types of Events**	**Event Code Used in Graphic Correlation Plots**	**DSDP 214** Srinivasan & Chaturvedi, (1992), Srinivasan and Sinha (1992) Northern Indian Ocean Depth in meters below seafloor	**DSDP 219** Srinivasan & Singh (1992), Srinivasan and Sinha (1992) Arabian Sea Depth in meters below seafloor	**ODP 763A** Sinha and Singh, 2008 Eastern Indian Ocean Depth in meters below seafloor
Globigerinoides obliquus	LO	1	30.51	24.45	14.61
Globorotalia tosaensis	LO	2	11.88	10.95	11.66
Globigerinoides fistulosus	LO	3	19.99	25.95	30.66
Globorotalia truncatulinoides	FO	4	21.54	28.95	43.66
Globorotalia multicamerata	LO	5	24.49	31.95	43.66
Globorotaliar plesiotumida	LO	6	51.40	45.45	49.66
Pulleniatina primalis	LO	7	60.90	48.45	59.16
Globorotalia tosaensis	FO	8	43.40	34.95	59.16
Dentoglobigerina altispira	LO	9	41.98	31.95	64.16
Globigerinoides fistulosus	FO	10	46.40	42.47	70.16
Neogloboquadrina dutertrei	FO	11	27.45	30.51	57.66
Sphaeroidinellopsis seminulina	LO	12	44.90	42.47	72.16
Neogloboquadrina acostensis	LO	13	79.95	57.45	49.66
Pulleniatina obliquiloculata	FO	14	68.90	43.95	71.51
Globorotalia margaritae	LO	15	46.40	42.47	73.65
Sphaeroidinella dehiscens	FO	16	84.45	54.45	81.66
Globorotalia cibaoensis	LO	17	68.90	NR	68.66
Globorotalia crassaformis	FO	18	63.90	45.45	91.13
Globoturborotalita nepenthes	LO	19	67.40	49.95	76.66
Globorotalia.tumida	FO	20	93.43	69.48	98.66
Pulleniatina praecursor	FO	21	82.95	49.95	99.69
Pulleniatina primalis	FO	22	109.33	82.50	106.66
Pulleniatina praecursor	LO	23	NR	33.45	49.66
Globigerinoides extremus	LO	24	NR	18.45	34.16
Globoturborotalita decoraperta	LO	25	NR	31.95	13.16

Oceanographic setting of the investigated holes from the Northern and Eastern Indian Ocean

DSDP Hole 219 was drilled on Leg 23 (Whitmarsh *et al*., 1974) on the crest of the Laccadive- Chagos Ridge ($9^0$1.75 ' N, $72^0$52.67 ' E; water depth 1764 m) in the north-western Indian Ocean, South-eastern Arabian Sea (Fig. 1), near an upwelling zone (Gupta and Thomas, 1999). Based on the occurrence of high organic carbon content in the top 100 meters of sediments at Hole 219, and the presence of pyritic layers and burrows, Whitemarsh *et al*. (1974) indicated that the hole has been experiencing upwelling since the Early Miocene. In post-Early Miocene time, Hole 219 experienced deposition of nanno ooze, mixed with a 20 to 35 percent detrital component. Gradually the hole experienced more and more upwelling. DSDP Hole 214 is located on the Ninetyeast Ridge in the tropical Northern Indian Ocean (Fig.1). The hole lies at a water depth of 1665 m, which is well above calcium carbonate compensation depth and is almost free from any dissolution effect.

A reliable planktic foraminiferal biostratigraphy requires that the hole is free from reworked sediments (Boltovsky 1978). The DSDP Hole 214 is situated under the Equatorial divergence close to the northern boundary of the South Equatorial Current (Tchernia, 1980) and thus is influenced by Indonesian Throughflow (ITF) (Fig.1). Modelling studies suggest that ITF variability has a significant role in ocean heat transport (Cane and Molnar, 2001). The ITF variability is either controlled by sea-level changes in response to glacial stages (Sinha *et al*., 2006; Vleeschouwer *et al*., 2018) or El Niño induced reduction in the Western Pacific Warm Pool (Sinha *et al*., 2006) or due to northward movement of Australian Plate and restricted circulation through the Indonesian Seaway (Srinivasan and Sinha 1998; Cane and Molnar, 2001). ODP Hole 763A is located on the Exmouth Plateau off the western margin of Australia at a water depth of 1367.5 meters and, like the other two holes, has excellent preservation of planktic foraminifera free from reworking (Sinha and Singh, 2008). The hole is influenced by the warm Leeuwin Current flowing from North to South and cold West Australian Current flowing from South to North (Fig.1). The hole is located in the region where equatorward winds dominate like other eastern boundary regions of the world. However, in modern times, the region does not experience any regular, continuous equatorward flow and there is no evidence of coastal upwelling (Smith, 1992). This is due to the nullifying effect of Leeuwin Current (Sinha *et al*., 2006). However, in the Late Neogene-Quaternary, the hole experienced episodes of upwelling related to the weakening of the Leeuwin Current due to either reduction in ITF due to El Niño or due to lowering of sea level as a result of the expansion of the Antarctic ice cap (Sinha *et al*., 2006). These three holes under different oceanographic settings in a North-South and East-West transect have been chosen to compare and contrast the planktic foraminiferal biostratigraphies, estimate numerical ages of the planktic foraminiferal events, and identify synchronous and diachronous events.

Sequential order of Late Neogene –Quaternary planktic foraminiferal events

The biostratigraphic charts for DSDP holes 219 (Srinivasan and Singh, 1992, Srinivasan and Sinha, 1992), 214 (Srinivasan and Chaturvedi, 1992, Srinivasan and Sinha, 1992), and ODP Hole 763A (Sinha and Singh, 2008) provide depth in meters below seafloor for each planktic foraminiferal event (FO and LO).Table-1 provides the depths of the events at all three holes. As expected, the sequential order of the events from old to young is not similar in all the holes due to diachronism.

Graphic Correlation amongst DSDP holes 219, 214 and ODP Hole 763A

Shaw's graphic correlation method (Shaw, 1964) was applied to correlate the three holes. ODP Hole 763A was chosen as Standard Reference Section (SRS). Shaw's graphic correlation is based on finding the maximum stratigraphic range of the fossil species in a region. Initially, a Standard Reference Section (SRS) is chosen amongst the sections to be correlated. The SRS should be a section free from hiatuses, should have a good sediment accumulation rate and preferably with some known synchronous events like paleomagnetic events (Edwards, 1984; Dowsett, 1988, 1989a, 1989b; Srinivasan and Sinha, 1991, 1992; Sinha and Singh, 2008; Kaushik *et al*., 2020). We selected ODP Hole 763A as SRS because a detailed planktic foraminiferal biochronology with numerical age estimates has been available for this hole (Sinha and Singh, 2008). The method requires SRS to be correlated with several sections one by one. Each paleontological event (FO and LO) has two coordinates; one is its depth in meters at SRS and the other in the section to be correlated. The common events are plotted on an X-Y graph and an array of points is obtained. Applying the principle of linear regression combined with the paleontologist's knowledge and assessment of the FOs and LOs based on the presence/absence of evolutionary lineages, a line of correlation (LOC) passing through or close to the maximum number of points is positioned (Edwards, 1984, Dowsett, 1988, 1989a, 1989b; Srinivasan and Sinha 1992). The modern and paleobiogeographic distribution of planktic foraminiferal species is also considered while positioning the LOC (Kaushik *et al*., 2020). Once the Line of Correlation is positioned, the ranges (depths) of FOs and LOs are corrected only in SRS based on the notion that the earliest FO and latest LO represent total stratigraphic ranges. The following method was employed.

First round of Graphic correlation

In the first round of graphic correlation, the SRS was one by one correlated with holes 214 and 219. After correction with Hole 214, the ranges were corrected in SRS and modified SRS was designated as ODP Hole 763A $(SRS)_{-214}$. This modified SRS was correlated with Hole 219.

