Ocean circulation in the tropical Indo-Pacific during early Pliocene (5.6–4.2 Ma): Paleobiogeographic and isotopic evidence

M S SRINIVASAN and D K SINHA

Department of Geology, Banaras Hindu University, Varanasi 221 005, India.

A comparison of late Neogene planktic foraminiferal biogeography and stable isotopic records of shallow dwelling and deep dwelling planktic foraminifera from DSDP sites 214 (Ninetyeast Ridge, northeast Indian Ocean) and 586B (Ontong-Java Plateau, western Equatorial Pacific) provides a clue to the nature of the ocean circulation in the tropical Indo-Pacific during early Pliocene.

The present study reveals that the late Neogene planktic foraminiferal data from the eastern and western sides of the Indonesian Seaway are very similar. The only distinct inter-ocean difference however is the absence of *Pulleniatina spectabilis* from the Indian Ocean. This species makes its first evolutionary appearance in the Equatorial Pacific at about 5.6 Ma (Early Gilbert reversed) and ranges up to 4.2 Ma (Top Cochiti subchron). The complete absence of *Pulleniatina spectabilis* from the Indian Ocean is attributed to blocking of westward flow of tropical waters of the Pacific to the Indian Ocean resulting in a major change in ocean circulation in the tropical Pacific and Indian oceans during 5.6 to 4.2 Ma.

In order to understand the nature of this blockage, isotopic depth ranking of selected planktic foraminifera was carried out which reveals that the Indonesian Seaway became an effective biogeographic barrier to deep dwelling planktic foraminifera and thus it may be interpreted that the shallow sills that mark the Seaway in modern times were present as early as 5.6 Ma.

The distribution of *Pulleniatina spectabilis* throughout the Equatorial Pacific reveals that Modern Equatorial Pacific Under Current (Cromwell Current) flowing towards east at a depth of 200–300 m (which is also the depth habitat of *Pulleniatina spectabilis*) was present at the beginning of the Pliocene (5.6 Ma).

As a sequel to the blocking of the Indonesian Seaway and the resultant interruption in the flow of central Equatorial Current System of the Pacific to the west there was an increase in the western Pacific Warm Pool Waters and strengthening of the gyral circulation in the Pacific and Indian Oceans. This eventually triggered the intensification of the Asian Monsoon System.

1. Introduction

The ocean circulation plays a vital role in storing and transporting vast quantities of heat, fresh and saline water, carbon, oxygen, nitrogen and other nutrients and influences the earth's climate and fundamental processes in the biosphere. Of particular interest is the upper part of the ocean water column i.e., mixed layer which directly interacts with the atmosphere and produces a multitude of climatic patterns. In the low latitudes, the circulation in the upper part of the water column is largely caused by stresses from the atmosphere and relative positions of land masses control the path of circulation. The present oceanic circulation system has resulted from a series of adjustments and readjustments of the continents as a result of plate motion operating through geologic time. During the late Cenozoic changes in the surface water circulation of the oceans have resulted from changes in the ocean continent geometry including closing and

Keywords. Planktic foraminifera; paleobiogeography; oxygen and carbon isotopes; Asian monsoon; ocean circulation.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **109**, No. 3, September 2000, pp. 315–328

opening of the ocean gateways e.g., opening of the Tasman Seaway and the Drake passage resulting into development of circum-Antarctic circulation; closure of Tethys Seaway between the eastern Mediterranean and Indian Ocean, closure of Indonesian and central American Seaways all resulting into the diminishing Equatorial Circulation and establishment of modern hydrographic pattern in the low latitudes (Srinivasan 1996, 1999). Major changes in the surface water circulation has affected greatly the oceanic plankton community whose quantitative distribution (temporal and spatial) as thanatocoenose provide important clues to infer the history of changes in the upper part of the water column.

Planktic foraminifera are one of the most important groups of microfossils used for reconstructing the past oceanic circulation. Changes in planktic foraminiferal biogeographic patterns have been used to infer oceanographic changes in the upper part of the water column (Bradshaw 1959; Ingle 1967; Bandy 1968; Kennett and Vella 1975; Bé 1977; Vincent and Berger 1981; Keller 1981(a,b); Kennett 1982; Kennett and Srinivasan 1983; Kennett *et al* 1985; Elmstorm and Kennett 1985; Srinivasan and Singh 1991; Srinivasan and Sinha 1991, 1992, 1997, 1998; Sinha and Srinivasan 1996). Besides this, the studies on the oxygen and carbon isotopic composition of planktic foraminiferal tests have enabled ranking them according to their depth habitat and this information on depth stratification of planktic foraminifera has been used to infer oceanographic changes at various depths in the upper part of the water column (Keller 1985; Gasperi and Kennett 1992).

The present study aims at understanding the nature of ocean circulation across the Indonesian Seaway during late Cenozoic based on planktic foraminiferal biogeographic and isotopic evidence. Since the begining of the Miocene the Indonesian Seaway has played a crucial role in bringing about profound changes in equatorial circulation both in the Indian and Pacific oceans by influencing the volume of Pacific outflow into the Indian Ocean (Kennett *et al* 1985; Srinivasan and Sinha 1998). The Seaway has acted as a leaky barrier from time to time influencing the volume of Pacific outflow into the Indian Ocean through the late Cenozoic. The closure of the Indonesian Seaway is not a one time event but has occurred more than once in response to tectonic movements in the Indonesian region during the Mio-Pliocene. During the Quaternary, the eustatic fall of sea level due to glacial maxima resulted in the temporary blocking of this Seaway. The changing volume of the Pacific outflow into the Indian Ocean results in variation in the amount of western Pacific Warm Pool and Gyral circulation in the tropical Pacific and Indian oceans which in turn has profound effect on El Nino event (Gordon and Fine 1996). Thus, the determination of timings and nature of the closure of this Seaway is vital for getting a better insight into the oceanographic and climatic changes that occurred in the tropical Indo-Pacific region during the late Cenozoic. Further, this tropical zone of the ocean has been the focus of attention for paleoceanographic and paleoclimatic researches (Gordon and Fine 1996). The sea surface here receives the greatest amount of solar heat which is then transferred by currents far beyond this zone determining the climate and the weather over a large portion of the globe. Intensive transfer of kinetic energy from the atmosphere into the oceans occur in this zone of trade winds, the most stable of the earth's wind system.

2. Modern ocean circulation in the tropical Indo-Pacific

The surface water circulation in the tropical Indo-Pacific in modern time is marked by weak westward flow of tropical waters from the Pacific into the Indian Ocean through the Indonesian Seaway. The water enters from the Central Equatorial Current System of the Pacific, a very small part of which flows into the Indian Ocean (South Equatorial Current) and a small part returns as East Australian Current in an anticlockwise motion causing gyral circulation in the waters of the Pacific (figure 1). This incoming of the relatively excess fresh waters from the western Pacific to the Indian Ocean through the Indonesian Seaway is an important regulator of the meridional overturning of these oceans and hence perhaps of the global thermohaline circulation (Gordon and Fine 1996). Further the seepage of warm water out of Pacific affects the volume of the Western Pacific Warm Pool which has great influence on El Nino.

3. Paleobiogeographic and isotopic approach

Planktic foraminifera have long been used as tracers of the oceanic surface water circulation in many regions (Kennett *et al* 1985). In this paper, by comparing planktic foraminiferal biogeography across the Indonesian Seaway an attempt has been made to infer the nature of surface water connection between the tropical Indian and Pacific oceans. Recent observations on the depth habitat of planktic foraminifera based on oxygen and carbon isotopic depth rankings provided a better insight into the evolution of structure in the upper part of the water column (Gasperi and Kennett 1992). By employing oxygen and carbon isotopic method an effort has been made to understand the vertical structure of the water column in the tropical Indo-Pacific.

