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A journey through morphological micropaleontology to molecular micropaleontology

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Micropaleontology has undergone a remarkable change over the past 150 years. With the recognition of biostratigraphic utility of microfossils in petroleum exploration, micropaleontology received a new impetus from the early descriptive stage to noticeable and exciting trends in the early part of the 20th century. The changes have been primarily in the areas of systematics of smaller benthic foraminifera, biostratigraphy and precision in paleoecology mainly to cater the needs of oil companies. This marks the first major milestone - the development of *Industrial micropaleontology*. A dazzling shift in micropaleontology occurred in the seventies and eighties with the advent of intensive scientific ocean drilling programmes and availability of new instrumentation and analytical techniques to study microfossils. In addition, efforts to evolve multiple microfossil biostratigraphies and their integration with other fields such as magnetostratigraphy, stable isotopic stratigraphy, carbonate stratigraphy, computer application and more recently with molecular biology opened up multifaceted approach to micropaleontological research. This was indeed another important milestone in the history of development of micropaleontology. This led to a qualitative change in research emphasis in the areas of correlation, paleobiogeography, plankton evolution, paleoclimatology and paved way for new research areas like paleoceanography and molecular micropaleontology. Of late, microfossils have emerged as a very powerful and reliable tool to trace past variations in monsoon and to characterize tsunamigenic sediments. Thus, the subject of micropaleontology is becoming more and more important branch of Earth System Science for finding solutions to contemporary issues and that its future is indeed very bright.

[**Key words**: Paleontology, morphology, molecular studies, foraminifera, DSDP]

Introduction

The last four decades have experienced dramatic expansion in the scope of Earth Science, particularly in exploring oceanic depths, atmosphere, cryosphere and remote Precambrian lithosphere. Micropaleontology played a very powerful role in development of these and other new fields. The microscopic size, abundant occurrence, wide geographic distribution in sediments of all ages and almost all environments rendered microfossils very useful in solving geologic problems.

The rapid development of micropaleontology, particularly during the last few decades owes much to the Deep Sea Drilling Programme (DSDP) which enabled to recover undisturbed deep sea sequences by advanced coring technology and other technological advances. Integration of micropaleontology with other allied fields resulted in pioneering findings. This resulted in the transformation of micropaleontology from mere descriptive to more interpretative science and opened up new and exciting areas of research in Earth Sciences. In this paper an attempt has been made to provide a glimpse of this changing scenario in the study of micropaleontology as we survey through the last 150 years or so.

I have divided this changing scenario into a number of milestones. Here, I would like to mention that these milestones are not necessarily in sequential order but somewhat overlapping as well. Also, I would like to point out that, though I have used the term *Micropaleontology* in the title of the paper, I would confine myself to oceanic micropaleontology, particularly foraminifera, which has fascinated me through all these years.

Phase I: Development prior to World War I

The birth of systematic micropaleontology appears to be in A.D. 1660, when Antonie van Leeuwenhoek carried out study of microfossils and foraminifera were the first group of microfossils to receive attention of early naturalists (Herodotus, 5th century B.C.; Strabo, 7th century B.C.). The other earliest micropaleontologists included Beccarius who described and illustrated microfossils from the

Pliocene marine sands of Bologna (Italy) and Janus Plancis, who published a monograph on the foraminifera of the shore sands of the Adriatic Sea. The binomial nomenclature introduced by Linne'[1], which is the basis for modern biological systematics, greatly simplified the problem of nomenclature, and was applied to some 15 species of foraminifera, providing generic and specific names to them.

By and large, micropaleontological studies during the middle of 19th century centered around the biological affinity of foraminifera and other microfossil groups. As micropaleontology during this period was still in its infancy, the subject of recent foraminifera was chosen by many for their study. Sea bottom samples collected by many expeditions such as H.M.S. *Challenger* Expedition (1884), the *Investigator* (1895), *Albatross* (1897), *Snellius* I Expedition (1920s), *Siboga* Expedition (1930, 1932), *Discovery* Reports (1933), the *John Murray* expedition, etc. provided material for the study of foraminifera. In addition, there are few accounts of the foraminifera of the Mauritius[2] and Gulf of Mannar[3,4]. Continued investigations on recent foraminifera led to many important contributions by Carpenter *et al*.[5] and Lister[6] including the discovery of microspheric and megalospheric test growth stages and information on their life histories.

The second half of the 19th century witnessed the classic study of German micropaleontologists Reuss, Schwager, Karrer, Stache and English workers which included N.C. Williamson, W.K. Parker, T.R. Jones, W.B. Carpenter, H.B. Brady, and C. D. Sherborne on foraminifera. Among these the most important descriptive studies was H.B. Brady's monumental monograph on Recent foraminifera recovered by H.M.S. *Challenger*[7]. Conrad Schwager, Felix Karrer and Guido Stache who studied Hochstetter's (1856) collection published full descriptions of several new fossil foraminiferal species in the *Novara* expedition report[8] in 1866. The fist comprehensive foraminiferal study in India was carried out by Schwager from the samples collected by Hochstetter from the Pliocene of Car Nicobar Island during the course of *Novara* expedition in 1856. These were later revised by Hornibrook[9] and Srinivasan & Sharma[10].

In contrast to Reuss and Schwager's work, the early British micropaleontologists regarded foraminifera to exhibit wide individual variation and, therefore, considered them unimportant for stratigraphic studies. Later workers however rejected this view. Contemporaneous with research on foraminifera, major studies on Radiolaria (Haeckel, 1862-1887) and on Ostracoda (Sars, 1866-1872) provide evidence to the intensive descriptive work in micropaleontology during this time. It is astonishing that after this vigorous beginning, except foraminifera, interest in the study of other microfossil groups got subdued and this trend continued well into the 20th century.

Phase II: Development after World War I (1920-1940)

A sudden and rapid expansion of exploration activities to discover new oil fields during the first world war, triggered the studies of microfossils once again as it proved to be reliable tool in oil exploration. This major cause revived the interest in micropaleontology and resulted in a dazzling change from descriptive studies on foraminiferal taxa to applied aspects of biostratigraphic correlation in search of more oil fields. As a result micropaleontology received a new impetus and noticeable trends have appeared in the early 1920's.

It is interesting to note that intensive search for petroleum in Southeast Asia by the Dutch oil companies in the early 1920's spurred interest in foraminiferal studies, particularly the larger foraminifera. Van der Vlerk & Umbgrove[11] based on biostratigraphic ranges of larger foraminifera first proposed the "**Letter Stage**" classification for the Tertiary sequences of the Indonesian Archipelago. These stages have been correlated by various workers with the subdivisions of the International Stratigraphic scale. The work of Van der Vlerk & Umbgrove[11] received wide acceptance in dating and correlating the Cenozoic marine sequences from the tropical Indo-Pacific region based on larger foraminifera. Thus, the Dutch micropaleontologists have the credit for initiating study of the larger foraminifera in great detail and for establishing them as a reliable tool for biostratigraphic zonation and correlation of oil wells. This indeed is an important milestone in the development of micropaleontology.

With the development of *Industrial micropaleontology* and swift discovery of new oil fields, the demand for more experts in micropaleontology increased. This led to the introduction of formal courses in micropaleontology as part of the curriculum in Earth Sciences. During the World War I (1914-1918) micropaleontology was introduced as a formal course by Jossia Bridge at the

Missouri School of Mines, by H.N. Coryell at Columbia University and by F.L. Whitney at the University of Texas.

The year 1924, however, marks an important milestone in the development of micropaleontology. J.J.Galloway and H.G. Schenck started teaching micropaleontology at Columbia University and Leland Stanford University respectively. In the same year J.A. Cushman established the Cushman Foundation for Foraminiferal Research at Sharon, affiliated to Harvard University. Formal courses in micropaleontology were initiated at the University of Chicago during 1928-1929 under Prof. C.G. Cronies. In 1928, the first edition of Cushman's **Foraminifera** appeared, followed by Galloway who published **Manual of Foraminifera** in 1933[12] and Glaessner's **Principles of Micropaleontology** appeared in 1941[13]. Another pioneer contributor to the advancement of stratigraphic and taxonomic micropaleontology, particularly in the Gulf Coast region was Helen J. Plummer, whose publications contributed much to the importance of micropaleontology.

Near the end of the 19th century MatajiroYokoyama initiated the study of micropaleontology in Japan. Through sincere efforts of his followers such as H. Yabe, Y. Ozawa, S. Hanzawa, Y. Otuka and K. Asano the status of micropaleontology was brought to its present level of excellence. Besides North America and Japan, Frederick Chapman, George Kreuzberg, Walter J. Parr and H. J. Finlay published large number of papers dealing with New Zealand foraminifera during twenties and thirties. H. J. Finlay, who is considered as father of New Zealand micropaleontology, emphasized the importance of foraminifera in stratigraphy, through a series of publications (1939-1947) entitled *"New Zealand Foraminifera: Key Species in Stratigraphy"*.

The classic studies by Kleinpell[14], Le Roy[15,16], and Glaessner[17] on Tertiary smaller benthic foraminifera disapproved the general assumption that the greater endemism and the same species receiving different names in different regions from different workers have made smaller benthic foraminifera less important in inter-regional correlation. Glaessener[17] listed 44 species of smaller benthic foraminifera recorded from more than one locality of the Indo-Pacific region and considered them as Miocene index. Thus during 1920^s and 30^s, interest in micropaleontology was focused on describing smaller benthic foraminifera and larger foraminifera mainly for the purpose of biostratigraphic zonation, age determination and correlation which were extensively utilized by Oil Companies.

Phase III: Development after World War II (1940-1960)

Detailed descriptive work on microfossils during the post war period led to affinities and morphogenetic studies and classificatory approach to a "Natural System". There have been many different family classifications proposed and these early classifications were primarily based on gross features of test morphology.

