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Review Article

Indian Contributions to Marine Micropaleontology (2010-2015)

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An overview of the research contributions made during the last five years by the Indian scientists in the field of marine micropaleontology is presented. Large scale micropaleontological studies employing assemblages of various microfossil groups (mainly foraminifera, pteropods, ostracodes and nannoplanktons) and their geochemical proxies have been carried out on deep sea sediment cores from the Indian Ocean. These integrated studies provided better insights to our understanding of past changes in surface and deep ocean circulations on different time scales and their relationships to seasonal variations of monsoon climate. It was observed that the foraminiferal abundances and diversity in the Arabian Sea are mainly driven by the variation in monsoonal intensity. Within the present day oxygen minimum zone (OMZ), benthic diversity increased during the cold stadials when the monsoon circulation was weak, the productivity was low resulting to a weak OMZ. The enhanced inflow of Antarctic Intermediate Water (AAIW) ventilated the deep water column during this period. In the southern Bay of Bengal, the contribution of southern ocean deep water increased during the last glacial maximum, as compared to the Holocene with greater influence of North Atlantic Deep Water (NADW). For the first time boron isotope-based pCO_2 of seawater was reconstructed from the eastern Arabian Sea. The results obtained have major implications in understanding the effect of monsoon on the efficiency of carbon pump in geological records. Numerous studies have reconstructed the variability of the Indian monsoon by using several parameters suggest a significant spatial variability of the Indian monsoon rainfall triggered by natural and anthropogenic perturbations over different time scales.

Keywords: Micropaleontology; Marine; Paleoceanography; Paleoclimate

Introduction

The remains of microscopic fauna and flora preserved in ocean floor sediments are excellent and reliable tracers of past changes in marine environment. Thus, ‘Marine Micropaleontology’ has led to the major advancement of paleoceanography in understanding various oceanographic processes in the geological past. Hence, this fast growing discipline of Geoscience has been playing crucial roles in unraveling the evolutionary history of global ocean basins; their past circulation, hydrographic, climatic and biotic patterns. Traditionally, the direction of marine micropaleontology research has mainly been of two folds: (i) investigating ecological control on modern biota in terms of their distribution patterns, growth and morphologic characteristics; correspondence between biocoenoses, thanatocoenoses and taphocoenoses and related processes in order to establish reliable tracers for past ocean conditions ; and (ii) paleoceanographic and paleoclimatic reconstructions using these tracers in fossil assemblages. Also micropaleontological biostratigraphy remains to be important for accomplishing a precise time-frame essential for global ocean and climate change studies including biologic evolution through time particularly for the periods older than the Pleistocene. Although, there is a major shift in emphasis from taxonomic studies to paleoceanography/paleoclimate, significant improvements have been made in recent years on taxonomic concepts of various microfossil taxa/groups, which is a fundamental requisite for micropaleontologic studies and better interpretations of fossil records. The

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important microfossil groups widely used in paleoceanographic/paleoclimatic reconstructions are foraminifera, nannoplanktons, pteropods, ostracodes and radiolaria and diatoms. A very significant recent development is the increased use of stable oxygen and carbon isotopes and elemental composition of foraminiferal tests in paleoceanographic reconstructions.

The Indian scientists keeping pace with recent development in analytical and field techniques have made significant contributions in diversified research aspects of marine micropaleontology during the last four-five years. The major contributions like previous years remain to be primarily based on foraminiferal studies. Nevertheless, comparable researches on other microfossil groups such as nannoplanktons, ostracodes and pteropods are accelerating.

Although, the northern Indian Ocean (mainly the Arabian Sea and the Bay of Bengal) continues to be the main area of Indian micropaleontological research, important contributions have also been made from other areas of world oceans, critical to better understand dynamics of global ocean and climate change. The participation of Indian scientific community in the major international programs such as Integrated Ocean Drilling Program now as International Ocean Discovery Program (IODP) and International Geosphere Biosphere Program (IGBP) has positioned Indian contributions in marine micropaleontology on par with international advancement in the field. During the last decade, increased attention is paid to the Quaternary records because of the necessity to gain better understanding of ocean- climate variability on high resolution scale, its dynamics and teleconnections in context to the current rapid change in global climate. Hence, a large number of studies were undertaken on relatively short gravity/piston cores retrieved from the Arabian Sea, Bay of Bengal and Andaman Sea and important contributions on monsoon climate and oceanographic variability on glacial/interglacial and also on millennial to centennial scales were made. Simultaneously, the Ocean Drilling Program (ODP) and IODP cores were also studied to obtain valuable information on longer time scale for the entire Neogene period and also on short time scale for the Quaternary.

