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LATE NEOGENE PLANKTIC FORAMINIFERAL BIOCHRONOLOGY OF THE ODP SITE 763A, EXMOUTH PLATEAU, SOUTHEAST INDIAN OCEAN

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ABSTRACT

The late Neogene section of ODP Hole 763A, Exmouth Plateau, southeast Indian Ocean, has been biostratigraphically subdivided into eight planktic foraminiferal zones. The zones are similar to those of the tropical northern Indian and tropical western Pacific Oceans. The sequential order of planktic foraminiferal events has been determined, and 32 late Neogene planktic foraminiferal events have been identified. A major faunal turnover (22 events) occurs between 80 and 45 meters below seafloor (mbsf), spanning 1.6 million years between 3.6 Ma and 2 Ma and may be related to the stresses transmitted to the upper ocean due to major cooling associated with Northern Hemisphere glaciation.

Based on integration with magnetostratigraphy, numerical age estimates of planktic foraminiferal events have been determined for the first time from the southeast Indian Ocean. A comparison with the published dates for these events from other parts of the world suggests that 14 events are reliable for correlation over a wide geographic range. The useful synchronous events are the *Globorotalia tosaensis* FO (2.84 Ma), the *Globorotalia tosaensis* LO (0.59 Ma), the *Globigerinoides extremus* LO (1.87 Ma), the *Globigerinoides fistulosus* FO (3.26 Ma), the *Globigerinoides fistulosus* LO (1.73 Ma), the *Dentoglobigerina altispira* LO (3.05 Ma), the *Dentoglobigerina globosa* LO (3.18), the *Neogloboquadrina dutertrei* FO (2.77 Ma), the *Sphaeroidinellopsis* LO (3.35), the *Globorotalia margaritae* LO (3.38 Ma), the *Globorotalia crassaformis* FO (4.41 Ma), the *Globoturborotalita nepenthes* LO (3.44 Ma), the *Globorotalia tumida tumida* FO (5.10 Ma) and the *Pulleniatina primalis* FO (5.70 Ma). In contrast, the other events are diachronous and considered unsuitable for inter-oceanic correlation. The Pliocene-Pleistocene boundary is marked at ODP Hole 763A by the LO of *Globigerinoides fistulosus*, which is a synchronous event over a wide latitudinal range and occurs close to the top of the Olduvai Event (Chron C2n; 1.77 Ma). The Miocene-Pliocene boundary is approximated by the first evolutionary appearance of *Globorotalia tumida tumida* from its ancestor *Globorotalia plesiotumida* and occurs close to base of Thvera magnetic event (C3n.4n; 5.23 Ma). Recognition of both of these epoch boundaries is in accord with the International Commission on Stratigraphy. The detailed planktic foraminiferal biochronology developed for Hole 763A will aid correlation and dating of various paleoceanographic events over the last 6 million years in the southeast Indian Ocean.

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INTRODUCTION

The relatively rapid rate of evolution in planktic foraminifera, due to continuous stresses imposed by climatic changes at the atmosphere-water interface, has made them excellent biostratigraphic markers for the Cenozoic. Their facies-independent distribution, due to their planktonic mode of life, has further added to their biostratigraphic value. Their size, abundance and diversity in marine sediments and the relative continuity in their stratigraphic records permit observations at a level more detailed than is available within other groups of microfossils (Berggren, 1969). Strong latitudinal provincialism in planktic foraminifera was established with gradual increase in the latitudinal thermal gradient with progressive cooling after the Eocene warmth (e.g., Savin, 1977; Miller and others, 1987; Stott and Kennett, 1990). On one hand, this biogeographic provincialism enabled scientists to employ cool-versus-warm planktic foraminifera for paleoceanographic interpretation, whereas on the other hand, this led to erection of separate zonal schemes for tropical, temperate and mid latitudes. The planktic foraminiferal biostratigraphies established in different parts of the world have aided study of distinct phylogenetic lineages under contrasting climatic and oceanographic regimes and raised questions about the applicability of any one zonal scheme over a broad geographic range. Difficulties were experienced in correlating zonal boundaries due to observed diachrony of the planktic foraminiferal events. Due to availability of good-quality deep-sea cores, considerable progress has been made in the field of Neogene planktic foraminiferal biostratigraphy and biochronology in the last decade. This has led to improvement in the precision and accuracy of late Neogene geochronology (Hilgen, 1987; Hilgen and Langereis, 1988, 1989; Shackleton and others, 1990; Mankinen and Darlymple, 1979; Cande and Kent, 1995; Berggren and others, 1995a, 1995b). An excellent synthesis of the magnetostratigraphy, isotopic radiochronology, astrochronology and global biostratigraphic datums, including planktic foraminiferal events, was presented by Berggren and others (1995a, 1995b).

The sequential order of planktic foraminiferal events is commonly dissimilar—even within a short geographic range—due to the time transgressive nature of appearance and extinction events (Dowsett, 1988; Srinivasan and Sinha, 1992). The cause of such diachrony is not yet fully understood, though logically this is attributable to either intrinsic factors (including genetic change, population dynamics, phylogenetic change) or extrinsic factors [including opening and closing of ocean gateways (Jenkins, 1974; Srinivasan and Sinha, 1998) or paleoclimate, which influences speciation and extinction rates, taxonomic longevity and latitudinal range (Parker and others, 1999)]. It is imperative to critically examine the timing of the first and last occurrences (FOs and LOs) of any fossil because establishing the correct sequential order of the events is essential to understanding of the underlying causative factors. Micropaleontologists devise various methods to differentiate synchronous and diachronous biostratigraphic events, and one such approach is to observe whether the appearances and extinction events are part of the evolutionary process or mere migratory events. Migratory appearances can be distinguished from phylogenetic appearances by tracing the ancestor and descendent relationships. A number of appearance and extinction events of planktic foraminifera, earlier considered good for correlation (e.g., *Globorotalia truncatulinoides* FO widely used to mark the Pliocene-Pleistocene Boundary), were found to be diachronous between oceanic provinces, though they maintain their utility because of synchroneity within limited regions.

It has been possible to estimate numerical ages for a large number of planktic foraminiferal events based on integration of biostratigraphy and magnetostratigraphy combined with Shaw's (1964) graphic correlation method. Integration of late Neogene planktic foraminiferal biostratigraphy with magnetochronology has led to the estimation of numerical ages for planktic foraminiferal events from different regions of the world ocean (Hodell and Kennett, 1986; Weaver and Clement, 1986, 1987; Dowsett, 1988; Channel and others, 1988, 1990; Raymo and others, 1989; Zachariasse and others, 1989; Glacon and others, 1990; Zizderveid and others, 1991; Langereis and Hilgen, 1991; Srinivasan and Sinha, 1992; Chaisson and Leckie, 1993; Chaproniere and others, 1994; Berggren and others, 1995a, 1995b; Chaisson and Pearson, 1997; Kucera and Kennett, 2000). Such an exercise has been useful in providing a compatible time framework for DSDP and ODP sites from different latitudes and longitudes, enabling precise correlation of paleoceanographic events recorded at each such site. However, a review of the above referenced publications reveals that the numerical ages of planktic foraminiferal events determined in different areas show greater variation than expected and suggested a need for establishing biochronologies for more areas where such data is lacking.

NEED FOR LATE NEOGENE PLANKTIC FORAMINIFERAL BIOCRONOLOGY FROM THE SOUTHEAST INDIAN OCEAN

Though substantial work has been carried out on the planktic foraminiferal biostratigraphy and biochronology of the northern and central Indian Ocean (e.g., Leg 22: McGowran, 1974; Berggren and others, 1974; Berggren and Poore, 1974; Srinivasan and Chaturvedi, 1992; Berggren and others, 1974. Leg 23A: Fleisher, 1974; Akers, 1974a, b; Srinivasan and Singh 1992; Srinivasan and Sinha, 1992. Leg 24: Vincent and others, 1975. Leg 25: Zobel, 1974. Leg 29: Jenkins, 1975), few detailed studies have been made on the planktic foraminiferal biostratigraphy and biochronology from the southeastern Indian Ocean (Leg 26: Boltovskoy, 1974a, 1974b). The remainder is mainly taxonomic in nature (Akers, 1974a, 1974b; Rögl, 1974). Furthermore, the biostratigraphic studies lack integration with magnetostratigraphic data from the southeast Indian Ocean.

MODERN OCEANOGRAPHIC SETING OF SITE 763A

The major circulation features affecting the ODP Hole 763A (20°35.20′ S latitude; 112°12.50′ E longitude) in the present-day ocean are the South Equatorial Current (SEC), the West Australian Current (WAC) and the Leeuwin Current (LC). The SEC carries low-salinity tropical waters from the western Pacific through the Indonesian Archipelago into the eastern Indian Ocean. Under the combined influence of pressure differences and sea level gradients, the accumulated pool of warm water then flows southwards along the West Australian coast around Cape Leeuwin and is known as the Leeuwin Current (Wells and others, 1994; Fig. 1). Beneath the LC, which is the only southward-flowing surface current in the region, the cold West Australian Current carries high-salinity waters northward. This current in turn influences water masses as deep as 2000 m (Tchernia, 1980) and is part of a major Southern Hemisphere gyre moving anticlockwise in the Indian Ocean. It is worthwhile to mention here that the southeast Indian Ocean off Western Australia is the only eastern boundary current region undergoing no upwelling in spite of predominating equatorward winds as there is no continuous equatorward flow within 1000 km of the coast (Smith, 1992; Veeh and others, 2000). To the contrary, there is a strong poleward flow of warm water through the LC against the prevailing equatorward winds (Creswell and Golding, 1980). Hole 763A is situated in the region influenced by both the warm LC from the north, flowing as deep as 200 m, and the cold WAC from the south, Thus, the hole contains a mixture of typical warm- and cold-water planktic foraminifera.

The Indonesian Throughflow links the oceanographic and climatic changes in the southeast Indian Ocean to the Western Pacific Warm Pool during the late Neogene. Hence, changes induced by El Niño and the Southern Oscillation modulate the strength of the Leeuwin and West Australian Currents as well as waxing and waning of the Antarctic ice sheet (McGowran and others, 1997; Zachariassee, 1992; Sinha and others, 2006). In particular, the southeastern Indian Ocean off Western Australia serves as a link between the Western Pacific and Indian Oceans via the Indonesian seaway. Changes in this part of the ocean have a profound effect on the circulation and heat budget of the Indian Ocean and the Indian Monsoon (Sinha and others, 2006). Under this unique oceanographic set up, the goal of this study is to determine the order of late Neogene planktic foraminiferal events and their stratigraphic ranges.