ODP Hole 763A (SRS) vs DSDP Hole 214 (Fig. 2)

The depths of planktic foraminiferal events (Table-1),

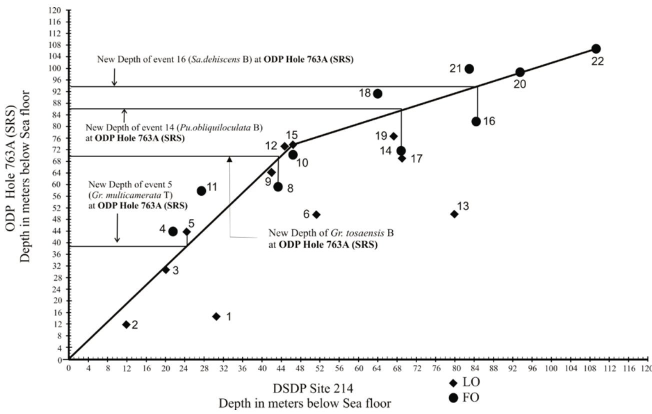


Fig. 2. Graphic correlation between ODP Hole 763A (SRS) and DSDP Hole 214. The Line of Correlation (LOC) has been positioned based on our assessment of the faunal events, including their water mass preferences and presence/ absence of evolutionary lineages. The top of the core represents 0 meters at both axes. The LOC consists of two segments. The first segment of the LOC passes near events 2,3,4,5,9,10,12 and 15, and in the second segment, the LOC joins events 15, 20 and 22 and passes near event 21. It may be noted that all the FOs which fall towards the left (above) of LOC represent a longer range at SRS (Earliest FOs) and all the LOs that fall towards the right of LOC represent a longer range in SRS (Latest LOs). The FOs falling towards the right of LOC represent a longer range at DSDP Hole 214 and thus, the depth has been corrected at SRS by linear interpolation from LOC. Similarly, the LOs falling towards the left of LOC represents a longer range at DSDP Hole 214, and thus its depth is corrected in the SRS by a similar method. After making corrections in SRS, the ranges of planktic foraminiferal species represent the maximum range at SRS. The new SRS is now designated at SRS763-$_{214}$ with corrected depths (Table-2). For event codes, refer to Table-1.

which were common to ODP Hole 763A (SRS) and DSDP Hole 214, were plotted on an X-Y graph. The SRS as per convention was plotted on Y-axis while the first section to be correlated, which in this case was DSDP Hole 214, on the X-axis (Fig. 2)

The Line of Correlation (LOC) has been positioned based on our assessment of the faunal events, including their water mass preferences and presence/ absence of evolutionary lineages. The planktic foraminiferal events, which were diachronous, were treated in the following manner. If the ranges of planktic foraminiferal events are longer in SRS, then all the LOs will fall towards the right of the LOC, and all the FOs should fall towards the left of the LOC. If any LO falls towards the left of the LOC, it means the LO is earlier at SRS as compared to the section being correlated in which the LO represents (latest extinction) and thus, based on linear interpolation, its range (depth) is corrected on SRS. If the FO falls on the right side of the LOC, it means the First Occurrence at SRS is later than the section being correlated in which it shows the earliest appearance and thus, the depth is corrected at SRS. With such corrections, the SRS now incorporates the earliest FOs and the latest LOs based on the correlation between two sections. The ranges of planktic foraminiferal species were corrected in SRS in the above manner. The new SRS was termed SRS-763$_{-214.}$ The connotation means that this section has incorporated corrections in SRS based on graphic correlation from DSDP Hole 214 (subscript- the name of the site which has been correlated).

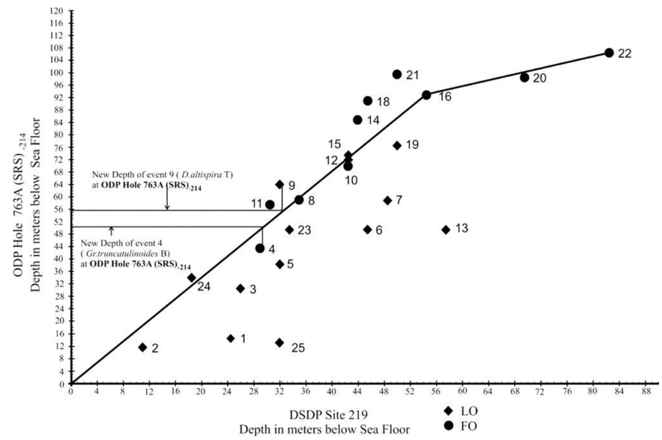


Fig. 3. Graphic correlation between ODP Hole 763A (SRS) $_{-214}$ and DSDP Hole 219. The line of Correlation (LOC) has been positioned based on our assessment of the faunal events, as described in the caption of Fig.2. The LOC consists of two segments. The first segment of the LOC passes near events 2,24,4,11,9,8,23, 10,15,12, and 16 and in the second segment, it joins events 16, 20 and 22. By the logic described in the caption of Fig.2, the depth of the FOs and LOs were corrected in SRS763A-$_{214}$. After correction, the ranges of planktic foraminiferal species represent the maximum range at SRS763A-$_{214}$. The new SRS is now designated at ODP Hole (SRS763) $_{-214-219}$ with corrected depths.

ODP Hole 763A (SRS) -$_{214}$ vs DSDP Hole 219 (Fig.3)

The new SRS (ODP Hole 763A (SRS) -$_{214}$) was then correlated with DSDP Hole 219 and the LOC was positioned based on considerations discussed earlier. Ranges of planktic foraminiferal species were again corrected in the SRS-763-$_{214,}$ making it SRS-$_{763\text{-}214\text{-}219}$ (Fig.3)

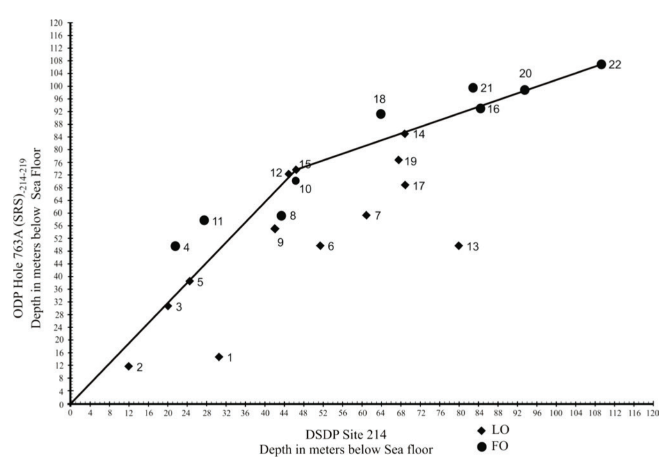


Fig. 4. In the second round of Graphic correlation, the ODP Hole 763A (SRS)-$_{214\text{-}219}$ on the Y-axis incorporates the corrected depth of planktic foraminiferal events from the first round of graphic correlation from DSDP holes 214 and 219. This new SRS is being correlated with DSDP Hole 214 again. Note that now all the LOs fall towards the right of the LOC and all the FOs fall towards the left of the LOC. This indicates that the stratigraphic ranges have been stabilized in the SRS.

Table-2: Depth in meters below sea floor of Late Neogene-Quaternary Planktic foraminiferal events at DSDP holes 219, 214 (Northern Indian Ocean) and ODP Hole 763A (Eastern Indian Ocean). NR= Not recorded. Note the bracketed depth in the last column are corrected age at 763A (SRS) based on two round of graphic correlation. With corrected age, the ODP hole 763A represents Composite Standard Reference Section (CSRS) for the Eastern and Northern Indian Ocean.

Planktic foraminiferal Events	**Type of Events**	**Event Code Used in Graphic Correlation Plots**	**DSDP 214** Srinivasan & Chaturvedi, (1992), Srinivasan and Sinha (1992) Northern Indian Ocean Depth in meters below seafloor	**DSDP 219** Srinivasan & Singh (1992), Srinivasan and Sinha (1992) Arabian Sea Depth in meters below seafloor	**ODP 763A** Sinha and Singh,2008 Eastern Indian Ocean Depth in meters below seafloor Bracketed depth represent corrected depth in CSRS
Gs.obliquus	LO	1	30.51	24.45	14.61
Gr.tosaensis	LO	2	11.88	10.95	11.66
Gs.fistulosus	LO	3	19.99	25.95	30.66
Gr.truncatulinoides	FO	4	21.54	28.95	43.66**(49.5)**
Gr.multicamerata	LO	5	24.49	31.95	43.66**(38.5)**
Gr.plesiotumida	LO	6	51.40	45.45	49.66
Pu.primalis	LO	7	60.90	48.45	59.16
Gr.tosaensis	FO	8	43.40	34.95	59.16**(69.0)**
D.altispira	LO	9	41.98	31.95	64.16**(55.0)**
Gs.fistulosus	FO	10	46.40	42.47	70.16
N.dutertrei	FO	11	27.45	30.51	57.66
Ss. seminulina	LO	12	44.90	42.47	72.16
N.acostensis	LO	13	79.95	57.45	49.66
Pu.obliquiloculata	FO	14	68.90	43.95	71.51**(85.0)**
Gr.margaritae	LO	15	46.40	42.47	73.65
Sa.dehiscens	FO	16	84.45	54.45	81.66**(93.0)**
Gr.cibaoensis	LO	17	68.90	NR	68.66
Gr.crassaformis	FO	18	63.90	45.45	91.13
Gg.nepenthes	LO	19	67.40	49.95	76.66
Gr.tumida tumida	FO	20	93.43	69.48	98.66
Pu praecursor	FO	21	82.95	49.95	99.69
Pu primalis	FO	22	109.33	82.50	106.66
Pu.praecursor	LO	23	NR	33.45	49.66
Gs.extremus	LO	24	NR	18.45	34.16
Gg.decoraperta	LO	25	NR	31.95	13.16

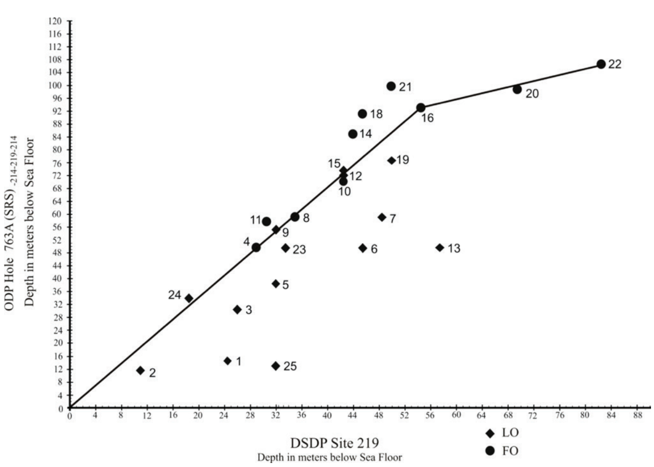


Fig.5. In the second round of Graphic correlation, the SRS763A-$_{214-219-214}$ on Y-axis incorporates the corrected depth of planktic foraminiferal events from the first and second round (Two rounds with DSDP Hole 214 and one with DSDP Hole 219). This new SRS is being correlated with 219 second time. Note that now all the LOs fall towards the right of the LOC and all the FOs fall towards the left of the LOC and thus, the ranges appear to have been stabilized and no correction is needed.