The classification proposed by Cushman[18] was widely accepted until 1950^s. His hypothetical families based on chamber arrangement gave very little consideration to phylogeny in his generic classification. From detailed investigations and enormous data on the sequence of microfossils, it is now clear that many foraminiferal genera are polyphyletic in origin. Hence, it was realized that if foraminiferal classification is to be a natural scheme, it has to take into account the detailed information on phylogeny and should avoid grouping together morphologically similar but phyletically different species in the same genus.

As a general rule, foraminiferal genera are distinguished by differences in aperture or internal structure or chambering, while size, shape and surface ornamentation and coiling changes are the main basis for differentiating species. In subsequent classifications, efforts were made to classify foraminifera based on several other criteria such as wall composition and microstructure, chamber arrangement, apertural modifications, life habits and habitats, ontogenic changes, and stratigraphic ranges. Attempts were also made in the fifties and sixties to classify foraminifera mainly based on tooth plates[19] and wall structure[20]. These approaches could not get wide acceptance due to difficulty in preparing thin sections of foraminifera and the influence of ecological factors on the nature of wall structures and preservation of tooth plates. A new approach to foraminiferal classification was proposed by King & Hare[21] based on amino acid composition of test of recent planktic foraminifera. The study revealed that each species has a distinct amino acid pattern that differs from other species. Somehow this approach also did not find much acceptance.

The biologic heterogeneity of the fossil groups included in micropaleontology does not permit a meaningful classification based on biological affinity. This has paved way to the grouping of microfossils based on test composition[22,23]. This has been more practical and utilitarian approach since it combines microfossil groups occurring together in different type of sediments and environments. This approach also highlights the close relationship between test composition, geochemical cycles of the oceanic realm as well as the processes operating in the lithosphere, hydrosphere, atmosphere, and cryosphere. Since the time of d'Orbigny, more than 8000 papers were published on foraminifera alone. According to Loeblich & Tappan[24] there are about 100 families, over 1200 genera and 3000 species of foraminifera described in the literature. The Catalogue of Ellis & Messina[25] lists most of these genera and species. These vast arrays of foraminiferal morphotypes are grouped into about 35 schemes of classification. The details of these classifications are discussed in Loeblich & Tappan[26].

In addition to classification, 1950s mark another important phase in the study of foraminifera. During this time there was a shift from employing foraminifera, primarily for biostratigraphic purpose to infer ecology and paleoecology. This is because more and more students took to this field as oil companies were looking for graduates with this background. Probably foremost of the important attributes possessed by the microfossils is their abundance in sedimentary rocks which makes them ideal for paleoecological studies.

Studies by Bandy and his team[27,28] on the distribution of recent benthic foraminifera resulted in a classic set of papers with general title "*Ecology and Paleoecology of some California Foraminifera*". Bandy's studies also dealt with the Cenozoic paleobathymetric histories of the Los Angeles and Ventura basin, clearly revealing the use of biofacies analysis in estimating rates of subsidence and sediment accumulation (Fig. 1). Bandy first utilized a form of cumulative frequency diagrams in these papers which are still commonly referred to as "BANDY-Grams" and which clearly demonstrated the usefulness of quantitative analysis of foraminiferal faunas.

Extensive studies on modern foraminiferal faunas clearly revealed general correlation of foraminiferal structure with environment. Landmark papers dealing with the evolution of concepts and methods in foraminiferal paleoecology appeared from the year 1950 onwards[27, 29-34].

Ellison[29] stressed the importance of quantitative study in micropaleontology to interpret depositional environments. Curtis[35] was able to work out four bathymetric zones to interpret oscillation in water depth, based principally on the inverse frequency relationship of two most common species in a vertical sequence. The significance of foraminiferal test morphology in paleoecological interpretation was also highlighted through a series of contributions by Bandy & Arnal[27], Hendrix[31], Berger[34], and Frerichs[36]. Hendrix[31] correlated morphologic features with sediment type distinguishing between heavy strongly ornamented forms in massive sediments and thinner less ornamented forms in laminated sediments. Frerichs[36] related certain morphologic characters such as keels and accessory apertures to extinctions and radiations concluding that these two may be related to temperatures. Clark & Bird[37] applied frequency distributions of generic and family group whose modern environments are known for supplementing data with other quantitative measures such as benthic/planktic and arenaceous/non arenaceous ratios.

Berger[34] designed a theoretical approach to the morphology-environment problems by use of computer generated models. He demonstrated that the chamber ratio (Ratio between successive chamber radii) is a prime variable related to many morphological measurements. It is an easily measured parameter which could be used in defining separate paleoecological groups. Further, the transfer function method developed by Imbrie & Kipp[38] and based on factor analytical approach is now widely used for several Late Cenozoic microfossil groups. Gevirtz *et al.*[39] demonstrated how to apply cluster analysis of distribution of dead organisms for recognition of biofacies and identification of relict faunas.

In recent years morphometric analysis of microfossils has gained importance by the development of image analysis techniques, which are being increasingly automated. The morphometric procedure of Lohman[40] specially offers much promise for shape analysis of microfossil populations. Application of image analysis techniques has just begun and promises to be one of the exciting areas for future study in micropaleontology.

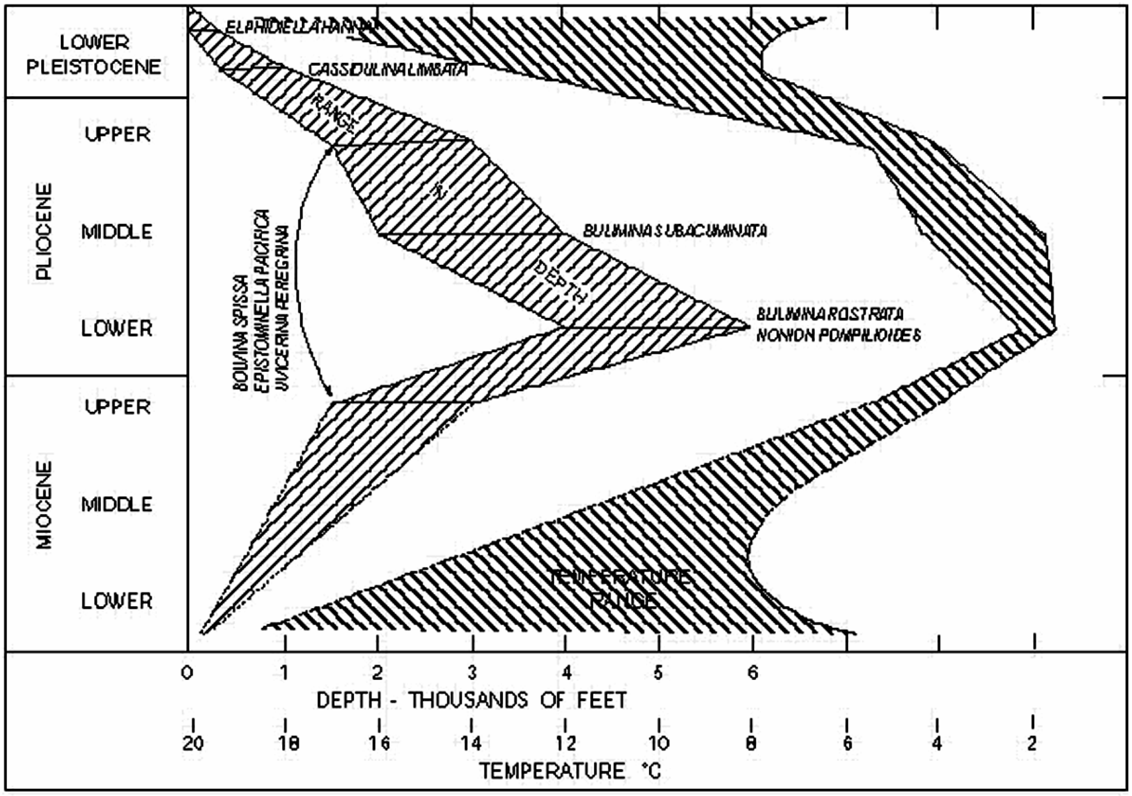

Fig. 1—Depth-temperature variation during the later Cenozoic in the Ventura basin (modified after Bandy[27]).

Another useful study is by Nigam and his coworkers[41,42] who highlighted the importance of benthic foraminifera as pollution indicators. Their studies also demonstrated how the proloculous size variation in recent benthic foraminifera can be used for paleoclimatic studies. Thus, with the growing interest to reconstruct paleoenvironment at finer resolution, the need for assessment of the quality of micropaleontological data was also emphasized.

In addition to papers dealing with distribution and environmental significance of both modern and fossil benthic foraminifera, Bandy and his coworkers[27,28] published several papers illustrating the use of planktic foraminifera for paleoclimatic and paleoceanographic analyses, a subject which assumed great importance in eighties. Almost all the studies on ecology and paleocology emphasized the intimate relationship of fossils and sediments and continue to remind us of the importance of basing an interpretation on multiple criteria.

Phase IV: Development due to technological advancements (1960-1980)

Increasing demand of fossil fuel by the industrially advanced nations since late fifties and sixties prompted to undertake vigorous search for hydrocarbons in the deep sea regions. Further, realization of the immense importance of planktic foraminifera in hydrocarbon exploration of deep water basins attracted the attention of large number of micropaleontologists to take up this study. As a result, late fifties and sixties witnessed great emphasis in planktic foraminiferal research. Several important publications on stratigraphic and systematics of Tertiary planktic foraminifera by Bolli[43], Blow[44] and Parker[45] highlighted their use in long distance correlation.

Another important milestone in the history of development of micropaleontology is marked by the advent of Deep Sea Drilling Programme (DSDP) in 1968. Deep Sea Drilling and its successor Ocean Drilling Programme (ODP) employed micropaleontology extensively in the study of deep sea marine sequences. As a result, much new data came to light on stratigraphic ranges, geographic distribution and plankton evolution. Examination of large number of DSDP and ODP cores from wide ranging latitudes resulted in several new workable zonations for planktic foraminifera, calcareous nannofossils, radiolarians and diatoms. The present knowledge on the zonation of these groups that have been established is largely based on deep sea cores. These zonal schemes also enabled to refine the zonations proposed earlier on uplifted marine sequences such as Mediterranean Stratotype sections, Caribbean and Andaman-Nicobar Islands.