THE PLANKTIC FORAMINIFERAL ASSEMBLAGE AT HOLE 763A

The planktic foraminiferal assemblages at the Hole 763A exhibit a mixture of a typical warm-water fauna dominated by the *Globigerinoides* group and a typical cool-water fauna dominated by the *Globoconella* group. A warm-water fauna, consisting mostly of the *Globigerinoides* group dominates the latest Miocene and Early Pliocene assemblage. The invasion of a temperate assemblage comprising members of the *Globoconella* group began in the Late Pliocene. Throughout the section, there are intervals where

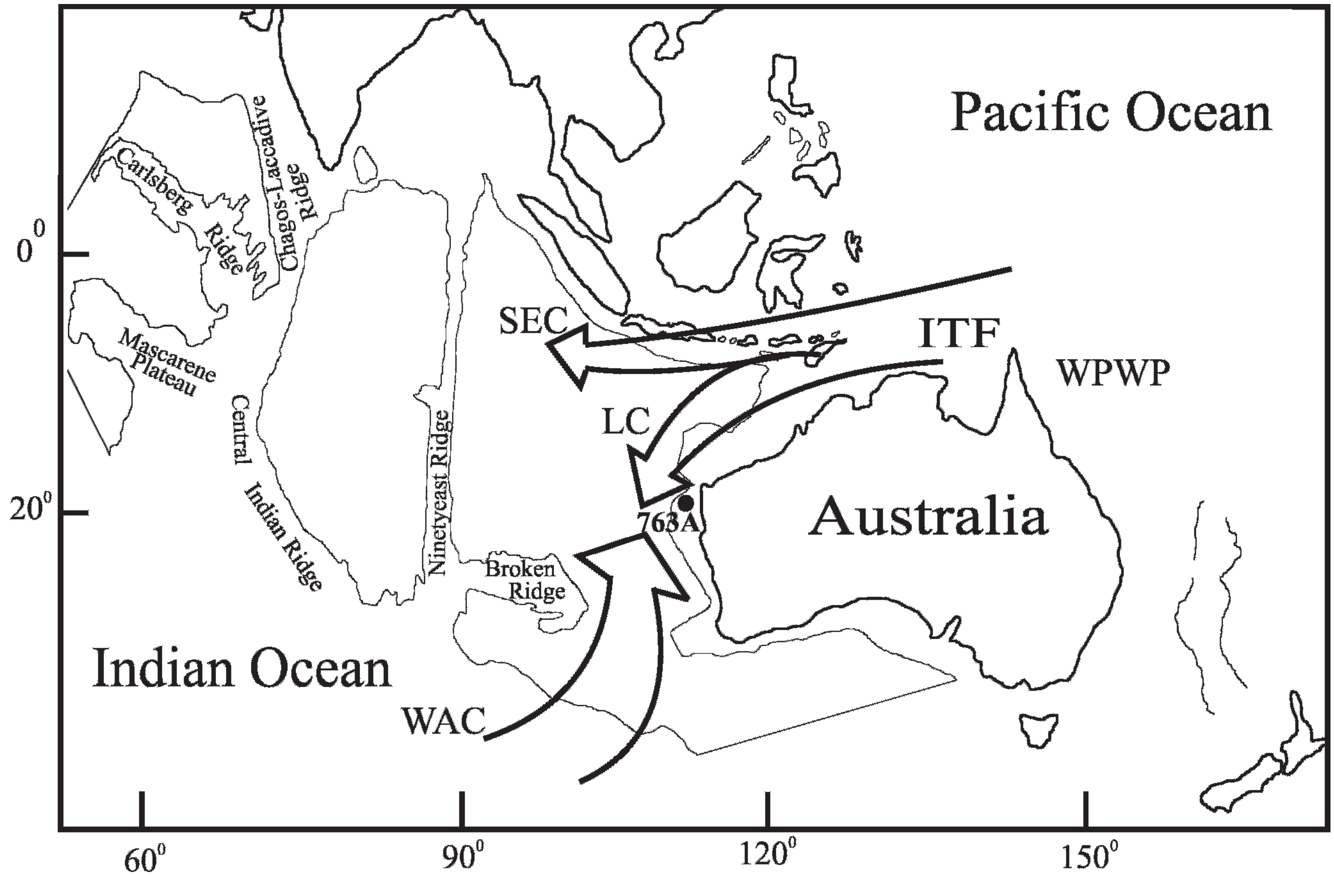

FIGURE 1. Location and modern oceanographic setting of ODP Hole 763A. LC= Leeuwin Current, WAC= West Australian Current, SEC= South Equatorial Current, WPWP= Western Pacific Warm Pool, ITF = Indonesian Throughflow. The isobath shown is 4000 m (figure modified after Luyendyk and Davies, 1974).

the upwelling indicator species, *Globigerinita glutinata*, shows episodic abundance. Downcore variations in the relative abundance of these two groups, with occasional dominance of the upwelling-indicator species *Gt. glutinata* and *Globigerina bulloides*, reflect the relative dominance of the Leeuwin and West Australian Currents and associated upwelling. The preservation of the planktic foraminifera is excellent with little or no dissolution.

In the present study, detailed qualitative and quantitative analyses of planktic foraminifera from ODP Site 763A on the Exmouth Plateau of the southeast Indian Ocean have been carried out in order to a) elucidate the planktic foraminiferal biostratigraphic zonation of ODP Site 763A; b) document the sequential order of planktic foraminiferal events; c) integrate the biostratigraphy with magnetochronology to estimate the numerical ages of the late Neogene planktic foraminiferal events and compare the estimated ages with those from other parts of the world ocean. The study provides a precise time framework for correlating late Neogene paleoceanographic events at ODP Site 763A of the southeast Indian Ocean.

BIOSTRATIGRAPHY

There have been serious problems in the application of one set of tropical zonations (Blow's zonation) to the Indian Ocean. It is unreasonable to expect any set of zones to be uniformly applicable to all the regions because planktic foraminiferal species are not themselves uniformly distributed. With the application of the graphic correlation method to deep-sea planktic foraminiferal events (Dowsett, 1989a, 1989b; Srinivasan and Sinha, 1991, 1992), it has become firmly established that a number of planktic foraminiferal events are diachronous over even a small latitudinal range. Further, integration of planktic foraminiferal datum levels with those of magnetochronology has shown that zonal boundaries are frequently diachronous and cannot be taken as synchronous over a wide latitudinal range. However, a number of planktic foraminiferal species have synchronous appearances and extinctions in a number of deep-sea sequences (Srinivasan and Sinha, 1992). Thus, it becomes important to establish detailed biochronologies for individual regions of the world oceans in order to correlate paleoceanographic events. The zonal scheme followed for ODP Hole 763A is after Srinivasan and Kennett (1981a, b) and Srinivasan and Sinha (1992) for equatorial Pacific Site 289 (re-cored as Hole 586B) and Srinivasan and Chaturvedi (1992) for the northern Indian Ocean. The only difference is the non-recognition of the *Globorotalia margaritae* Zone because the base of this zone is marked by the highest occurrence of *Globoturborotalita nepenthes*, which at the Hole 763A becomes extinct quite early. After the ranges of selected planktic foraminiferal species at Hole 763A were established (Fig. 2), the first (and last) occurrence events were recorded by noting depth of the lowest (or highest) sample in which the taxon was searched for but not found following Dowsett (1989b). These two depths define the stratigraphic uncertainty of the fossil event at Hole 763A (Table 1). The planktic foraminiferal zones recognized for the examined site and a comparison of these zones with those of Berggren and others (1995a, b) has been provided in Figure 3.

LATE NEOGENE EPOCH BOUNDARIES

Miocene–Pliocene Boundary

At ODP Hole 763A, the evolutionary first appearance of *Globorotalia tumida tumida* from its ancestor *Globorotalia plesiotumida* coincides with the base of the Thvera magnetic event (C3n.4n; Fig. 3, 4) and has been adopted to approximate the base of the Pliocene or the Miocene-Pliocene boundary. Though Berggren and others (1995a) quoting Srinivasan and Sinha (1992) provided an age estimate of 5.6 Ma for the first appearance of *Gr. tumida tumida*, they placed the Miocene-Pliocene boundary at the base of Thvera magnetic event (C3n.4n) within their PL1 Zone (*Globorotalia tumida- Globorotalia cibaoensis* Subzone). The Miocene-Pliocene boundary (base of the Zanclean beds of Sicily) has been calculated by Hilgen and Langereis (1988) to lie approximately five precession cycles below the Thvera, with an estimated age of 5.33 Ma.

Pliocene–Pleistocene Boundary

For several years, the Pliocene-Pleistocene boundary was placed at the first evolutionary appearance of *Globorotalia truncatulinoides* in both the Atlantic and Indo-Pacific provinces (Bolli and Saunders, 1985). Earlier, some authors placed the Pliocene-Pleistocene boundary at the extinction level of *Dentoglobigerina altispira* (Lamb and Beard, 1972; Stainforth and others, 1975) but the level of this extinction was found to be much earlier—in the Late Pliocene both in the Indian and Southwest Pacific oceans (Srinivasan and Sinha, 1992). Marking the base of the Pleistocene with a planktic foraminiferal event is complicated by changes in ocean circulation resulting from severe climatic changes caused by glacial-interglacial intervals. The changes preclude synchronous planktic foraminiferal events over a wide latitudinal range. Haq and others (1977) revised the age of Pliocene-Pleistocene boundary at Le Castella, the stratotype of the Calabrian at Santa Maria di Catanzaro, and in deep-sea sediments in six piston cores. The boundary was correlated by multiple overlapping criteria to a level equivalent to, or slightly younger than, the top of the Olduvai Event, giving a revised estimate of $\sim$1.6 Ma for the age of the boundary. The Pliocene-Pleistocene boundary was, thus, made coeval with the earliest of four major climatic deteriorations in the Pleistocene, reconciling paleoclimatic concepts with the chronostratigraphic definition of the epoch (Berggren and others, 1995a). According to the International Stratigraphic Commission (Gradstein and others, 2004) the Global Stratotype Section and Point (GSSP) for the base of the Pleistocene Series is defined as the base of the marine claystones that conformably overly the sapropelic Marker Bed "e" in the Vrica section, Italy. The Vrica section is located 4 km south of the town of Crotone in the Marchesato Peninsula, Calabria, Italy (39°02′ 18.61″ N, 17°08′ 05.79″ E; Gradstein and others, 2004). The planktic foraminiferal event marking the boundary in the type section is the extinction level of *Globigerinoides obliquus extremus* and the boundary is some 3–6 m (representing a period of 10,000–20,000 years) above the top of the Olduvai Normal Polarity Subchron (Aguirre and Pasini, 1985; Bassett, 1985), with an estimated age of 1.81 Ma (Lourens and others, 2005).