Second Round of Graphic correlation

ODP Hole 763A (SRS) -$_{214-219}$ Vs DSDP Hole 214

In the second round of Graphic Correlation, first, the GC was done between SRS-763-$_{214-219}$ and DSDP Hole 214. It was found that all the ranges were stabilised after the first round. All the FOs plot to the left of LOC, and all the LOs plot towards the right of LOC, indicating that no further correction was needed. (Fig.4).

ODP Hole 763A (SRS)- $_{-214-219-214}$ vs. 219 (Fig.5)

Next, the new SRS763A$_{-214-219-214}$ was correlated with DSDP 219. (Fig.5). It was found that the ranges were stabilized as all the FOs fall towards the left of the LOC and all the LOs fall towards the right of the LOC. This condition represents a situation where the SRS becomes CSRS (Composite Standard Reference Section) (Edwards, 1984), and the ranges of planktic foraminiferal species represent maximum ranges (earliest FOs and latest LOs) (Fig. 5). Thus the ODP Hole (SRS) 763A-$_{214-219-214}$ became Composite Standard Reference Section (CSRS) 763A-$_{214-219-214-219.}$ The suffix is self-explanatory as it indicates two rounds of graphic correlation. Table-2 gives the corrected depths at CRRS (Composite Standard Reference Section) after two

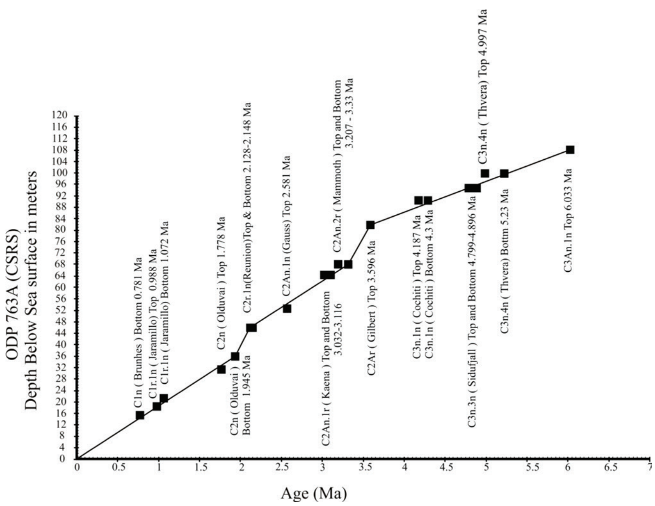


Fig.6. Age–depth curve for ODP Hole 763A (CSRS). Ages of Paleomagnetic chrons are after GTS-2012. Paleomagnetic stratigraphy after Cheng Tang (1992). Modified after Sinha and Singh (2008).

rounds of graphic correlation. Six such corrections were done and corrected depths have been given in bracket in the relevant coloumn.

ESTIMATION OF NUMERICAL AGES OF PLANKTIC FORAMINIFERAL EVENTS

Since paleomagnetic stratigraphy was available for ODP 763A (Tang, 1992, Sinha and Singh, 2008) with the revised ages of the Chrons (GTS, 2012), the numerical ages of Late Neogene-Quaternary planktic foraminiferal events were determined for the CSRS (Fig. 6). Based on the linear interpolation from LOC between CSRS and DSDP Hole 214 and CSRS and DSDP Hole 219, the corresponding depths of all the planktic foraminiferal events at both the holes were determined at CSRS. This led to numerical age estimation of Late Neogene-Quaternary planktic foraminiferal events at CSRS, ODP Hole 763A, DSDP Hole 214 and DSDP Hole 219 shown in Table -3.

A final table (Table -3) represents the numerical ages of Late Neogene –Quaternary planktic foraminiferal events at CSRS (763A), 214 and 219. This table gives the regional diachrony, and the extent of diachronism in millions of years which has been discussed in the subsequent section.

RESULTS

Late Neogene-Quaternary planktic foraminiferal events in Northern and Eastern Indian Ocean

Based on our two rounds of Graphic correlation and numerical age estimation, as given in Table-3, we classify the Late Neogene-Quaternary Planktic foraminiferal events into the following three categories. The abbreviations have been

Table-3. Numerical ages estimated for Late Neogene - Quaternary planktic foraminiferal events at CSRS, ODP 763A, DSDP 214 and DSDP 219. Note that the ages in CSRS are earliest for FOs and Latest for LOs.

Planktic Foraminiferal Events	Type of Events	Event Code	CSRS Estimated numerical ages in Ma	DSDP Hole 219 Estimated numerical ages in Ma	DSDP Hole 214 Estimated numerical ages in Ma	ODP Hole 763A Estimated Numerical ages in Ma	Difference between maximum and minimum age in Ma
Gs.obliquus	LO	1	0.75	2.05	2.3	0.75	1.75
Gr.tosaensis	LO	2	0.65	1.05	1.05	0.65	0.4
Gs.fistulosus	LO	3	1.65	2.1	1.65	1.65	0.45
Gr.truncatulinoides	FO	4	2.35	2.35	1.85	2.05	0.5
Gr.multicamerata	LO	5	1.95	2.6	1.95	2.05	0.65
Gr.plesiotumida	LO	6	2.35	3.55	3.5	2.35	1.2
Pu.primalis	LO	7	2.85	3.8	3.6	2.85	0.9
Gr.tosaensis	FO	8	3.3	2.85	3.3	2.85	0.5
D.altispira	LO	9	2.6	2.6	3.2	3.1	0.6
Gs.fistulosus	FO	10	3.4	3.4	3.4	3.4	0
N.dutertrei	FO	11	2.95	2.95	2.05	2.75	0.9
Ss. seminulina	LO	12	3.45	3.45	3.45	3.45	0
N.acostensis	LO	13	2.35	4.85	4.5	2.35	2.5
Pu.obliquiloculata	FO	14	3.9	3.5	3.9	3.4	0.5
Gr.margaritae	LO	15	3.45	3.45	3.45	3.45	0
Sa.dehiscens	FO	16	4.65	4.65	4.65	3.6	1.05
Gr.cibaoensis	LO	17	3.35	NR	4.0	3.35	0.65
Gr.crassaformis	FO	18	4.45	3.55	3.7	4.45	0.9
Gb.nepenthes	LO	19	3.5	3.95	3.9	3.5	0.45
Gr.tumida tumida	FO	20	5.2	5.2	5.2	5.2	0
Pu praecursor	FO	21	5.3	3.9	5.3	5.25	1.4
Pu primalis	FO	22	6.05	6.05	6.05	6.05	0
Pu.praecursor	LO	23	2.35	2.75	NR	2.35	0.4
Gs.extremus	LO	24	1.85	1.85	NR	1.85	0
Gg.decoraperta	LO	25	0.7	2.6	NR		1.9

used for three categories. IO represents the Indian Ocean. Cat stands for category.