Several extensive reviews based on DSDP data have been published, specially on Neogene planktic foraminifera, providing better understanding of their evolution and oceanic biostratigraphy[46-57]. In addition, micropaleontological studies were also concerned with;

i. Variation in the temporal and spatial distribution and abundance of water mass related planktic foraminifera in order to get a better insight into the oceanographic changes in the upper part of the ocean water column.

ii. Variation in temporal and spatial distribution and abundance of benthic foraminifera and tracing the pathways of vigorous bottom water currents, and the resulting deep sea hiatuses especially during the Late Cenozoic. These studies provided better understanding of the bottom water productivity and rate of organic input to the sea floor.

Another intriguing result based on the studies on the distribution of recent deep sea benthic foraminifera is that their distribution is not static as previously believed, but, appears to be controlled more by the nature and distribution of bottom water masses[58,59]. Further, the distribution of modern deep sea benthic foraminifera enables to identify the areas of least effect of bottom water currents and minimum sediment accumulation. Such sites are ideal for locating the submarine nuclear installations. In addition, recognition of pathways of vigorous bottom water current is important as one can monitor the impact of nuclear wastes dumped in the oceans by the advanced nations. Thus, by the end of eighties, the DSDP and ODP publications brought out enormous data on marine microfossil distribution in space and time for world oceans. To utilize these enormous multidimensional data-sets for further synthesis, there is a need for global or regional data base. As suggested by Saraswati[60] it is right time that we in India take initiative to create a micropaleontological data base (on net based data base) which would stimulate young researchers to look for new areas of research in micropaleontology.

Continued innovations in oceanic biostratigraphy led to the recognition of datum level concept using first and last appearances and coiling changes in planktic foraminifera for precise correlation of DSDP sequences[61-63].Another problem encountered during the course of study was difficulties while attempting to correlate Neogene planktic foraminiferal datums in the Indian Ocean with the datum planes recorded from the Pacific and Atlantic. This difficulty was due to the selective distribution of some zonal markers with thin test below the lysocline. Berger[64] proposed a solution susceptibility ranking of modern planktic foraminifera on the basis of laboratory as well as field experiments. Taking clue from this study, Jenkins & Orr[65] proposed a new zonal scheme, for the Cenozoic of the tropical eastern equatorial Pacific, based on the solution resistant planktic foraminiferal species to define zonal boundaries. Further, examination of large number of deep sea cores from wide ranging latitudes resulted in modifications to Blow's[66] N-zonal scheme (see Fig. 2). It was realized that major evolutionary lineages in tropical and temperate areas are sufficiently different to require maintenance of separate zonal schemes. An overview of the history of tropical/mid and high latitude (temperate and transitional) Neogene biostratigraphy is provided by Srinivasan[67].

During the Late 70^{s} and 80^{s} there has been considerable debate amongst micropaleontologists regarding the nature of evolution, e.g., punctuated equilibrium vs. phyletic gradualism. While most studies revealed evidences of phyletic gradualism, the evolution of *Globoconella* clade showed both phyletic gradualism and punctuated equilibrium[68]. Perhaps the most significant finding from the study of DSDP cores is that almost all evolution of calcareous planktic microfossils occurred outside the Antarctic and sub-Antarctic regions. Some lineages began in temperate areas and later abandoned these areas for the tropics. In contrast, marked and widespread evolution occurred within siliceous microfossils in the Southern Ocean during the Neogene[53,54].

Concomitant with the beginning of the DSDP was the advent of Scanning Electron Microscope (SEM) for the study of microscopic objects. As a result a new trend emerged in the seventies from morphological studies of microfossils to minute surface ultrastructural studies providing new insight into the systematics, phylogeny, phenotypic variation, taphonomy and paleoenvironmental reconstructions.

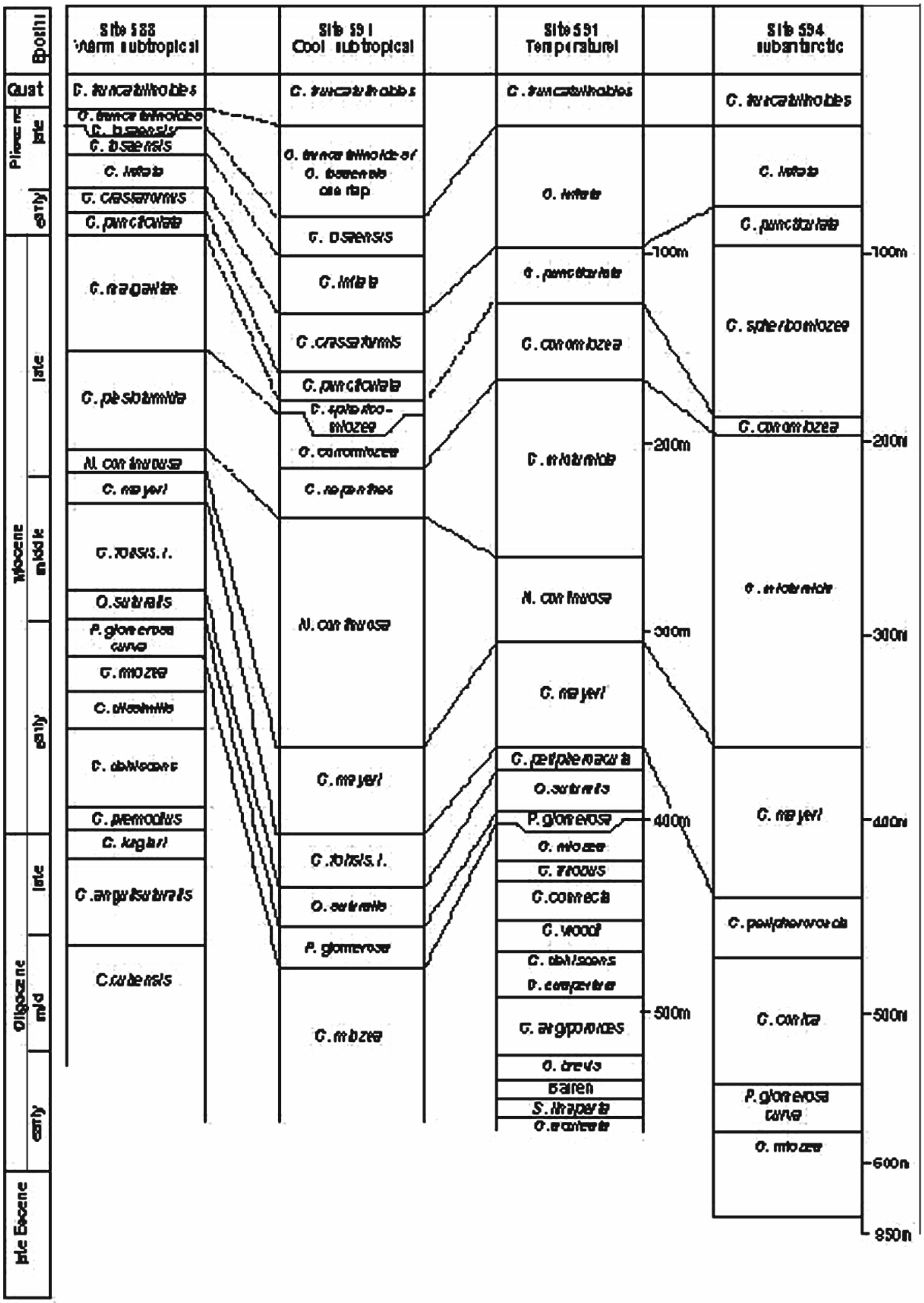

Fig. 2—Four planktic foraminiferal zonal schemes used for Leg 90 DSDP sites with datums used for intersite correlation (modified after Jenkins & Srinivasan[122]).

Several special publications which appeared in the late seventies and early eighties reflect this new trend in micropaleontology. Another important observation made as a result of SEM studies of planktic foraminifera was the ultrastructures change consistently with changing latitudes and reflect a close link with water masses[69,70]. Thus, the combined impetus provided by the advent of Deep Sea Drilling Project and application of scanning electron microscope, the oceanic micropaleontology expanded greatly during the seventies, making another important milestone in the changing face of micropaleontology (Fig. 3).

Phase V: Development due to Integration with allied disciplines (1980- to present)

One of the most important milestones in the changing face of oceanic micropaleontology in the eighties is the birth of a new discipline in Earth System Science- **Paleoceanography**. It is the youngest branch of Earth Sciences largely born of the Deep Sea Drilling Project and continues to be nourished by it.

The eighties also witnessed the development of multiple microfossil approach to micropaleontologic research. The abundance and well preserved calcareous and siliceous microfossils and the relative completeness of the stratigraphic record in the deep sea cores render these organisms ideal for establishing multiple microfossil biostratigraphies. The inconsistency in the distribution and abundance of any single microfossil group throughout the studied section reveal the need for employing multiple microfossil approach. The study conducted so far reveal that various microfossil groups serve as complimentary to each other for attaining enhanced biostratigraphic resolution[71]. It is expected that examination of large number of DSDP and ODP cores rich in diverse microfossil groups will offer an opportunity to employ multiple microfossil approach and could open many new fields of enquiry in micropaleontological research.