Based on their detailed study applying graphic correlation to planktic foraminiferal events in the Indian and the southwest Pacific Oceans, Srinivasan and Sinha (1991, 1992) concluded that the *Globigerinoides fistulosus* LO is a synchronous event between those oceans and is coincident with the top of Olduvai Subchron. Later, Berggren and others (1995a, b) added that this event is also synchronous in the Atlantic Ocean and placed the top boundary of the PL6 Zone (the base of Pleistocene) at the last appearance of *Gs. fistulosus*.

In the present study at ODP Hole 763A, the *Globigerinoides fistulous* LO also coincides with the top of the Olduvai Subchron (Figs. 3, 4) and has been taken to mark the Pliocene-Pleistocene boundary. However, the FO of *Globorotalia truncatulinoides* at the site lies distinctly below the Pliocene-Pleistocene boundary.

Planktic Foraminiferal Zones Recorded at ODP Hole 763A

The planktic foraminiferal Zones recognized at the ODP Hole 763A in ascending stratigraphic order are as follows (Fig. 3).

Globorotalia plesiotumida Interval Zone

Definition. Biostratigraphic interval between the first occurrence of *Globorotalia plesiotumida* and the first occurrence of *Pulleniatina primalis*.

Thickness. 2.80 meters.

Age. Late Miocene.

Remarks. The zone corresponds to the lower part of Zone N17 of Blow (1969), the *Globorotalia plesiotumida* Zone of Jenkins and Orr (1972), Zone N17A of Srinivasan and Kennett (1981a) and the *Globorotalia humerosa* Zone of Bolli and Saunders (1985). This zone corresponds to the *Globigerinoides extremus/Gr. plesiotumida-Globorotalia lenguaensis* Interval Zone (M13b) of Berggren and others (1995b; Fig. 3). The earliest sample studied here lies within this zone and, thus, the base of the zone could not be recognized.

Pulleniatina primalis Interval Zone

Definition. Biostratigraphic interval between the first occurrence of *Pulleniatina primalis* and the first occurrence of *Globorotalia tumida tumida*.

Thickness. 8.0 meters.

Age. Late Miocene.

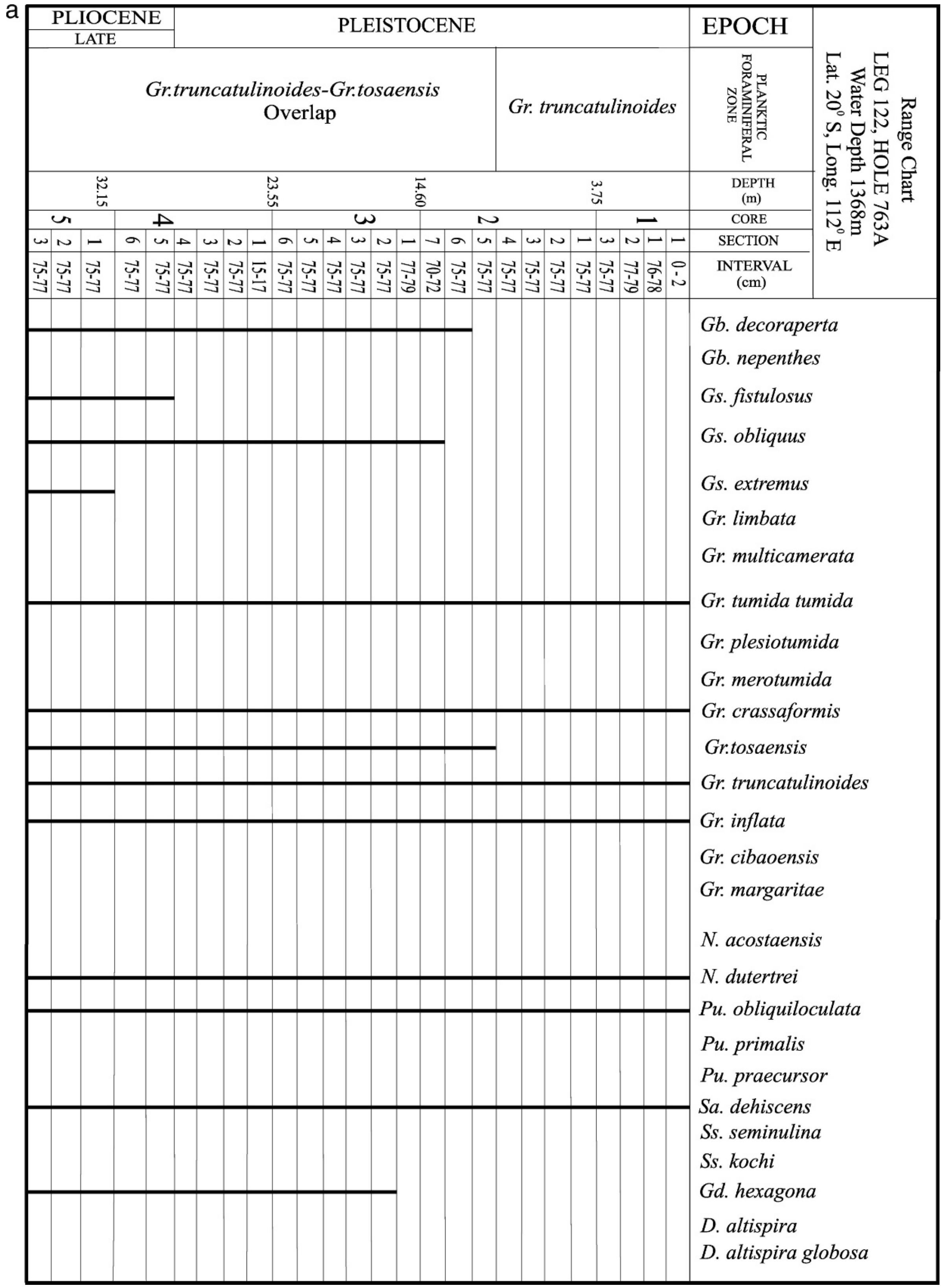

FIGURE 2a. Stratigraphic ranges of important late Neogene planktic foraminiferal species at ODP Hole 763A.

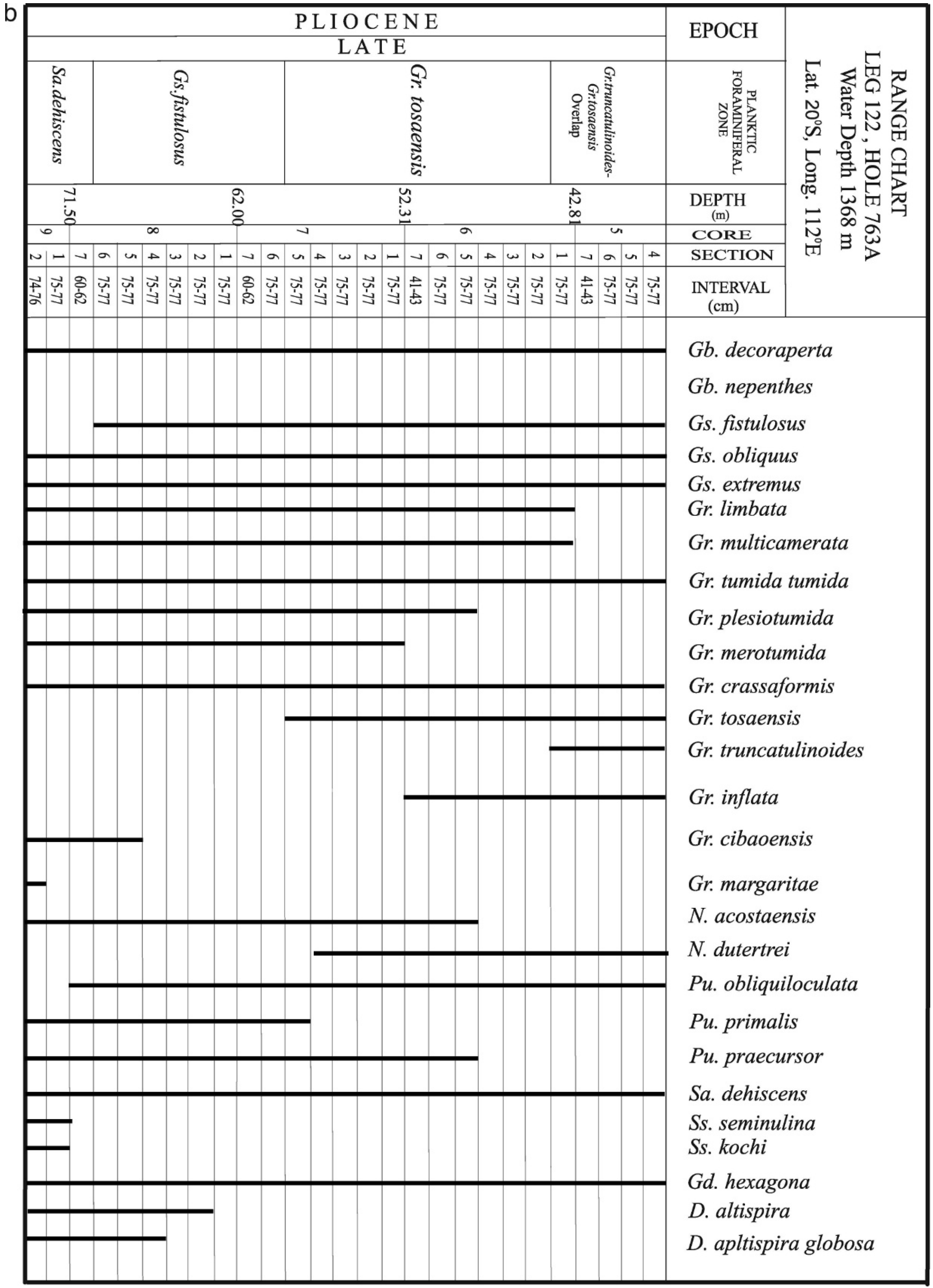

FIGURE 2b. Stratigraphic ranges of important late Neogene planktic foraminiferal species at ODP Hole 763A.