Category-1 (IO-Cat-1)

The events which are synchronous in all three holes or two holes (when not recorded at the third hole) and thus very reliable for stratigraphic correlation. These include

a) *Globigerinoides fistulous* FO
b) *Sphaeroidinellopsis seminulina* LO
c) *Globorotalia margaritae* LO
d) *Globorotalia tumida tumida* FO
e) *Pulleniatina primalis* FO
f) *Globigerinoides extremus* LO

Category-2 (IO-Cat-2)

The events which are synchronous at two holes and thus have limited value for stratigraphic correlation. These are fairly synchronous events.

a) *Globorotalia tosaensis* LO (DSDP holes 214 and 219)
b) *Globorotalia multicamerata* LO (DSDP holes 214 and ODP 763A)
c) *Globoigerinoides fistulosus* LO (DSDP holes 214 and ODP 763A)
d) *Globorotalia plesiotumida* LO (DSDP holes 219 and 214)
e) *Globorotalia tosaensis* FO (DSDP holes 219 and ODP763A)
f) *Dentoglobigerina altispira* LO (DSDP holes 214 and ODP 763A)
g) *Pulleniatina obliquiloculata* FO (DSDP 219 and ODP 763A)
h) *Sphaeroidinella dehiscence* FO (DSDP 214 and 219)
i) *Globoturborotalita nepenthes* LO (DSDP 214 and 219)
j) *Pulleniatina praecursor* FO (DSDP 219 and ODP 763A)

Category-3 (IO-Cat-3)

The events which are diachronous and thus have different ages at all three holes. These are not reliable for stratigraphic correlation.

a) *Globigerinoides obliquus* LO
b) *Globoturborotalita decorparta* LO
c) *Globorotalia truncatulinoides* FO
d) Pulleniatina primalis LO
e) *Neogloboquadrina dutertrei* FO
f) *Neogloboquadrina acostaensis* LO
g) *Globorotalia cibaoensis* LO
h) *Globorotalia crassaformis* FO
i) *Pu. praecursor LO*

DISCUSSION

Considering all the three categories, we find that there are seven FOs (3 in IO-Cat-1 and 4 in IO-Cat-2), which are synchronous either at all three holes or two holes compared to eight synchronous LOs (2 in IO-Cat-1 and 7 in IO-Cat-2). However, we see five LOs that are diachronous compared to only two FOs (IO-Cat-3). For many biostratigraphic studies, the FOs are preferred in scientific work because they are not plagued by problems of reworking by bioturbation, erosion, and bottom currents (Spencer-Cervato *et al*., 1994). However, the overall data set, which is nevertheless small here, there is no significant difference between the number of FOs and LOs in any categories. Johnson and Nigrini (1985) found in their study on Radiolarians that diachronism was more frequent in FOs than in LOs. We do not find any evidence of such a phenomenon in planktic foraminiferal events, though, in this limited area, we find FOs to be more reliable.

Extent of Diachronism

The estimated numerical ages of Late Neogene-Quaternary planktic foraminiferal events at CSRS, ODP 763A, DSDP Hole 219 and DSDP Hole 214 have been given in Table 3. We observed that the maximum extent of diachronism is 2.5 Ma for one event only. To have a general view of the extent of diachronism, we divided the events into four groups. The first group is synchronous events where diachronism is 0. The second group constitutes events with the extent of diachronism between 0.4 to 0.65 Ma, the third group between 0.9 to 1.2, and the last group between 1.4 to 1.75 Ma. Fig. 6 shows that the maximum events cluster in the second group where diachronism is less than 1.2 Ma (Fig.7). Except group 4, we find the majority of the Late Neogene-Quaternary planktic foraminiferal events in Northern and Eastern Indian oceans to be reasonably reliable for stratigraphic correlation. Thus besides the six synchronous events, the diachronous events with the extent of diachronism less than 1.2 Ma are useful for biostratigraphic correlation. The diachronism may also be due to the sampling interval at various holes, which is 1.5 Meters. So the stratigraphic uncertainties could account for the maximum part of this extent of diachronism.

Oceanographic factors influencing stratigraphic ranges of planktic foraminifera at the three holes

Before discussing the causative factors behind diachronism, one must first ensure that diachronism is not because of the variability due to sample spacing, incomplete recovery, the author's taxonomic biases, etc. Many causative factors for diachronism have been discussed by workers, including changes in latitudinal thermal gradients, habitat migration, and adaptation, changes in water mass conditions, strengthening, weakening of major ocean currents, etc. ODP Hole 763A in the eastern Indian Ocean is under the influence

Extent of Diachronism	No of events
0 My- Synchronous Events	06
0.4 My - 0.65 My	09
0.9 My - 1.2 My	06
1.4 My - 2.75 My	04

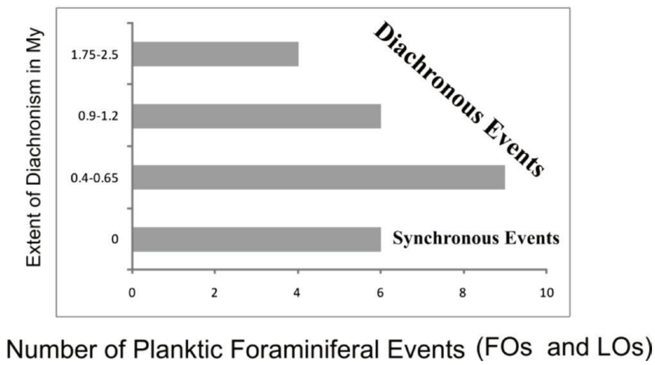


Fig.7. The extent of Diachronism in Late Neogene –Quaternary planktic foraminiferal events.

of warm Leeuwin Current flowing from the north and cold West Australian Current flowing from the south. The other two holes, DSDP Hole 219 and 214 in the Northern Indian Ocean, have entirely different oceanographic settings. However, the three areas remain connected through Indonesian Throughflow, which feeds Leeuwin current, influencing ODP Hole 763A and South Equatorial current influencing DSDP Hole 214 and, to a less extent, Hole 219. We expect a change in ITF to be more effective for Hole 214 and 763A (Fig.1) though the species FO and LO will be more influenced by the habitat expansion, contraction and migration or a sudden change in the structure of the upper water column owing to paleoclimatic changes. Besides the ITF, both the DSDP Hole 219 and 214 are affected by the Inter-Tropical Convergence Zone (ITCZ). Hole 219 is located in a setting that is influenced by upwelling. Thus, productivity changes coupled with loss of water mass stratification sustained for a long time in the geological past in response to long-term changes in monsoon mode can profoundly affect the planktic foraminiferal populations. DSDP Hole 214 is mostly influenced by the ITF (Auer *et al*. 2019) and lies below equatorial divergence. We have discussed the diachronous planktic foraminiferal events of Category IO-Cat-2 and IO-Cat-3 in a palaeoceanographic context, also giving due consideration to the known ecological preference of the species in question, its evolution and possible migration to places from its seat of evolution. Our discussion is constrained by the lack of information on surface water palaeoceanographic changes at both the DSDP holes 214 and 219. Some information about the surface water palaeoceanographic changes is available in Wright and Thunnell (1988), and bottom water palaeoceanographic changes at DSDP Hole 214 (Gupta and Srinivasan 1992) and 219 (Gupta and Thomas,1999) but not of much relevance here. We have taken some information from Auer *et al*. (2019), Sinha *et al*. (2006) on the variation in ITF through Pliocene- Pleistocene. The palaeoceanographic changes at Hole 763A were discussed by Sinha *et al*. (2006), Sinha and Singh (2007) and Sinha and Singh (2008). Thus the diachrony in planktic foraminiferal events, which, to a great extent, are controlled by palaeoceanographic changes in the upper water column itself provide some information about the prevailing palaeoceanographic conditions. Still, the interpretations can be confirmed only if we have an independent palaeoceanographic record of surface waters for the holes examined. Thus our discussion on the diachronous events is based on water mass preferences of the species in question and some information available on palaeoceanographic changes in Pliocene –Pleistocene in the Indian Ocean near the examined holes. We also see an opportunity to use diachronism itself as a proxy for the palaeoceanographic changes that might have occurred. We have discussed in detail the diachronous planktic foraminiferal belonging to Category 2 (IO-Cat-2) (Fig. 8a-b) and Category 3 (IO-Cat-3) (Figs. 9a-b).

Fairly Synchronous Planktic Foraminiferal events (IO-Cat-2) (Figs. 8a-b)

This category includes fairly synchronous events. They show synchroneity between two sections, while in the third section, the numerical age estimate is different. We have tried to organize the discussion by first looking at the ecological / water mass preference of the species based on available literature and then what factors could have caused its early or later appearance/disappearance in a particular section. While in many cases a logical explanation has been reached yet in some cases, the diachronism cannot be explained.

Globorotalia tosaensis FO and LO - Takayanagi and Saito (1962) erected the species *Globorotalia tosaensis* from the Nobori formation and considered this species a transitional form between the interpreted evolutionary lineage of *Gr. crassaformis* to *Gr. truncatulinoides*. Blow (1969) postulated that the *Gr. tosaensis* branched off from *Gr. crassaformis* stock in mid-Pliocene times, and its stratigraphic range overlaps with its descendent *Gr. truncatulinoides*, and became extinct in the early Pleistocene. Thus it is considered that *Gr. tosaensis* is a transitional form. It is very intriguing to note that this evolution represents one nonreversible change and one reversible change. The *Gr. crassaformis* to *Gr. tosaensis* is marked by an increase in the number of chambers in the final whorl from four to four and a half in *Gr. crassaformis* to five in *Gr. tosaensis* and *Gr. truncatulinoides* but the keel disappeared in transitional form *Gr. tosaensis* and reappeared in its descendent *Gr. truncatulinoides*. Thus the evolution represents a keeled to non –keeled to keeled form. From a magnetostratigraphically calibrated sequence, Berggren (1969) reported that keel development, once initiated on the last formed chamber, extended progressively around the outer whorl in 0.05 my (Ciffeli and Scott, 1986). Though the cause of losing a keel and later developing once again is not known, Kennett and Geitzenauer (1969) found in a Southeast Pacific core that the percentage of keeled specimens fluctuated widely (8%-98%) and the higher percentages of keeled specimens were associated with the more tropical type of assemblages. The study by Kennett and Geitzenauer (1969) indicates that a regional, watermass factor might have been responsible, with the tropical waters being more favourable to the spread of keeled forms (Ceffeli and Scott, 1986). Thus the available information points toward a change

