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RECENT ADVANCES IN NEOGENE PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY, CHEMOSTRATIGRAPHY AND PALEOCEANOGRAPHY; NORTHERN INDIAN OCEAN

M.S. SRINIVASAN
DEPARTMENT OF GEOLOGY, BANARAS HINDU UNIVERSITY

ABSTRACT

High biogenic sedimentation rates in the Neogene at DSDP sites 214, 216 and 217 from the crest of the Ninetyeast Ridge provide an exceptional opportunity to evaluate Neogene biostratigraphy, chemostratigraphy and paleoceanography in the Northern Indian Ocean. Of the three sites examined, only site 214 has a superb, continuous sequence with abundant planktonic foraminifera throughout the Neogene. Stratigraphic ranges of planktonic foraminifera enabled recognition of 24 zones, from Late Oligocene to Pleistocene, useful for interoceanic correlation. Detailed study of the stratigraphic ranges of the continuous sequences particularly in the Pliocene has led to the further refinement of the existing late Neogene planktonic foraminiferal zones in the tropical Northern Indian Ocean. These refinements have been introduced to the enhance Neogene biostratigraphic resolution in the deep sea sections of the Northern Indian Ocean as well as in the uplifted marine sequences of Andaman - Nicobar Isalnds. Major epoch boundaries are marked by the following species, Pliocene/Pleistocene, the last appearance of *Globigerinoides fistulosus*; Miocene/Pliocene, appearance of *Globorotalia tumida*; Oligocene/Miocene, the appearance of *Globoquadrina dehiscens*.

Data on Oxygen and Carbon isotopic ratios and Carbonate preservation of Neogene deep sea sequences have provided a number of Chemostratigraphic signals which appear to be systemic in nature reflecting changes in the Chemistry of the Ocean. These chemical signals have successfully been used to subdivide the late Quaternary Carbonate record into numbered stages, and have greatly enhanced our understanding about paleoceanographic and paleoclimatic history of the Ocean through the Neogene. One of the most useful applications of Chemostratigraphy in recent years has been to evaluate the synchroneity of biostratigraphic datums. Recognizable changes in Stable isotope composition, shifts or events also serve as Chronostratigraphic markers where biostratigraphic correlation is difficult between sites underlaying different water masses.

Detailed quantitative analyses of planktonic foraminiferal assemblages from DSDP sites 214, 216 and 217 (Ninetyeast Ridge) were carried out to determine the nature of faunal turnover during the Neogene in the Northern Indian Ocean. Abundance distribution of dominant species indicate close similarities in faunal assemblages of law-latitude regions of the Pacific and Indian Ocean. Quantitative planktonic foraminiferal data integrated with Oxygen and Carbon isotopic record reveal intervals of major paleoceanographic events during 22 Ma, 13-14 Ma, 11Ma-12Ma, 6.2Ma-5.2Ma and 1.8 Ma. The intervals of major faunal turnover observed reflect global climatic and paleoceanographic events coincident with regional tectonism.

INTRODUCTION

The Neogene period represents one of the most crucial intervals in the geologic history of our planet, not only in crustal evolution but also in the evolution of Himalayan mountain chain concomitant with the destruction of Tethys and evolution of Indian Ocean including the enormous Bengal Fan. It also marks an important stage in the development of global climates which appears to have triggered human evolution. These events are well preserved in deep sea record. Thus, the study of planktonic foraminifera from Indian Ocean deep sea cores, has a direcat relevance to the time and extent of tectonic events, and climatic changes in the entire Indian plate.

The Deep Sea Drilling Project (DSDP) during the last two decades, has provided an unprecedented opportunity to study cores recovered from world oceans for detailed analyses of microfossil biostratigraphy and evolution. Most of these studies have concentrated on low - latitude regions where numerous sections with uncomplicated biostratigraphy have been cored by the Deep Sea Drilling Project. As planktonic foraminifera represent one of the three major microfossil groups (with Calcareous nannofossils and radiolaria) continuously employed for biostratigraphic subdivision and correlation of deep sea cores, "Initial Reports of the Deep Sea Drilling Project" always incorporate a major section on the Neogene planktonic foraminifera. As a result some refinements in the existing planktonic foraminiferal zonations were introduced and new Zonal schemes were developed.

BIOSTRATIGRAPHY

The latitudinal provincialism of planktonic foraminifera that has developed due to the evolution of global climates, consequent to polar ice-sheet formation during the Neogene has led to the establishment of numerous biostratigraphic zonal schemes. Bolli (1957 a,b,c) first published a planktonic foraminiferal zonal scheme for the Caribbean Paleocene to Miocene and has subsequently subdivided the Pliocene and Pleistocene into zones and subzones (Bolli and Bermudez, 1965 : Bolli, 1966 a,b, 1970 : Bolli and Premoli Silva, 1973 : Bolli and Saunders, 1985). The zonal scheme of Bolli has been emended by few later workers (Lamb and Beard, 1972 : Smith and Beard, 1973 ; Stainforth *et al.*, 1975 : Srinivasan, 1977).

Banner and Blow (1965) and Blow (1969, 1979) proposed almost a parallel zonal scheme with 43 biozones to subdivide the Middle Eocene to Holocene and introduced an "abbreviated letter and numerical method of naming the zones". Even though the "abbreviated letter and numerical method of designating the zones" has been found objectionable (Bolli, 1966 ; Jenkins and Orr, 1972 ; Srinivasan, 1977) to existing stratigraphic codes, it is widely used planktonic foraminiferal zonal scheme today (Parker, 1967, 1973 ; Brönnimann and Resig, 1971; Raju, 1971 ; Poag, 1972 ; Berggren, 1971 a,b; Berggren and Van Couvering, 1973, 1974; McGowran, 1974; Fleisher, 1974; Ujiie, 1975; Vincent *et al.* 1975 and Vincent, 1977). Later, Berggren (1973), Parker (1973) and Cita (1973) have introduced new subdivisions corresponding to Zone N 18 to N21 of Blow (1969), based on the data from Atlantic and Mediterranean deep sea cores. Other changes to the scheme have more recently been proposed by Srinivasan and Kennett (1981 a,b), who emended Zone N 12 and N 13 and subdivided Zone N 4 into N 4A and N 4B and Zone N 17 into N 17A and N 17B.

The fundamental difference between the Neogene zonal schemes of Blow (1969, 1979) and Bolli (1966 a, b; 1970) is that Blow has placed much greater emphasis on placing boundaries at critical levels within evolutionary lineages such as *Globorotalia s.l.*, *Orbulina* and *Sphaeroidinella*. In general, Bolli's (1966, a, b; 1970) zonal boundaries are more easily identifiable than Blow's (1969, 1979) because they are not based so much on changes within evolutionary lineages (Fig. 1).

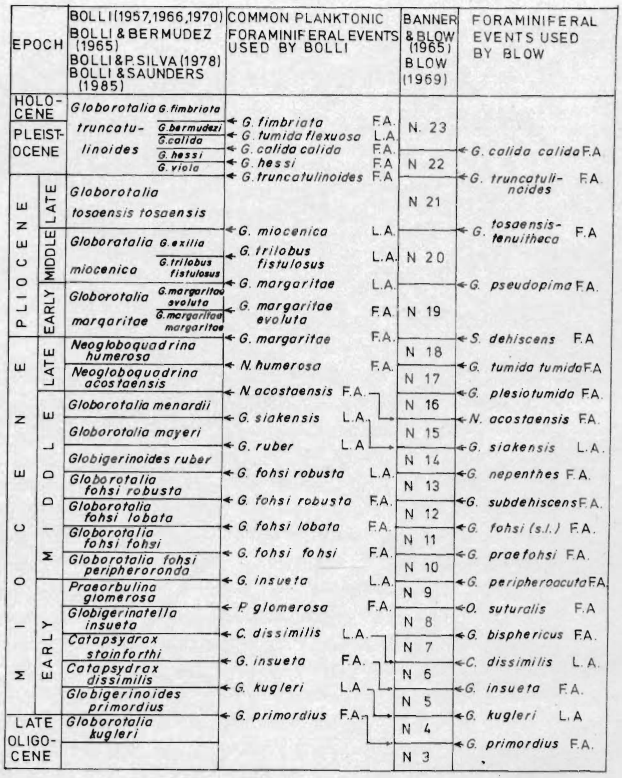

Fig. 1: Comparison of zonal definitions between Bolli's (Left) and Blow's (Right) zonations, F.A. & L.A. denote first and last appearances, respectively.

Planktonic foraminifera vary considerably with respect to their resistance to dissolution. Carbonate dissolution plays a major role in effecting the quality, continuity and aerial distribution of planktonic foraminifera in the world oceans. Both Bolli (1957b; 1966 a,b, 1970) and Blow (1969, 1979) did not take dissolution into consideration in their selection of zonal marker species. Thus, sequences deposited below the lysocline often lack the zonal markers employed in Blow's and Bolli's scheme. Jenkins and Orr (1971, 1972) recognised this problem and proposed a zonal scheme for the tropical regions based on solution resistant species (Fig. 2), many of which are different from those of Bolli (1957; 1966a, b, 1970) and Blow (1969, 1970).