4. Material and methods

The material consists of late Neogene deep sea cores from DSDP site 214 located on the Ninetyeast Ridge,

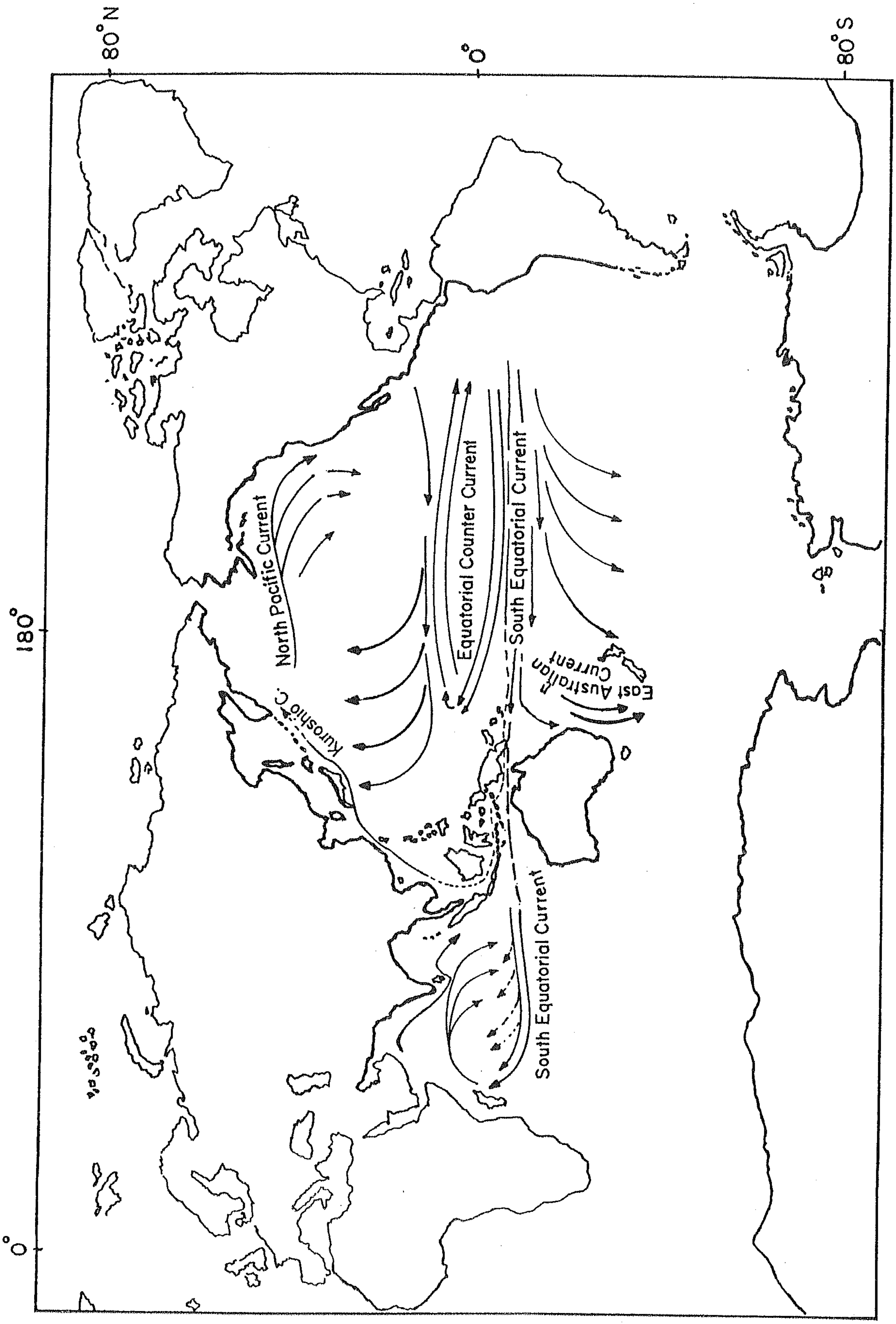

Figure 1. Modern surface water circulation in the tropical Indo-Pacific.

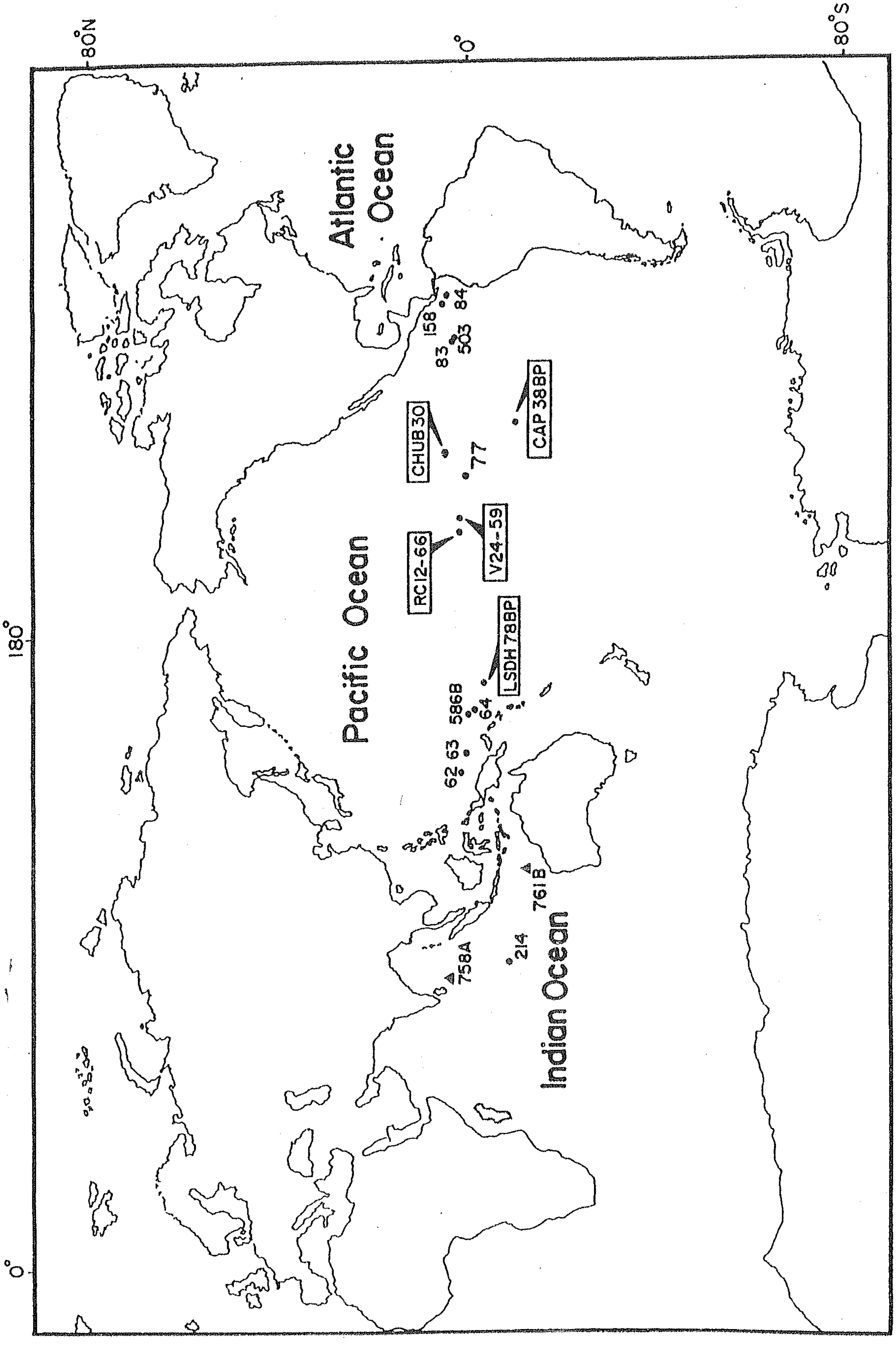

Figure 2. Location map of the cores discussed in the present study.