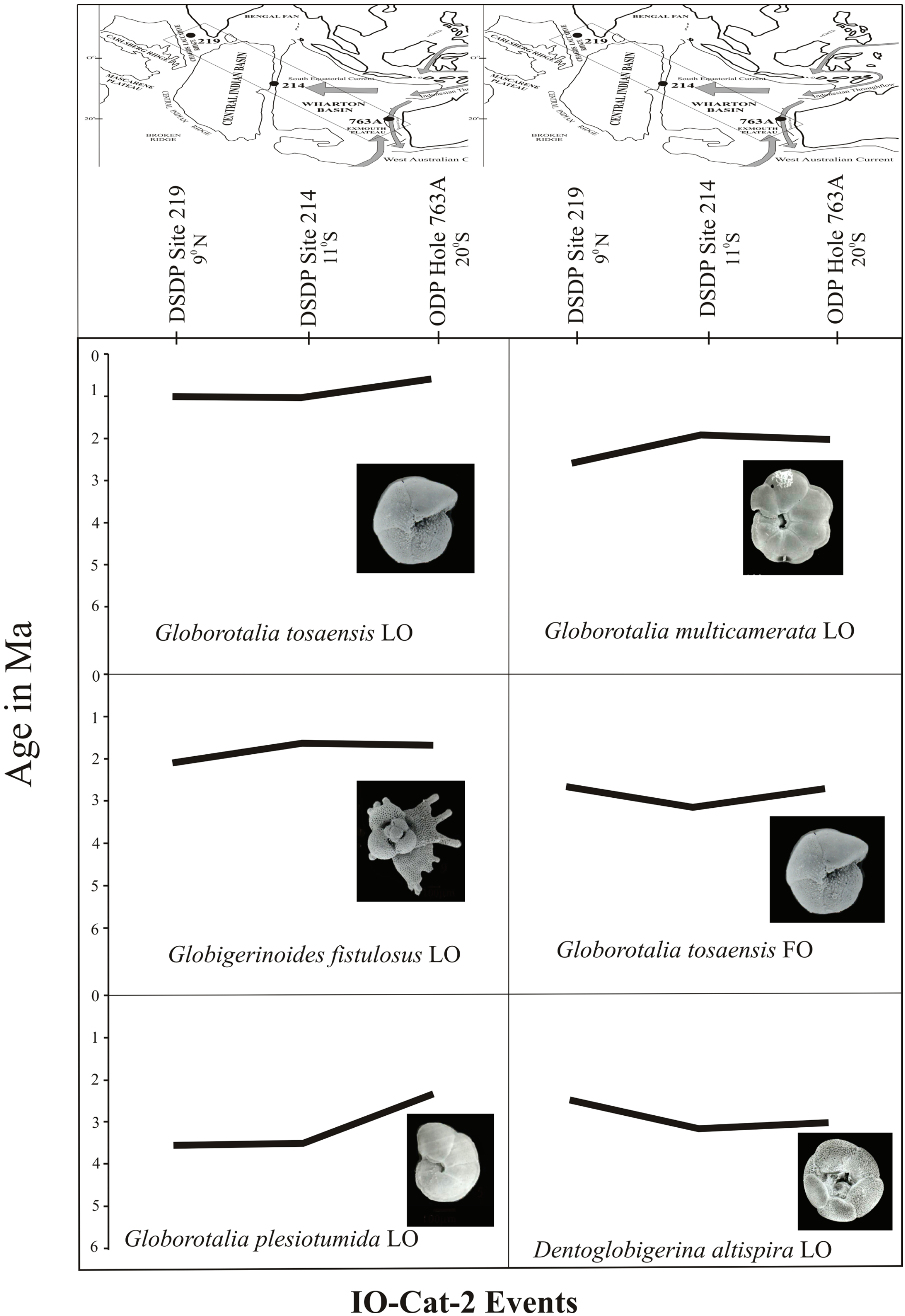


Fig.8a. Fairly Synchronous planktic foraminiferal events of Category IO-Cat-2

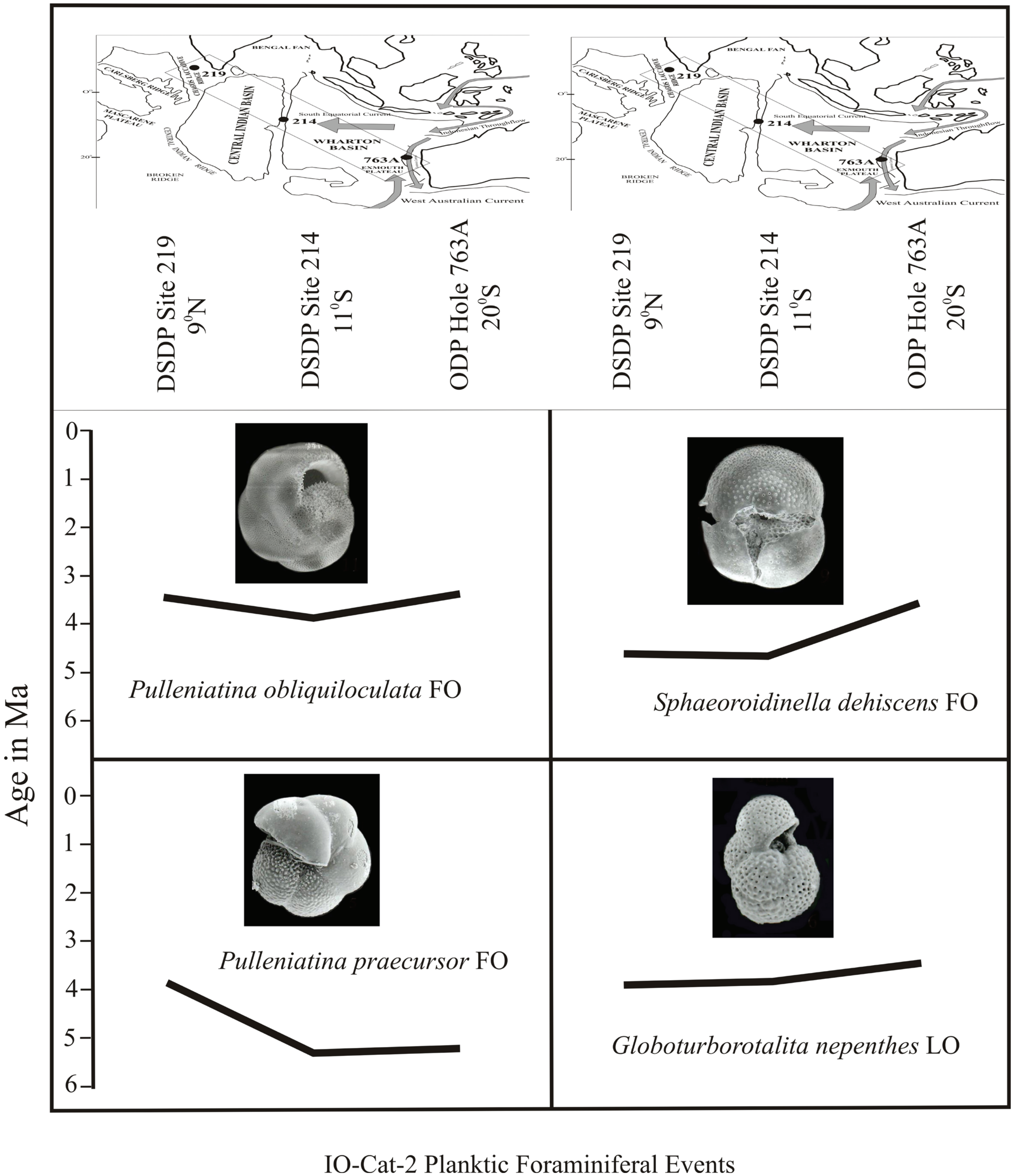


Fig. 8b. Fairly Synchronous Planktic foraminiferal events of category IO-Cat-2

in water mass preference for the *Gr. crassaformis* to *Gr. tosaensis* to *Gr. truncatulinoides* evolution. Considering all the above studies one should expect early extinction of *Gr. tosaensis* in tropical waters and its late survival in cooler waters. Our results corroborate this expected hypothesis. The *Globorotalia tosaensis* LO is synchronous between DSDP holes 214 and 219. The estimated age of the LO is 1.05 Ma at both the holes 219 and 214, and at ODP Hole 763A, the LO occurs quite later at 0.65 Ma which is also the age reported by many other workers (Berggren *et al* 1995a, b). Considering previously published ages for this event close to 0.65Ma, the LO appears to occur quite early at the northern Indian Ocean holes. Thus we may interpret the early extinction at 214 and 219 due to a change in water mass condition, and more influence of warm waters might have caused early extinction. Now the question is what factors account for this warm condition. One reason can be the South Equatorial Current and the other can be climatic warming in the Northern Indian Ocean. Do we have independent evidence for such warming in the northern Indian Ocean around 1.05 Ma? Though we do not have specific information about the surface water oceanographic changes in the northern Indian Ocean around 1.05Ma, the event is almost coincidental to Marine Isotope Stage 31 (MIS 31), which was considered as an extreme interglacial stage by Scherer *et al*. (2008). The FO of *Gr. tosaensis* involves loss of keel and considering the studies by Kennett and Geitzenauer (1969) we may expect this sympatric evolution to have occurred from *Globorotalia crassaformis ronda* stock due to cooler water conditions. As the FO is earliest at DSDP Hole 214 we infer that at 3.3 Ma due to reduced Indonesian Throughflow or a change in nature of Throughflow from Warmer South Pacific to cooler North Pacific waters (Cane and Molnar, 2001) must have caused this early evolution of *Gr. tosaensis* at 214. Such conditions appeared about 0.5 Ma later at Hole 219 probably due to intense upwelling and at Hole 763A due to enhanced influence of cold West Australian Current (Sinha *et al*, 2006) (Fig.8a)