These above zonal schemes are not globally applicable despite such earlier claims (Blow, 1969) as the species and lineages employed as zonal markers are confined to the tropical and subtropical water - masses. This led to the establishment of an entirely different biostratigraphic schemes for temperate to polar regions than those employed for the tropics (Jenkins, 1967, 1971, 1975, 1985; Kennett, 1973; Kaneps, 1975; Poore and Berggren, 1975). The most important scheme is that of Jenkins (1966a, 1967, 1971) based on New Zealand marine sequences. Kennett (1973) introduced two new zonal schemes for the faunal assemblages in the Warm Subtropical and Cool Subtropical Water -mass in the South Pacific, which differs significantly from that of Jenkins (1971). Studies by Jenkins and Srinivasan (1986) reveal that zonal schemes are empirical and their recognition is dependent on the paleogeographic limitations of zonal markers in the Neogene.

In recent years, the quality of Neogene DSDP cores obtained from South Pacific enabled Srinivasan and Kennett (1981 a,b) and Jenkins and Srinivasan (1986) to establish a somewhat more detailed zonation than that of Jenkins (1971). Even these zones are largely based on *Globorotalia s.l.* reflecting the importance of these evolutionary lineages in temperate areas. Comprehensive reviews of the current status of Neogene low -latitude planktonic foraminiferal biostratigraphy as revealed by various DSDP Projects, including zonations datum levels, and paleoceanography have been presented by Srinivasan and Kennett (1981 a, b), Kennett and Srinivasan (1983) and Bolli and Saunders (1985).

EPOCH		PLANKTONIC FORAMINIFERAL ZONES	DEFINITION OF ZONAL BOUNDARIES
PLEISTOCENE		*Pulleniatina obliquiloculata*	
			← *G. fistulosus* L.A.
PLIOCENE	UPPER	*Globigerinoides fistulosus*	
			← *G. fistulosus* F.A.
	LOWER	*Sphaeroidinella dehiscens*	
			← *S. dehiscens* F.A.
MIOCENE	UPPER	*Globorotalia tumida*	
			← *G. tumida* F.A.
		Globorotalia plesiotumida	
			← *G. plesiotumida* F.A.
	MIDDLE	*Globoquadrina altispira*	
			← *G. fohsi lobata* L.A.
		Globorotalia fohsi lobata	
			← *G. fohsi lobata* F.A.
		Globorotalia fohsi fohsi-peripheroacuta	
			← *G. peripheroacuta* F.A.
		Globorotalia peripheroronda	
			← *P. glomerosa curva* L.A.
		Praeorbulina glomerosa curva	
			← *P. glomerosa curva* F.A.
	LOWER	*Globigerinoides bisphericus*	
			← *G. bisphericus* F.A.
		Globoquadrina venezuelana	
			← *C. dissimilis* L.A.
		Catapsydrax dissimilis	
			← *G. kugleri* L.A.
		Globorotalia kugleri	
			← *G. kugleri* F.A.

Fig. 2: Tropical Neogene planktonic foraminiferal zonation of Jenkins and Orr (1971, 1972). F.A. and L.A. denote first and last appearances, respectively.

NEOGENE PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF THE NORTHERN INDIAN OCEAN

Studies involving Indian Ocean Neogene planktonic foraminifera have been much neglected compared to other world oceans. Scientific interest in indian Ocean developed mainly after the International Indian Ocean Expedition (IIOE) during 1959 -1965. With the entry of D/V *Glomar Challenger* in the Indian Ocean on Legs 22 through 29 in the 1970's, a mass of new data of varying quality on both stratigraphic ranges and geographic distribution of planktonic foraminifera in the Northern Indian Ocean became available. Investigations revealed that high species diversity, good preservation and uncomplicated stratigraphy have provided a high resolution biochronology for the low - latitude areas. In contrast, the generally low species diversity among planktonic foraminiferal faunas and intervals of Carbonate dissolution have made it difficult to obtain a similar biostratigraphic record for the middle and high latitude regions.

Prior to Deep Sea Drilling programme in the region, nearly all the documentation of species had come from the uplifted marine sequences on land bordearing the Indian Ocean. One of the most significant studies in the area is that of Srinivasan and his Co-workers who described planktonic foraminifera from the Andaman-Nicobar Neogene sequences (Srinivasan, 1969, 1975, 1977, 1984, 1988; Srinivasan and Sharma, 1973 a,b, 1974; Srinivasan and Srivastava, 1974, 1975; Srinivasan and Singh, 1978; Srinivasan and Azmi, 1979; Srinivasan and Dave, 1984, 1985). Planktonic foraminifera which are abundant and well preserved provide unique opportunity to compare and correlate Andaman - Nicobar sequences with the deep sea sections. The sequences on Andaman and Nicobar Islands are important because of their strategic position in the Northern Indian Ocean, an area where few other good Neogene marine sequences exist except for DSDP sections. By examining a large number of overlapping sections exposed on these islands, Srinivasan (1977, 1984) has been able to produce an almost complete sequence of tropical Neogene planktonic foraminiferal zones, which are comparable with the DSDP biostratigraphic record. A detailed investigation of DSDP cores from Northern Indian Ocean located adjoining to these islands enabled to refine the zonal scheme, especially in the late Neogene of Andaman - Nicobar sequences.

During the last two years, once again Indian Ocean became the centre of drilling activities, when attempts were made by a team of Oceanographers from the Ocean Drilling Programme (ODP) to explore this ocean. Scientists on board JOIDES RESOLUTION drilled 62 sites during 1987-88 and Leg 115 (Mascarene Plateau) was the first of a nine Leg ODP exploration in the Indian Ocean. The ODP programme successfully culminated in Leg 123 and site 765 of this Leg contains the deepest cased oceanic hole in the world. Investigations on these sites when completed would bring out a veritable explosion of new data on Neogene foraminiferal biostratigraphy, tectonic and paleoceanographic history of the Indian Ocean which has remained poorly known to this date.

The main objective of this paper is to present a summary of the new development accomplished with regards to the Neogene planktonic foraminiferal biostratigraphy in the tropical Indian Ocean region. The study is based on the data from Leg 22, DSDP sites 214,216,216A,217 (Ninetyeast Ridge) and land - based sections from Andaman-Nicobar Islands.

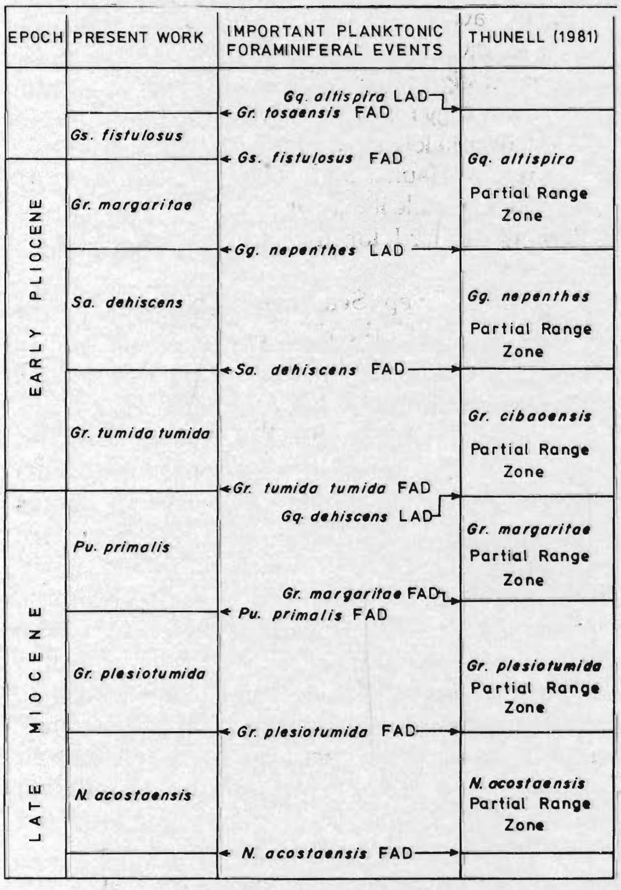

Fig. 3: Comparison of Late Miocene - Early Pliocene zonal definitions between Thunell (1981) and the zonation adopted in the present work. FAD and LAD denote first and last appearance datums, respectively.

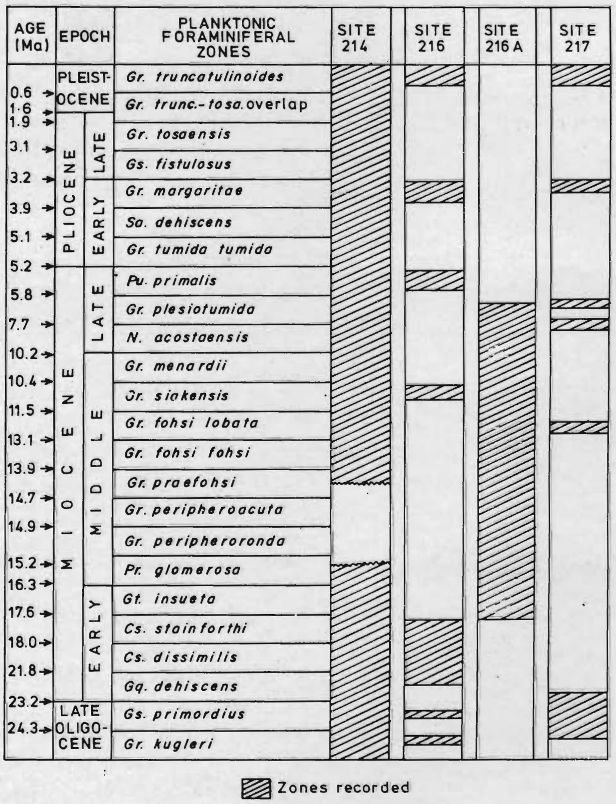

Fig. 4: Zones recorded in the DSDP sites examined.