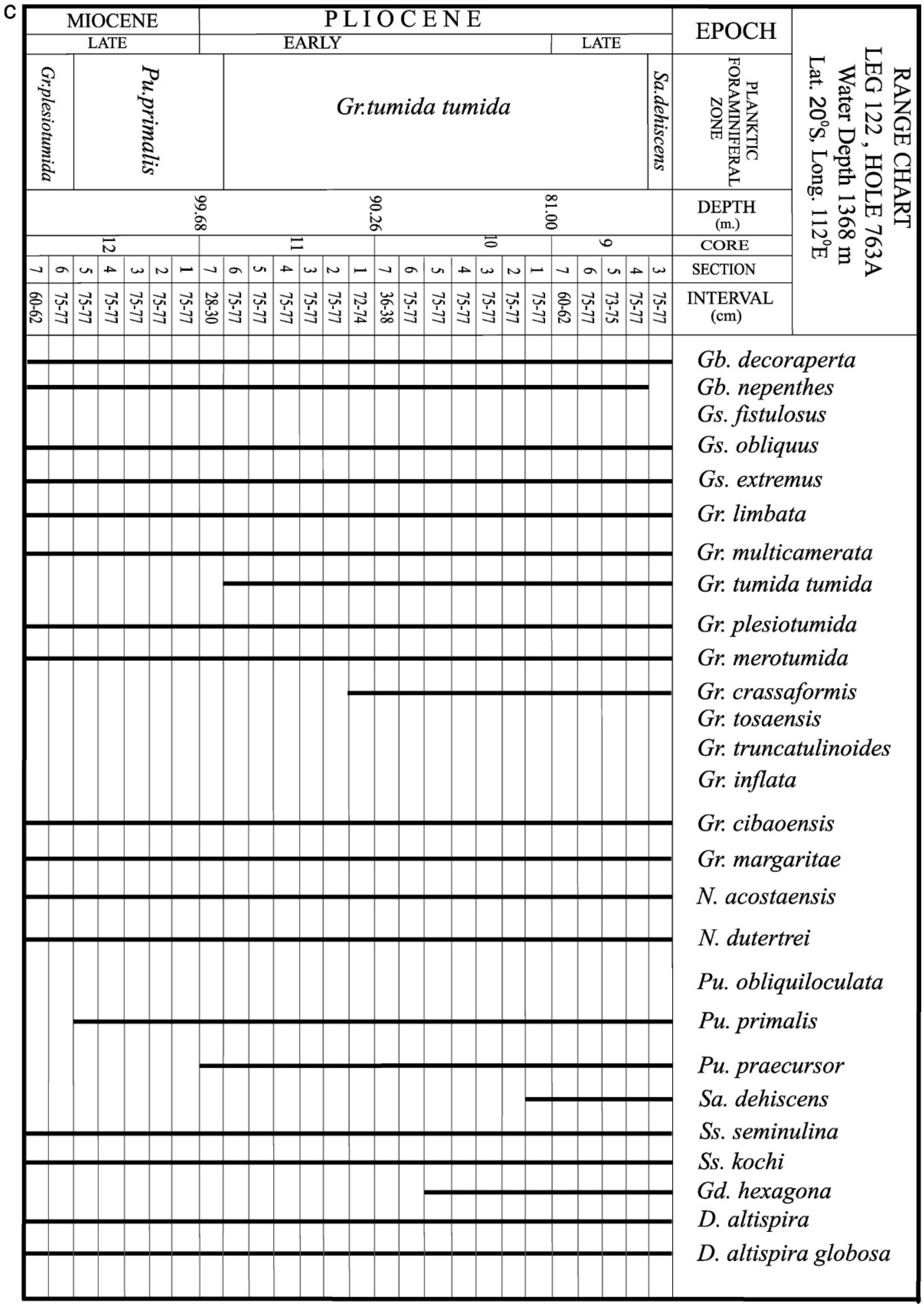

FIGURE 2c. Stratigraphic ranges of important late Neogene planktic foraminiferal species at ODP Hole 763A.

TABLE 1. Stratigraphic position of the upper and lower bounds of planktic foraminiferal events at ODP Hole 763A. FO = first occurrence, LO= last occurrence.

Planktic foraminiferal species	Type of event	Depth (m)	
		Lower	Upper
Gs. obliquus	LO	14.61	13.16
Gr. tosaensis	LO	11.66	10.15
Gd. hexagona	LO	16.66	15.17
Gb. decoraperta	LO	13.16	11.65
Gs. fistulosus	LO	30.66	29.15
Gs. extremus	LO	34.16	32.15
Gr. truncatulinoides	FO	45.15	43.66
Gr. limbata	LO	43.66	42.82
Gr. multicamerata	LO	43.66	42.82
Pu. praecursor	LO	49.66	48.10
Gr. inflata	FO	53.15	52.32
Gr. plesiotumida	LO	49.66	48.10
Gr. merotumida	LO	53.16	52.32
Pu. primalis	LO	59.16	57.65
Gr. tosaensis	FO	60.65	59.16
D. altispira	LO	64.16	62.65
D. altispira globosa	LO	67.16	65.65
Gs. fistulosus	FO	71.50	70.16
N. dutertrei	FO	59.15	57.66
Ss. seminulina	LO	72.16	71.50
N. acostaensis	LO	49.66	48.10
Ss. kochi	LO	72.16	71.50
Pu. obliquiloculata	FO	72.16	71.51
Gr. margaritae	LO	73.65	72.16
Gd. hexagona	FO	89.10	87.66
Sa. dehiscens	FO	83.15	81.66
Gr. cibaoensis	LO	68.66	67.15
Gr. crassaformis	FO	92.85	91.13
Gb. nepenthes	LO	76.66	75.15
Gr. tumida tumida	FO	99.68	98.66
Pu. praecursor	FO	100.63	99.69
Pu. primalis	FO	108.15	106.66

Remarks. Srinivasan and Kennett (1981a) subdivided Blow's (1969) Zone N17 into a lower N17A and an upper N17B, based on the first evolutionary appearance of *Pulleniatina*, a solution-resistant form that occurs commonly in deep-sea sections from tropical and subtropical areas. The *Pulleniatina primalis* Zone corresponds to Zone N17B of Srinivasan and Kennett (1981a). Srinivasan (1984) and Srinivasan and Dave (1984) described the zone from the Andaman-Nicobar marine sequences. The top of this zone also demarcates the Miocene-Pliocene boundary. The zone is broadly equivalent to the upper part of the *Globorotalia plesiotumida* Zone of Jenkins and Orr (1972) and the upper part of *Globorotalia humerosa* Zone of Bolli and Saunders (1985). The top of this zone coincides with the top of the *Globorotalia lenguensis*-*Globorotalia tumida* Interval Zone (M14) of Berggren and others (1995b; Fig. 3).

Globorotalia tumida tumida Interval Zone

Definition. The biostratigraphic interval between first occurrence of *Globorotalia tumida tumida* and the first occurrence of *Sphaeroidinella dehiscens*.

Thickness. 17.0 meters.

Age. Early Pliocene.

Remarks. The zone was described from eastern equatorial Pacific DSDP sites by Jenkins and Orr (1972). The first evolutionary appearance of *Globorotalia tumida tumida* from its ancestor *Globorotalia plesiotumida* also marks the Miocene-Pliocene boundary (Berggren, 1973; Berggren and Poore, 1974; Berggren and others, 1974; Fleisher, 1974; Vincent, 1977; Srinivasan and Sinha, 1992) and coincides with base of Chron C3n.4n at the examined site. This occurrence is in conformity with the definition of the Miocene-Pliocene boundary by the International Commission on Stratigraphy (Gradstein and others, 2004). This zone is equivalent to Zone N18 of Blow (1969) and the *Globorotalia margaritae* Subzone of Bolli and Saunders (1985). The *Gr. tumida tumida* Zone also corresponds to the lower part of the *Gr. tumida*-*Globorotalia cibaoensis* Concurrent Range Zone (PL1a) of Berggren and others (1995b; Fig. 3).

Sphaeroidinella dehiscens Interval Zone

Definition. The biostratigraphic interval between the first occurrence of *Sphaeroidinella dehiscens* and the first occurrence of *Globigerinoides fistulosus*.

Thickness. 11.50 meters.

Age. Late Pliocene.

Remarks. The definition of the zone is exactly that proposed for the *Sphaeroidinella dehiscens* Zone by Jenkins and Orr (1972), specifically the biostratigraphic interval between the first evolutionary appearance of *Sa. dehiscens* to the appearance of *Globigerinoides fistulosus*. The zone is equivalent to the lower part of Zone N19 of Blow (1969) and the *Globorotalia margaritae evoluta* Subzone of Bolli and Saunders (1985). The zone also corresponds to the *Gr. margaritae–Sphaeroidinellopsis seminulina* Interval Zone (PL3) of Berggren and others (1995b; Fig. 3).

Globigerinoides fistulosus Interval Zone

Definition. The biostratigraphic interval between first occurrence of *Globigerinoides fistulosus* and the first occurrence of *Globorotalia tosaensis*.

Thickness. 11.0 meters.

Age. Late Pliocene.

Remarks. The zone was originally defined by Jenkins and Orr (1972) based on the total range of *Globigerinoides fistulosus*. Srinivasan (1988) divided the zone of Jenkins and Orr (1972) into a lower *Gs. fistulosus* Zone and an upper *Globorotalia tosaensis* Zone, with the boundary between the two zones marked by the evolutionary first appearance of *Gr. tosaensis*. The zone roughly corresponds to Zone N20 of Blow (1969) and the lower part of *Gs. fistulosus* Zone of Jenkins and Orr (1972). The zone corresponds to the *Sphaeroidinellopsis seminulina*-*Dentoglobigerina altispira* Interval Zone (PL4) of Berggren and others (1995b; Fig. 3).

Globorotalia tosaensis Interval Zone

Definition. The biostratigraphic interval between the first occurrence of *Globorotalia tosaensis* and the first occurrence of *Globorotalia truncatulinoides*.