Another unique development that occurred as a result of examination of continuous coring facilitated to record geomagnetic reversal history of these cores. Successful integration of multiple microfossil

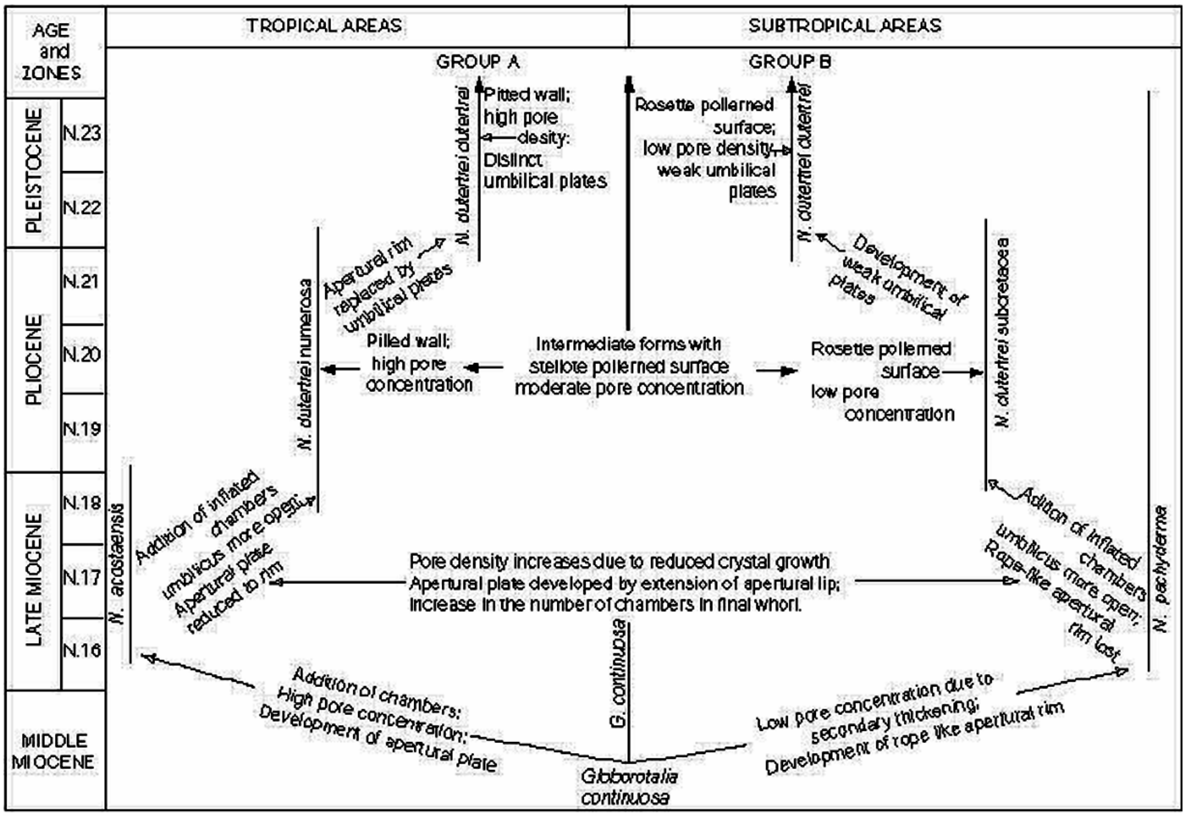

Fig. 3—Suggested evolutionary phenotypic relationship in the Late Cenozoic *Neogloboquadrina dutertrei* plexux (modified after Srinivasan & Kennett[123]).

biostratigraphies with paleomagnetic stratigraphies and radiometric ages provided correlation of calcareous and siliceous microfossil zones with increasing accuracy[72-75]. Thus, the oceanic micropaleontological research moved into interdisciplinary phase. Numerous high resolution biostratigraphies integrated with magnetic reversal events and radiometric dates have been generated that has led to improved age assignments of Cenozoic Epoch boundaries (Figs.4, 5).

Another important trend that emerged as a result of the study of the DSDP sequences is the application of quantitative techniques in biostratigraphic correlation. Although the basic ground work was laid in sixties[76] it

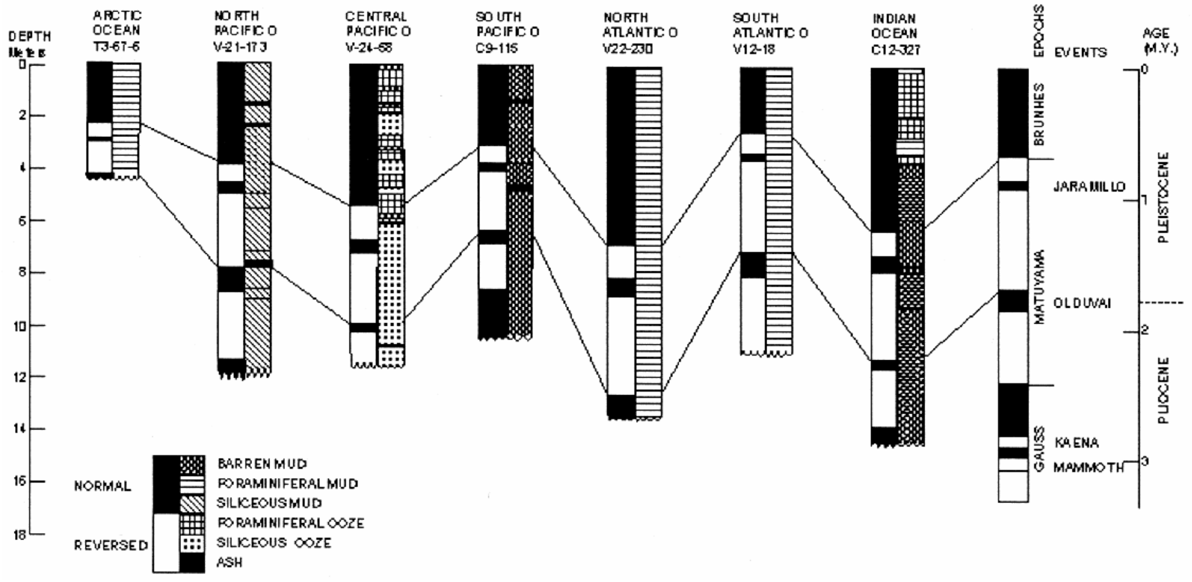

Fig. 4—Paleomagnetic correlation of cores from the Arctic, Pacific, Indian, and Atlantic Oceans, all of which contain different fossil assemblages and have varying lithologies.

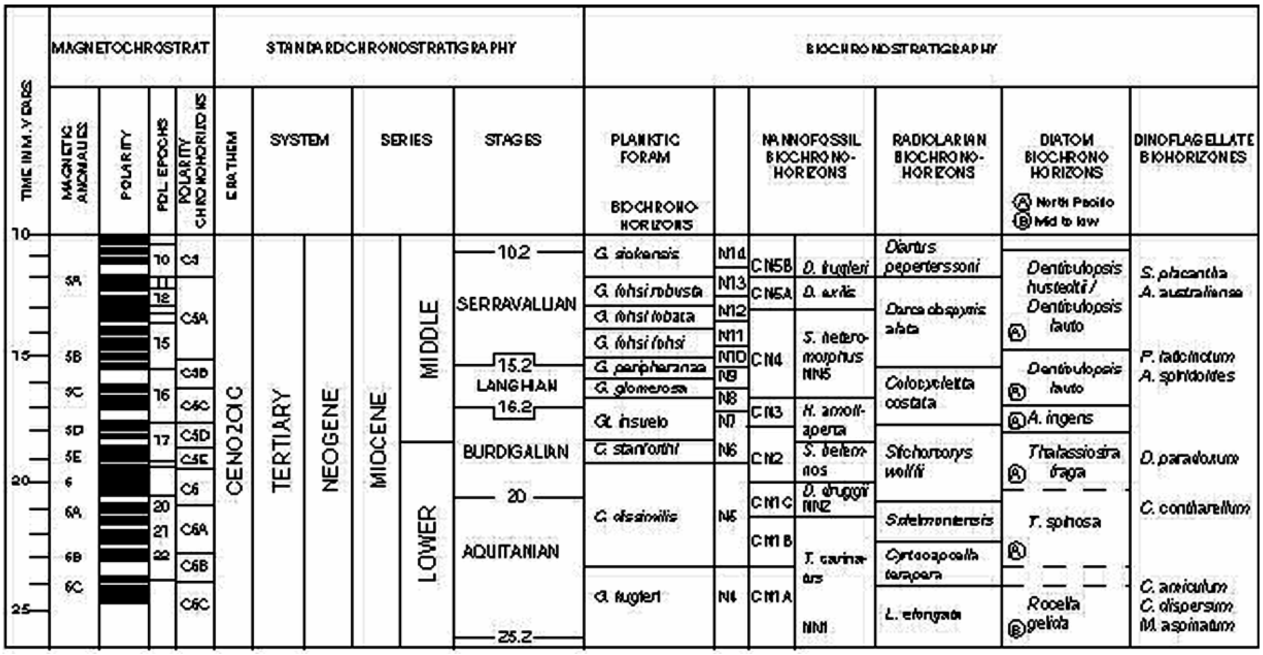

Fig. 5—Early to middle Miocene multiple microfossil biostratigraphies integrated with magnetoradiochronology (modified after Srinivasan[67]).

was only in the late eighties and nineties the importance of quantitative correlation techniques- the Graphic Correlation method and the potential of deep sea cores for such study was realized[77,78]. This method enables us to identify synchroneity and diachroneity of microfossil datums and to determine the seat of evolution and path of migration of oceanic microfossils through the Cenozoic.

Eighties also witnessed a number of paleobiogeographically oriented researches on the DSDP cores which provided important clues with regard to the plankton evolution and Paleoceano-graphy (Fig. 6).