In the present overview, significant contributions published during 2010-15 under the following topics are provided; and if by chance any omission of published work by any authors, which does not fall within the scope of this article should not be implied as ignorance and negligence of the authors.

Microfossils as Tracers of Past Ocean Environment and Climate: Ecology and Taxonomy of Modern Biota

The interest in micropaleontological research pertaining to modern test-forming organisms mainly foraminifera, ostracodes, nannoplanktons has continued in recent years, though at relatively low level, but with interesting results. Past climatic reconstruction relies on understanding the relationship between climatic/oceanographic parameters and distribution patterns and morphological characteristics of modern biota (living and dead) in water and surficial sediment.

Northern Indian Ocean

In recent years, some important pattern distribution studies of modern benthic foraminifera (Nisha and Singh, 2012; Mazumder and Nigam, 2014) and ostracodes (Baskar *et al.*, 2013, 2015; Sridhar *et al.*, 2015) in Indian coastal waters have been made. Nisha and Singh (2012) examined benthic foraminiferal assemblages from shelf-upper slope off central West Indian coast and identified four major biofacies with characteristic assemblages related to varied hydrographic conditions, nature of substrates and organic matter content across the continental margin. The benthic foraminiferal assemblage study in a core within the oxygen minimum zone off Goa enabled Bharti and Singh (2013) to discover a new species *Bulimina arabiensis*, which they suggested to be a useful paleoceanographic indicator particularly for the oxygen condition of bottom water within the OMZ. The distribution of benthic foraminifera in surface sediments also suggests characteristic benthic foraminifera for both the seasonal shallow water hypoxia (*Fursenkoina*) and perennial intermediate depth oxygen minimum zone (*Bolivina*, *Bulimina* and *Uvigerina*) of the Arabian Sea (Mazumder and Nigam, 2014). This information is extremely helpful to reconstruct past OMZ intensity and extent. *Asterorotalia trispinosa* dominated the shallow water low salinity regions of the Ayeyarwaddy Delta Shelf off Myanmar, suggesting that temporal changes in its abundance can be used to infer changes in monsoon intensity (Panchang and Nigam, 2014).

The field and laboratory culture studies were carried out to understand foraminiferal response to various physico-chemical parameters. Laboratory culture experiments on marginal marine benthic foraminifera suggest a wide range of salinity tolerance (20-35 psu) (Kurtarkar *et al.*, 2011; Saraswat *et al.*, 2015). The study also indicates that benthic foraminifera are adversely affected by changes in fresh water discharge (Saraswat *et al.*, 2015). Extremely hyposaline conditions frequently observed in riverine influx dominated shallow water regions led to dissolution of the calcareous tests. The differential response to salinity was attributed to the drop in pH associated with the hyposaline waters (Saraswat *et al.*, 2015). Similar to the large salinity tolerance, benthic foraminifera also have a wide temperature tolerance (20-35°C). The optimum temperature for growth and especially for reproduction is; however, very narrow, as compared to salinity (Saraswat *et al.*, 2011). Other than the natural ecological stressors, anthropogenic inputs also affect benthic foraminifera, resulting in deformities (Linshy *et al*., 2013). Therefore, a clear distinction should be made between the effects of natural ecological stressors and anthropogenic inputs on benthic foraminifera in shallow water regions.

A detail account of taxonomic descriptions and ecology of recent ostracodes from southeast coast were provided (Baskar *et al*., 2013, 2015; Sridhar *et al*., 2015). Hussain *et al*. (2013) also analyzed ostracode assemblages from tsunamigenic deposits along the coast of Tamil Nadu.