Neogene planktonic foraminifera from Leg 22 were initially examined by McGowran (1974) and by Berggren *et al.,* (1974). In both studies biostratigraphic ranges were correlated to the planktonic foraminiferal zones of Blow (1969). A summary of Neogene planktonic foraminiferal biostratigraphic findings for the Indian Ocean has been presented by Vincent (1977) based on compilation of all DSDP Initial Reports. In a recent work on the low-latitude marine sequences of the late Miocene to early Pliocene age, Thunell (1981) used site 214 from the Northern Indian Ocean for a detailed biostratigraphic study but unlike McGowran (1974), Berggren *et al.*, (1974) and Vincent (1977), Thunell (1981) adopted taxa for defining the zones. A comparison of the zones identified by Thunell (1981) and zones adopted in the present work, is shown in figure 3.

Of the three sites examined from the Ninetyeast Ridge, only site 214 has a superb, almost continuous sequence of abundant planktonic foraminifera through the entire Neogene. However, a minor hiatus covering an interval from the upper part of *Praeorbulina glomerosa* Zone to lower part of *Globorotalia praefohsi* Zone (early Middle Miocene) is recorded in this site. At site 214 the Middle Miocene is very much condensed; *Gg. nepenthes* first appears at the same level as the last appearance of *Gr. fohsi lobata* and zone corresponding to Zone N 13, therefore, is not represented. Since detailed study of the Neogene sequences was not the main objective of sites drilled during Leg 22, time constraints did not allow sites 216 and 217 being continuously cored. The thickness of the uncored intervals in these sites ranges from 40 m to 18 m. Therefore, it was not possible to identify all the biostratigraphic boundaries recorded at site 214 in these sites (Fig. 4).

The Neogene planktonic foraminiferal biostratigraphy of the uplifted deep sea sequences of Andaman-Nicobar Islands in the Northeastern Indian Ocean, which lie adjoining to the DSDP site 217 on the eastern flank of Ninetyeast Ridge has been extensively worked out by Srinivasan (1977, 1984) (Fig. 5). The zonal scheme established by Srinivasan (1977, 1984) is applicable to the DSDP section for the Miocene interval with some amendments based on new data. Such zonations as well as those proposed by Jenkins and Orr (1972), Bolli and Premoli Silva (1973) and Stainforth *et al.*, (1975), could not be utilized for most of the Pliocene because the zonal markers are missing.

A detailed study of the stratigraphic ranges from close sampling intervals particularly in the Pliocene has led to the further refinement of the existing late Neogene planktonic foraminiferal zones in the tropical Northern Indian Ocean. Based on the DSDP data *Sphaeroidinella dehiscens* Zone of Srinivasan (1977, 1984) has been emended and new subdivisions have been introduced for the Pliocene interval corresponding to Zone N 19 and Zone N 20 (Blow, 1969). For the late Pliocene and Pleistocene intervals the warm-subtropical zonation of Kennett (1973) has been followed.

Recently Srinivasan *et al.*, (1987), and Srinivasan and Chaturvedi (1988a, b; 1989) carried out a detailed examination of planktonic foraminifera of sites 214, 216 and 217 (Ninetyeast Ridge) which led to refining as well as emending a set of zones for the Indian Ocean Neogene, initially developed in Andaman-Nicobar Islands (Srinivasan, 1977, 1984). These refinements have been introduced to enhance the Neogene biostratigraphic resolution in the deep sea cores of the Northern Indian Ocean as well as the uplifted deep sea sequences on Andaman-Nicobar Islands.

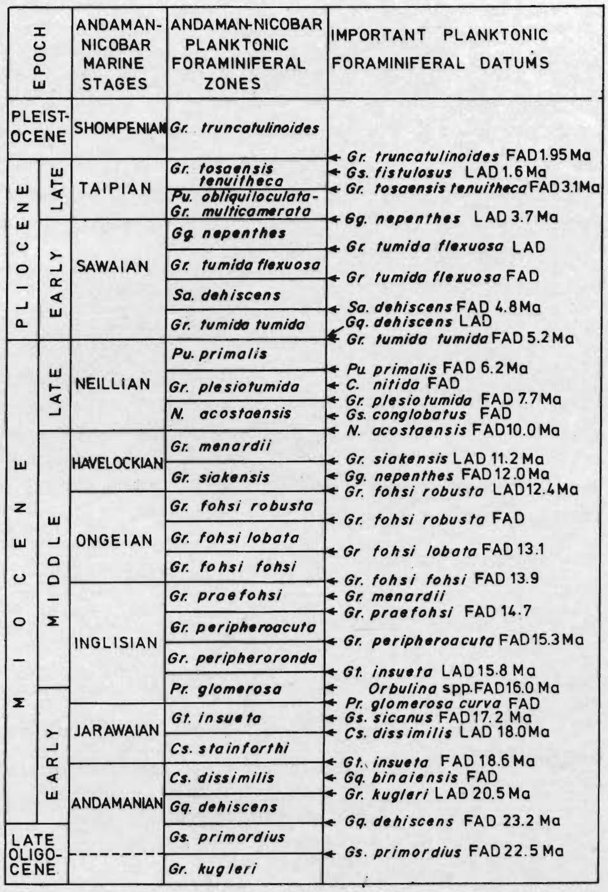

Fig. 5: Neogene planktonic foraminiferal zones established in the Andaman - Nicobar Islands, Northeastern Indian Ocean (Srinivasan 1977, 1984). FAD and LAD denote first and last appearance datums, respectively.

Figure 6 gives the zonal scheme established for the tropical Northern Indian Ocean region based on stratigraphic ranges of planktonic foraminifera from the DSDP sites. The zonal boundaries are defined by the initial evolutionary appearances and extinctions of selected taxa. Major epoch boundaries are marked by the following species; Pliocene/Pleistocene, the last appearance of *Globigerinoides fistulosus*; Mio-

AGE (Ma)	EPOCH		PLANKTONIC FORAMINIFERAL ZONES	ZONAL MARKER		SITE
	PLEISTOCENE		*Gr. trùncatulinoides*			
0.6				*Gr. tosaensis*	LAD	214
			Gr. trunc. - tosa. overlap			
1.6						
1.9				*Gr. truncatulinoides*	FAD	214
	PLIOCENE	LATE	*Gr. tosaensis*			
3.1				*Gr. tosaensis*	FAD	214
			Gs. fistulosus			
3.2				*Gs. fistulosus*	FAD	214
		EARLY	*Gr. margaritae*			
3.9				*Gg. nepenthes*	LAD	214
			Sa. dehiscens			
5.1				*Sa. dehiscens*	FAD	214
			Gr. tumida tumida			
5.2				*Gr. tumida tumida*	FAD	214
	MIOCENE	LATE	*Pu. primalis*			
5.8				*Pu. primalis*	FAD	214
			Gr. plesiotumida			
7.7				*Gr. plesiotumida*	FAD	214,216A,217
			N. acostaensis			
10.2				*N. acostaensis*	FAD	214,216A
		MIDDLE	*Gr. menardii*			
10.4				*Gr. siakensis*	LAD	214,216A
			Gr. siakensis			
11.5				*Gr. fohsi lobata*	LAD	214,216A
			Gr. fohsi lobata			
13.1				*Gr. fohsi lobata*	FAD	214,216A
			Gr. fohsi fohsi			
13.4				*Gr. fohsi fohsi*	FAD	214,216A
			Gr. praefohsi			
14.7				*Gr. praefohsi*	FAD	216 A
			Gr. peripheroacuta			
14.9				*Gr. peripheroacuta*	FAD	216 A
			Gr. peripheroronda			
15.2				*Gt. insueta*	LAD	216 A
			Pr. glomerosa			
16.3				*Pr. glomerosa*	FAD	214,216A
		EARLY	*Gt. insueta*			
17.6				*Cs. dissimilis*	LAD	214,216A
			Cs. stainforthi			
18.0				*Gt. insueta*	FAD	214
			Cs. dissimilis			
21.8				*Gr. kugleri*	LAD	214,216
			Gq. dehiscens			
23.2				*Gq. dehiscens*	FAD	214,217
	LATE OLIGOCENE		*Gs. primordius*			
24.3				*Gs. primordius*	FAD	214
			Gr. kugleri			

Fig. 6: Neogene planktonic foraminiferal zones and zonal markers in Northern Indian Ocean DSDP sites.

cene/Pliocene, appearance of *Globorotalia tumida*; Oligocene/Miocene, the appearance of *Globoquadrina dehiscens* (Fig. 7). Comparison of the succession of planktonic foraminiferal events in the Indian Ocean with the sequences from the tropical Pacific revaeals a remarkable similarity. The striking difference, however, is the complete absence of *Pulleniatina spectabilis* from the Indian Ocean sequences which appears to be due to the effective closing of Indonesian-Sea way during the Middle Miocene.