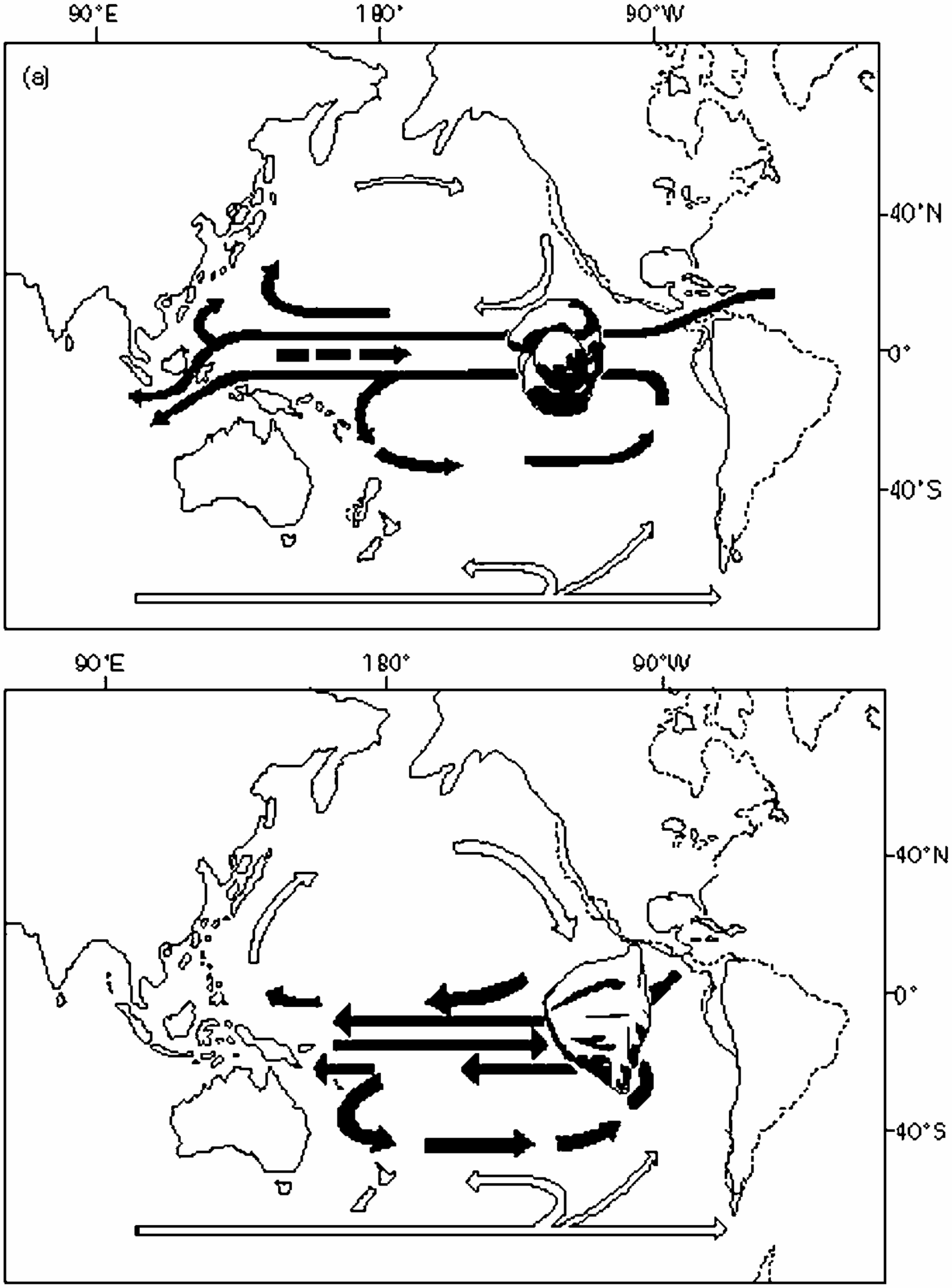

Fig. 6—Tropical surface circulation in the Pacific (a) during Late Miocene (6.4 to 5.6 Ma) based on biogeographic distribution of *Pulleniatins primalis* and (b) during Early Pliocene (5.6 to 4.2 Ma) based on biogeographic distribution of *Pulleniatina spectabilis* (modified after Srinivasan & Sinha[80]). Black arrows represent warm ocean current and white arrows represent cold ocean current.

Extensive paleobiogeographic studies carried out on DSDP cores from the Southwest Pacific and high latitudes of the southern hemisphere indicated that certain taxa such as *Jenkinsina samwelli*, *Pulleniatina spectabilis* etc. provide definite clues regarding the initiation of Circum Antarctic circulation and closing and opening of ocean gateways and the resultant changes in ocean circulation during the Cenozoic[50,79,80].

A revolutionary trend emerged in oceanic micropaleontology in the late seventies and eighties with the application of stable isotopes in microfossils and their significance. This led to the development of stable isotope stratigraphy, a stratigraphy which we owe mainly to the contributions of Shackleton & Kennett[81] and Douglas & Savin[82]. Most of the papers published in the eighties and nineties employing stable isotopes of calcareous microfossils have in someway or other directed towards understanding the thermal gradients of the ocean, vertical water mass differentiation, depth stratification of foraminifera and paleoceanographic reconstructions during the Cenozoic[79, 83-87].One of the most useful applications of stable isotopes in micropaleontology has been to evaluate the synchroneity of microfossil datums[88]. In addition, the stable isotopes of oxygen in

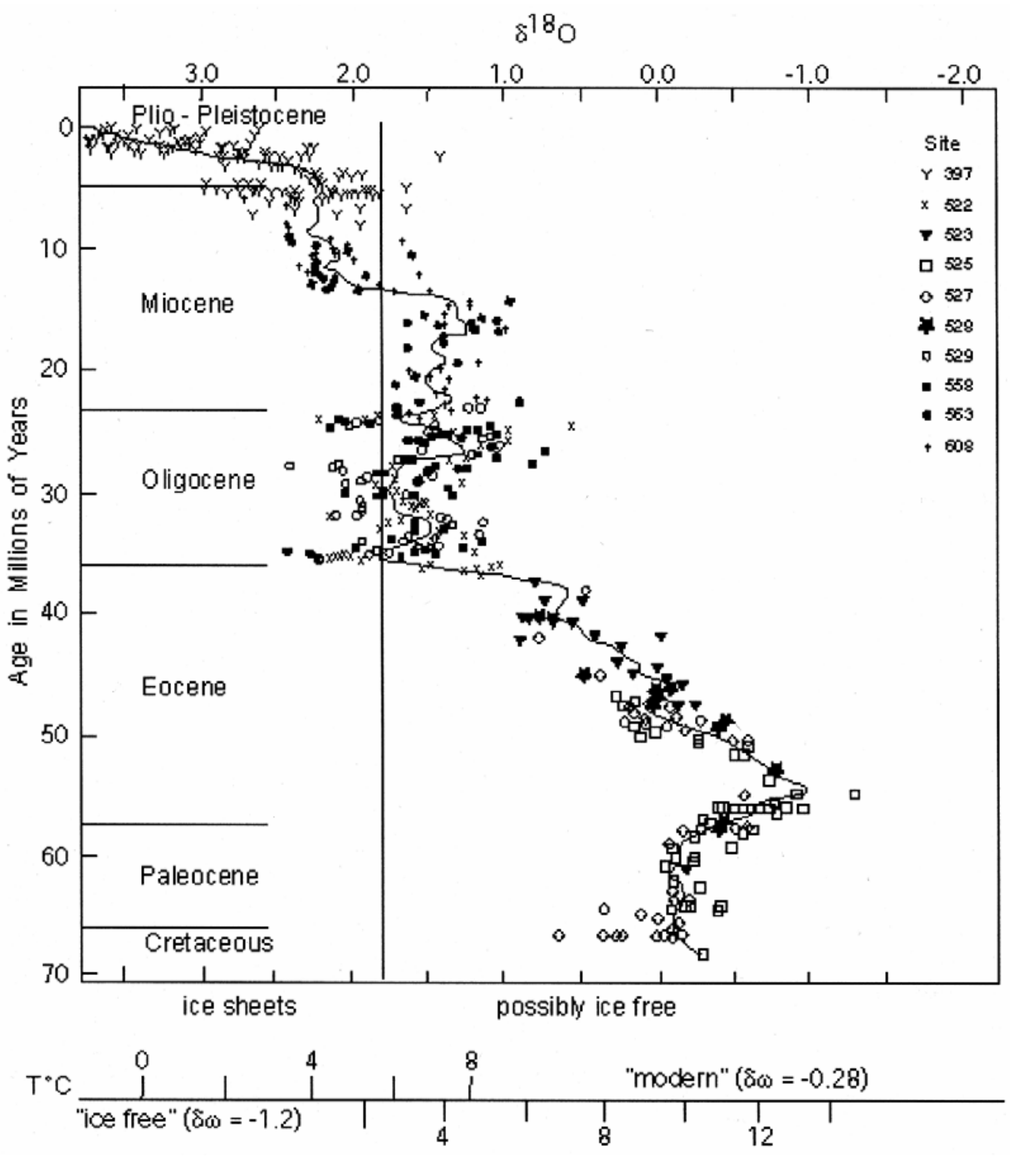

Fig. 7—Composite benthic foraminiferal oxygen isotope record for the Atlantic DSDP sites (modified after Miller *et al.*[89]). Note progressive general cooling since the Eocene.

foraminiferal and nannofossil tests provide a good quantitative indication of global climate change[89]. Thus stable isotopic studies in micropaleontology contributed significantly to the global climate change programme (Fig. 7).

The behavior of carbon isotopes on the other hand is less well understood as compared to oxygen isotopes. The carbon isotopes measured in the tests of benthic foraminifera provide a history of deep water circulation changes and large scale variations in the cycling of carbon between the atmosphere, biosphere and oceans. Besides the oxygen and carbon isotopes, strontium isotopes have recently been used as additional tool to improve stratigraphic correlation between deep sea sequences and the marginal marine sequences and the dating of transgressive and regressive cycles on continental margins.