Southern Ocean (Indian Sector)

Diatoms are one of the major phytoplankton groups in polar and sub-polar marine environments exhibiting a narrow range of ecological preferences, especially in terms of sea-surface temperature and sea ice conditions. The physico-chemical conditions of surface waters also control the characteristics and distribution of coccolithophores, the other important phytoplankton group in polar frontal region, which is known to be the most vital carbonate producers in the pelagic environment. A significant progress has been made on the knowledge of ecological control on modern distribution patterns of diatoms, coccolithophores and silicoflagellates in Indian sector of Southern Ocean by the research group at the National Centre for Antarctic and Ocean Research (NCAOR) (Mohan *et al.*, 2011; Nair *et al.*, 2015; Shetye *et al.*, 2011, 2013, 2014; Patil *et al.*, 2013, 2014a, b, 2015). The valuable information on relationship between modern oceanographic parameters and phytoplankton assemblage characteristics gathered through these studies has great importance in paleoceanographic reconstructions using fossil records (eg. Mohan *et al.*, 2011; Nair *et al.*, 2015). Mohan *et al.*, (2011) in their studies on modern diatoms from surface sediments in Enderby Basin, evaluated the potentiality of this group as a proxy for paleo sea-ice estimation. A new variety of a diatom *Trigonium arcticum* from the Prydz Bay, East Antarctica was also reported and this was suggested to be a sea-ice indicator for paleo sea-ice (Nair *et al.*, 2015). Detailed studies on modern calcareous phytoplanktons in the polar frontal region suggested seasonal control on their abundances and size (Patil *et al.*, 2013). Morphological variations in an ecologically sensitive species *Emiliania huxleyi* was investigated in detail and five morphotypes related to diverse hydrographic conditions were recognised (Patil *et al.*, 2014a). It was observed that the heavily calcified forms have preference to the warm high saline oligotrophic waters; whereas weakly calcified forms prefer elevated nitrate and phosphate concentrations. Patil *et al.* (2014b, 2015) reported a siliceous haptophytes (*Prymnesium neolepis* and *Petasaria heterolepis*) from the Southern Indian Ocean waters, which is an interesting observation.

The oxygen and carbon isotope ratios of the planktic foraminifera from the plankton nets and the surface sediment samples in the Southern Ocean was measured by Tiwari *et al.* (2011), in order to evaluate whether foraminiferal tests preserved in sediment faithfully record the overlying surface water characteristics. They found that the $\delta^{18}O$ values of planktic foraminifera in both the plankton net and core-top sediment are primarily governed by the SST variations associated with the frontal structure of the Southern Ocean. Whereas, the $\delta^{13}C$ values are related to change in productivity fluctuations, which also increase pole-ward (both in the plankton net and sediment samples) due to influx of nutrients via melting ice.

Paleoceanographic/Paleoclimatic reconstructions

Northern Indian Ocean

A number of studies on foraminiferal assemblages (planktic and benthic) in northern Indian Ocean subsurface sediment sections have been carried out by Indian scientists in order to better understand changes in sea-surface and -bottom conditions on longer to short time scales and their linkages to south Asian Monsoon circulation and global climates. Gupta *et al.* (2015) in their recent studies from the Oman margin, using foraminiferal abundance combined with geochemical proxy records suggested the initiation of southwest monsoon during the late Middle Miocene at ~ 12.9 Ma. Benthic foraminifera are considered as good indicators of past changes in benthic environment related to deep water circulation and surface productivity. Valuable information on paleoceanographic conditions and its linkages to monsoon intensity and global climate is gathered from benthic foraminiferal diversity, morphology and species/group abundance records. Yuvaraja *et al.* (2014) based on their study from the western Arabian Sea suggested that diversity and abundances of selected benthic taxa are primarily governed by the monsoonal intensity on longer time scales. Singh *et al.* (2015a) investigated temporal changes of diversity patterns in benthic foraminiferal assemblages in sediment cores retrieved from the oxygen minimum zone (OMZ) offshore Goa on high resolution time scale. They reported millennial scale changes in diversity, corresponding to the northern Hemisphere climatic events. Major increase in diversity occurred during the North Atlantic cold Heinrich events when the monsoon circulation was at its weakest mode; primary productivity and export flux of organic matter was low and the OMZ was weak. It was also suggested that these were the periods of better ventilation due to enhanced inflow of AAIW. During the last glacial maximum (LGM), the benthic diversity decreased and this was suggested to be related to a strong OMZ, attributed to the enhanced winter monsoon driven productivity and weak deep ocean circulation. Benthic foraminiferal records from the Maldive Ridge studied by Sarkar and Gupta (2014) show major changes at mid-Brunhes climatic transition and this has been attributed to the change in Indian Ocean Equatorial Westerlies-Eastward Equatorial Current (IEW-EEC) circulation. They further inferred that there is an opposite relationship between IEW shift and the Indian Ocean Dipole.