AGE (Ma)	EPOCH		BOUNDARY MARKER		SITE
	PLEISTOCENE				
1·6			*Globigerinoides fistulosus*	LAD	214
	PLIOCENE	LATE			
3.2			*Globigerinoides fistulosus*	FAD	214
		EARLY			
5.2			*Globorotalia tumida tumida* *Globoquadrina dehiscens*	FAD LAD	214 214
	MIOCENE	LATE			
10.2			*Neogloboquadrina acostaensis*	FAD	214, 216 A
		MIDDLE			
16·3			*Praeorbulina glomerosa*	FAD	216 A
		EARLY			
23.2			*Globoquadrina dehiscens*	FAD	214, 217
	LATE OLIGOCENE				

Fig. 7: Major epoch boundaries and markers used in the present study.

CHEMOSTRATIGRAPHY

The stratigraphic record is an outcome of an exogenic system consisting of geologic setting, changes in sea level, changes in geochemical reactions in the sea and the earth, climate and processes of sediment formation. This system in conjuction with telluric and astronomic signals gives rise to both lithologic and biostratigraphic imprints some of which are useful in global correlation (e.g. Tappan, 1968). The exogenic system generates useful direct geochemical signals in lithologic units, which serve as markers for geologic events.

Global sea level fluctuations in response to major changes in climate produce changes in Ocean chemistry (O_2, CO_2, fertility) which can be detected in deep sea record as global chemostratigraphic markers. In addition, sea level changes have bearing on rate of sedimentation (Davies *et al.*, 1977) and distribution of deep sea hiatuses (Moore and Heath, 1977). Just as paleomagnetism led to the establishment of a Magnetostratigraphy, the application of Chemostratigraphic signals such as stable isotope record and carbonate cycles, in lithologic succession may lead to geochemical stratigraphy or Chemostratigraphy. A beginning has already been made in this

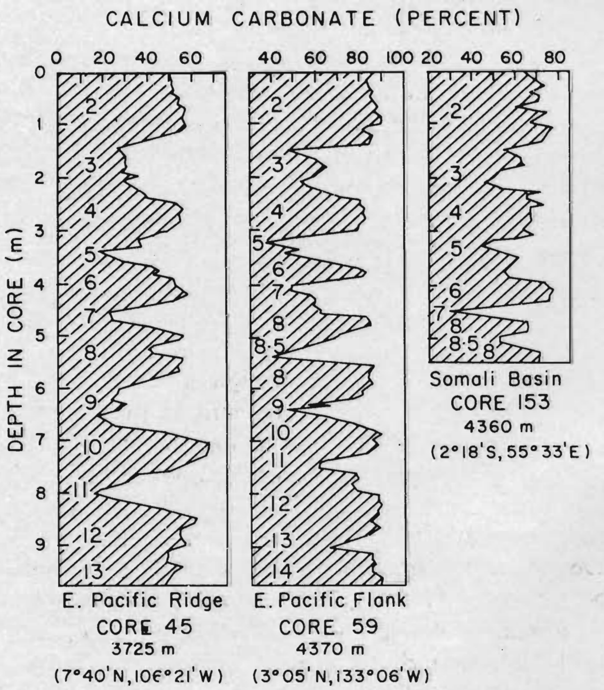

Fig. 8: Carbonate dissolution cycles in the Indo-Pacific, Swedish Deep Sea Expedition. Note the striking similarities in these records. (After Berger and Vincent, 1981).

direction by Arrhenius (1952) on the carbonate cycles in the equatorial Pacific (Fig. 8) and Emiliani (1955) who first used the isotopic record to subdivide the Quaternary sequence.

Recent studies have revealed that certain Chemostratigraphic signals are global in nature, and integration of Chemostratigraphic and biostratigraphic records can lead to a high resolution global Event Stratigraphy. Global geochemical signals are most easily detected in the deep sea record because of the minimum regional interference, in oceanic realm. In recent years, increasing efforts have been directed toward detecting and documenting various Chemostratigraphic signals from the Neogene deep sea sequences. The investigations reveal that Chemostratigraphic signals such as isotopic records and Carbonte Cycles appears closely linked with climatic and sea level changes, at least in the Neogene.

Since the studies of Emiliani (1955) on the stable isotope of foraminifera from deep sea cores the isotopic records have been extensively used in extracting global signals, and interpertation of these signals in terms of regional modulation. Isotopic compositions of foraminiferal tests (O and C) holds the key to a number of central problems in paleoceanography such as paleotemperature estimation, development of vertical as well as horizontal water mass stratification and the evolution of ocean climate during the past. Investigations conducted by Emiliani (1955), Shackleton and Opdyke (1973, 1976), Bender and Keigwin (1979) Haq *et al.*, (1980); Vincent *et. al.*, (1985) and Oberhansli (1986) on the stable isotope stratigraphies of the Neogene deep sea sequences have established Oxygen and Carbon isotope records to be systemic in nature and hence can provide useful Chemostratigraphic signals for global

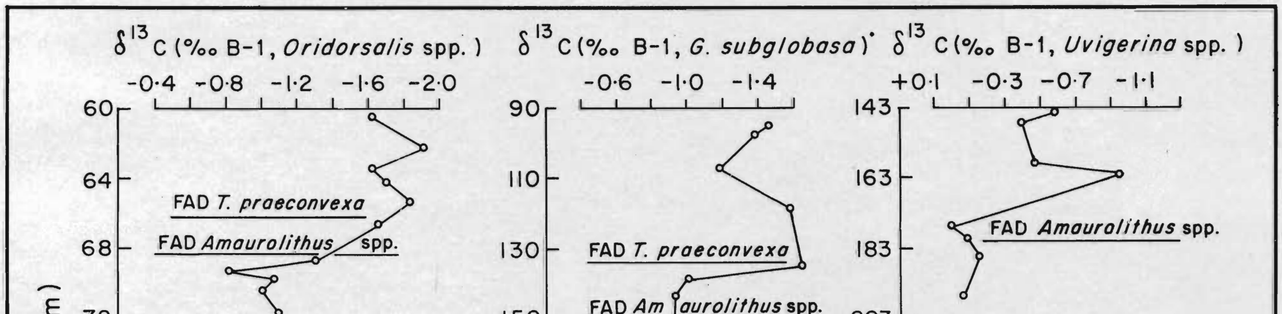

Fig. 9. Late Miocene Carbon isotopic Stratigraphies for benthic foraminifera at DSDP Sites and occurrence of two phytoplankton datum levels. (Data from Haq *et al.*, 1980).

correlation. These studies further indicate that for the late Neogene, Oxygen isotope record provides the standard Chemostratigraphic signal whereas, Carbon isotope signal assumes greater significance for the Miocene.

The Oxygen isotope record is largely a reflection of increase and decrease in continental ice volume, hence both of climate and sea level (Shackleton and Opdyke, 1973). Detailed Oxygen isotopic record of Quaternary deep sea cores enabled Emiliani (1955) and Shackleton and Opdyke (1976) to divide the sequence into 23 isotopic stages. The stage boundaries defined are based on times of rapid isotopic change in the oceans, thus they can be easily recognised even in sediments that have accumulated quite slowly. In addition to stratigraphic application, the Oxygen isotopic record in the Quaternary also enabled to gain greater understanding of the climatic and sea level oscillations. The systemic and global nature of these events is readily demonstrated by correlating Pacific, Atlantic and Indian Ocean Oxygen isotopic signals.

One of the most useful applications of chemostratigraphy in recent years has been to evaluate the syn-