Globorotalia multicamerata LO - Ceffeli and Scott (1986) discussed at length the evolution of menardiform species. Generally, the menardiform species have five to six chambers in the outer whorl. According to Ceffeli and Scott (1986), the experimentation done by the menardiform species to develop more number of chambers was not successful and all such forms became extinct before the Pleistocene. These forms included, amongst others *Globorotalia multicamerata*. But the environmental causes behind such extinctions were not understood. Such extinction occurred in all the major oceans ((Parker, 1973; Keigwin, 1982). *Globorotalia multicamerata* LO is almost synchronous between holes 763A (2.05 Ma) and 214 (1.95 Ma). However, it becomes extinct quite early at DSDP hole 219. As discussed above, oceanographic changes at DSDP hole 219 are dominated by changes in upwelling. We presume that *Globorotalia multicamerata* has the same ecological preferences as its ancestor *Globorotalia menardii,* a thermocline dweller. We interpret the shrinking of thermocline at hole 219 due to the upwelling to be a cause of the early extinction of *Globorotalia multicamera* at Hole 219 (Fig.8a). *Globorotalia menardii* and *Globorotalia limbata*, the ancestors of *Globorotalia multicamerata*, might have responded to the changes in oceanographic conditions by increasing the size of the test (Knappertsbusch 2016), and the clan preferred increasing test size than increasing the number of chambers probably to migrate to lower depths.

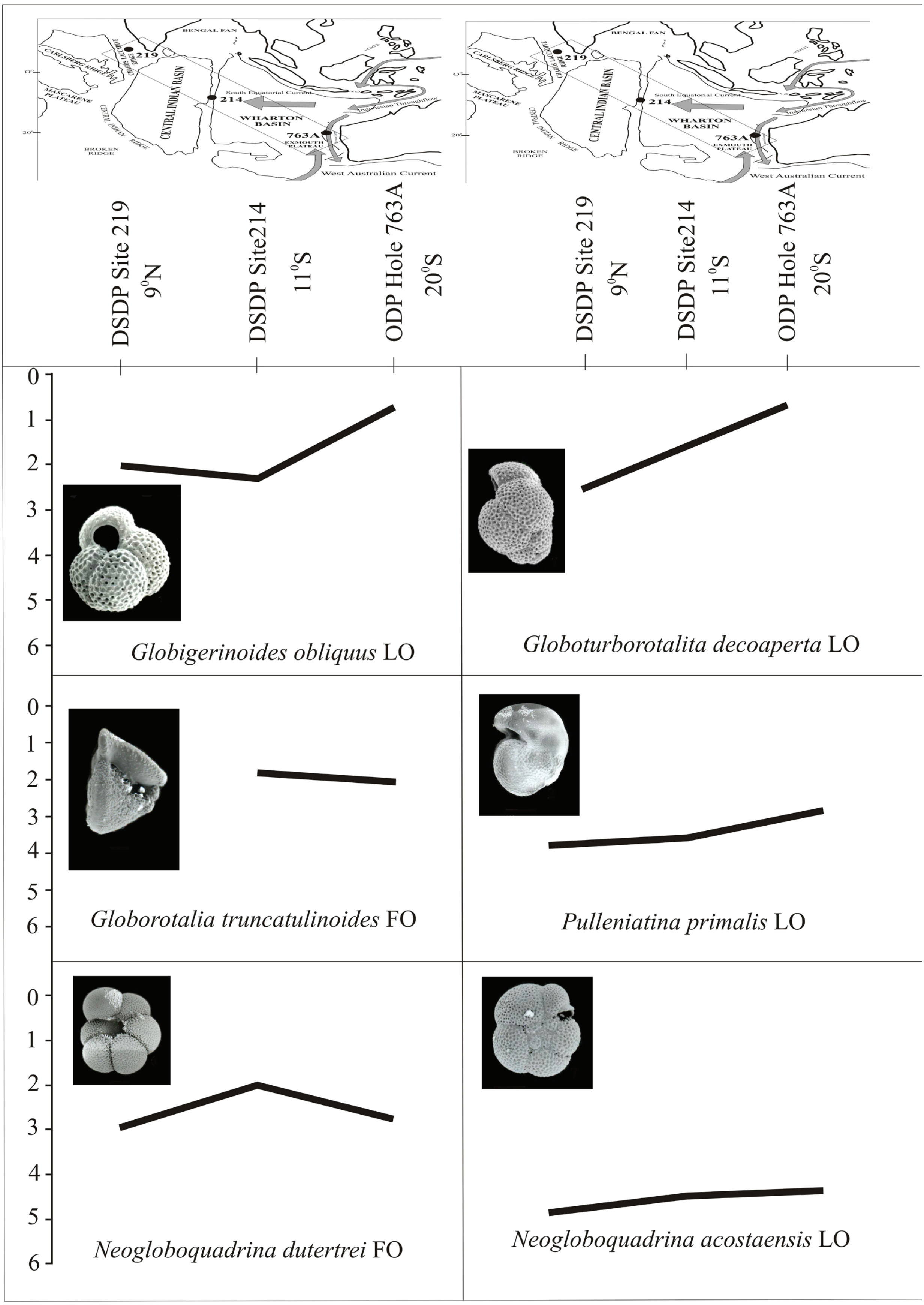
Globigerinoides fistulosus LO - *Globigerinoides fistulosus* LO has been employed to mark Pliocene-Pleistocene boundary before the boundary itself was lowered down to coincide with the base of the Gelasian Stage (GTS 2012). Srinivasan and Sinha (1992) showed this event to co-occur with the top of the Olduvai Normal event in Southwest Pacific Deep Sea Cores. *Globigerinoides fistulosus* is a mixed layer dweller and evolved from *Globigerinoides saculifer* by developing multiple digitate extensions in the last few chambers (Kennett and Srinivasan, 1983); thus, and its ecological preference can be presumed as a warm mixed layer. The species makes LO at 1.65 Ma at holes 214 and 763A which is close to ages reported by other workers (Berggren *et al*, 1995a,b, Wade *et al* 2011, Kaushik *et al*, 2020). Its early extinction at DSDP Hole 219 can be attributed to prevailing monsoonal upwelling conditions, which might have resulted in the loss of upper water mass stratification. Hole 219 is located in an upwelling regime (Whitemarsh *et al*., 1974).

Globorotalia plesiotumida LO - Banner and Blow (1965) considered *Globorotalia merotumida*, *Gr. plesiotumida*, and *Gr. tumida* as members of gradually evolving lineage and employed for late Miocene-Early Pliocene biostratigraphic zonation of tropical sequences. All three species have overlapping stratigraphic ranges. The three species have gradational forms also and the taxonomic assignment is sometimes difficult. The extinction of *Globorotalia plesiotumida* can be considered as independent of any environmental factors and gradual sympatric speciation of *Globorotalia tumida* occurred replacing the population of *Gr. plesiotumda*.

This event is synchronous within the northern Indian Ocean and occurs at 3.5 Ma, however, at Hole 763A, the event is quite late and occurs at 2.35 Ma. *Globorotalia plesiotumida* evolved to *Globorotalia tumida tumida* by developing the more tumid test. The habitat of *Gr. plesiotumida* thus can be presumed as the thermocline which is the habitat of its descendent. We propose that in cooler waters the sympatric speciation of *Globorotalia tumida* occurred synchronously with other parts of the Indian Ocean but the replacement of *Globorotalia plesiotumida* was delayed in cooler waters. The late survival of this species at 763A might have been due to prevailing colder conditions under the West Australian current.

Dentoglobigerina altispira LO - *Dentoglobigerina altispira* LO shows synchroneity between DSDP Hole 214 and 763A. However, at DSDP hole 219, it shows its latest LO at 2.6 Ma. This species is a warm mixed-layer dweller (Spezzaferri, 1994; Srinivasan and Sinha 2000) based on isotopic depth stratification. Spezzaferri, (1994) considered this species as an indicator of warmer water at low latitude. Thus despite the DSDP Hole 2019 located in an upwelling regime, the species would have survived late at DSDP Hole 219, probably due to the warmer conditions at low latitude.