In a pioneering study, Beets[90] demonstrated the Late Cenozoic Cenozoic Sr- isotope variations in sediments recorded at ODP Leg 117 in the western Arabian Sea, Indian Ocean. This 13 Ma long record which has been calibrated with biostratigraphy and magnetostratigraphy displays a stepwise increase of the Sr-isotope ratio consisting of an alternation of periods with a steep increase and periods with no increase (Fig. 8). Interestingly, a similar increasing trend in $\delta^{18}O$ was recorded during the Late Cenozoic by Miller *et al*[89].

Another chemostratigraphic approach has been the use of Cadmium/Calcium ratios in benthic foraminifera for paleoceanographic interpretations. Recent efforts by Raja *et al.*[90] to study magnesium and strontium composition of Recent symbiotic bearing benthic foraminifera is an important step in this direction. These studies are still in their infancy and need to be established firmly. The relationship between marine geochemistry and micropaleontology is another unexplored field of research especially pertaining to the area of carbonate and silica dissolution. Future research programmes should be

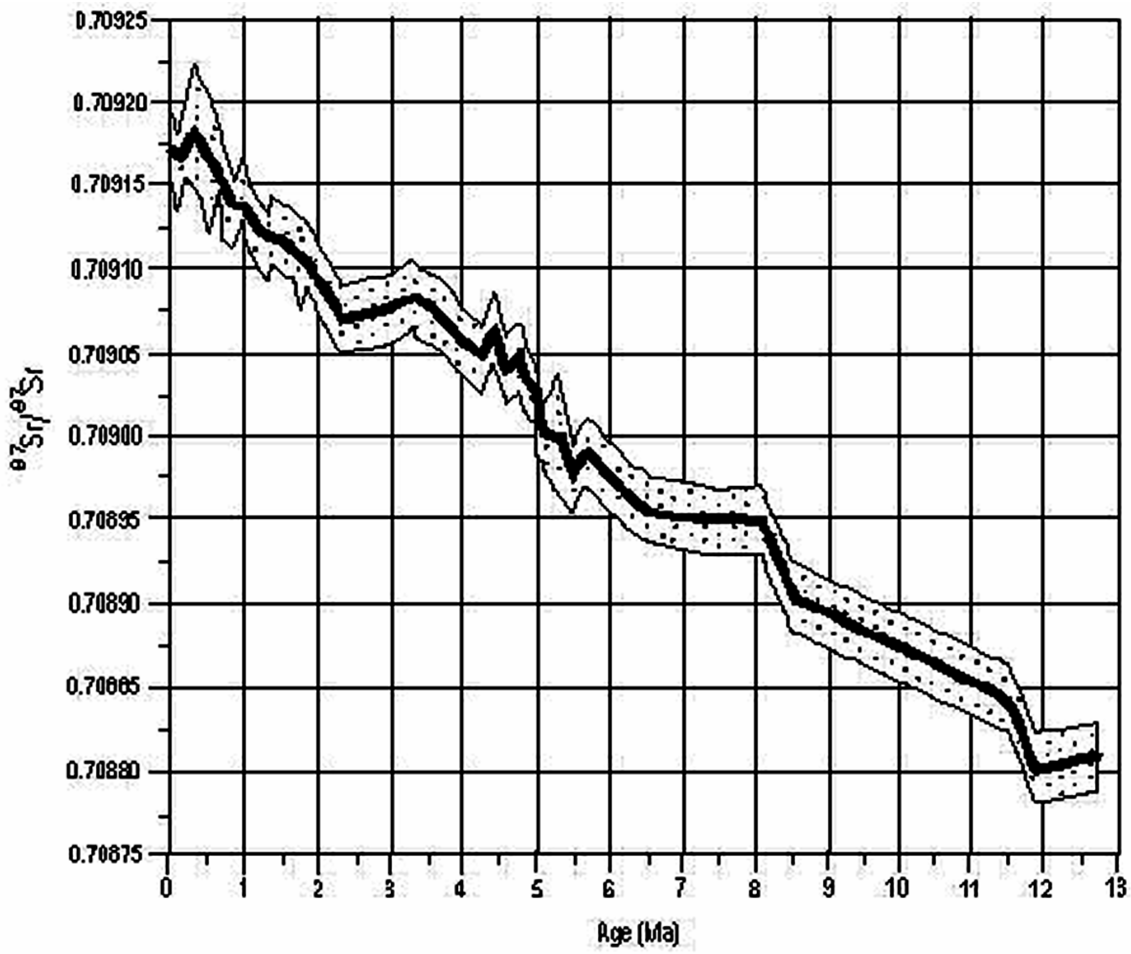

Fig. 8—Western Arabian Sea calibrated Sr isotope curve compiled from the data measured by Beets[90].

focused on more refinements in the documentation of Sr-isotope variations in the paleo-ocean. Further, variations among the different stable isotopic trends, such as oxygen, carbon, strontium, etc. during the Late Cenozoic have to be inter- calibrated in order to gain a better understanding of the chemical evolution of the oceans.

Although the oceans cover more than 70% of the Earth's surface, information on marine biodiversity patterns is far from satisfactory, compared to that of the terrestrial biodiversities. A large scale survey of the marine biodiversity in different oceanic environments has revealed world wide consistency, despite obvious differences in environmental conditions of the various oceanographic regimes. In general, there is an increase in marine biodiversity during the Cenozoic and more strikingly with the beginning of the Neogene (Fig. 9). Studies conducted so far on factors controlling temporal fluctuations in plankton diversity, rates of evolution, and extinction reveal that evolutionary acceleration of planktic foraminifera are coincident with major global oceanographic changes[92]. Interestingly species diversity and rates of evolution among calcareous plankton also show a positive correlation with the $^{18}O/^{16}O$ paleotemperature curve, suggesting that the climate is one of the primary factors influencing the evolution of plankton[93-95].

The marked Late Cenozoic radiation and diversification recorded in marine plankton resulted into the modern planktic and benthic assemblages[55]. Post-extinction recovery, fundamental changes in

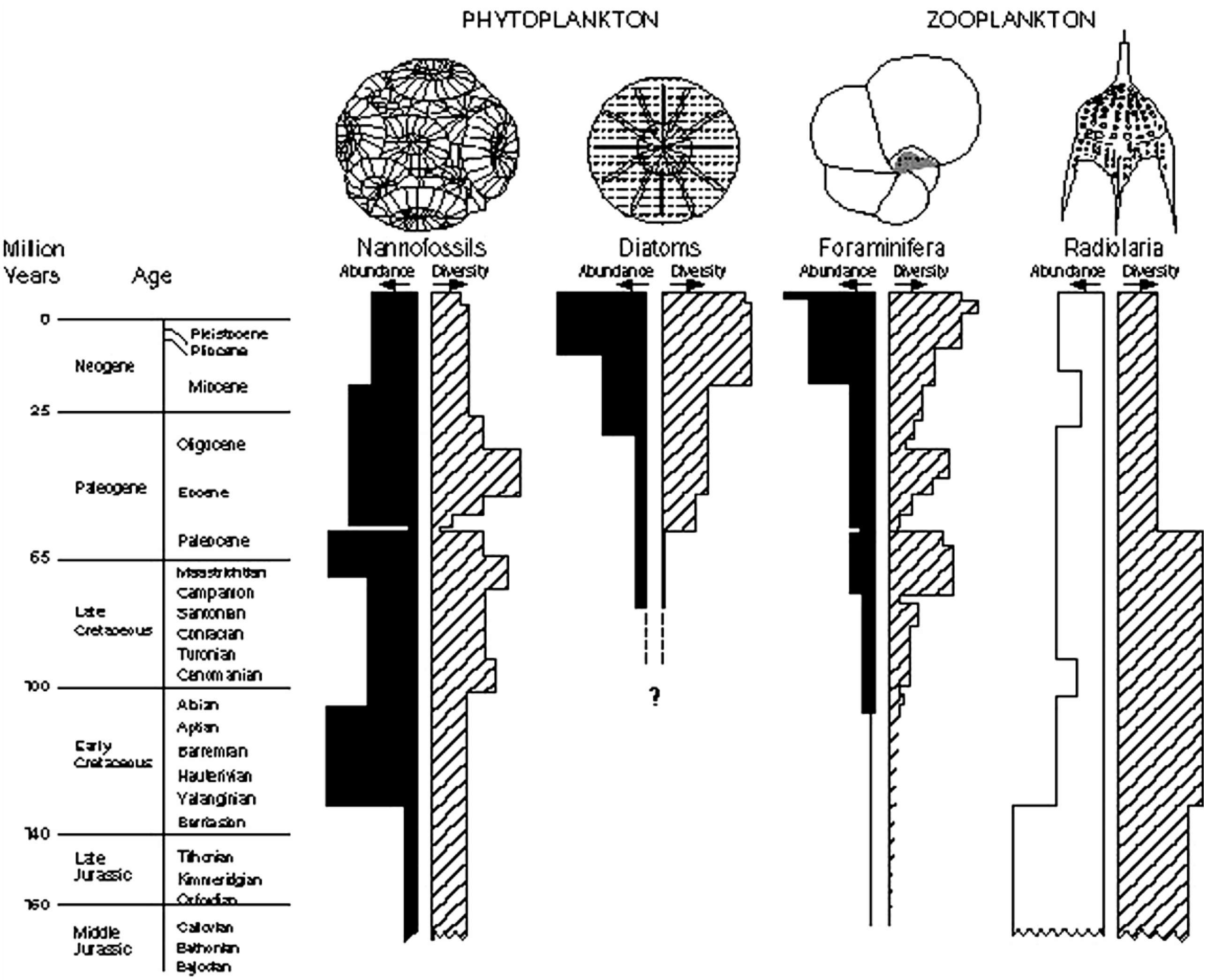

Fig. 9—Geological time scale with generalized abundance and taxonomic diversity of major skeletonized marine plankton groups (plants and animals) normalized to known maxima in each group. Compiled from various resources (after COSOD II, 1987).

ocean circulation, provincialization, and changing nutrient regimes appear to have contributed to this remarkable microfaunal turnover. The relative effects of these and other oceanographic processes need to be studied in detail for a better understanding of the modern marine biodiversity. Marine biodiversity in space and time is still an unexplored area of research. Such studies are crucial as biodiversity issues may shape the future of global exploration for the oil and gas industry.