In recent years, several studies have also been carried out on the eastern Arabian cores to estimate paleo-temperature and paleo-salinity variations by using paired measurements of oxygen isotope and Mg/Ca in a surface dwelling planktic foraminifera. Tiwari *et al.* (2015) reconstructed centennial scale record of sea surface temperature (SST) variations in the eastern Arabian Sea since mid-Holocene. The SST record was used to determine paleo-salinity changes related to Indian summer monsoon (ISM) precipitation variability. The long-term trend indicates that the precipitation has declined since mid-Holocene, similar to the solar activity over the past 5000 years. They found that the summer monsoon precipitation declined concurrently with the recent periods of strong solar minima (Maunder, Spörer, Oort, and Wolf), but lagged by a couple of hundred years beyond 1300 years before present. This non-stationary phase relationship between the ISM and the solar activity on short time scale suggests the possible influence of the tropical coupled ocean-atmosphere phenomenon. Mahesh and Banakar (2014) attempted to infer past changes in salinity and temperature gradients between northern and southern sectors of the eastern Arabian Sea during the LGM and the Holocene. Their data support previous view of weakened summer monsoon and strengthening of winter monsoon during the LGM (Singh *et al.*, 2011). The paleo-SST record from the Lakshadweep Sea, however, suggests relatively cold sea surface temperature prior to the LGM at ~ 27 Ka (Mahesh *et al.*, 2011). Kessarkar *et al.* (2013) reported that the intensification of Indian summer monsoon started at the onset of the Bolling-Allerod event at ~ 15.2 ka, which is in agreement with previous reports from the Bay of Bengal (Govil and Naidu, 2011). From the sub-centennial scale planktic foraminiferal Mg/Ca based paleo-temperature record generated from a core collected from the southeastern Arabian Sea, covering the last 32 kyr, it is inferred that the sea-surface temperature at the Last Glacial Maximum was lower by 2.7±0.5°C, as compared to that during the pre-industrial time. From the record, it was further inferred that the deglacial warming started prior to the rise in atmospheric CO_2. The $\delta^{18}O$ and Ba/Ca analysis on surface dwelling planktic foraminifera in the same core, suggests that the last ice age termination was marked by two prominent weak monsoon intervals (Saraswat *et al.*, 2013). In a similar study from the equatorial Indian Ocean, relatively higher seawater salinity during the last interglacial period (Marine Isotopic Stage 5e), as compared to that during the Holocene was suggested based on paired $\delta^{18}O$ and Mg/Ca analysis of surface dwelling planktic foraminifera (Saraswat *et al.*, 2012). Additionally, the study further revealed that the winter time insolation gradient between equator and northern latitudes controls the monsoon intensity during glacial interval (Saraswat *et al.*, 2012).

The Arabian Sea is unique because of its well developed OMZ at intermediate depths impinging the continental margins. In recent years, the interest in study of the Arabian Sea OMZ variation both in space and time and its causal mechanism and consequence has increased substantially because of its implications on changes of biogeochemical cycles and nutrient inventory contributing to global climate change. Furthermore, this OMZ ecosystem can be considered as a natural laboratory of oxygen depleted condition and will be ideal to evaluate how various calcifying biota responded to changes in past ocean oxygen condition and acidification. Such study has major implications on our understanding of future scenario of marine life in context to rising atmospheric CO_2 concentration resulting ocean acidification. The pteropods being aragonitic in composition are found to be good indicator of the intermediate water oxygen condition, as their preservation condition in sediment is related to the ACD variation driven by the OMZ intensity. Singh and his research group in the last few years has made detailed studies on late Quaternary pteropods from the Arabian Sea Indian margin OMZ and suggested that the OMZ intensity varied in past on millennial scale. Furthermore, it was suggested that past changes in monsoon induced primary productivity, export flux of organic carbon, combined with deep water ventilation condition in concert with global climate perturbations results variation in the OMZ intensity. However, the role of externally sourced deep water masses in water column oxygenation influencing the eastern Arabian Sea OMZ was poorly known until recently. Addressing this vital issue, Naidu *et al.* (2014) using pteropod dissolution index provided better insights into our understanding of factors driving temporal changes in the OMZ intensity. They demonstrated that the better preservation of pteropods during northern Hemisphere cold periods is related to the deepening of the ACD, because of a weak OMZ resulted due to reduced monsoon driven productivity and greater intrusion of oxygenated Antarctic Intermediate Water. This observation highlights OMZ intensity, rapid climate change teleconnections through both ocean and atmosphere.