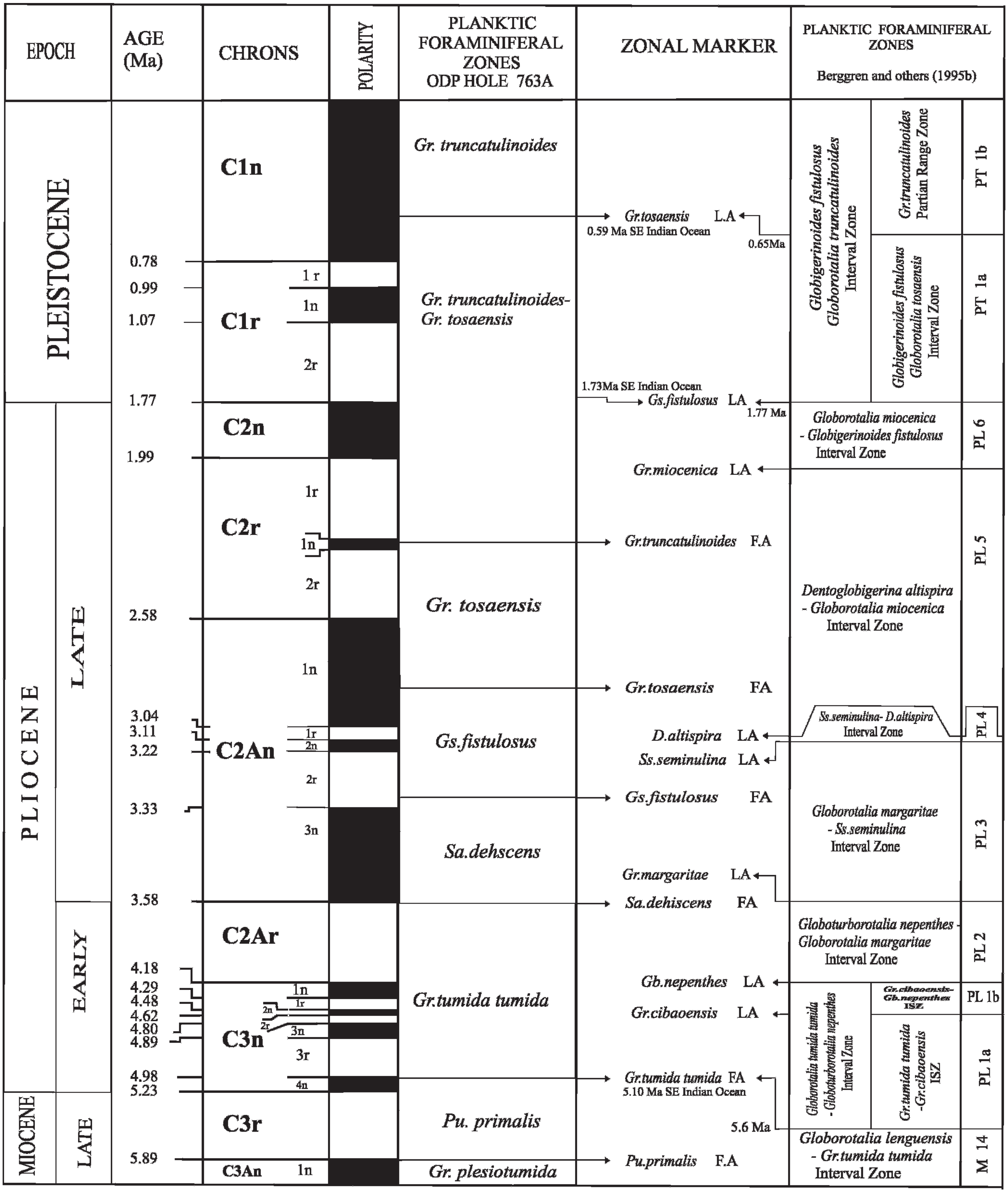

FIGURE 3. Late Neogene planktic foraminiferal zones and zonal markers at ODP Hole 763A, Exmouth Plateau, Southeast Indian Ocean, integrated with magnetic polarity stratigraphy. The zones have been compared with those of Berggren and others (1995b). The figure also shows the zonal markers used by Berggren and others (1995b). The magnetic polarity stratigraphy is after Cheng Tang (1992) and the numerical ages of the polarity chrons are after Berggren and others (1995b).

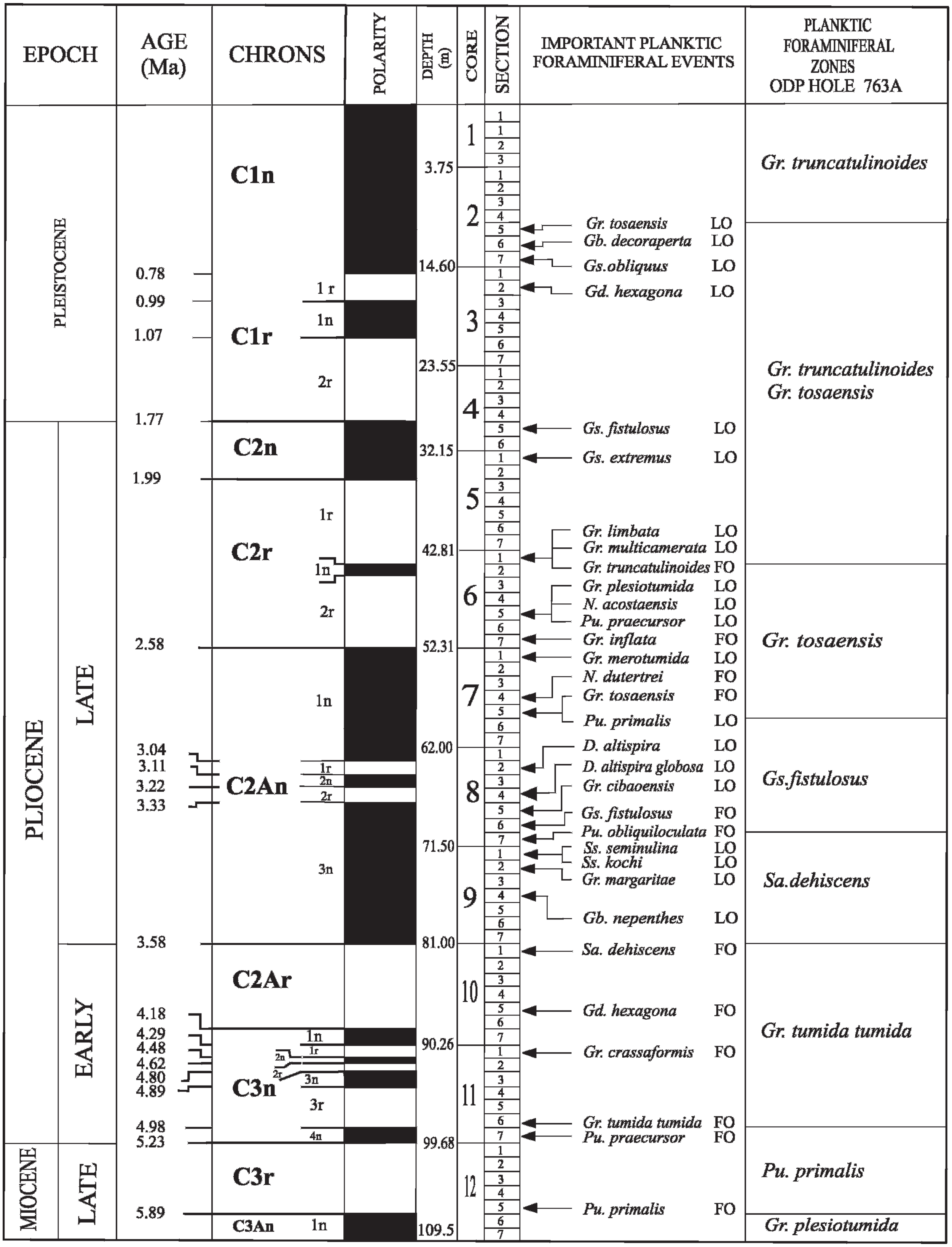

FIGURE 4. Late Neogene planktic foraminiferal Zones integrated with magnetic polarity stratigraphy and the sequential order of planktic foraminiferal events recognized at ODP Hole 763A. Magnetic polarity stratigraphy is after Cheng Tang (1992) and ages of magnetic chron boundaries are after Berggren and others (1995a, b).

Thickness. 15.50 meters.

Age. Late Pliocene.

Remarks. The zone was originally described by Kennett (1973) from the warm subtropical DSDP sites of Leg 21 and later by Jenkins and Srinivasan (1986) from Leg 90 sites. The zone is equivalent to Zone N21 of Blow (1969), the *Globorotalia tosaensis tenuitheca* Zone of Srinivasan (1977) and the upper part of the *Globigerinoides fistulosus* Zone to the *Gr. tosaensis tenuitheca* Zone of Bolli and Saunders (1985). This zone corresponds to the *Dentoglobigerina altispira-Globorotalia miocenica* Interval Zone (PL5) of Berggren and others (1995b; Fig. 3).

Globorotalia tosaensis-Globorotalia truncatulinoides Concurrent Range Zone

Definition. The biostratigraphic interval between the first occurrence of *Globorotalia truncatulinoides* and the last occurrence of *Globorotalia tosaensis*.

Thickness. 32.0 meters.

Age. Late Pliocene-Pleistocene.

Remarks. This zone was originally defined by Kennett (1973) from southwest Pacific deep-sea cores based on the joint occurrence of *Globorotalia tosaensis* and *Globorotalia truncatulinoides*. Srinivasan and Chaturvedi (1992) recorded this zone from the Indian Ocean. This zone is equivalent to the lower part of Zone N22 (Blow, 1969) and to the *Globorotalia viola* Subzone of Bolli and Premoli Silva (1973). The zone also broadly corresponds to the lower part of the *Pulleniatina obliquiloculata* Zone of Jenkins and Orr (1972). The *Globigerinoides fistulosus-Gr. tosaensis* Zone (PT1a) of Berggren and others (1995b) corresponds to this zone (Fig. 3).

Globorotalia truncatulinoides Interval Zone

Definition. The biostratigraphic interval above the last occurrence of *Globorotalia tosaensis* to the present-day.

Thickness. 11.66 meters.

Age. Pleistocene.

Remarks. This zone was originally described by Kennett (1973) from southwest Pacific deep-sea cores. It corresponds to the *Globorotalia truncatulinodes* Partial Range Zone (PT1b) of Berggren and others (1995b; Fig. 3).

LATE NEOGENE PLANKTIC FORAMINIFERAL EVENTS IN THE SOUTHEAST INDIAN OCEAN

The Datum Level Concept

The datum plane or datum level concept has received increasing acceptance among biostratigraphers during the past decade. The concept was originally defined by Hornibrook (1966) to be a correlation plane joining levels in rock sequences that, on paleontological or other grounds, appear to be "isochronous" and the "most favoured paleontological grounds" have been the evolutionary appearance and extinction of planktonic microfossil taxa. Later, several authors used the concept of datum levels based on first and last occurrences levels recognized in various deep-sea sequences across the world. The levels of first and last occurrences of planktic foraminifera provide useful time markers in the pelagic deep-sea sequences. Recent, integrated work on biomagnetoradio-chronology has shown that the synchrony of such FOs and LOs of planktic foraminiferal species is the exception rather than the rule. Oceanographic and climatic changes play a key role in introducing diachrony into local first and last occurrences of planktic foraminifera. Estimating the extent of diachrony is important because it not only refines and makes our biochronologies reliable but also the inherent causes of diachrony throw light on the controlling paleoceanographic changes.