Table 1. *Location of the cores discussed in the present work.*

Site	Latitude	Longitude	Water depth (M)	Physiographic province
DSDP 214	11° 20.21′S	88° 43.08′E	1665	Ninetyeast Ridge,
ODP 758A	05° 23.49′N	90° 21.67′E	2923.6	Northeast Indian Ocean
ODP 761B	16° 44.22′S	155° 32.10′E	2167.9	Wombat Plateau, Indo-Pacific
DSDP 586B	00° 29.84′S	158° 29.89′E	2208	Ontong Java Plateau, Western Equatorial Pacific
RC-12-66	02° 36.06′N	148° 12.08′W	4755	Central Equatorial Pacific
V24-59	02° 34′N	145°.32 W	4662	
DSDP 77	00° 28.90′N	133° 13.70′W	4290	
DSDP 83	04° 02.08′N	95° 44.25′W	3645	
DSDP 84	05° 44.92′N	82° 53.29′W	3096	Eastern Equatorial Pacific
CHUB 30	07° 17.07′N	127° 24.06′W	3640	
DSDP 158	06° 37.36′N	85° 14.16′W	1953	
DSDP 503	04° .04′S	168° 02 E	3672	
DSDP 62	01° 52.02′N	14° 56′E	2591	
DSDP 63	00° 50.02′N	147° 53.03′E	4472	Caroline Ontong Java Region
DSDP 64	01° 44.05′S	158° 36.05′E	2052	Equatorial Southwest Pacific
CAP38BP	14° .16′S	119° .11′W	3400	Eastern Tropical Pacific
LSDH78BP	04° .31′S	168° .02 E	3208	Western Equatorial Pacific

northeast Indian Ocean and DSDP site 586B positioned at the Ontong Java Plateau, western Equatorial Pacific (figure 2, table 1). Graphic correlation method was employed to compare and contrast the late Neogene planktic foraminifera between the northeast Indian Ocean and western Equatorial Pacific. In addition, quantitative planktic foraminiferal data from the two sites were also compared (Srinivasan and Sinha 1998). The absolute ages of the planktic foraminiferal datums in the examined sites are based on integration of biochronologic data with paleomagnetic stratigraphy (Barton and Bloemendal 1985) employing Graphic correlation method (Srinivasan and Sinha 1992). The revised ages for the magnetic chron boundaries were recently provided by Berggren *et al* (1995a,b) which have been adopted in this paper.

Analyses for oxygen and carbon isotopic composition of selected planktic foraminifera were carried out with the assistance of Prof. J P Kennett at the University of California, Santa Barbara, USA. Values are given in delta notation as per mil deviation of the ^{18}O or ^{13}C ratios of the sample from that of the PDB standard. The analyses were carried out for three species of planktic foraminifera i.e *Pulleniatina spectabilis, Dentoglobigerina altispira* and *Globigerinoides sacculifer* in order to rank them according to their depth habitat. The data are provided in table 2. These three species were selected for isotopic analyses because of the following reasons.

- Comparison of faunal data between the two oceans reveals absence of *Pulleniatina spectabilis* from the Indian Ocean and its presence in abundance in the Equatorial Pacific.

Table 2. *Oxygen and carbon isotopic composition (PDB) of selected planktic foraminiferal species from DSDP site 586 B, Western Equatorial Pacific.*

Planktic foraminiferal species	$\delta^{18}O$	$\delta^{13}C$
Pulleniatina spectabilis	−1.121	+1.054
Globigerinoides sacculifer	−1.290	+2.425
Dentoglobigerina altispira	−1.237	+1.761

- The isotopic depth ranking of *Pulleniatina spectabilis* is not available as yet.
- *Dentoglobigerina altispira* and *Globigerinoides sacculifer* have been earlier ranked as shallow dwelling forms (very close to surface) based on oxygen and carbon isotopic composition. These two species were picked up for isotopic study from the same sample in which they co-occur with *Pulleniatina spectabilis* to further ascertain their relative depth ranking.

5. Observation

Figures 3 and 4 show the sequential order of late Neogene planktic foraminiferal events at DSDP site 214 (northeast Indian Ocean) and 586B (western Equatorial Pacific) respectively. A comparison of the planktic foraminiferal assemblages between the two sites reveal:

- Both of these sites contain an uninterrupted record of late Neogene planktic foraminiferal succession.
- The quantitative planktic foraminiferal data (Srinivasan and Sinha 1998) at the two sites show that the abundance and coiling patterns exhibited by