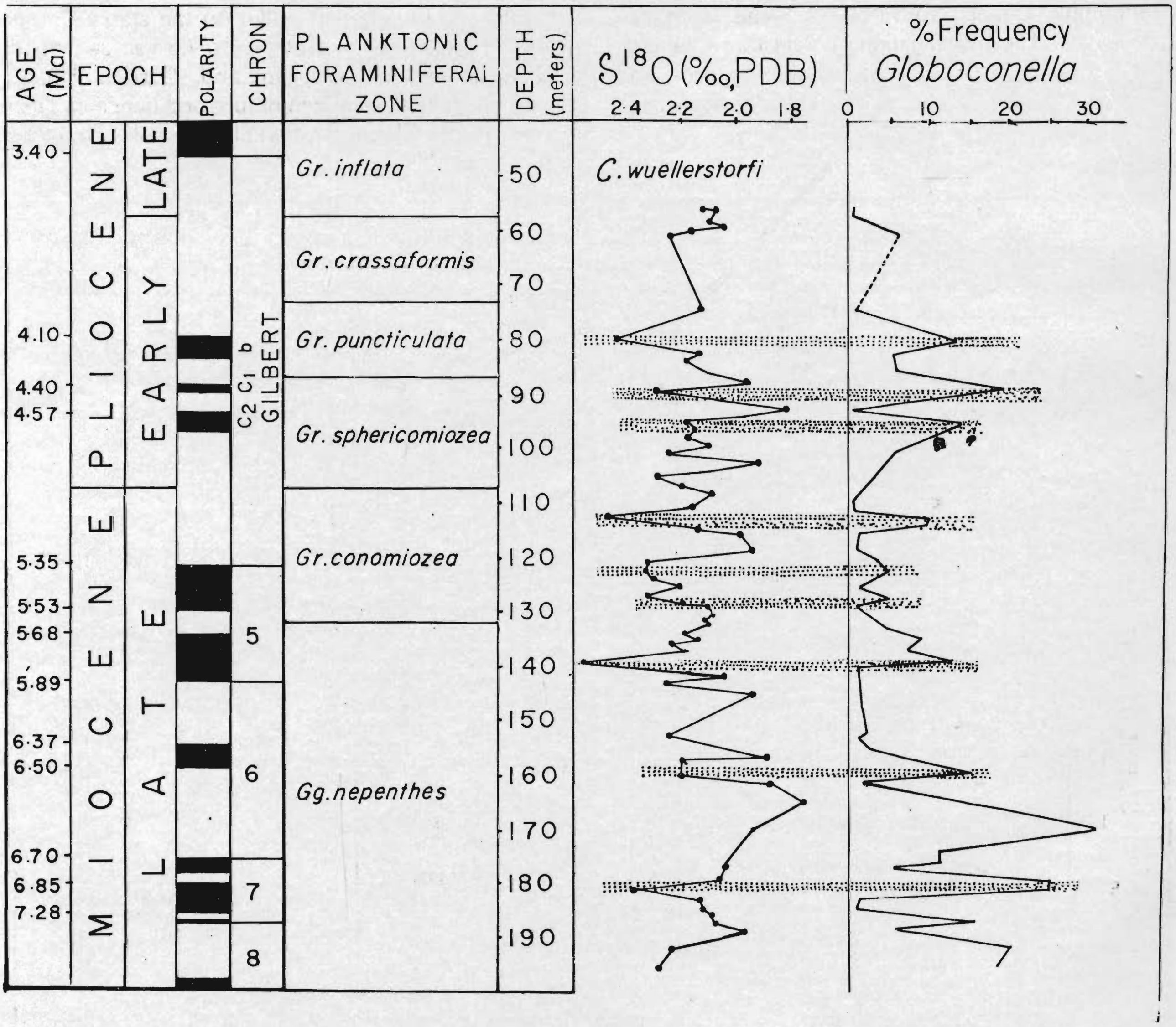

Fig. 10. Integrated biomagnetoradioisotopic chronology at DSDP site 588. Note the increase in $\delta^{18}O$ values coinciding with *Globoconella* maxima.

chroneity of biostratigraphic datums. Such a test was conducted by Theirstein *et al.*, (1977) on Late pleistocene Coccolith datums. These authors demonstrated the synchroneity of the last appearance datum of *Pseudoemilliania lacunosa* within the early part of Oxygen isotope stage 12, and first appearance of *Emilliania huxlei* in late Oxygen isotope stage 8, throughout the world ocean.

Similarly, a comparison of late Miocene biostratigraphic events with the isotopic event reveals that the Chron-6 negative Carbon shift which occurs in Magnetic Epoch-6, can be detected in the isotopic stratigraphies of a large numer of DSDP sites from world ocean. The Chron-6 negative Carbon Shift is invariably preceded by the first appearance datum of *Amaurolithus* spp. (Haq. *et. al.*, 1980), strongly advocating synchroneity, both for the isotope record and biostratigraphic datum (Fig. 9). The shift is considered to reflect a geologically instantaneous change in the rate of turn over of oceanic circulation (Bender and Keigwin, 1979). Because of its extremely widespread occurrence throughout the oceanic sediment sequences (Haq *et al.*, 1980; Vincent *et al.*, 1980) and its age, Chron-6 negative Carbon Shift is most certainly related to the paleoceanographic changes associated with the latest Miocene global cooling and resultant regression cycle and contribution of organic matter depleted in $\delta^{13}C$ to the ocean from erosion. An integrated biomagnetoradioisotopic chronology for the late Neogene sequence at DSDP site 588 is

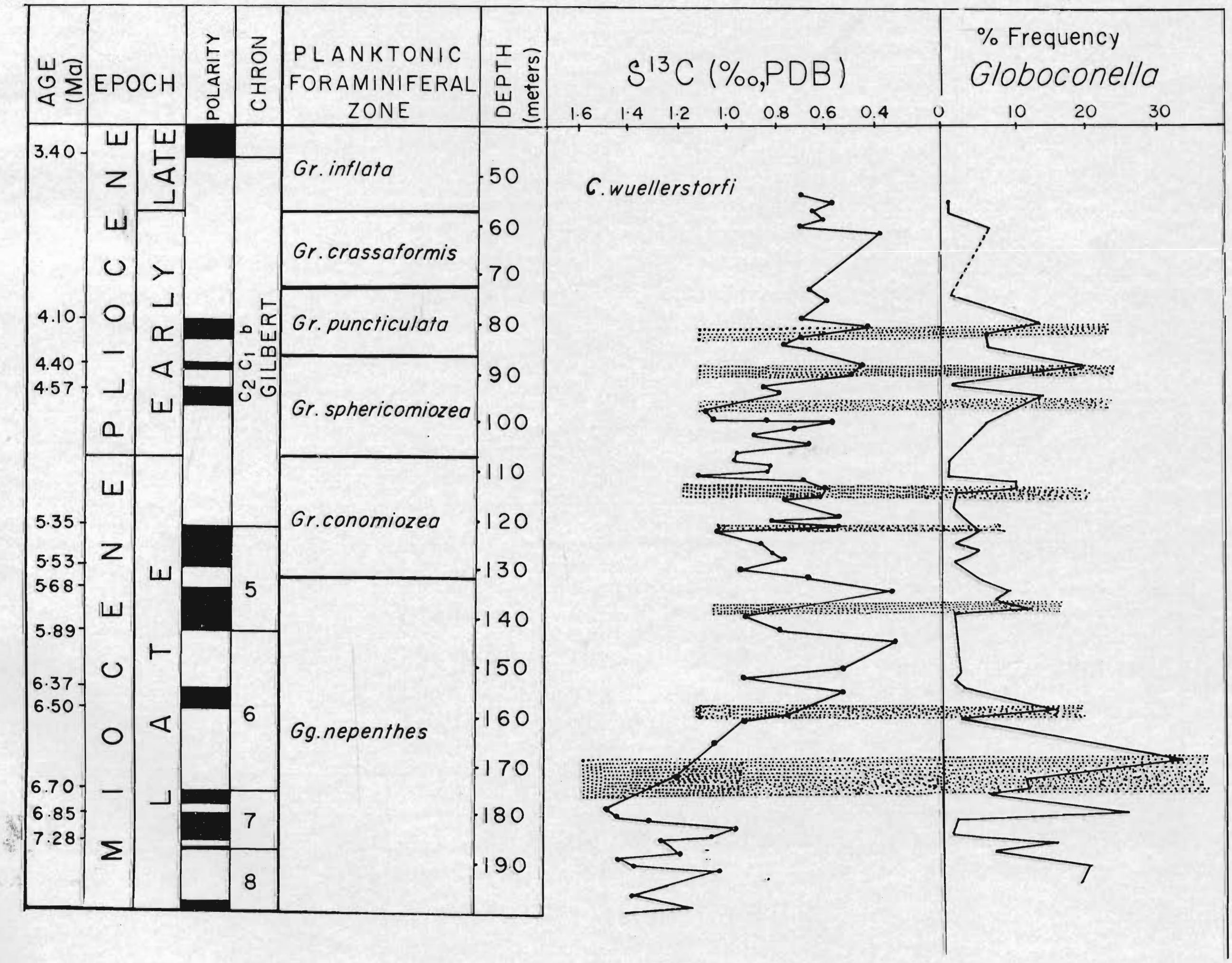

Fig. 11. Integrated biomagnetoradioisotopic chronology at DSDP site 588. Note the decrease in $\delta^{13}C$ values coinciding with *Globoconella* maxima.

presented in figures 10 and 11. The coincidence of marked increase in frequency of *Globoconella*, a characteristic temperate group and increase in $\delta^{18}O$ (Fig. 10) and marked decrease in $\delta^{13}C$ (Fig. 11) signifies cooling events.

Besides isotopic records, carbonate preservation in deep sea cores also provides strong Chemostratigraphic signals in the Neogene. Marked fluctuations or dissolution spikes observed during specific time intervals have global geochemical significance and can be used for correlation of cores under different oceanic regions (Fig. 12). The mechanisms which produce marked carbonate fluctuations are yet to be fully understood. However, studies conducted so far, reveal that pronounced carbonate minima, are closely associated with marked increase in $\delta^{18}O$ of deep sea benthic foraminifera. The co-occurrence of Carbonate minima, climatic cooling and regression events is also documented in the late Neogene record from Indian Ocean (Srinivasan and Chaturvedi, 1989).

Thus, the systemic nature of Chemostratigraphic signals (i.e. Oxygen and Carbon isotope record and Carbonate cycles) is now well established through world wide correlation. Investigations especially in the Neogene have revealed that Chronology of Chemostratigraphic events in conjuction with magnetostratigraphy and biostratigraphy enabled to identify diachronism of biostratigraphic datums and a concomitant regional paleoceanographic change.

The integrated approach involving Biostratigraphy, Chemostrtigraphy and Magnetostratigraphy now being conducted by the Cenozoic Paleoceanography (CENOP) group is expected to bring out much new information on the major Neogene global events in the near future.

PALEOCEANOGRAPHY

The cruises of the D/V *Glomar challenger* have provided an unprecedented opportunity to study a vast and immensely valuable collection of core samples from hundreds of drilled sites in all Oceans since 1968. The collection represents a large part of the Cenozoic and Mesozoic record of Oceans. The study of core samples enables us to reconstruct the geologic history of the Ocean basins which have experienced dynamic change through geologic time because of plate tectonics. The changes that have occurred during the development of the Ocean systems have strongly affecated all other major components of the earth: the lithosphere, atmosphere, cryosphers, and biosophere. Study of evolutionary development of ocean systems through geologic time has become known as paleoceanography.