Though, various approaches have been devised to interpret climatic changes in the past, foraminifera by virtue of their minute unicellular body with hard calcareous or siliceous test, offer an excellent and reliable tool for paleoclimatic reconstructions. For such studies, the most conventional methods adopted include variation in foraminiferal abundance, benthic/planktic ratio, changes in coiling directions, chemical composition, isotopic variations etc. In recent years attempts were made to confirm many of these above traditional methods through culture experiments[96], but there have been only limited success in this direction.

Of late microfossils have emerged as very powerful and reliable tool to trace the evolution and variability of the Asian monsoon[97-101], Extensive studies on the paleobiogeography of Neogene planktic foraminifera[80] and their isotopic depth stratification revealed that evolution of Asian monsoon occurred at about 11-12 Ma, and its intensity increased during 8.5 Ma and 5 Ma with weaker intensities from 5 Ma to 2 Ma. Recent studies have shown that there is a positive link between major upheavals of Himalaya including the Tibetan Plateau, effective closure of Indonesian Seaway and increase in the strength of the Asian monsoon[102,103].

Nigam & Khare[98, 104] in an interesting study developed a technique which utilizes the morphogroups of benthic foraminifera as tracers of paleomonsoon (Fig. 10). Further, Nigam & Sarkar[41] observed that mean proloculus size have significant inverse relationship with temperature and salinity and this can be used as a tool to study paleomonsoonal precipitations. Further important advances have been made in demonstrating relationship between monsoon upwelling and test size variations in some planktic foraminifera through the last 19000 years B.P. from the Oman margin, Arabian Sea[99] (Fig.11).

In India, efforts have been made during the last few years to establish foraminiferal culture programme by Nigam and his co-workers. As pointed out by Nigam *et al.*[105] foraminiferal culture programme renders another opportunity to attempt molecular systematic analysis of foraminifera, which is the latest approach to assess climatic changes and some taxonomic problems[106,107]. Out of several approaches to study the so called “Global Warming”, foraminifera have been extensively used for deciphering climatic changes (cooling/warming), transgressive and regressive cycles, accelerated sea level changes, rate of erosion and accumulation , changes in monsoon patterns, upwelling, frequency of cyclonic storms, tsunamis etc., which are the topics of contemporary relevance. Although foraminifera are widely used in paleoecologic and paleoceanographic reconstructions, relatively little is known about their life history and growth rates. An understanding of factors influencing growth in microfossils is of crucial importance in the micropaleontologist’s efforts to paleoecologic interpretations.

It was Adshead[108] who first attempted to study living planktic foraminifera in culture and later she presented a detailed description of pseudopodia variability and behavior of globigerinids during their

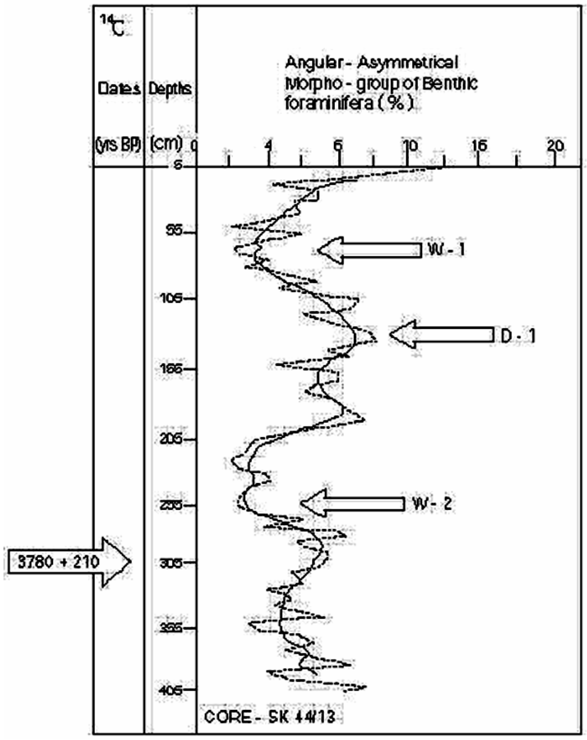

Fig. 10—Percentage distribution of angular-assymetrical form of benthic foraminifera in core SK 44/13 and paleoclimatic reconstructions. D= Dry Period; W= Wet Period (mdified after Nigam & Khare[104]).

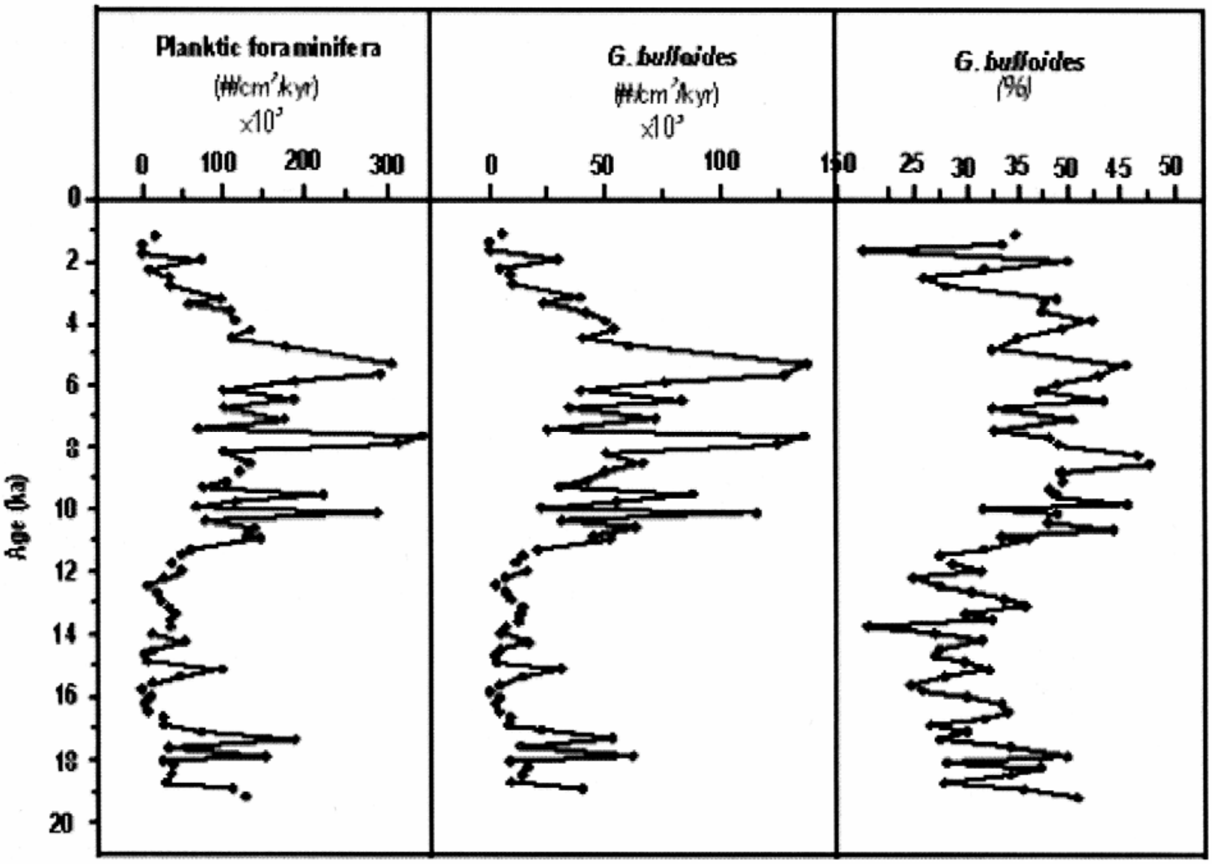

Fig. 11—Mass accumulation rates of total planktic foraminifera and *G. bulloides*, and relative abundance of *G. bulloides* through the last 19 Kyr at ODP site 723A which are used as indices of upwelling (modified after Naidu & Malmgren[99]).

existence in cultures. Another admirable contribution on culture of planktic foraminifera is that of Bé & Anderson[109] who described gametogenesis in *Hastegerina pelagica*. So far no serious attempt has been made to culture deep sea benthic foraminifera, even though culturing of planktic and some shallow water benthic foraminifera has been carried out intermittently since the pioneering work of Adshead[110] and Bé & Anderson[109] in the sixties and seventies. Recent studies reveal that culturing of deep sea benthic foraminifera in the laboratory is possible and the taxa can be maintained at least for few months. Morphological studies suggest that phenotypic variation is related to environmental factors and that taxonomy is a function of test ultrastructure and biomineralization. The general potential of morphological research in paleoecology-paleoceanography is high and there is much scope in the years ahead to explore this field of research through culturing foraminifera under laboratory conditions.

Another exciting area which offers great promise for future studies is the coincidence of microfaunal extinctions and radiation events with microtektite horizons and magnetic reversal changes (Fig. 12). These studies would enable us to gain a better understanding of the effect of extraterrestrial impacts on earth's process[111,112].

In the nineties there has been growing awareness to understand better the ocean atmosphere interaction processes and their role in controlling Earth's climate. Such interaction can be understood to a great extent by studying modern particulate flux in the ocean employing sediment trap techniques. Thus, the studies pertaining to the quality and quantity of particulate matter down to the floor of the modern ocean have been intensified in the last few years under the JGOFS project. Detailed planktic foraminiferal studies with total particulate flux carried out on sediment trap from the Bay of Bengal provided important clues to the relationship between monsoon intensity, planktic foraminiferal abundance, particulate flux and biogeochemical parameters of ocean water[113].