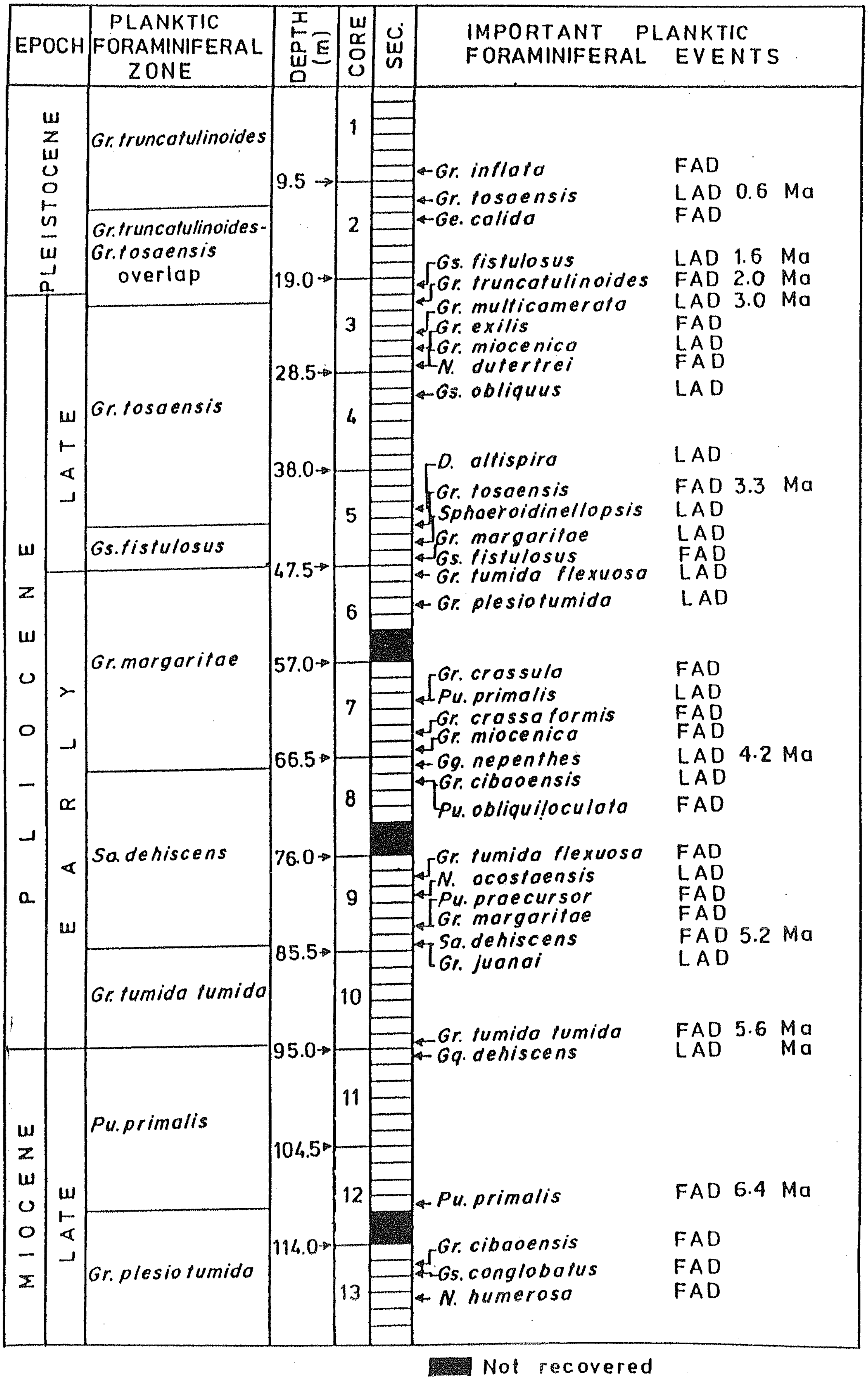

Figure 3. Late Neogene planktic foraminiferal zones and important planktic foraminiferal events at DSDP site 214, Ninetyeast Ridge, Northeast Indian Ocean (after Srinivasan and Chaturvedi 1992).

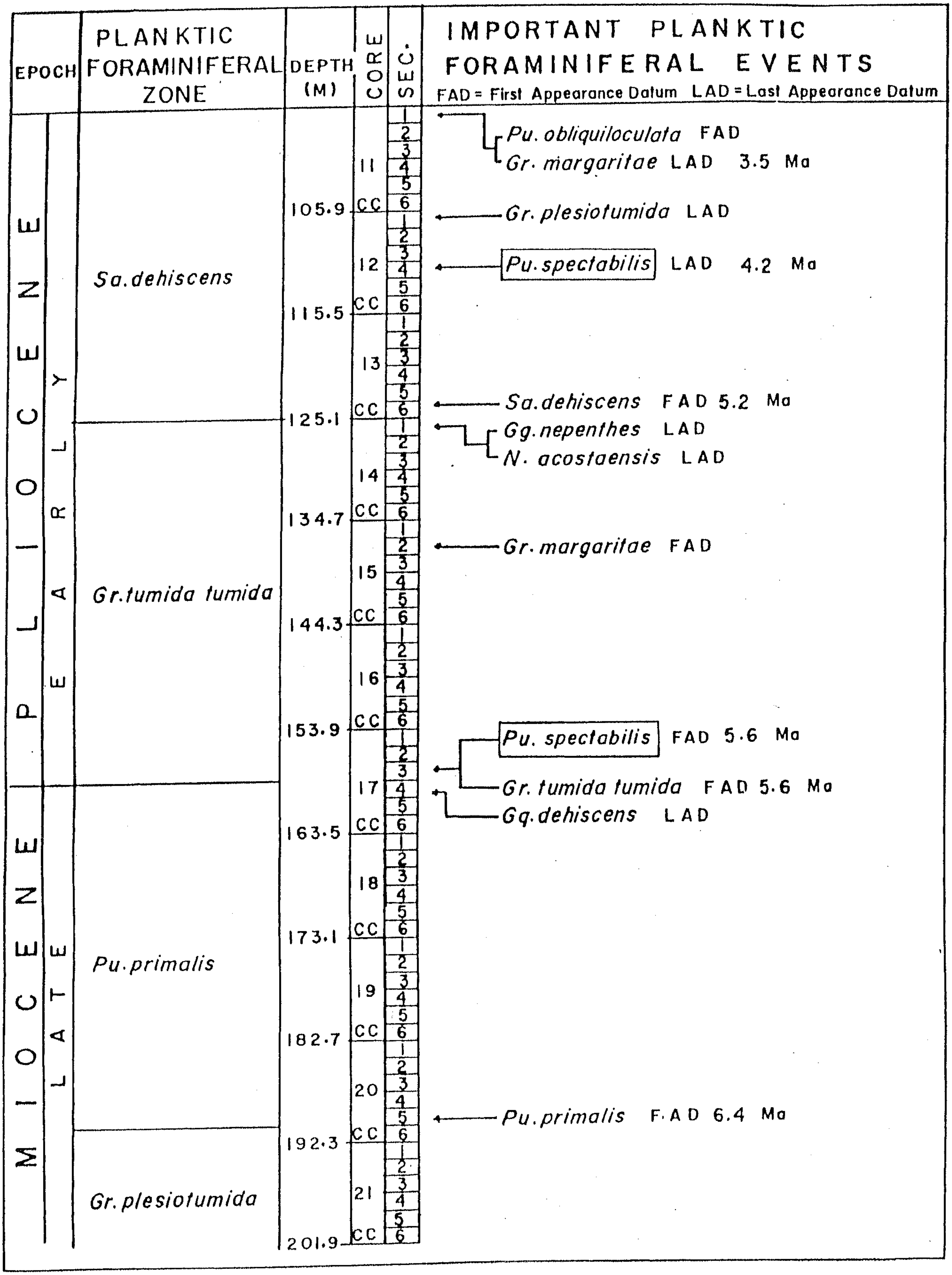

Figure 4. Late Neogene planktic foraminiferal zones and important planktic foraminiferal events at DSDP site 586 B, Ontong Java Plateau, western Equatorial Pacific (after Srinivasan and Sinha 1998).