Paleoceanography, one of the youngest branches of Earth Sciences, was largely born of the Deep Sea Drilling Project and continues to be nourished by it. Recently, significant progress has been made in our understanding of the paleoceanographic evolution mainly by the workers under the Cenozoic Paleocea-

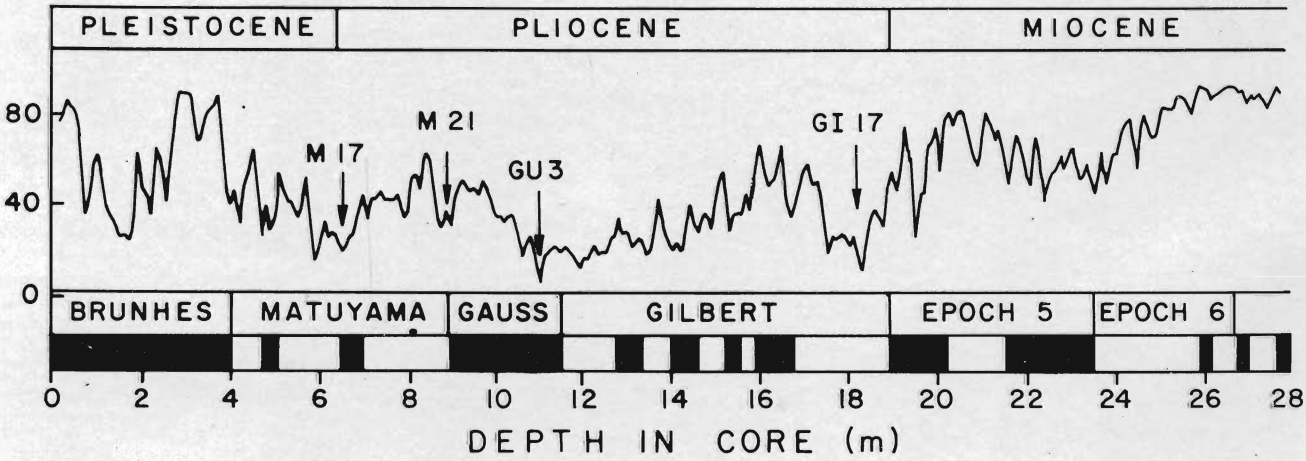

Fig. 12. Carbonate stratigraphy and Magnetostratigraphy of core Rc 12-66, equatorial Pacific. Note the pronounced carbonate minima (M 17, M 21, Gu 3, and GI 17).

nography Programme (CENOP). A number of paleoenvironmental syntheses of existing DSDP data by CENOP workers have enabled in etablishing a basic framework of Cenozoic global Paleoceanographic change, providing a basis for future studies (Kennett, 1985). In India paleoceanographic studies are relatively a recent field of research activity.

NEOGENE OCEANOGRAPHY OF THE NORTHERN INDIAN OCEAN

Many events critical to the development of our modern oceans took place during the Neogene. For this region, intensive studies on the Neogene deep sea cores from the Northern Indian Ocean are being conducted to improve our understanding of the history and effects of surface and bottom water circulation patterns, planktonic and benthic biogeographic development, history of biogenic productivity and Calcium Carbonate and siliceous deposition and dissolution. The Neogene Oceanography of the Indian Ocean has not been investigated in much detail as in the Atlantic and Pacific. Nevertheless, the studies conducted so far, reveal the general trend of Oceanographic changes recorded in the Atlantic and Pacific (Srinivasan and Chaturvedi, 1988b, 1989; Wright and Thunell, 1988). The changes particularly for Miocene (23.2 Ma to 5.2 Ma) are in good agreement with the data from the surrounding oceans. This report briefly highlights the major Paleoceanographic events that occurred in the Northern Indian Ocean during the Neogene, based on quantitative changes in planktonic and benthic foraminifera and Oxygen and Carbon isotopes in foraminiferal carbonate (Fig. 17).

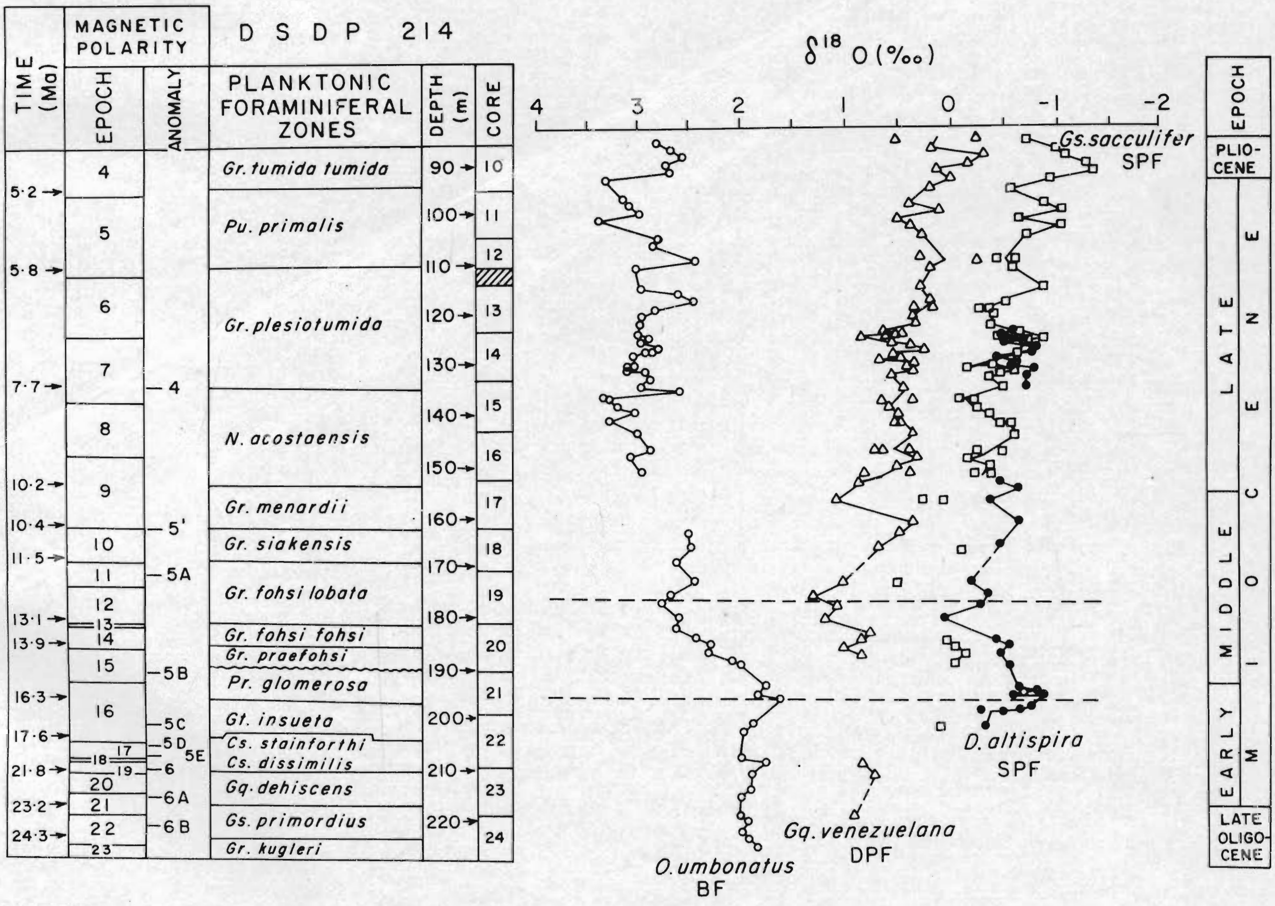

Fig. 13. Integrated Miocene planktonic foraminiferal biostratigraphy, oxygen isotope stratigraphy and magneto-radiochronology at DSDP site 214. Oxygen isotopic stratigraphies after Vincent *et al.*, (1985) and ages after Saito (1977, 1984) and Berggren *et al.*, (1985).

EARLY MIOCENE

Quantitative planktonic foraminiferal analyses of Miocene sections (DSDP Sites 214, 216, 216A and 217) reveal intervals of major faunal changes: 22 Ma (earliest Miocene); 13 -14 Ma, 11 - 12 Ma (Middle Miocene) and 6.2 Ma (Late Miocene). The Early Miocene is marked by a sudden and distinct increase in species diversity, proliferation of *Globigerinoides* spp., and changes in planktonic foraminiferal assemblages. Coincident with the faunal change, there is a gradual decrease in $\delta^{18}O$ values that reach minimum values between 19.5 Ma and 16 Ma, reflecting a climax of Neogene warmth, (Fig. 13). The striking feature of Miocene Carbon isotope stratigraphy is the broad Early to Middle Miocene positive excursion observed in both planktonic and benthic records (Vincent *et al.*, 1985). The excursion begins with a shift towards high $\delta^{13}C$ values by 1% (Chron - 16 Carbon shift) in the latest Early Miocene (approximately 17.5 Ma to 16.5 Ma) corresponding to the climax of Neogene warmth (Figs 13, 14). The increased Carbonate dissolution interval during 21.8 Ma to 17.6 Ma documented from Atlantic and Pacific is also recorded in the examined sites suggesting intensification of circum — Antarctic current. The hiatus recognised at the Early Miocene/Middle Miocene boundary reflects a vigorous bottom water activity.