Pulleniatina obliquiloculata FO - *Pulleniatina obliquiloculata* is a thermocline dweller and abundant in tropical water masses. Its earliest appearance at Hole 214 at 3.9 Ma is quite intriguing as this hole is under the influence of thermocline waters from Indonesian Throughflow. At the



IO-Cat-3 Planktic Foraminiferal Events

Fig.9a. Diachronous planktic foraminiferal events of Category IO-Cat-3

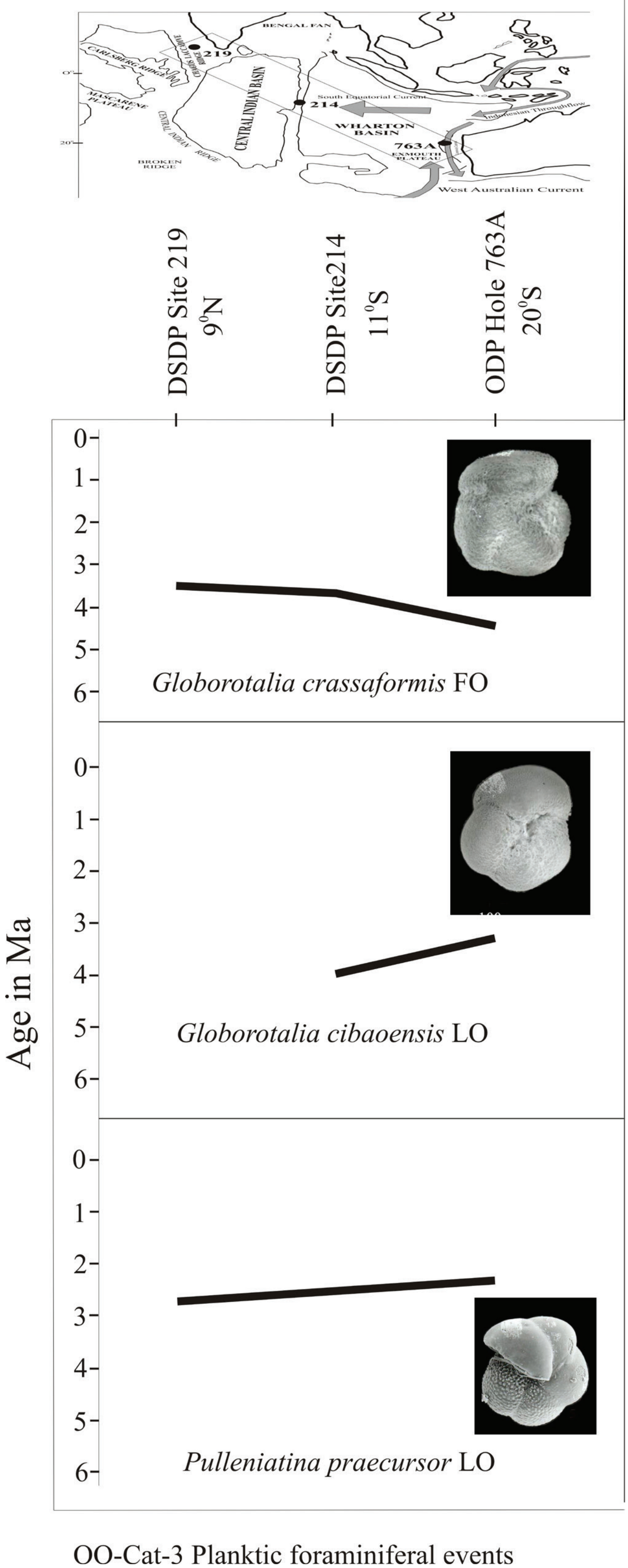


Fig.9b. Diachronous planktic foraminiferal events of Category IO-Cat-3

other two holes, it appears only 0.4 Ma later. Thus a well-developed thermocline and stratified water coloum are inferred at 214 around 3.9 Ma favouring the early evolution of this species. The extent of diachrony is very small considering the sample spacing.

Sphaeroidinella dehiscens FO - *Spaheroidinela dehiscens* is a typical warm water species and is found abundant in equatorial waters. This species evolved from *Sphaeroidinellopsis seminulina* in tropical waters. Srinivasan and Sinha (1991) showed this species to successively appear at younger stratigraphic levels in a north-south transect at southwest Pacific DSDP holes. The species FO is synchronous at 219 and 214 at 4.65 Ma and appears later at southernmost Hole 763A located at cooler latitudes. This we attribute to water mass preference of *Sa. dehiscens*.

Globoboturborotalita nepenthes LO - *Gb. nepenthes* evolved from *Gb. druryi* by developing a protruding thumb-shaped final chamber (Kennett and Srinivasan, 1983). The ancestral species *Gb. woodi* is a temperate water form and if ecological preferences of the genus remain the same, *Gb. nepenthes* late survival at cooler water mass Hole 763A (3.5 Ma) seems logical. However, it disappeared earlier at the northern Indian ocean holes 214 and 219 (~3.9 Ma) which are located in relatively warmer water masses. . The LO of *Gb. nepenthes* seems youngest at Hole 763A, which is under the influence of West Australian current.

Pulleniatina praecursor FO - *Pu. praecursor* FO occurs earliest at Hole 214 at 5.3 Ma, just like its descendent *Pu. Obliquiloculata*. At both the holes 763A and 219, it appears later. As in the case of *Pu. obliquiloculata* we attribute it to early evolution because of a well-developed thermocline at DSDP Hole 214. However the sympatric evolution and gradual replacement of the ancestral *Pu. praecursor* by the descendent *Pu. obliquiloculata* must have been influenced by the variation in the thermocline.

Diachronous Planktic Foraminiferal events (IO-Cat-3) (Figs. 9a-b)

Globigerinoides obliquus LO - The latest (youngest occurrence) occurrence of *Globigerinoides obliquus* is documented at ODP Hole 763A at 0.75 Ma while it disappears earlier at DSDP 219 (2.05 Ma) and DSDP Hole 214 (2.3 Ma). Sinha and Singh (2008) considered the very late LO of *Globigerinoides obliquus* to low trophic levels of surface waters. Presuming that the ecological preferences of the species have not changed with time, we can assign oligotrophic surface waters as favourable conditions for *Globigerinoides obliquus* as in the case of its descendent *Globigerinoides ruber*. Its early disappearance at DSDP Hole 214 around 2.3 Ma indicates high productivity or eutrophic conditions. Gupta and Srinivasan (1992) based on *Uvigerina* abundance stated that at 2.4 Ma, the surface waters at Site 214 were highly productive. Such eutrophic conditions might have been responsible for the early extinction of *Globigerinoides obliquus* at DSDP 214. For DSDP Hole 219 similar situations were found by Gupta and Thomas (1999) who identified the interval 2.4 -1.8 Ma as highly productive and poorly oxygenated. At Hole 763A only episodic upwelling occurred identified by Sinha *et al*. (2006) as PL events, and generally, as in modern times, the western margin of Australia is the only region where despite northward prevailing winds, there is no upwelling due to nullifying effect of the Leeuwin Current (Sinha *et al*., 2006).

Thus late LO of *Globigerinoides obliquus* in the Eastern Indian Ocean can be attributed to oligotrophic conditions of the mixed layer. Jenkins (1991) observed that *Gs. obliquus* with some other species showed a pattern of gradual retreat from mid-latitude towards lower latitudes prior to final extinction. Jenkins (1992) gave a possible explanation for the apparent retreat to lower latitudes of some of the species of planktic foraminifera as climatic deterioration that led to glacial periods. But the present study observed a contradictory situation. *Gs. obliquus* becomes extinct earlier at lower latitude holes. Thus we consider the oligotophic conditions/ trophic level to be more effective in controlling the stratigraphic ranges.

Globoturborotalita decorparta LO - *Globoturborotalita decoaperta* evolved from *Globoturborotalita woodi* (Kennett and Srinivasan, 1983). However, Bolli and Saunders (1985) believed that *Gb*. *decoraperta* evolved from *Gb. druyi*. Though both these studies attributed the ancestor species as *Globoturborotalita woodi* which occurs in the modern ocean and is a temperate planktic foraminiferal species. Spezzaferri *et al*. (2018) also attributed the geographic distribution of all *Globoturborotalita species* to cold oceans. *Gb. decoaperta* shows early LO at warm water DSDP Hole 219 at 2.6 Ma which is probably due to its biogeographic preference of cold waters. It shows its late survival at ODP Hole 763A where Sinha *et al*. (2006) detected several cold events due to intensification of the West Australian Current as a result of Antarctic ice-sheet expansion. The LO of *Gb*. *decoraperta* at 0.7 Ma is the youngest age so far reported. Thus this diachronism is due to water mass preference. At DSDP Hole 214 this event is not recorded.