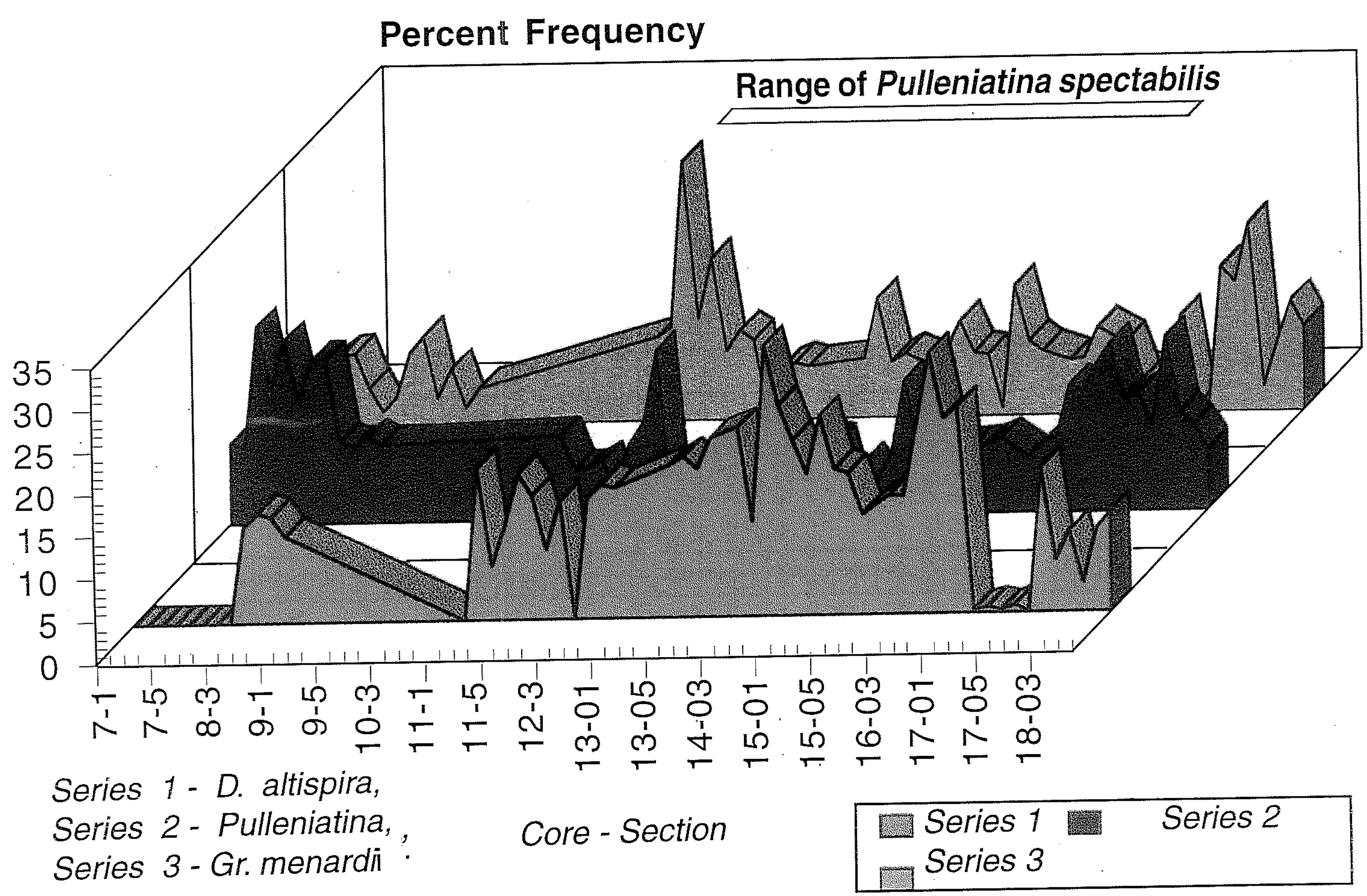

Figure 5. Relative abundance of *Dentoglobigerina altispira* (surface dwelling planktic foraminifera) vs *Pulleniatina* and *Globorotalia menardii* (deep dwelling planktic foraminifera) at DSDP site 586 B, western Equatorial Pacific.

Pulleniatina, *Globorotalia* and *Menardella* are very much similar.

- The most striking difference between the two sites however is the complete absence of planktic foraminiferal species *Pulleniatina spectabilis* from the Indian Ocean site 214 (figure 3) and its presence at the western Equatorial Pacific site 586B (figure 4). At this site, the species occurs from core 17–3 to core 12–4 in the early Pliocene (early Gilbert Reversed to Top of Cochiti Subchron, 5.6–4.2 Ma). It was Kennett and Srinivasan (1983) who first pointed out that *Pulleniatina spectabilis* is confined to the tropical Pacific and is not an Indo-Pacific species as considered earlier. The published data on the late Neogene planktic foraminifera from ODP site 758A (Jenkins and Gamson 1994), ODP site 761B (Zachariasse 1992), DSDP site 62 (Bronnimann and Resig 1971), DSDP sites 77, 83 and 84 (Orr and Jenkins 1980), DSDP site 158 and 503 (Kaneps 1973; Keigwin 1976, 1982), Core V-24-59 (Hays *et al* 1969), Core RC-12-66 (Saito *et al* 1975), Core CAP 38 BP and LSDH 78P (Parker 1967) also reveal that *Pulleniatina spectabilis* is completely absent from the Indian Ocean and is restricted to tropical Pacific only.
- *Pulleniatina primalis* which is the ancestral form of *Pulleniatina spectabilis* is present in both the tropical Indian and Pacific oceans (figures 3 and 4).
- A comparison of relative abundance of *Pulleniatina, Globorotalia menardii* and *Dentoglobigerina altispira* at site 586 B indicates that occurrence of *Pulleniatina spectabilis* is accompanied by a sudden increase in the abundance of *D. altispira* and a simultaneous decrease in abundance of *Globorotalia menardii* and *Pulleniatina* (figure 5).
- The oxygen and carbon isotopic data for *Pulleniatina spectabilis, Dentoglobigerina altispira* and *Globigerinoides sacculifer* (table 2) indicate that δ^{18}O value is higher for *Pu. spectabilis* than those for *D. altispira* and *Gs. sacculifer* whereas δ^{13}C value for *Pu. spectabilis* is lower than those of *D. altispira* and *Gs. sacculifer.*

6. Discussion

It is now well established that modern planktic foraminifera are sensitive tracers of the surface and near surface water masses and their distribution in the deep sea sediments is largely reflected by prevailing patterns of surface water circulation. *Pulleniatina primalis* which is the ancestral form of *Pulleniatina spectabilis* occurs both in the Indian Ocean and tropical Pacific (figure 6a). On the other hand, the presence in abundance of *Pulleniatina spectabilis* in the tropical Pacific and its absence in the Indian Ocean suggest that this species was prevented from emigration into the Indian Ocean because of the development of a barrier at the Indonesian Seaway causing the severing of surface water circulation between the two oceans (figure 6b). In order to understand the nature of this barrier and the resultant changes in circulation, a comparison of oxygen and carbon isotopic data of *Pulleniatina spectabilis*, with known shallow dwellers *Dentoglobigerina altispira and Globigerinoides sacculifer* was made.

The isotopic data reveal higher value of δ^{18}O and lower value of δ^{13}C for *Pulleniatina spectabilis* than those of the shallow water forms *D. altispira* and *Gs. sacculifer* thereby suggesting *Pulleniatiana spectabilis* to be a deep dwelling planktic foraminifera. Gasperi and Kennett (1992) ranked the planktic foraminifera according to depth habitat based on oxygen and carbon isotopic composition of their tests. The basic assumptions are:

(1) each species calcified its test in isotopic equilibrium with sea water,
(2) water temperatures are highest at the surface and decrease with depth and
(3) oxygen isotopic fractionation is temperature dependent so that shallow dwelling species have lower δ^{18}O values relative to the deep dwelling species,
(4) Carbon isotopic values in planktic foraminifera change vertically in the upper part of the water column such that δ^{13}C values are higher in surface waters due to high biological productivity and decrease with depth as respiration and decay of organic matter recycles ^{12}C rich CO_2 back to the water.

Thus the planktic foraminiferal species are ranked using their relative δ^{18}O values from lowest (shallow) to highest (deep) and their δ^{13}C values from highest (shallow) to lowest (deep). The present isotopic analysis for *Pulleniatina spectabilis* reveals highest δ^{18}O values and lowest δ^{13}C values as compared to known shallow water species *Dentoglobigerina altispira* and *Globigerinoides sacculifer.* This comparison clearly suggests *Pu. spectabilis* to be a relatively deep water form (200–300 m).

It would be worthwhile to mention here that the reported occurrence of *Pulleniatina spectabilis* in the equatorial Pacific lies in the region which in modern time is marked by a strong eastward flowing Equatorial Pacific Undercurrent (Cromwell Current) at a depth of $\sim$200–300 m. Considering the depth habitat of *Pulleniatina spectabilis* (200–300 m) and its reported occurrence in the equatorial Pacific (figure 7), it is suggested that the Cromwell Current was present in the Equatorial Pacific as early as 5.6 Ma.