Naidu *et al.* (2012) and Narale *et al.* (2015) have explored the possibility of using dinoflagellate cyst as a paleoceanographic proxy to reconstruct the salinity variability in the Bay of Bengal and Arabian Sea respectively. These studies reveal that OMZ and associated productivity variations govern the dynoflagellate cyst abundance in the northern Indian Ocean. For the first time, an attempt has been made in the country to reconstruct the pCO_2 levels in the Indian Ocean by using shell weights, shell sizes and boron isotope ratios and boron/calcium ratio of selected planktic foraminifera from the Indian Ocean. In this context, numerous papers (Naik *et al.*, 2011, 2014; Naik and Naidu, 2014; Naik and Naidu, 2015; Naik *et al.*, 2015) dealt with carbonate chemistry and shell weights of planktic foraminifera with conclusive evidences inferring that planktic foraminifera shell calcification and hence, shell weights depend upon [CO=3] of surface waters, where in they calcify. These studies document that pCO_2 along the eastern Arabian Sea have varied between ~160 and 300 μatm during the last 23 kyr. The ΔpCO_2, the sea-air pCO_2 difference, is relatively small during the last glacial maximum and becomes more negative toward the Holocene, with the exception of a significant excess during the last deglaciation centered on the Bølling-Ållerød. Throughout the record, ΔpCO_2 is predominantly negative, probably as a result of enhanced biological productivity (and higher nutrient and carbon utilization) during the southwest monsoon. A strong coupling between ΔpCO2 and strength of SW monsoon was noticed, which tempts to suggest that boron isotopic ratios in planktic foraminifera might be another promising proxy to understand the role of monsoon on the efficiency of carbon pump in the geological records.

Similar to the Arabian Sea, the seasonally reversing monsoon wind system produces pronounced spatial patterns in surface ocean circulation, biological productivity and vertical fluxes of biogenic and lithogenic materials in the Bay of Bengal (BOB) and the Andaman Sea (AS). As these basins receive large volume of freshwater, the effects of the monsoon on the seasonal variations in surface hydrography are more distinct, comparable to the Arabian Sea. Additionally, earlier studies have found evidences of presence of externally sourced deep water masses influencing physico-chemical characteristics of deep waters in the basin. Therefore, there is increasing interest in the study of sediment records from the BOB and the AS, in order to reconstruct history of seasonal monsoon variability and related surface (SST, SSS, upper water stratification) and deep ocean hydrographic conditions. Some earlier studies have indicated larger variations in the north-south salinity gradients in the BOB, related to the Indian summer monsoon (ISM) precipitations since the last glaciation. Recent investigations on oxygen and carbon isotopes of selected planktic and benthic foraminifera show large changes in characteristics of surface and deep waters in southern BOB (Raza *et al.*, 2014) and in northeastern Indian Ocean (Ahmad *et al.*, 2012). It is evident from the planktic oxygen isotope record that ISM was intensified during 6-7 ka, followed by an abrupt decline at ~ 5 ka (Ahmad *et al.*, 2012). Present day, deep water masses in southern BOB is significantly influenced by the external circumpolar deep water (CDW), which is a mixture of NADW and southern ocean deep water. The stable carbon isotope of benthic foraminifera is a proxy useful to decipher deep ocean circulation, water mass characteristics and its sources. Ahmad *et al.* (2012) and Raza *et al.* (2014) suggested greater influence of NADW during the Holocene, whereas contribution of southern ocean deep water enhanced during the last glacial maximum.

The planktic foraminiferal assemblages combined with oxygen isotope and Mg/Ca ratio of selected surface planktic species have been effectively used to record last glacial-Holocene changes in sea surface conditions (temperature, salinity, upper water stratification) in the Bay of Bengal and Andaman Sea related to summer vs winter monsoon intensity. The abundance record of *Pulleniatina obliquiloculata* was used to infer past changes in thermocline depth in the Andaman Sea. Sijin Kumar *et al.* (2011) noticed low abundance of this taxon during the cold Younger Dryas and the last glacial maximum and related these abundance minima to the deepening of thermocline depth. Temporal variations in *A. trispinosa* abundance in a core collected from the Ayeyarwaddy Delta front, off Myanmar, suggest a dry climate prior to 1650 AD and warm and wet climate since 1650 to present. Additionally, three episodes of freshwater influx are inferred at ~1675, 1750 and 1850 AD (Panchang and Nigam, 2012). The temporal variation in fossil pteropod preservation in Andaman Sea sediment cores was studied by Sijinkumar *et al.* (2014). Similar to the previous studies made from the Arabian Sea, these workers have also related the pteropod spikes in the Andaman Sea sediment to the better aragonite preservation, because of deepening of the Aragonite Compensation Depth (ACD), attributed to the low productivity and weakened summer monsoon intensity.