Detailed qualitative and quantitative analyses of planktic foraminifera enabled recognition of 32 first and last occurrence events (Figs. 4, 5) and estimation of their numerical ages. This study reports for the first time estimated numerical ages of Late Neogene planktic foraminiferal datum levels from the southeast Indian Ocean and a comparison with the numerical age estimates for these events from the world ocean (Table 2). These ages provide a precise time framework for the Late Neogene paleoceanographic events of the southeast Indian Ocean and can be used to correlate the events from other parts of the Indian and southwest Pacific Oceans.

Late Neogene Planktic Foraminiferal Events

The *Globigerinoides obliquus* LO

Vincent (1977) stated that the last appearances of *Globigerinoides obliquus* and *Globigerinoides fistulosus* occur at the same level close to the Pliocene-Pleistocene boundary. Srinivasan and Chaturvedi (1992) recorded the last appearance of *Gs. obliquus* below the *Globorotalia truncatulinoides* FO at Site 214 (northern Indian Ocean). Srinivasan and Sinha (1992) estimated an age of 1.8 Ma for *Gs. obliquus* LO in the northern Indian Ocean and 2.88 Ma in the southwest Pacific based on the graphic correlation method. The species makes its last appearance at Hole 763A in Section 763A-2H-7 at 14.61 mbsf at an estimated age of 0.76 Ma. The authors envisage the persistence of low trophic levels of surface waters in this region as a probable cause for survival of this species up to such a young level. Though *Gs. obliquus* has always been reported as fossil, Boltovskoy and Watanabe (1975) for the first time reported the occurrence of this species from recent sediment of the South Pacific Ocean. Aside from the report of Boltovskoy and Watanabe (1975), a comparison of the various age estimates of this event (Table 2) suggests the present estimate to be younger than all previously reported ages [e.g., late Pliocene, Kennett and Srinivasan, (1983); and early Pliocene, Chaisson and Leckie, (1993) at Site 806, the equatorial Pacific Ocean].

Bolli and Saunders (1985) mentioned a similar-looking species *Globigerinoides elongatus*, which occurs in the Holocene, and cautioned that confusion may arise in its distinction from *Globigerinoides obliquus extremus*. A symmetrical primary aperture positioned above the suture between two earlier chambers distinguishes the former. The authors have closely examined the specimens of *Gs. obliquus* recorded from the highest stratigraphic level, and we are sure of its identity—there is no confusion with *Gs. elongatus*. Thus, the present age estimate of the *Gs. obliquus* LO together with the reported occurrence of this species

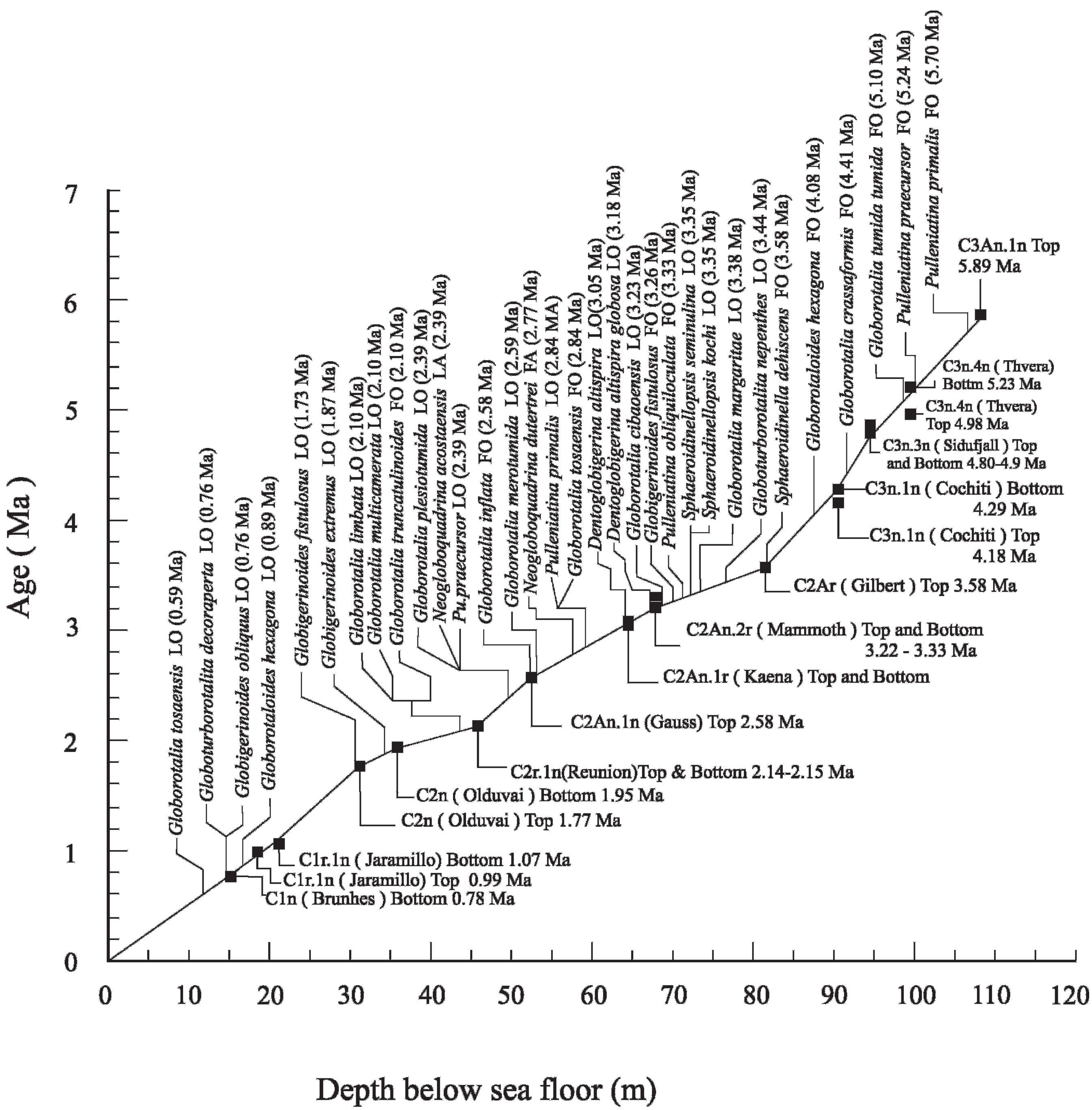

FIGURE 5. Late Neogene planktic foraminiferal events recognized at ODP Hole 763A in the present work shown on an age-depth plot. Magnetic polarity data are after Cheng Tang (1992) and ages of chrons are after Berggren and others (1995a, b).

from Recent sediments of the South Pacific Ocean by Boltovskoy and Watanabe (1975) suggests that this datum level is not reliable for approximation of the Pliocene-Pleistocene boundary.

The Range of *Globorotalia tosaensis*

The concept of *Globorotalia tosaensis* followed herein is that of Kennett and Srinivasan (1983), who define it by the total absence of a keel and five chambers in the final whorl. The evolutionary appearance of *Gr. tosaensis* from its ancestor *Globorotalia crassaformis ronda* occurs at Hole 763A in Section 763A-7H-05 at 59.16 mbsf at an estimated age of 2.84 Ma. Morphotypes grading between *Gr. crassaformis ronda* and *Gr. tosaensis* are frequent and have been encountered both before and after the *Gr. tosaensis* FO. The event occurs above the *Globigerinoides fistulosus* FO at Hole 763A as also recorded earlier by Srinivasan and Chaturvedi (1992) at Site 214 in the northern Indian Ocean. The initiation of Northern Hemisphere glaciation around 3.6 Ma (Mudelsee and Raymo, 2005) may be a plausible cause of the appearance of this non-keeled form for a short stratigraphic interval.

TABLE 2. Estimated numerical ages of late Neogene planktic foraminiferal events by various workers compared with those estimated in the present work at ODP Hole 763A, Southeast Indian Ocean.

Planktic foraminiferal species	Type of event	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Gs. obliquus	LO	1.8 [a], 2.88 [b]	1.3 ± 0.6														0.76
Gr. tosaensis	FO						3.35										2.84
Gr. tosaensis	LO	0.65 [a,b]					0.65										0.59
Gd. hexagona	LO																0.86
Gd. hexagona	FO																4.08
Gb. decoraperta	LO					1.70											0.67
Gs. extremus	LO						1.77	1.89									1.87
Gs. fistulosus	FO						3.35										3.26
Gs. fistulosus	LO		1.88	2.10	1.6		1.60										1.73
Gr. truncatulinoides	FO		1.92	2.10			2.00		2.00	2.00							2.10
Gr. limbata	LO		2.38	2.74													2.10
Gr. multicamerata	LO		3.11	3.00			3.09										2.10
Gr. inflata	FO		2.18	2.00			2.09				2.09	3.63					2.58
D. altispira	LO		3.11	3.00			3.09										3.05
D. globosa	LO																3.18
Gr. merotumida	LO																2.60
Gr. plesiotumida	LO		3.77	3.84	4.40												2.39
N. duturtrei	FO																2.77
N. acostaensis	LO																2.39
Sphaeroidinellopsis	LO		3.11	3.45			3.12		3.21		3.21		3.21	3.12			3.35
Sa. dehiscens	FO				5.60		3.25								3.6		3.58
Gr. margaritae	LO	3.58 [a,b]	3.85	3.37	3.58		3.58										3.38
Gr. ciboaensis	LO				5.0												3.23
Gr. crasssaformis	FO				4.7		4.50									4.5	4.41
Gb. nepenthes	LO		4.39	4.69	4.30		4.20										3.44
Gr. tumida tumida	FO				5.90		5.60										5.10
Pu. primalis	FO						6.4										5.70
Pu. praecursor	FO																5.24
Pu. obliquiloculata	FO																3.33
Pu. primalis	LO						3.65										2.84
Pu. praecursor	LO																2.39

1[a]. Srinivasan and Sinha (1992), Indian Ocean.
1[b]. Srinivasan and Sinha (1992), Southwest Pacific.
2. Chaisson and Pearson (1997), W. Atlantic.
3. Chaisson and d'Hondt (2000), W. Caribbean.
4. Curry and others (1995), ODP 154, Tropical Atlantic Ceara Rise.
5. Weaver and Raymo (1989), Eastern Tropical Atlantic.
6. Berggren and others (1995).
7. Maniscalco and Brunner (1998), Canary Islands.
8. Channel and others (1990), Mediterranean.
9. Lazarus and others (1995), Equatorial Atlantic.
10. Glacon and others (1990), Mediterranean.
11. Hodell and Kennett (1986), Southwest Pacific.
12. Langeries and Hilgen (1991), Mediterranean.
13. Weaver and Clement (1986, 1987), North Atlantic.
14. Kucera (1998).
15. Chaproniere and others (1994), W. Tropical Pacific.
16. This work, Southeast Indian Ocean.