The obstruction in the westward flow of tropical waters of the Pacific into the Indian Ocean caused an increase in the volume of western Pacific Warm Pool bringing favourable conditions for the warm surface dwelling planktic foraminifera e.g., *Dentoglobigerina*

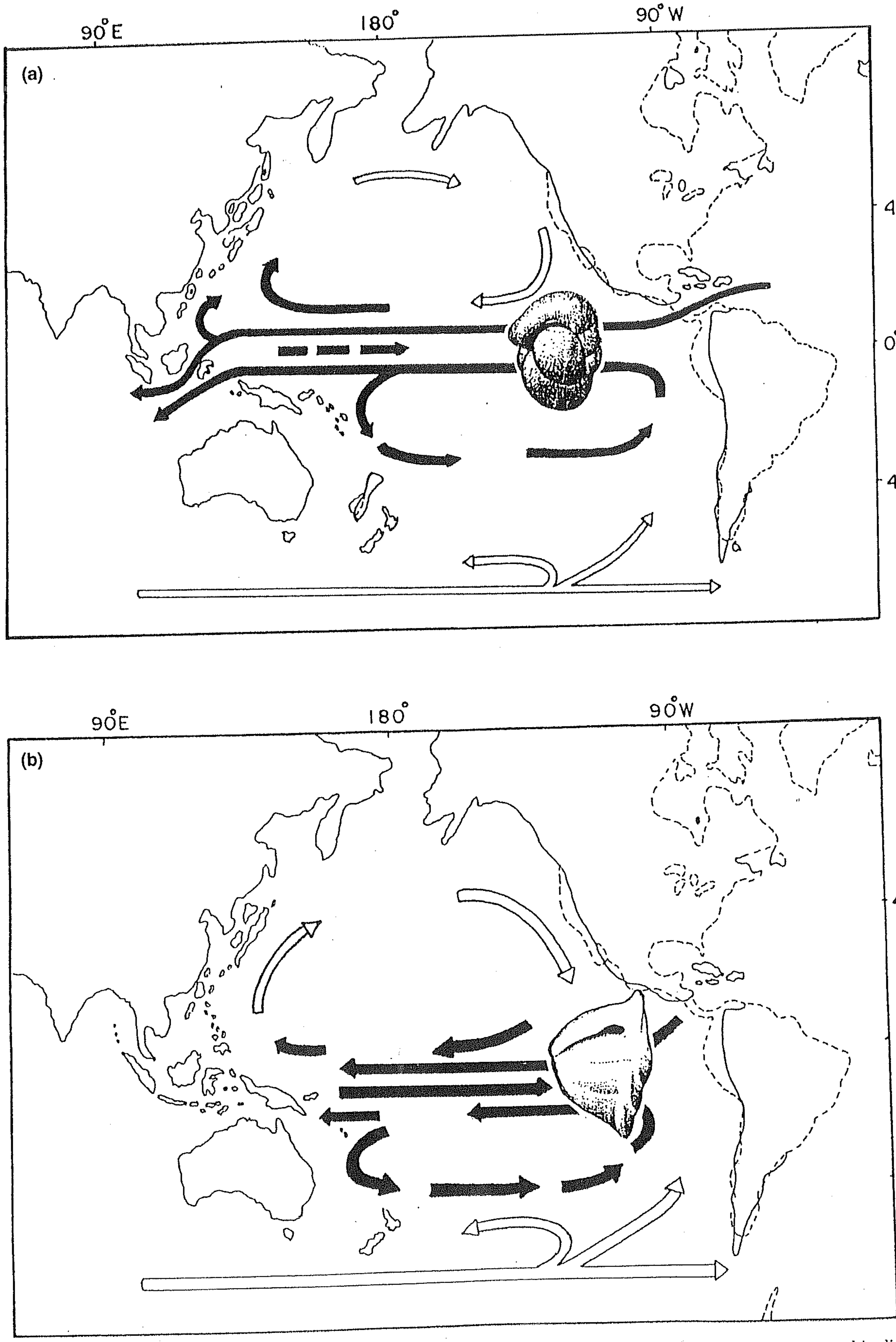

Figure 6. Tropical surface circulation in the Pacific (a) during late Miocene (6.4–5.6 Ma) based on biogeographic distribution of *Pulleniatina primalis* and (b) during early Pliocene (5.6–4.2 Ma) based on biogeographic distribution of *Pulleniatina spectabilis* (after Srinivasan and Sinha 1998). Black arrows represent warm ocean current and white arrows represent cold ocean current.

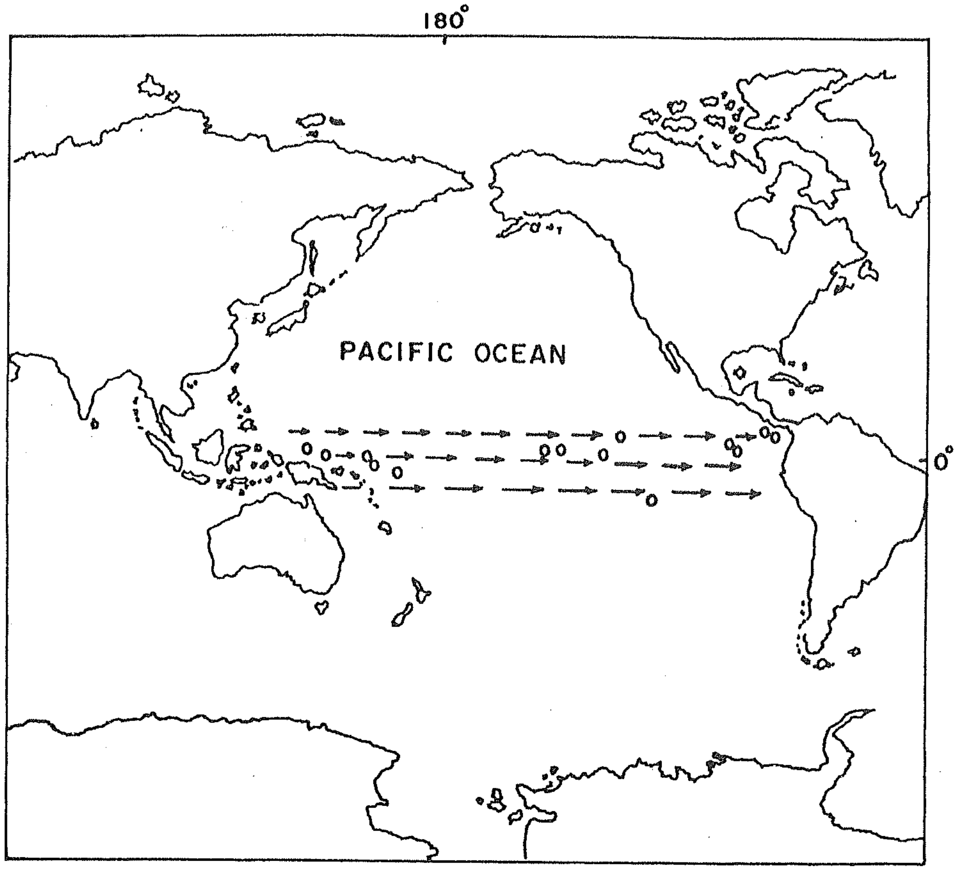

Figure 7. Modern Equatorial Pacific Under Current (Cromwell Current) and location of the cores (shown as circles) in which occurrence of *Pulleniatina spectabilis* has been reported.

altispira as revealed by very high abundance of this species as compared to low abundances of the deep dwelling forms *Globorotalia menardii* and *Pulleniatina* during the interval of occurrence of *Pulleniatina spectablis* at site 586B (figure 5).

During the last two decades several workers through their studies on Indo-Pacific deep sea cores and from land-based investigations on the Indonesian Island, inferred the timing of closing of the tropical Indo-Pacific Seaway. According to Edwards (1975) who proposed one of the earliest models for the Cenozoic paleocirculation in the Indo-Pacific, the gateway probably closed by the early middle Miocene.

Studies related to the Indo-Pacific ocean gateways employing biogeographic approach were attempted by the CENOP Group with their results appearing in a special publication edited by Kennett (1985).