Southern Ocean (Indian Sector)

The paleoclimatic study using Southern Ocean (SO) diatom records reveals a glacial shift in the Antarctic winter sea-ice limit up to the modern day Polar Frontal Zone of Indian sector of SO (Nair *et al.*, 2015). This study also revealed that glacial periods, north of the Polar Front were characterised by high diatom productivity. Shetye *et al.* (2013) studied the latitudinal shifts in the polar front over the last 48 kyr in the Indian sector of the Southern Ocean using silicoflagellate record. The record suggests a warming trend from the LGM to the Holocene. Further, it was also inferred that sea-surface temperature was warmer during 43-45 kyr, corresponding to the warming event recorded in the Antarctic ice core. The results point to a northern and southern shift in the polar front during LGM and 43-45 kyr respectively. The southward displacement of the frontal system is linked to an increase in SST, as inferred from the Byrd Antarctic ice core $\delta^{18}O$ and solar insolation data. The low dust flux, higher $\delta^{18}O$ and absence of an upwelling indicator diatom during the Antarctic warming event also suggest stronger thermal stratification during the Antarctic warming event, as compared to LGM.

The southwestern Indian Ocean is the conduit for transport of warm and saltier water from the Indian Ocean to the Atlantic Ocean. This region, therefore, holds the key for global climatic changes modulated by variation in thermohaline circulation. The temporal variation in planktic foraminiferal abundance, stable isotopic ratio ($\delta^{18}O$) and trace elemental ratio (Mg/

Ca) of planktic foraminifera *Globigerina bulloides* in a core collected from the Agulhas Recirculation Region in the southwestern Indian Ocean, suggest increased productivity, seasonally strong thermocline and enhanced advection of southern source water in the southwestern Indian Ocean during the last glacial period (Naik *et al.,* 2014).

Ocean Gateways and Paleo-circulation

The major plate tectonic events associated with opening or closing of marine gateways modulated global ocean circulation and climate patterns during the Neogene and the Quaternary periods. The changing plate boundaries in the equatorial regions resulted a restricted tropical inter-ocean circulation system, leading to the major paleoceanographic and climate changes during the Neogene (Srinivasan, 2003). Numerous studies in the past found evidences of closure and reopening of gateways between the north east Atlantic Ocean and the Mediterranean Sea; the closure of the deep central American seaway and the Indonesian seaway have great implications on evolution of global ocean circulation and climate including Asian monsoon system. This is being increasingly realized that the Mediterranean outflow in the north east Atlantic Ocean and the Indonesian throughflow from the Pacific to the Indian Ocean act as major switchboards in the global thermohaline circulation and significantly influence the low- to mid-latitude climatic patterns on short to long term time scales. The deep sea drilling by the IODP in previous years provided an unprecedented opportunity to the international scientific community to study long sediment cores from these critical areas of world oceans. The Indian scientists have made significant contributions on paleoceanographic evolution of these areas and its implications on regional and global climate change on different time scales. Singh *et al.* (2015b,c) carried out detailed foraminiferal assemblage studies on the Quaternary sediment cores from the Mediterranean sector of the NE Atlantic Ocean (Iberian margin), collected recently during the IODP Expedition 339 (Hernandez-Molina *et al.,* 2014). Using benthic foraminiferal and isotope proxy records, Singh *et al.* (2015b) inferred variability pattern of Mediterranean Outflow Water (MOW) in NE Atlantic Ocean on glacial/interglacial and millennial scales. The MOW was intensified during the cold stadials, whereas, it was sluggish during the warm interstadials within the interglacial marine isotope stages (MIS) 5 and 7. Their study, further, demonstrates a correlation of weakened MOW with sapropel layers of the Mediterranean Sea, suggesting strong coupling between climate and deep ocean overturning. A major shift in climate pattern by the emergence of 100 kyr periodicity during the Mid-Pleistocene Transition (MPT: 700-1250 ka) is an important issue of the Quaternary research. Singh *et al.* (2015c) recorded variations in composition of planktic foraminiferal assemblages at the IODP Site 1391 (Iberian margin), in response to glacial/interglacial scale oceanographic changes during the last 900 kyr. They observed a major change in glacial/interglacial pattern of surface ocean conditions at ~ 430 ka (Mid-Brunhes Event; MBE). An increase in the interglacial Southern Ocean temperature, productivity and CH4 concentration in the Antarctica ice core during the post-MBE period suggests teleconnections through oceanic-atmospheric processes.