Globorotalia truncatulinoides FO - The *Gr. truncatulinoides* FO has been repeatedly recorded near the base of the Olduvai Event (C2n) both in Atlantic and Pacific cores (Berggren *et al*, 1967; Hays and others, 1969). However Srinivasan and Sinha (1992) recorded the FO of *Gr. truncatulinoides* near Matuyama/ Gauss Boundary (2.58 Ma) in the Southwest Pacific. In the present study, we find this species to appear earliest at DSDP Hole 219 at 2.3 Ma and later at 763A at 2.05 Ma and at DSDP Hole 214 at 1.85 Ma. Though Srinivasan and Singh (1992) have not provided the species concept of *Gr*. *truncatulinoides*, but mentioned that the FO of this species occurs in core 4 section 4 which is the same as recorded by Fleisher (1974). However Flesiher (1974) included partially carinate forms also within *Gr. truncatulinoides* and thus we do not consider the FO at DSDP 219 to be reliable as many authors including Kennett and Srinivasan (1983), Schiebel and Hemleben (2017) consider only individuals with keel present in entire periphery of the final whorl in *Gr. truncatulinoides.* Schiebel and Hemleben (2017) stated that the periphery is keeled from the neanic stage onward and thus the forms as reported by Felisher (1974) as partially carinate might be *Gr. tosaensis/ truncatulinoides* plexus, also referred to by Srinvasan and Singh (1992). In view of this, we do not consider the FO at DSDP Hole 219 to be a true FO. Thus we discuss its FO only at holes 214 and 763A.

Gr. truncatulinoides is a deep dwelling species and evolved from *Globorotalia crassaformis* via *Globorotalia tosaensis* (Kennett and Srinivasan 1983, Spencer -Cervato, *et al*. 1994). The earliest appearance of *Globorotalia truncatulinoides* occurred at 2.8 Ma in the Southwest Pacific and it later migrated to the Indian Ocean and Atlantic (Spencer-Cervato, 1997). The migration occurred after 2.3 Ma. The evolution of *Gr. truncatulinoides* was considered to be sympatric amongst the populations of *Gr. crassaformis* by many (Spencer-Cervato *et al*, 1994). However, Blow (1969) considered the evolution from a transitional form *Globorotalia tosaensis.* The outside Pacific migration was envisaged by these authors (Spencer-Cervato *et al*, 1994) from the Indonesian seaway as a result of sea-level rise. Looking at our data we find the evolutionary appearance of *Gr. trancatulinoides* earliest at DSDP Hole 763A which is located in a relatively cooler water mass. Srinivasan and Sinha (1992) demonstrated the FO of *Gr. truncatulinoides* at Gauss /Mtuyama boundary at 2.58 Ma which supports the theory of Spencer Cervato *et al* (1994) that the evolution of *Gr. truncatulinoides* was earliest in the southwest Pacific. Srinivasan and Sinha (2000) based on their biogeographic studies concluded that Indonesian Seaway was partially closed for deeper and thermocline waters in the Early Pliocene. Migration of *Gr. truncatulinodes* which is a deep water form must have been initiated after Indonesian Seaway became fully open and thus we support the statements made by Spencer-Cervato *et al* (1997) that the species migrated through Indonesian Seaway into the Indian Ocean. Its successive appearances at Hole 763A, eastern Indian Ocean and later at DSDP 214 also support the above way of migration. However, Specer-Cervato *et al*. (1997) believed its appearance to be cryptogenic in the Indian Ocean. We disagree with this opinion and believe the migration occurred from the stage when *Globorotalia tosaensis* also evolved because a complete evolutionary lineage was shown to be present at all three holes. Though the successive younger appearance of *Gr. truncatulinoides* / *Gr. tosaensis* at 763A (2.05 Ma) and DSDP Hole 214 (1.85 Ma) supports its invasion into the Indian Ocean via Indonesian Throughflow, which reaches ODP 763A via Leeuwin Current and DSDP Hole 214 via South Equatorial Current, we believe that the evolution of *Gr. truncatulinodes* from its ancestor *Gr. toasensis* has independently occurred at both holes at different times. The FOs of ancestor species *Gr. crassaformis* and *Gr. tosaesnsis* confirm the views.

Pulleniatina primalis LO - Based on isotopic depth stratification *Pulleniatina* was established as a thermocline dweller (Srinivasan and Sinha 2000). *Pulleniatina* minimum events have been indicative of an increase in the depth of thermocline and its reduced niche (Liu *et al* 2013). *Pulleniatina primalis*, its descendent *Pulleniatina praecursor* and *Pulleniatina obliquiloculata* co-exist during some stratigraphic intervals indicating sympatric evolution. The Last appearance of *Pulleniatina primalis* is quire earlier in northern Indian ocean DSDP 219 (3.8 Ma) and 214 (3.6 Ma) than in Eastern Indian ocean ODP 763A (2.85 Ma)). The early disappearance of this species from the warmer northern Indian ocean thus might have been related to the increased depth of thermocline and its reduced thickness and increased sea surface temperatures. The late survival of *Pulleniatina primalis* in the Eastern Indian Ocean might have been due to shoaling of thermocline as a result of cooling of the eastern Indian Ocean (Karas *et al*., 2009, 2011).

Neogloboquadrina dutertrei FO - Kennett and Srinivasan (1983) considered *Neogloboquadrina dutertrei* to have evolved from *N. humerosa* within *Globorotalia toasensis* Zone in Late Pliocene. However, Bolli and Saunders (1985) in their range chart place FO of *N. dutertrei* at the base of Pliocene. This species shows its earliest appearance at DSDP Hole 219 (2.95 Ma) which is located in an upwelling zone (Whitemarsh *et al*.1974). The next younger appearance is at 763A at 2.75 Ma. The most delayed appearance of *N. dutertrei* is at DSDP Hole 214 at around 2.05 Ma. The species has been described by several workers and enough phenotypic variants of *N.dutertrei* have been described. Srinivasan and Kennett (1975) described two types of surface ultrastructures of *N. dutertrei*, one characteristic of cold water and the other of warm water. Thus due to the absence of taxonomic concepts regarding the surface ultrastructure, it is difficult to verify which of the phenotypes the authors (Srinivasan and Singh 1992 & Srinivasan and Chaturvedi 1992) mention. The appearance of *N. dutertrei* at different times at the three holes may be related to post-upwelling nutrient-rich conditions.

Globorotalia cibaoensis LO - The species becomes extinct earlier at the tropical Hole 214 and makes delayed extinction at Hole 763A perhaps owing to cool subtropical conditions. Kennet and Srinivasan (1983) believed *Globorotalia ciaboensis* to be of cool water affinity where it evolved to *Gr. crassula*. Its late LO is attributed to cool water conditions at Hole 763A. This event has not been recorded at DSDP 219.

Globorotalia crassaformis FO - *Globorotalia crassaformis* prefers deep waters (Kemle-von Mücke and Oberhanslie,1999), and the species requires very low oxygen levels to calcify its test (Cléroux *et al*.,2013). This species makes it first appearance at ODP Hole 763A at 4.45 Ma which is almost 1 Ma earlier than in the northern Indian Ocean. As per Kennett and Srinivasan (1983) *Globorotalia crassaformis* evolved from *Globorotalia crassula* in temperate areas. Thus its earliest presence at cooler Hole 763A is quite obvious. Later it migrated via the region occupied by Hole 214 to that of Hole 219.

Pu. praecursor LO - As described earlier *Pulleniatina* is a thermocline dweller and its niche shrinkage may be a factor for its early extinction at DSDP Hole 219. The speciation has been sympatric at all places. The species is a gradation between *Pu. primalis* and *Pu. obliquiloculata*. At Hole 763A it makes it late extinction because of probable shoaling of thermocline due to cooling of the eastern Indian Ocean (Karas *et al*., 2009, 2011b).

CONCLUSIONS

The graphic correlation amongst three deep sea sections (DSDP Hole 219, DSDP Hole 214 from Northern Indian Ocean and ODP Hole 763A from Eastern Indian Ocean) resulted in assessing the biostratigraphic usefulness of 25 important Late Neogene –Quaternary planktic foraminiferal events (FOs and LOs).

Based on two rounds of Graphic Correlation, the earliest FOs and latest LOs representing maximum stratigraphic ranges in the Indian Ocean were identified and a Composite Standard Reference Section was evolved representing maximum stratigraphic ranges.

The CSRS was integrated with magnetostratigraphy which yielded numerical age estimates for FOs and LOs of Late Neogene Quaternary planktic foraminiferal events for DSDP holes 219, 214 and ODP Hole 763A.

Based on the numerical age estimates of the planktic foraminiferal events, the extent of diachronism was estimated and the planktic foraminiferal events were divided into three categories, IO-Cat-1, IO-Cat-2 and IO-Cat-3. The first Category represents Synchronous events, the second represents fairly synchronous events while the third category represents diachronous events. The majority of the diachronous events have the extent of diachronism ranging between 0.4 and 1.2 Ma.

The main causative factors behind diachronism have been the water mass, changes in the structure of the upper water column and the gradual sympatric evolution and competition within ancestor and descendent populations. The majority of the diachronous events appear to be controlled by variation in water mass-related oceanographic changes at the three holes.

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