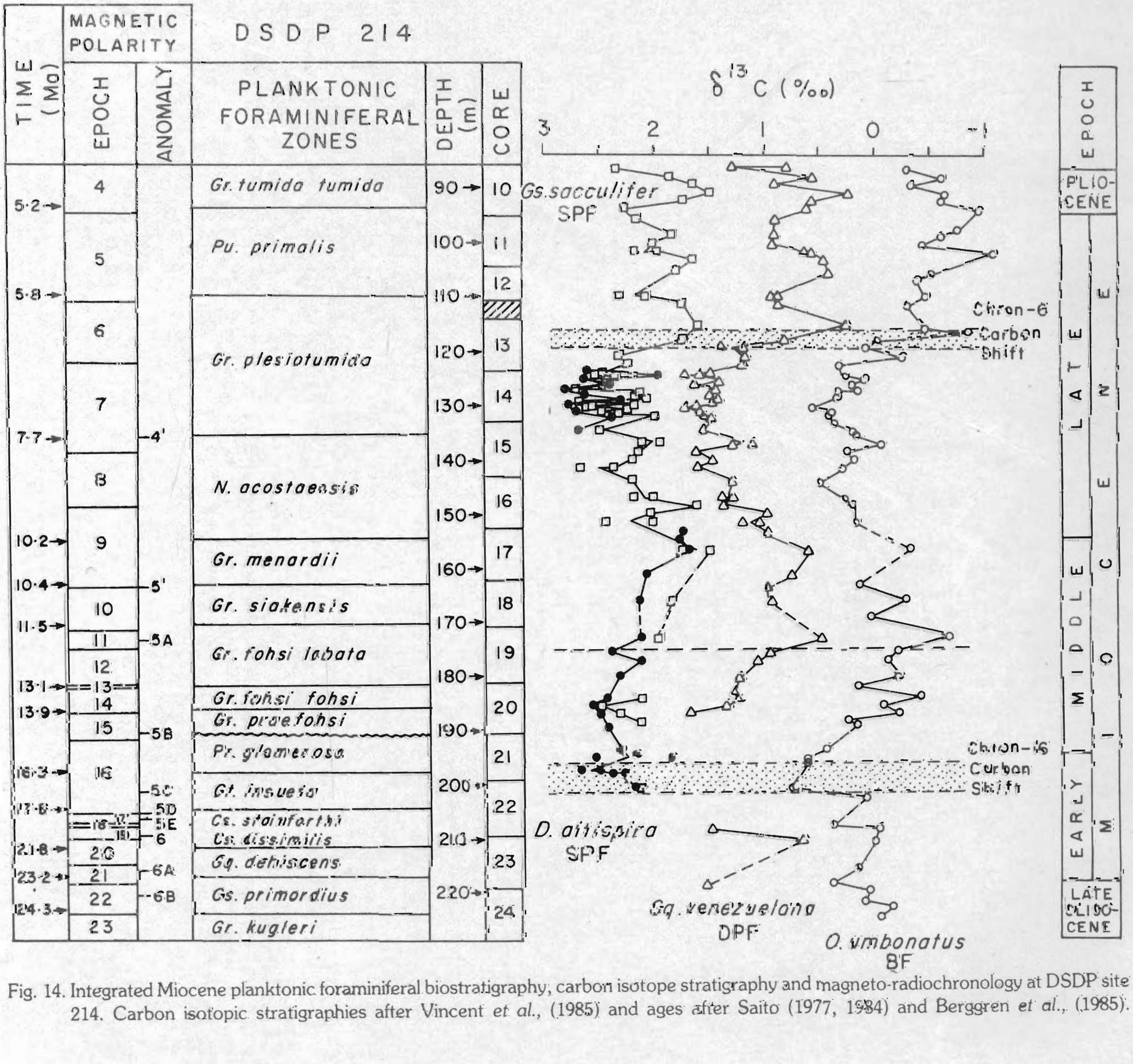

Fig. 14. Integrated Miocene planktonic foraminiferal biostratigraphy, carbon isotope stratigraphy and magneto-radiochronology at DSDP site 214. Carbon isotopic stratigraphies after Vincent *et al.*, (1985) and ages after Saito (1977, 1984) and Berggren *et al.*, (1985).

MIDDLE MIOCENE

Of the three sites examined only site 216A represents a continuous coring of the Middle Miocene sequence, which enabled to recognise the faunal trends based on quantitative changes in planktonic foraminifera. In general *Globoquadrina, Menardella* and *Globigerinoides* spp. show decrease in abundance in the *Globorotalia fohsi fohsi* and *Globorotalia fohsi lobata* Zones, followed by a sudden increasing trend from the *Globorotalia siakensis* Zone upwards (Fig. 15). It is interesting to note that *Globorotalia miozea* which is a characteristic temperate species occurs in the Middle Miocene of Northern Indian Ocean sites during the interval marked by the decrease in abundance of *Globigerinoides* spp., *Menardella* and *Globoquadrina*. The above observation suggests incursion of cool surface waters into this region during the Middle Miocene (13 Ma - 14 Ma). Other species exhibit small scale oscillations in the abundance and there are no significant faunal changes that distinguish the Middle Miocene from the Early Miocene.

Coincident with this faunal trend is the marked increase in benthic $\delta^{18}O$ values during 13 Ma - 14 Ma. The marked increase in benthic $\delta^{18}O$ values during 13 Ma - 14 Ma is interpreted as representing a major, permanent accumulation of the East Antarctic ice sheet and a cooling of bottom waters (Shackleton and Kennett, 1975). This has resulted in the development of steep temperature gradient between polar and tropical regions giving rise to enhanced faunal provincialization. The Middle Miocene Antarctic ice sheet formation appears to be responsible for the expansion of cool temperate waters towards the lower latitudes, and an increase in the degree of stratification of water column resulting in the rapid evolutionary growth of *Fohsella* lineage in the tropics. Coincident with major increase in $\delta^{18}O$ values and change in planktonic foraminiferal assemblage, there is a rapid replacement of Paleogene and earlier benthic foraminiferal species by the assemblage that dominate the late Neogene and modern deep sea environment. It is interesting to note that some of the largest changes in the assemblages of planktonic foraminifera in these sequences occur between 11 and 12 Ma which appear to be closely linked with the closing of the Indonesian sea way, separating the equatorial Indian Ocean from equatorial Pacific (Kennett *et al.*, 1985).

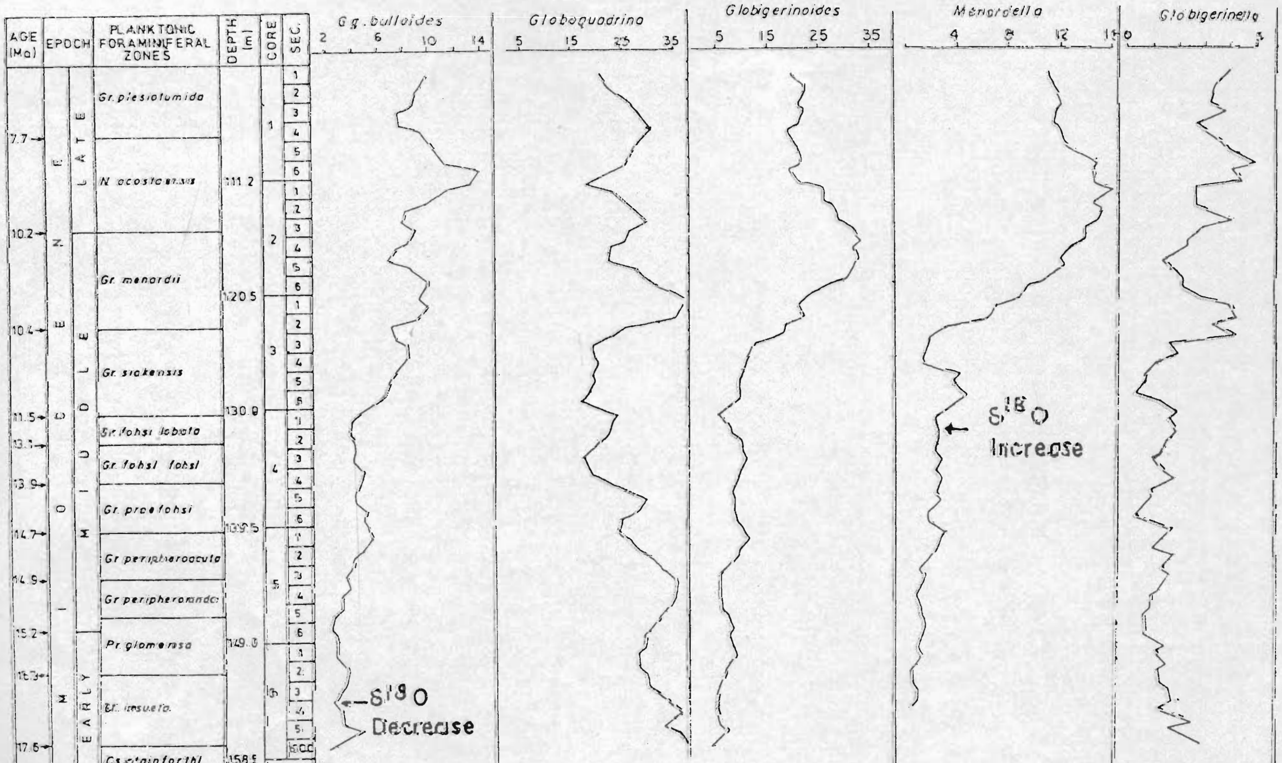

Fig. 15. Percentage frequency of *Gg. bulloides, Globoquadrina, Globigerinoides, Menardella* and *Globigerinella* for the Middle and late Miocene at DSDP Site 216A.