The LO of *Globorotalia tosaensis* occurs in Section 763A-2H-05 at 11.66 mbsf with an estimated age of 0.59 Ma. Before extinction, the population of *Gr. tosaensis* shows a steep decline. This event was also considered synchronous between the southwest Pacific and Indian Oceans by Srinivasan and Sinha (1992). Other numerical age estimates by various authors have been provided in Table 2. The event should be considered a useful datum level for subdivision of the Pleistocene interval.

The Range of *Globorotaloides hexagona*

Blow (1969) thought *Globorotaloides hexagona* evolved from *Globorotaloides variabilis*, but Kennett and Srinivasan (1983) suggested that it evolved from *Globorotaloides suteri* during the Early Miocene in Zone N18. At Site 763A, its FO occurs in Section 763A-10H-05 at 87.66 mbsf with an estimated age of 4.08 Ma. Considering the absence of its ancestor, either *Gd. variabilis* or *Gd. suteri*, the FO is purely cryptogenic and not an evolutionary first appearance. Unlike earlier reported occurrences of *Gd. hexagona* from recent sediments (Kennett and Srinivasan, 1983), the species became extinct in the southeast Indian Ocean in Section 763A-3H-02 at 16.66 mbsf with an estimated age of 0.86 Ma and does not continue to the Recent. Norris (1998) reported its absence from Pleistocene and Recent sediments of Leg 159 sites. Peters and others (2004) reported the species from modern plankton tows at a depth of 300–800 m in an Agulhas Current ring, suggesting that the species inhabits deep water.

The *Globoturborotalita decoraperta* LO

The species shows an evolutionary gradation with *Globoturborotalita woodi*. Only high-spired forms have been considered under *Globoturborotalita decoraperta* following the taxonomy of Kennett and Srinivasan (1983). The evolutionary appearance of *Gb. decoraperta* from its ancestor *Gb. woodi* during the Early-Middle Miocene was proposed by Kennett and Srinivasan (1983). However, *Gb. decoraperta* evolved from *Globoturborotalita druryi* according to Iaccarino (1985). The occurrence of this species is well documented from Middle Miocene to Late Pliocene but is never recorded from the Pleistocene (Iaccarino, 1985). However, in the present study, the LO of *Gb. decoraperta* occurs in Section 763A-2H-06 at 13.16 mbsf with an estimated age of 0.67 Ma. This occurrence shows that this species probably continued well into the Pleistocene in the Southeast Indian Ocean. Other age estimates have been provided in Table 2.

The *Globigerinoides extremus* LO

The *Globigerinoides extremus* LO occurs in Section 763A-5H-01 at 34.16 mbsf with an estimated age of 1.87 Ma. The event occurs very close to the top of the Olduvai Chron (C2n). Berggren and others (1995a) estimated an age of 1.77 Ma for this event. Bolli and Saunders (1985) also recorded the *Gs. extremus* and *Globigerinoides fistulosus* LOs at same level. At Site 219 in Arabian Sea, *Gs. extremus* occurs above the level of the *Gs. fistulosus* LO. Considering its synchronous nature in several deep-sea sections, this species can be used as an additional criterion for recognizing the Pliocene-Pleistocene boundary. A comparison of the ages for this event from various parts of the world ocean (Table 2) suggests that the *Gs. extremus* LO is fairly synchronous and a useful datum level for inter-ocean correlation.

The Range of *Globigerinoides fistulosus*

The initial appearance of *Globigerinoides fistulosus* has been documented consistently between the extinctions of *Globorotalia margaritae* and *Dentoglobigerina altispira* at DSDP Sites 214 and 219 in the Indian Ocean (Srinivasan and Chaturvedi, 1992; Srinivasan and Singh, 1992) as well as in paleomagnetically calibrated core V20-153 (Saito and others, 1976). This level is very close to the *Globorotalia tosaensis* FO, and the datum level was used to shorten Zone N21 of Blow (1969) in tropical biostratigraphy of the Indo-Pacific region (Srinivasan and Chaturvedi, 1992). At Hole 763A, the *Gs. fistulosus* FO occurs in Section 763A-8H-06 at 70.16 mbsf with an estimated age of 3.26 Ma. Srinivasan and Sinha (1992) discussed the importance of *Gs. fistulosus* LO to demarcate the Pliocene-Pleistocene boundary in southwest Pacific DSDP cores. At ODP Hole 763A, the event occurs in Section 763A-4H-05 at 30.66 mbsf with an estimated age of 1.73 Ma, very close to the top of Olduvai Subchron used to demarcate the Pliocene-Pleistocene boundary. Comparison of the numerical age estimates from other parts of the world ocean suggests this event to be useful for correlation (Table 2).

The *Globorotalia truncatulinoides* FO

Progressive development of *Globorotalia truncatulinoides* from its ancestor *Gr. tosaensis* has been clearly documented at Hole 763A. The *Gr. truncatulinoides* FO has been repeatedly recorded near the base of the Olduvai Event (C2n) both in Atlantic and Pacific cores (Berggren and others, 1967; Hays and others, 1969). Differentiation of *Gr. truncatulinoides* into finer morphological stages led several workers to question the validity of this taxon for delineating the Pliocene-Pleistocene boundary. Sprovieri and others (1980) on evidence from Capo Rosella, Sicily, Italy, reported its initial occurrence within the Late Pliocene and the variant *Gr. truncatulinoides excellesa* from the basal Pleistocene. It is worth mentioning that the new age of the Pliocene-Pleistocene boundary is 1.81 Ma, since then it was re-defined at a level close to the top of Olduvai Event rather than the base (Lourens and others, 2005).

Srinivasan and Sinha (1992), based on integrated biostratigraphy, magnetochronology and graphic correlation, demonstrated that the *Globorotalia truncatulinoides* FO coincides with the Matuyama-Gauss boundary (2.58 Ma) in southwest Pacific DSDP cores, thus questioning the utility of this datum level for denoting the Pleistocene base. However, these authors showed that this event is delayed in the northern Indian Ocean compared to the southwest Pacific. At Hole 763A, the *Gr. truncatulinoides* FO occurs in Section 763A-6H-01 at 43.66 mbsf with an estimated age of 2.10 Ma. Comparison of the published numerical ages suggests this to be a fairly synchronous event in the Indian and Atlantic Oceans (Table 2).

The *Globorotalia limbata* LO

Globorotalia limbata becomes extinct in Section 763A-6H-01 at 43.66 mbsf at an estimated age of 2.10 Ma. Few dates are available for this event from the literature (Table 2), however, the event is fairly synchronous over a wide latitudinal range.

The *Globorotalia multicamerata* LO

According to Cifelli and Scott (1986), the experiment of secreting many chambers by menardine *Globorotalia* was not successful, and all such forms, including *Globorotalia multicamerata*, became extinct in the Late Pliocene. At Hole 763A, the event occurs in Section 763A-6H-01 at 43.66 mbsf simultaneous with the *Globorotalia limbata* LO with an estimated age of 2.10 Ma. This age is younger than many of the previously reported ages (Table 2).

The *Globorotalia inflata* FO

Kennett and Vella (1975) and Malmgren and Kennett (1981) reported that *Globorotalia inflata* evolved from *Globorotalia puncticulata* during the Late Pliocene by increase the inflation of its chambers. This evolution is very well documented at Hole 763A, where morphotypes grade between the two species. At Hole 763A, the event occurs in Section 763A-6H-07 at 52.32 mbsf with an estimated age of 2.58 Ma, coinciding with the Matuyama-Gauss Boundary. Considering all the reported ages for this event, it seems that the appearance of this species is quite delayed at Site 763A, which is located well within the tropical latitudes. *Gr. inflata* is a typical temperate species, and its late occurrence at site 763A has been attributed to intensification of the West Australian Current. The arrival of the members of the *Globoconella* lineage (*Gr. inflata* and

Gr. puncticulata) at the site examined follows initiation of Northern Hemisphere glaciation. Considering all the published numerical ages, we suggest that the evolution of this species occurred in the southwest Pacific Ocean and that later the species migrated into other parts of the world ocean (Table 2).

The *Dentoglobigerina altispira* LO

Dentoglobigerina altispira evolved from *D. altispira globosa* in the Late Oligocene and the LO of *D. altispira* occurs very close to the *Globorotalia tosaensis* FO. Earlier workers like Vincent (1977) observed that the two events vary in their relative position in different sites in the Indian Ocean. Bolli and Saunders (1985) considered the extinction of this species to be a stratigraphically important event in the Middle Pliocene. At Hole 763A, *D. altispira* becomes extinct in Section 763A-8H-02 at 64.16 mbsf at an estimated age of 3.05 Ma. Considering the various numerical age estimates, the LO of *D. altispira* appears to be a synchronous event in the world oceans (Table 2) and should be considered an important marker for the Late Pliocene.

The *Dentoglobigerina globosa* LO

Dentoglobigerina altispira globosa is ancestral to *D. altispira* (Blow, 1969) and is differentiated by its low spire. At Site 763A, *D. altispira globosa* becomes extinct in Section 763A-8H-04 at 67.16 mbsf with an estimated age of 3.18 Ma, slightly earlier than the extinction level of *D. altispira*.

The *Globorotalia merotumida* LO

The *Globorotalia merotumida* LO occurs in Section 763A-7H-01 at 53.16 mbsf with an estimated age of 2.60 Ma and above the level of the *Globorotalia tosaensis* FO. It appears that the cause of the extinction of *Gr. merotumida* was the same as that for many Miocene forms in the Late Pliocene (like *Dentoglobigerina altispira*, *Gr. multicamerata*, *Globorotalia limbata*, *Sphaeroidinellopsis seminulina*, etc.). No earlier age estimates are available for this event.

The *Globorotalia plesiotumida* LO

The *Globorotalia plesiotumida* LO is followed by extinction of *Globorotalia merotumida* and has an estimated age of 2.39 Ma in Section 763A-6H-05 at 49.66 mbsf. A review of the published ages suggests that the species survived longest in the southeast Indian Ocean (Table 2).