Kennett *et al* (1985) quantitatively mapped the changing biogeographic patterns of the Pacific planktic foraminifera for three time slices in the Miocene: two in the early Miocene (22 and 16 Ma) and one in the late Miocene (8 Ma). They observed a distinct east-west tropical faunal provincialism during the early Miocene. This provincialism had essentially vanished by the late Miocene. Kennett *et al* (1985) interpreted this change to reflect initiation of Equatorial Under Current during the late middle Miocene (11–12 Ma) caused by the closure of the Indonesian Seaway.

Keller (1985) based on the studies related to the depth stratification of the Miocene planktic foraminifera and Romine and Lombari (1985) based on radiolarian assemblages from the western equatorial Pacific arrived at similar conclusions.

Srinivasan and Singh (1991) recorded the largest changes in the assemblages of planktic foraminifera occurring in the tropical Indian Ocean at about 11–12 Ma which they considered to have resulted due to the closure of the Indonesian Seaway as a consequence to the northward movement of Australia and tectonic evolution of the Indonesian Archipelago thus agreeing with the findings of the CENOP Group.

Recently Wei (1995) observed a southward shifting of the Tasman front and increase in the vertical temperature gradients in the southwest Pacific during the early Pliocene. This he attributed to an intensification in the western boundary current and development of warm pool waters in the western Equatorial Pacific as a result of the closing of Seaway in the New Guinea area.

Thus, the present study and the investigation carried out by Wei (1995) based on biogeographic and isotopic evidence suggest effective closure of Indonesian Seaway again during early Pliocene (5.6–4.2 Ma).

A tectonic model recently developed for the Philippine Sea and the western Pacific based on paleomagnetic and geological data reveals that collision between the Philippine Sea–Australia Plates during the early Miocene and subsequent westward (clockwise) motion of the Philippine Sea Plate related to Sunda land played a crucial role in the closure of the Indonesian Seaway (Ali *et al* 1993). According to Ali *et al* (1993) the Indo-Pacific gateway began to close gradually after 22 Ma constricting the gateway and impairing the westward flow of equatorial waters. The seaway got completely closed by the initiation of the Halmahera Arc at 11 Ma at the western edge of the south part of the Phillippine Sea as a result of the subduction of the Molucca Sea Plate.

Nishimura and Suparka (1997) based on tectonic considerations suggested that the Indonesian Seaway was effectively closed during early middle Miocene (17–15 Ma) and completely severed by about 6 Ma preventing further interchange between surface waters of the tropical Pacific and Indian Oceans.

Linthout *et al* (1997) suggested that the obduction and post obduction exhumation in the late Miocene (9.9–7.5 Ma) in the southern Banda Sea and also east of the Banda Sea played a major role in the closure of the Indonesian Seaway.

From the foregoing discussions it is evident that the closure of the Indonesian Seaway was not a one time event but has occurred more than once as a result of regional tectonism leading to the evolution of the Indonesian Archipelago during the Mio-Pliocene. During the Quaternary some channels of Seawater were closed and opened resulting from sea level changes caused by glacial maxima and also minor tectonic adjustments.

The timing of the reconstructions of the series of plate tectonic events in the Indonesian region during 22 Ma and 11 Ma (Ali *et al* 1993), 17–15 Ma and 6 Ma (Nishimura and Suparka 1997) and 9.9–7.5 Ma (Linthout *et al* 1997) is in agreement with the history of shallowing and eventual closure of the Indonesian Seaway as inferred from changes in biogeographic patterns and vertical thermal structure evolution of Late Neogene equatorial Pacific sea waters (Kennett *et al* 1985; Keller 1985; Romine and Lombari 1985; Srinivasan and Singh 1991; Srinivasan and Sinha 1997, 1998; and Wei 1995). Thus there appears to be a close link between the plate tectonic events, resultant circulation pattern and biogeographic changes in the tropical Indo-Pacific region.

7. Conclusion

The biostratigraphic data from the tropical Indian Ocean and western Equatorial Pacific are very similar.

- The only distinct difference is the absence of *Pulleniatina spectabilis* from the Indian Ocean and its presence in the tropical Pacific during early Pliocene (5.6–4.2 Ma).
- The absence of *Pulleniatina spectabilis* is interpreted to represent evidence of a biogeographic barrier between the tropical Indian and Pacific Oceans beginning at about 5.6 Ma. This is a strong evidence for the closure of the Indonesian Seaway by the earliest Pliocene (5.6 Ma).
- *Pulleniatina spectabilis* was exclusively a deep dwelling planktic foraminifera (> 200–300 m) as revealed from isotopic data and hence was prevented from migration into the Indian Ocean by the shallow sills in the Seaway. Thus these shallow sills that presently mark the Seaway were present as early as 5.6 Ma.
- The closure of the Indonesian Seaway has occurred more than once since the beginning of the Miocene in response to the tectonic activity in the Indonesian region and later in the Quaternary due to eustatic fall of sea level as a result of glacial maxima and minor tectonic adjustments.
- The intervals of major tectonic activity leading to the evolution of the Indonesian Archipelago also mark the periods of closure of the Indonesian Seaway and resultant changes in circulation pattern and biogeography. These intervals are during early Miocene (22 Ma), Middle Miocene (17–15 Ma), late middle Miocene (12–11 Ma), late Miocene (9.9–7.5 Ma) and early Pliocene (5.6–4.2 Ma). Thus there appears to be a close link between the plate tectonic events, resultant circulation pattern and biogeographic changes in the tropical Indo-Pacific region.
- The closing of the Indonesian Seaway resulted into increase in the western Pacific Warm Pool waters in the tropical Pacific and increased gyral circulation in the tropical Pacific and Indian oceans. Increased gyral circulation in the Indian Ocean acted as a triggering mechanism for the intensification of the Asian Monsoon System.

Acknowledgement

Thanks are offered to Prof. J P Kennett, University of Santa Barbara, USA, for providing isotopic data on selected species of planktic foraminifera. The samples for the present study were made available from the Deep Sea Drilling Project. Financial assistance from Special Assistance Programme (DSA Phase-II) of the UGC, New Delhi is thankfully acknowledged.

References

Ali J R, Spencer J R and Hall R 1993 The closure of the Indo-Pacific Ocean Gateway: A new plate tectonic perspective; *Proc. Int. Workshop on Neogene Evolution of Pacific Ocean Gateway*, (Indonesia: Bandar Lampung) 10–20

Bandy O L 1968 Cycles in Neogene paleoceanography and eustatic changes; *Paleogeography, Paleoclimatology and Paleoeology* **5** 63–73

Barton C E and Bloemendal J 1985 Paleomagnetism of sediments collected during Leg 90. Southwest Pacific In: *Initial Repts. DSDP* **90** 1273–1316

Bé A W H 1977 An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera; *Oceanic Micropaleontology* (ed) A T S Ramsay (London: Academic Press) **1** 1–100

Berggren W A, Kent D V, Swisher C C III, Aubry M P 1995a A revised Cenozoic geochronology and chronostratigraphy; *SEPM Special publication No. 54* 129–212

Berggren W A, Hilgen F J, Lagereis C G, Obradovich J D, Raffi I, Raymao M E and Shacleton N J 1995b Late Neogene chronology: New perspective in high resolution stratigraphy; *Geological Society of America Bull.* **107(11)** 1227–1287

Bradshaw J S 1959 Ecology of living planktonic foraminifera in the north and equatorial Pacific Ocean; *Contributions to Cushman foundation for foraminiferal research* **10(2)** 25–64

Bronnimann P and Resig J 1971 A Neogene globigerinacean biochronologic time scale for the southwest Pacific; *Initial Reports of the Deep Sea Drilling Project* **7(2)** 1235–1469

Edwards A R 1975 Southwest Pacific Cenozoic paleogeography and integrated Neogene paleocirculation model; *Initial Reports of the Deep Sea Drilling Project* **30** 667–684