An important contribution made through sediment trap study is regarding the life span of planktic foraminifera. Nigam *et al.*[114] on the basis of sediment trap study, postulated that, in general, the life spans of planktic foraminiferal species are of the order of few months instead of few days or few weeks as reported by earlier workers. In addition, the data generated by the sediment trap studies can provide a basic frame work for reconstructing Pleistocene–Holocene oceanographic and climatic changes based on short term variations in biogeochemical flux. This innovative approach raises a number of intriguing issues such as linkages between *biocoenose, thanatocoenose* and the newly coined term *"sidocoenose"* (Fig. 13). The results obtained so far also seek to correct several prevailing misconceptions with regard to paleoenvironmental interpretations. The study also emphasizes on the need to rationalize the usage of the concept of Principle *of uniformitarianism* in understanding ongoing geological processes.

Another new area of study pertaining to global climate change, is *Nanogeoscience,* which deals with geological processes involving particles no larger than 100 nanometers. Such particles play crucial roles in carbon sequestration and pollution. *Nanogeoscience* will help in learning how oceans capture atmospheric carbon and how these are converted into biogenic carbonates in the form of nannoplankton and foraminiferal tests, a complex process that plays a key role in our understanding of climate change.

The latest trend in foraminiferal research is the molecular approach to its taxonomy and phylogeny[106,115,116]. Using ribosomal DNA sequence analyses, attempts are now being made to trace the phylogeny of foraminifera (molecular phylogeny). Developments in molecular biology in near future will have a significant impact on the study of microfossils as well. Efforts have already been made in molecular characterization of fossil forms. Currently there are two main problems in molecular characterization of microfossil materials: firstly, survival of molecules in fossil records and secondly, contamination due to exogenous molecules. Hence, search for well preserved microfossils for molecular study will require a better understanding of taphonomic processes. Therefore, deep freezing of core material for such studies should continue to be part of any

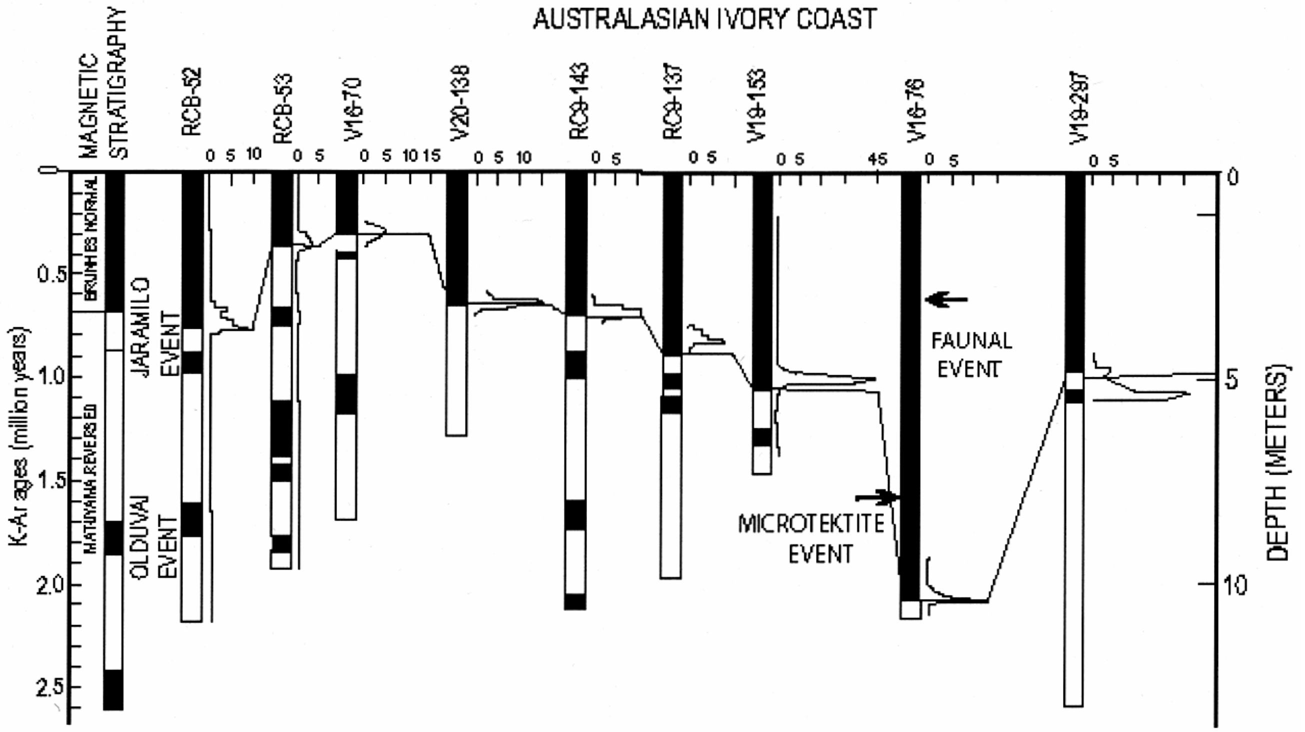

Fig. 12—Correlation of the microtektite horizons with magnetic reversal changes. The scale at the top right of each core indicates the number of microtektite per cm^3 of sample (modified after Gentner *et al*[124]).

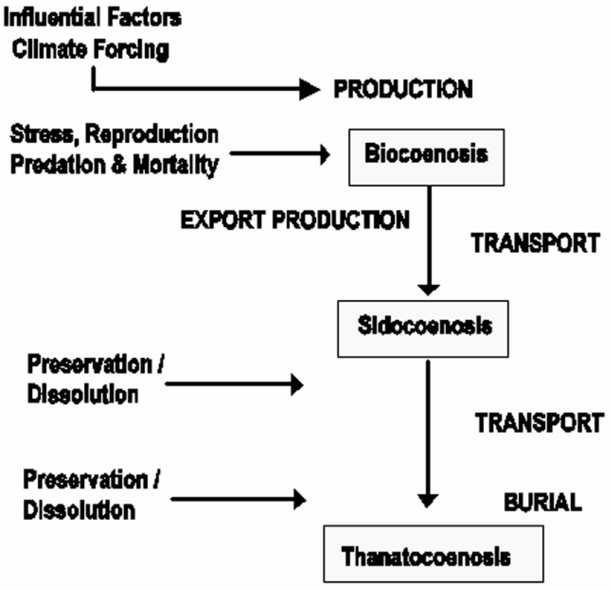

Fig. 13—Schematic illustration representing biocoenosis, sidocoenosis and thanatocoenosis and various processes associated with them in the oceanic environment (modified after Takahashi[125]).

future core curation. Hence any attempt to study molecular micropaleontology will require not only well preserved microfossils but also a better understanding of taphonomic processes. Further, the speculations that amino acids derived from fossil material could have formed during digenetic process and may not represent original protein need clarification[117].

According to Lindahl[118] fossil preservation in Amber is ideal as DNA is largely dehydrated and not exposed to microbial contamination. In an interesting finding De Salle *et al.*[119] reported DNA from 25 to 30 Ma old termite preserved in amber. The preservation potential of different types of biomolecules over geological periods has been the main focus of research in adopting molecular approach in micropaleontology.

With the development of Polymerase Chain Reaction (PCR) method in molecular biology, encouraging results have been obtained on molecular taxonomy of living foraminifera. The results have given better insights into the phylogenetic relationship between different groups of foraminifera. Further, researches on the DNA sequencing of recent foraminifera have revealed that origin of foraminifera dates back to Precambrian, and many even extend back a billion or more years[120]. Eventhough, molecular systematic analysis of foraminifera are yet to start intensively in India, a beginning has been made in this direction by Nigam and coworkers at the National Institute of Oceanography, Goa. Such studies utilizing mitochondrial DNA has been carried out for benthic foraminiferal species *Pararotalia nipponica* (Asano), using PCR technique[121]. The study opened up a new area for further research to get a better insight as to how climatic change triggers the genetic change responsible for reproduction and shaping of morphological characteristics.

Challenges for the future

The molecular micropaleontology is a growing and challenging field of research in the coming years. Joint efforts by molecular biologists and micropaleontologists on long term basis are needed to understand better the developmental genetics, behavioural genetics and immunogenetics to resolve some important issues, such as;

1. Cryptogenic appearances of certain species (eg. appearance of *Globorotalia kugleri* in the Late Oligocene)
2. Evolution of non-keeled form from keeled form and *vice-versa*
3. Development of kummer form chamber in certain species
4. Causes of evolutionary acceleration
5. Why larger foraminifera are large?
6. Limited paleobiogeographic distribution of some species within a short time span.
7. What caused certain taxa to survive even after great catastrophic events?
8. Role of DNA in bringing out dominant patterns of taxonomic and morphologic evolution following post - extinction recovery.

We are already in the beginning of the 21st century. What had happened during the last 150 years or so is simply remarkable. The rapid growth and fast development of micropaleontology, specially in the 1970s and 80s, owes much to accelerated sophistication in the methods of SEM and isotopic studies, spurred by the acquisition of undisturbed deep sea cores by advanced coring technology. The flexibility of the subject of micropaleontology to integrate with other allied fields led to new areas of research and brought out transformation from morphological micropaleontology to molecular micropaleontology in the 21th century. Micropaleontology is now a very broad and versatile field, continuously expanding its vistas in new dimensions.

The present generation of micropaleontologists in India through their strenuous efforts brought micropaleontological study in our country to its present level of excellence. It is not only one of the most actively pursued research subjects in India but also one which has made significant contributions in recent years to the Earth Sciences. These studies brought out a qualitative change in our understanding of the evolution of oceans, climate and marine biotic evolution through the Cenozoic.

The country possesses the institutional and human resource capabilities. These should be fine tuned to shift the focus to multifaceted research to address specific issues of contemporary relevance. The forgoing account is sufficient to highlight the fact that micropaleontology is becoming a more and more significant branch of Earth System Science and that its future is indeed bright.

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