The *Neogloboquadrina dutertrei* FO

The evolution of *Neogloboquadrina dutertrei* from its ancestor *N. humerosa* occurs in Zone N21 of the Late Pliocene (Kennett and Srinivasan, 1983). However, Bolli and Saunders (1985) placed its FO at the base of the Lower Pliocene. At Hole 763A, the species appears in Section 763A-7H-4 at 57.66 mbsf with an estimated age of 2.77 Ma near the top of the Mammoth (C2An.2r). This may be considered an important biostratigraphic datum.

The *Neogloboquadrina acostaensis* LO

At Hole 763A, the LO of *Neogloboquadrina acostanesis* occurs in Section 763A-6H-5 at 49.66 mbsf with an estimated age of 2.39 Ma.

The *Sphaeroidinellopsis* LO

The sequential extinctions of taxa such as *Sphaeroidinellopsis* spp. and *Dentoglobigerina altispira altispira* in the Late Pliocene immediately before and after the appearance of *Globorotalia tosaensis* at Site 214 of the northern Indian Ocean mirror those seen in equatorial Atlantic cores and are calibrated there, as well as in the Indian Ocean core V20-163, to paleomagnetic stratigraphy (Hayes and others, 1969; Saito and others, 1976; Srinivasan and Chaturvedi, 1992). Two species of *Sphaeroidinellopsis* have been recorded at the examined sites following the taxonomy of Kennett and Srinivasan (1983). These are *Sphaeroidinellosis seminulina seminulina* and *Sp. seminulina kochi*. At Hole 763A, their LOs occur almost at the same level and before the extinction level of *D. altispira* and the appearance level of *Gr. tosaensis*. At Hole 763A, both species become extinct at the same level in Section 763A-9H-01 at 72.16 mbsf, with an estimated age of 3.35 Ma. Considering the published numerical ages (Table 2), the LO of *Sphaeroidinellopsis* appears to be fairly synchronous in the world ocean and is a useful biostratigraphic datum level for inter-ocean correlation.

The *Sphaeroidinella dehiscens* FO

The lineage of planktic foraminifera leading from *Sphaeroidinellopsis seminulina* to *Sphaeroidinella dehiscens* has been widely used for stratigraphic subdivision of Neogene tropical marine sections (Kucera, 1998). The appearance of this species has been used to define the base of the *Sa. dehiscens* Zone at the examined site. At Hole 763A, the event occurs in Section 763A-10H-01 at 81.66 mbsf with an estimated age of 3.58 Ma. It appears from the published numerical ages (Table 2) that this event is sufficiently diachronous so that its application as a zonal marker beyond tropical latitudes warrants rethinking.

The *Globorotalia margaritae* LO

At Hole 763A, the LO of *Globorotalia margaritae* occurs in Section 763A-9H-02 at 73.65 mbsf with an estimated age of 3.38 Ma. The estimated ages from various parts of the world ocean (Table 2) suggest the event was fairly synchronous and useful for inter-ocean correlation.

The *Globorotalia cibaoensis* LO

The *Globorotalia cibaoensis* LO occurs at Hole 763A in Section 763A-8H-05 at 68.66 mbsf with an age estimate of 3.23 Ma. Earlier, Curry and others (1995) gave an age of 5.0 Ma for Hole 999A from the Caribbean Sea for this event and this age is earlier than the estimate of this work. Kennett and Srinivasan (1983), however, did not provide a numerical age for this event but gave its range as up to the early part of Zone N19 (Early Pliocene).

The *Globorotalia crassaformis* FO

This species shows a wide range of variation in its morphology, and several morphotypes have been reported by earlier workers and also in the present study. Its appearance is in Section 763A-11H-01 at Hole 763A at 91.13 mbsf with an age estimate of 4.41 Ma. Comparison with the other published ages suggests that the event should be considered a useful and synchronous biostratigraphic marker for correlation over a wide latitudinal range.

The *Globoturborotalita nepenthes* LO

Bolli and Saunders (1985) stated that *Globoturborotalita nepenthes*, though a useful biostratigraphic marker, is erratic in its appearance, restricting its consistent applicability as a zonal marker. Sometimes it is absent from an entire section. In the present study, the abundance of *Gb. nepenthes* is quite low as compared to other *Globigerina* species. At the 763A, the LO of this species occurs in Section 763A-9H-04 at 76.66 mbsf with an age of 3.44 Ma. A look at the various published ages suggests that the last occurrence of *Gb. nepenthes* can be considered moderately synchronous.

The *Globorotalia tumida tumida* FO

Globorotalia tumida tumida is strictly a tropical form, and its initial evolutionary appearance marks the Miocene-Pliocene boundary in the low latitude regions. Studies of Late Miocene and Early Pliocene sections in the tropical Indo-Pacific Ocean have shown that the evolutionary first appearance of *Gr. tumida tumida* is a synchronous event (Bolli, 1970; Jenkins and Orr, 1972; Parker, 1967; Srinivasan and Kennett, 1981a; Berggren and Poore, 1974; Ujjie and Samata, 1973; Fleisher, 1974; McGowran, 1974; Srinivasan and Chaturvedi, 1992; Srinivasan and Sinha, 1992). However, in Venezuela (Bermudez and Seiglie, 1963; Bolli and Premoli Silva, 1973), the Caribbean Sea and the Gulf of Mexico (Lamb and Beard, 1972), *Gr. tumida tumida* does not appear until the Pleistocene. Berggren (1993) stated that *Gr. tumida tumida* is predominantly an Indo-Pacific taxon and occurs sporadically in the Atlantic-Carribean region during the Pliocene.

At Hole 763A, the event occurs in Section 763A-11H-06 at 98.66 mbsf very close to the base of Chron C3n.4n (Thvera) with an estimated age of 5.10 Ma and has been taken to approximate the Miocene-Pliocene boundary.

The Ranges of *Pulleniatina primalis, Pulleniatina praecursor* and *Pulleniatina obliquiloculata*

The first evolutionary appearance of *Pulleniatina primalis* from its ancestor *Neogloboquadrina acostaensis* has been documented by Banner and Blow (1967) and Srinivasan and Kennett (1981a) from DSDP Sites 208 and 289, respectively, at the same biostratigraphic levels as those at Site 214 (Srinivasan and Chaturvedi, 1992). Banner and Blow (1967) proposed an evolutionary lineage beginning in the late Miocene with *Pu. primalis*, which evolves during the Pliocene through *Pulleniatina praecursor* to *Pulleniatina obliquiloculata* and in the Pleistocene to *Pulleniatina finalis*. The latter was considered by Kennett and Srinivasan (1983) to be a synonym of *Pu. obliquiloculata*. The lineage is well represented at the examined site, including morphotypes gradational between lineage members. The earliest member of the lineage, *Pu. primalis*, appears at Hole 763A in Section 763A-12H-05 at 106.66 mbsf with an estimated age of 5.70 Ma. The species gives rise to its descendent *Pu. praecursor* in Section 763A-11H-07 at 99.69 mbsf at 5.24 Ma. The evolution of *Pu. obliquiloculata* from its ancestor *Pu. praecursor* occurs in Section 763A-8H-07 at 71.51 mbsf with an estimated age of 3.33 Ma. Berggren and others (1995b) gave an age estimate of 6.4 Ma for the *Pu. primalis* FO, which is roughly close to that of this work. No published ages are available for the *Pu. praecursor* and *Pu. obliquiloculata* FOs. The last occurrence of *Pu. primalis* is recorded in Section 763A-7H-05 at 59.16 mbsf with an age of 2.84 Ma. Berggren and others (1995a) gave an age of 3.65 Ma for this event. The LO of *Pu. praecursor* occurs in Section 763A-6H-05 at 49.66 mbsf with an estimated age of 2.39 Ma.

CONCLUSIONS

1. Detailed qualitative and quantitative analyses of planktic foraminifera have enabled biostratigraphic subdivision of the late Neogene section of ODP Hole 763A into eight planktic foraminiferal zones. The zonal markers and the zones largely follow those of Srinivasan and Chaturvedi (1992) for the northern Indian Ocean and Srinivasan and Kennett (1981a, b) and Srinivasan and Sinha (1992) for the tropical western Pacific Ocean. The stratigraphic ranges of species recorded at Hole 763A do not permit application of the zonal scheme of Berggren and others (1995b). However, broad correlation is possible between the southeast Indian and Atlantic Oceans.
2. The LO of *Globigerinoides fistulosus* marks the Pliocene-Pleistocene boundary, and is synchronous over a wide latitudinal range. This event occurs close to the top of the Olduvai Event (Chron C2n; 1.81 Ma) and has been recorded at ODP Hole 763A. The Miocene-Pliocene boundary has been delineated by the first evolutionary appearance of *Globorotalia tumida tumida* from its ancestor *Globorotalia plesiotumida* and occurs close to the base of the Thvera magnetic event (C3n.4n; 5.23 Ma). Recognition of both these epoch boundaries is approximately in accordance with the International Commission on Stratigraphy (Gradstein and others, 2004).
3. Overall, 32 late Neogene planktic foraminiferal events have been identified at ODP Hole 763A. A major faunal turnover (22 events) is concentrated between 80 and 45 mbsf, which corresponds to 3.6–2.0 Ma. This rather short period (1.6 m.y.) of the major faunal turnover is partially coeval with major Northern Hemispheric glacial expansion at 2.5 Ma (Shackleton and others, 1984) and 2.7 Ma (Haug and others, 1999). Recently, Mudelsee and Raymo (2005) concluded that

Northern Hemisphere glaciation started ~3.6 Ma and closed ~2.4 Ma.

4. A number of events are synchronous over a wide latitudinal range and are, thus, considered good for correlation. Based on integration with magnetostratigraphy, numerical age estimates of these events have been provided. These include the *Globorotalia tosaensis* FO, the *Globorotalia tosaensis* LO, the *Globigerinoides extremus* LO, the *Globigerinoides fistulosus* FO, the *Globigerinoides fistulosus* LO, the *Dentoglobigerina altispira* LO, the *Dentoglobigerina globosa* LO, the *Neogloboquadrina dutertrei* FO, the *Sphaeroidinellopsis* LO, the *Globorotalia margaritae* LO, the *Globorotalia crassaformis* FO, the *Globigerina nepenthes* LO, the *Globorotalia tumida tumida* FO and the *Pulleniatina primalis* FO. Other events are diachronous and considered inadequate for correlation over a wide latitudinal range.
5. The precise time framework developed for Hole 763A will aide dating of paleoceanographic events for the last 6 million years in the southeast Indian Ocean.

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