LATE MIOCENE

At site 214 there are number of intervals in the Late Miocene marked by increase in abundance of *Globigerina bulloides* corresponding to a marked decrease in the abundance of *Globigerinoides* spp. At site 216A *Gg. bulloides* shows a major increase in the *N. acostaensis* Zone, corresponding to a marked decrease in abundance of *Globoquadrina* and *Globigerinoides* spp. (Fig. 15). The peaks of abundance of *Gg. bulloides* in the sequence reflect intervals of cooling. Faunally determined cooling event within the Late Miocene at Site 214 coincides with Oxygen isotopic changes in benthic and planktonic foraminifera (Vincent *et al.*, 1985).

The most significant isotopic event of the latest Miocene is the Chron - 6 event, at about 6.2 Ma with δ13C shift to low values by about 1% in all foraminiferal records (Fig. 14). This event also corresponds to the rapid increase in foraminiferal $\delta^{18}O$ (Vincent *et al.*, 1985) and marked abundance of *Uvigerina*. The negative Chron - 6 shift is considered to reflect a geologically instantaneous change in the rate of turnover of oceanic circulation and coincides with the late Miocene global climatic cooling and the resultant lowering of sea-level. The observed intervals of major faunal turnover reflect paleoceanographic changes associated with global climatic events and coincident with regional tectonism.

PLIOCENE

The beginning of the Pliocene is marked by the increase in the abundance of *Globigerina* spp., about 15% corresponding to the low frequency of keeled *Globorotalia* (Fig. 16). There is a general increasing trend in *Globoquadrina* from less than 8% to nearly 14% through most of the Pliocence. The peaks of abundance of *Pulleniatina* roughly coincide with the abundance of *Globorotalia*. Although no isotopic data for the sites examined is available for the Pliocene and Pleistocene, the data on faunal changes reveal two major expansions of cool surface waters, one during the early Pliocene (5.2 Ma) and the other at the end of Pliocene (1.8 Ma).

PLEISTOCENE

A closer study of the faunal trends of *Globigerina* spp. and keeled *Globorotalia* appear to be more meaningful than other planktonic foraminifera for

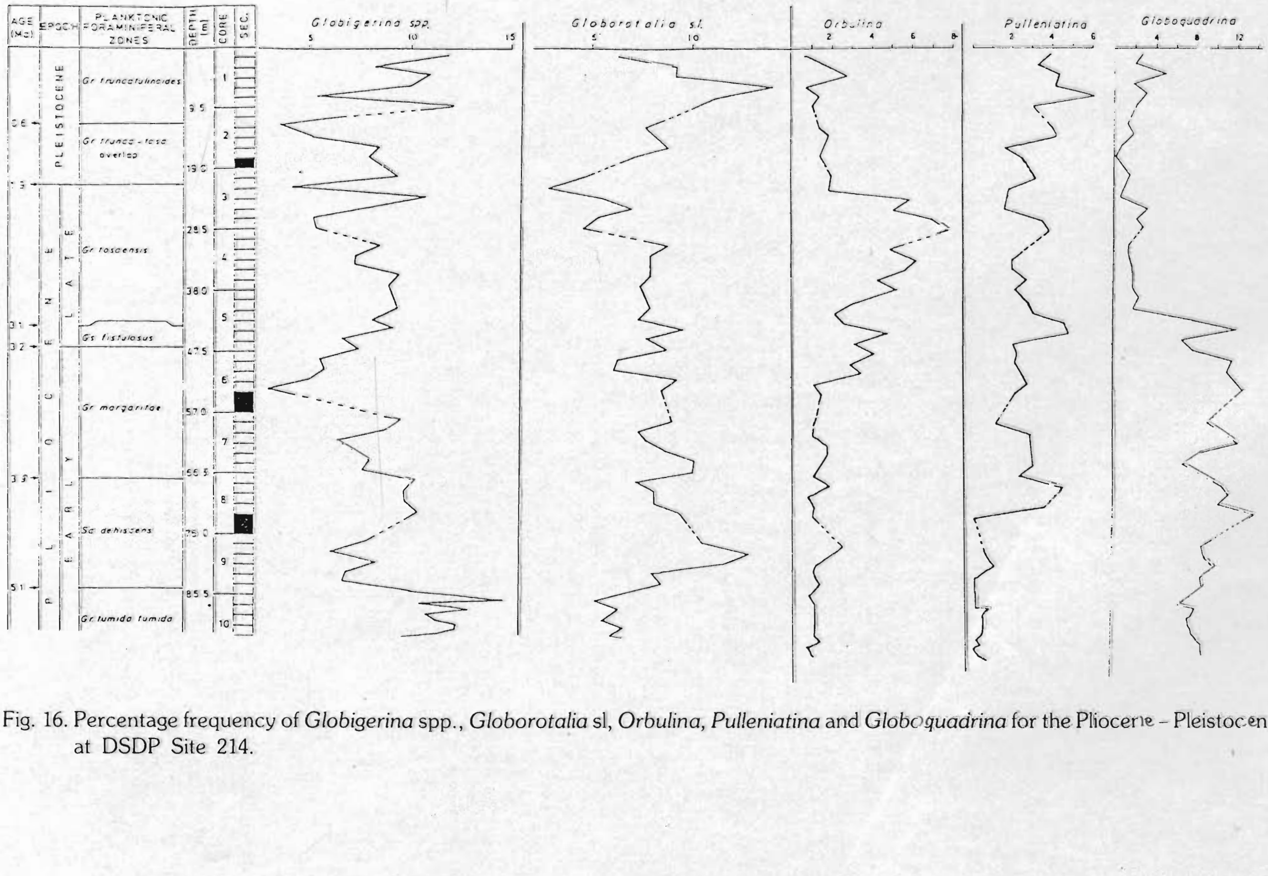

Fig. 16. Percentage frequency of *Globigerina* spp., *Globorotalia* sl, *Orbulina*, *Pulleniatina* and *Globoquadrina* for the Pliocene – Pleistocene at DSDP Site 214.

AGE (Ma)	EPOCH		MAJOR ISOTOPIC EVENTS	MAJOR OCEANIC MICROFAUNAL EVENTS		TECTONIC AND PALEOCEANOGRAPHIC EVENTS IN TROPICAL INDIAN OCEAN
0·6	PLEISTOCENE		← δ^{18}O Increase	Major shift in coiling mode in *Menardella* & *Pulleniatina*	↑ DECLINING STAGE ↓	Surface water cooling
1·6	PLIOCENE	LATE				
1·9						
3·2			← δ^{18}O Increase	Evolutionary acceleration and extinction of tropical early Neogene forms		Surface water cooling
3·9		EARLY				
5·2	MIOCENE	LATE	δ^{18}O Increase	Evolutionary acceleration Major faunal turnover		Surface water cooling due to northward expansion of Antarctic waters
5·8						
6·2			← Negative Carbon Shift	Abundance of *Uvigerina*		Antarctic Ice volume expansion Global regression of sea level
7·7			← δ^{18}O decrease	Increased latitudinal provincialism		Steepening of thermal gradients
10·2		MIDDLE			↑ EQUILIBRIUM STAGE ↓	
11·5						Closing of Indonasian Sea Way Development of Pacific Equatorial under current
13·1			δ^{18}O Increase Negative Carbon Shift	Evolutionary acceleration and major turnover in deep sea benthic foraminifera		East Antarctic Ice sheet formation. Development of vertical and horizontal water mass stratification.
13·4						
14·7						
15·2						
16·3		EARLY	← Positive Carbon Shift	↑ Increase in species diversity		Reactivation of AABW wide-spread deep sea hiatus
17·6					↑ DIVERSIFICATION STAGE ↓	
18·0			δ^{18}O lowest values for the Neogene	Evolutionary acceleration Proliferation of *Globigerinoides*		Climatic optimum
19·5				Dissolution of carbonate microfossils		Increased carbonate dissolution Expansion and intensification of Circum-Antarctic Current.
21·8			↑ δ^{18}O decreasing trend	Major evolutiory radiation in oceanic Microfossils		Opening of the Andaman Sea
23·2	OLIGOCENE	LATE				
24·3						Establishment of Circum-Antarctic Current.

Fig. 17. Major neogene isotopic, microfaunal and paleoceanographic ev..nts in the tropical Indian ocean.

paleotemperature interpretations. The marked increase in abundance of *Globigerina* and corresponding decrease in abundance of *Globorotalia* immediately above the Pliocene/Pleistocene boundary suggests expansion of cool waters towards the tropical northern Indian Ocean. The Pliocene/Pleistocene boundary is marked by cool interval. Based on *Globigerina* Vs. *Globoratalia* percentage at least two intervals of expansion of cool temperate waters, towards tropical northern Indian Ocean is inferred during the Pleistocene. Major change in faunal turnover including the coiling change particularly during the late Miocene and late Pliocene appears to be due to accelerated evolution triggered by climatic and paleoceanographic changes (Fig. 17).

The faunal assemblage from core top of the examined sites indicates a trend towards increase in abundance of *Globigerina* in association with sporadic occurrence of *Globorotalia inflata* (a characteristic temperate species). This gives a positive clue to the influence of cool temperate waters towards the tropical northern Indian Ocean in the recent times.

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