Bhaumik *et al.* (2014) studied late Neogene records of planktic foraminiferal assemblages and carbon and oxygen isotopes of a benthic foraminifera and a deep dwelling planktic species at the ODP site of the Blake Ridge and inferred closing of the Central American Seaway at around 2.2 Ma. The presence of high salinity surface water in the region between 1.2 and 2.2 Ma due to intensification of Gulf Stream was inferred, based the faunal and isotope records.

An attempt has been made to understand the paleoceanographic changes in the eastern Indian Ocean in response to effective closure of Indonesian Seaway during the Pliocene (Singh and Rai, 2011; Rai and Singh, 2012). The detailed taxonomic description of the late Neogene agglutinated benthic foraminiferal species at the Exmouth Plateau, along with paleobathymetric and paleoecologic comments, were provided by Singh *et al.* (2014). Based on benthic foraminiferal records, Rai and Singh (2012) inferred high upwelling induced productivity in the beginning of the Late Pliocene (~3.0 Ma), and suggested it to be related to the effective closing of Indonesian Seaway, resulting major change in the source of Indonesian through flow waters from the south Pacific warm, saline to the north Pacific cooler and fresher waters. Gupta and his research team made detailed studies on temporal changes of benthic foraminiferal diversity and abundances at the ODP sites of southeastern Indian Ocean and suggested that they are linked with variations in surface productivity condition and surface water stratifications, in response to high-latitude climate induced oceanographic changes during the Neogene (Singh *et al.,* 2012, Gupta *et al.,* 2013; Verma *et al.,* 2013).

Paleocene-Eocene Thermal Maximum (PETM)

The early Paleogene period is important in the Earth's climatic evolution, as this was the time when previous green-house state of the Earth was transformed to ice-house state. This transformation was not the gradual, but consisting series of global warm events, most prominently during the Paleocene/Eocene transition, known as Paleocene-Eocene Thermal Maximum (PETM). This event is characterized by a large input of carbon, ocean acidification and global temperature increase, more than the present day. Therefore, geological investigation of this time-slice is crucial, in context of our understanding of climate change dynamics. Recent studies on carbon isotope stratigraphy of Cambay and Kutch basins have established the signatures of Eocene hyper-thermal events in western India. Saraswati and co-workers have attempted biostratigraphic zonations to constrain these marine sections for the corresponding thermal events (Saraswati, 2011; Saraswati *et al.*, 2012). Recently, Khanolkar and Saraswati (2015) studied how shallow marine foraminifera responded to these thermal events in India, that was located near the equator during the Early Eocene. They recorded low-diversity and dwarfed foraminifera comprising triserial planktic and biserial benthic types during the Paleocene-Eocene Thermal Maximum (PETM). The foraminifera attained high diversity and normal size and became major producers of carbonates during the Early Eocene Climatic Optimum.

Several studies on various microfossil groups from the Neogene land-based marine sections were also conducted, mainly for biostratigraphic purposes. A collection of review papers pertaining to the Miocene biostratigraphy and paleoceanography was provided in a Special Publication of the Paleontological Society of India (2014) [Srinivasan (p.1-3); Raju (p.5-51); Singh and Gupta (p.101-109); Singh and Verma (p.111-119); Rai and others (p.121-134) and Sharma (p.161-169]. A text book on 'Micropaleontology: Principles and Applications", authored jointly by P K Saraswati and M S Srinivasan is published recently by Springer (2016). This book is useful for students and young researchers, as it addresses basic principles of micropaleontology, morphology, ecology and geologic history of major microfossil groups, and their applications in biostratigraphy, paleoceanography, paleoclimatology and basin analysis.

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