Elmstorm K M and Kennett J P 1985 Late Neogene paleoceanographic evolution of site 590, Southwest Pacific; *Initial Reports of the Deep Sea Drilling Project* **90** 1361–1381

Gasperi J T and Kennett J P 1992 Isotopic evidence for depth stratification and paleoecology of Miocene planktonic foraminifera: Western Equatorial Pacific DSDP site 289; *Pacific Neogene, Environment, Evolution and Events* (eds) Tsuchi and Ingle 117–147 (Tokyo University Press)

Gordon A L and Fine R A 1996 Pathways of water between the Pacific and Indian Oceans in the Indonesian Seas; *Nature* **379** 146–149

Hays J D, Saito T, Opdyke N D and Burkle L H 1969 Pliocene and Pleistocene sediments of the equatorial Pacific: Their paleomagnetic, biostratigraphic and climatic record; *Geological Society of America Bulletin* **8** 1481–1513

Ingle J C Jr 1967 Foraminiferal biofacies variation and the Miocene-Pliocene boundary in southern California; *Bulletin of American Paleontology* **52(236)** 217–394

Jenkins D G and Gamson P 1994 Neogene planktonic foraminifera from Ocean Drilling Programme leg 121: Four sites on Broken ridge and Ninetyeast Ridge, Indian Ocean; *Proc Int. Workshop on Neogene evolution of Pacific Ocean gateways* 51–64 Bander Lampung Indonesia

Kaneps A G 1973 Cenozoic planktonic foraminifera from the eastern equatorial Pacific Ocean; *Initial reports of the deep Sea drilling project* **16** 713–745

Keigwin L D Jr 1982 Neogene planktonic foraminifers from Deep sea Drilling Project Sites 502 and 503; *Initial reports of the deep sea drilling project* **68** 269–288

Keigwin L D Jr 1976 Late Cenozoic planktonic foraminiferal biostratigraphy and paleoceanography of the Panama basin; *Micropaleontology* **22** 419–422

Keller G 1981a Planktonic foraminiferal fauna of the equatorial Pacific suggest Early Miocene origin of present ocean circulation; *Marine Micropaleontology* **6** 269–295

Keller G 1981b Miocene bichronology and paleoceanography of the north Pacific; *Marine Micropaleontology* **6** 535–551

Keller G 1985 Depth stratification of planktonic foraminifers in the Miocene ocean; The Miocene Ocean: Paleogeography and Biogeography; *Geological Soc. Amer. Memoir* **163** 177–195

Kennett J P 1982 *Marine Geology* (Englewood Cliffs N J Prentice-Hall)

Kennett J P 1985 The Miocene Ocean: Paleogeography and Biogeography; *Geological Society of America Memoir* **163**

Kennett J P, Keller G and Srinivasan M S 1985 Miocene planktonic foraminiferal biogeography and paleoceanographic development of the Indo-Pacific region; The Miocene Ocean: Paleogeography and Biogeography; *Geological Society of America Memoir* **163** 197–236

Kennett J P and Srinivasan M S 1983 Neogene Planktonic Foraminifera: A Phylogentic Atlas, (New York: Hutchinson Ross Publ. Co.)

Kennett J P and Vella P 1975 Late Cenozoic Planktonic Foraminifera and paleoceanography at DSDP site 284 in the cool subtropical southwest Pacific; *Initial reports of the deep sea drilling project* **29** 769–800

Linthout K, Helmers H and Sopaheluwakan 1997 Late Miocene obduction and microplate migration around the southern Banda Sea and the closure of the Indonesian Seaway; *Tectonophysics* **281** 17–30

Nishimura S and Suparka S 1997 Tectonic approach to the Neogene evolution of Pacific-India Ocean gateways; *Tectonophyics* **281** 1–16

Orr W N and Jenkins D G 1980 Eastern equatorial pacific Pliocene-Pleistocene biostratigraphy; *Memorial to O L Bandy* (eds) Ingle *et al* Cushman Foundation Special Publ. **19**, 278–286

Parker F L 1967 Late Tertiary biostratigraphy (Planktonic Foraminifera) of tropical Indo-Pacific deep sea cores; *Bulletin of American paleontologists* **52(235)** 115–208

Romine K and Lombari G 1985 Evolution of the Pacific circulation in the Miocene: Radiolarian evidence from DSDP site 289; The Miocene Ocean: Paleogeography and Biogeography, *Geological Society of America Memoir* **163**, 273–290

Saito T, Burkle L H and Hays J D 1975 Late Miocene to Pleistocene biostratigraphy of equatorial Pacific sediments *Late Neogene Epoch boundaries* (eds) Saito T and Burkle L H) 226–244 (New York: Micropaleontology Press)

Sinha D K and Srinivasan M S 1996 Late Neogene quantitative planktic foraminiferal biochronology and paleoceanography of DSDP site 588, Southwest Pacific; *Contr. XV Indian Colloq. Micropal. and Strat. DehraDun* 295–304

Srinivasan M S 1996 Oceanic Micropaleontology, Major advances since the beginning of DSDP *Presidential Address, XV Indian Colloq. On Micropal. and Strat.* Dehra Dun 34p

Srinivasan M S 1999 Paleoceanography: Evolution of oceans through the Cenozoic In: *Ocean science trends and future directions* (ed.) B L K Somayajulu INSA, Academia Books International 113–128

Srinivasan M S and Chaturvedi S N 1992 Neogene planktonic foraminiferal biochronology of the DSDP sites along Ninetyeast Ridge, northern Indian Ocean In: Ishizaki and Saito (eds.) *Centenary of Japanese Micropaleontology* 175–178

Srinivasan M S and Singh A D 1991 Planktonic foraminiferal evidence for the Neogene paleoceanographic changes in the Indian Ocean *3rd Int. Symposium IGCP-246 Chiangmai Univ Thailand* 179–205

Srinivasan M S and Sinha D K 1991 Improved correlation of the Late Neogene planktonic foraminiferal datums in the equatorial to cool subtropical DSDP sites, Southwest Pacific: Application of the Graphic correlation method; *Mem. Geol. Soc. India* **No 20**, pp 55–93

Srinivasan M S and Sinha D K 1992 Late Neogene planktonic foraminiferal events of the Southwest Pacific and Indian Oceans: A comparison; *Pacific Neogene, Environment, Evolution and Events* (eds) R Tsuchi and James C Ingle Jr (Japan: University of Tokyo Press) 203–220

Srinivasan M S and Sinha D K 1997 Ocean circulation changes in the tropical Indo-Pacific during 5.6–4.2 Ma: Paleobiogeographic and isotopic evidence *Abst International Conference on Isotopes in the Solar System*, PRL Ahmedabad 213

Srinivasan M S and Sinha D K 1998 Early pliocene closing of the Indonesian Seaway: Evidence from northeast Indian Ocean and Southwest Pacific deep sea cores; *Journal of Asian Earth Sciences, Elsevier UK* **16(1)** 29–44

Vincent E and Berger W H 1981 Planktonic foraminifera and their use in paleoceanography in: (ed.) Emiliani C *The oceanic lithosphere* (New York: Wiley Interscience) 1025–1120
Wei Kuo Yen 1995 Southward shifting of the Tasman front at 4.4 Ma: paleobiogeographic and isotopic evidence *Oji Seminar on "Neogene Evolution of Pacific ocean gateways"* Kyoto, Japan, IGCP Project 355 (Abst.) 63
Zachariasse W J 1992 Neogene planktonic foraminifers from sites 761 and 762 off northwest Australia; *Proc. Ocean Drilling Programme Scientific Results* **122** 665–675

MS received 18 December 1999; revised 28 August 2000