Status Report 2016-2019

Marine Micropalaeontology: An Overview of Indian Contributions During 2016-2019

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(Received on 19 September 2019; Accepted on 29 September 2019)

Marine micropaleontology concerns biostratigraphy for dating and correlation of deep time sequences as well as in palaeoceanography to understand the marine processes of the past. For this, marine micropalaeontology utilizes detailed studies on exclusively marine microbiota such as foraminifers, nannofossils, diatoms, dinoflagellates, and others. This article discusses (in detail) our present state of palaeoceanographic knowledge based on marine micropalaeontology studies in the Indian sector. A detailed literature survey showcases that numerous studies have been carried out in deep time (Jurassic - Neogene) as well as Quaternary sediments utilizing marine microfossils from India. These studies from different geological periods and regions within the Indian territory such as Jurassic (Kutch Basin), Cretaceous and Cretaceous–Paleogene (K-Pg) transition (western, peninsular and northeast India), Palaeogene (northeast and western India), Neogene (Andaman & Nicobar Islands, northeast Indian Ocean), Quaternary (Indian Ocean, Southern Ocean, coastal and estuarine regions of peninsular India) have provided better insights to our previous understandings on various aspects that include biostratigraphy, paleoenvironment, evolution, ocean/land-climate variability, its dynamics and teleconnections.

Keywords: Micropaleontology; Biostratigraphy; Depositional Environment; Paleobiogeography; Paleocangraphy; Paleoclimate.

Introduction

Marine micropaleontology embraces studies on a diverse group of microfossils and modern microbiota that may be auto- or heterotrophic, planktic or benthic. The majority of marine microfossils own permineralized skeletons that are either composed of one or several common skeletal materials. For instance, in foraminifers, calcareous nannofossils, and coralline algae the skeletal material is composed of calcium carbonate; radiolarians, diatoms, silicoflagellates have skeletons composed of silica; skeletal material in acritarchs, chitinozoa, dinoflagellates, and scolecodonts is formed by organic compounds while conodont's skeleton is made up of calcium phosphate. The efficacy of marine microfossils in geosciences and allied fields is due to their small size, profuse occurrence in variable marine environments, and broad geographic distribution in sediments spanning almost the entire geological time

scale i.e., from Precambrian to Recent times. Over the years, marine microfossils have been consistently found their utilization in the field of biostratigraphy, paleoenvironmental interpretations and in recording global ocean and climate change fluctuations. In recent times, much emphasis has been on the utilization of marine microfossils in seismic calibration(s), sequence stratigraphy and related research. Moreover, the study of marine microfossils is indispensable for the oil and gas sector, where marine micropaleontology is used as a tool to steer horizontal drilling of reservoirs for cost-effective production of hydrocarbons.

Keeping pace with global trends on the advancement of research on marine microfossils, the last few years/decades have witnessed remarkable contributions by micropaleontologists working on deep time (Jurassic-Neogene) as well as Quaternary sediments, in the Indian sector. In this context, the present review discusses (in detail) our present state

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Fig. 1: Known global and Indian ranges of Jurassic foraminifera from the Dharang Member, Habo Formation, Habo dome, Kutch, Gujarat (after Talib *et al.*, 2017)

of palaeoceanographic knowledge based on marine micropalaeontology studies in the Indian sector. Apart from discussing recent research utilizing biological proxies, the present article also showcases recent studies on nonbiological proxies (e.g., inorganic geochemistry, stable isotopic studies) that have been utilized in paleo-reconstructions along with biological proxies. Besides, we also discuss the active participation of Indian researchers in International research programs that include the International Ocean Discovery Program (IODP), International Geosphere-Biosphere Program (IGBP), Pliocene Arctic Climate Teleconnection (PACT). This aspect of discussion reveals another dimension (at par with international requisites in the field of micropaleontology) i.e., vital data has been generated by researchers to understand the dynamics of ocean currents, deep-sea processes and paleoclimatic variations. Numerous high-resolution records from the Arabian Sea, Bay of Bengal, Southern Ocean (Indian sector) and terrestrial record from India have provided

a good understanding of ocean/land-climate variability, its dynamics and teleconnections in the context of current rapid change in global climate. IODP-India has also provided support to Indian scientists and researchers to carry out cutting edge geoscientific research through the IODP consortium from different oceanic regimes.

The great utility of marine microfossils for interpretation of the stratigraphic age and environment of deposition made them one of the most used tools from the Jurassic to Neogene palaeontological research in India. The enhanced understanding and refinement of the biostratigraphic ranges of various microfossils are prerequisites for delineation of geological processes in the earth's history and primarily to facilitate better identification of signals of paleoenvironmental variability even up to the boundary of the global climate events. The Quaternary sediments were used for micropaleontological studies as a tool to decipher the past oceanic processes,

Fig. 2: Dinoflagellate cysts from Patasar Shale Member, Wagad Uplift, Kutch (after Riding *et al.*, 2017)

productivity variations, past sea surface temperature and salinity, CO₂ outgassing. Herein, significant contributions by Indian researchers in the field of marine micropaleontology during the years 2016 - 2019 have been summarized. This is to note that for a better understanding of the readers, the sections in the article have been categorized in a chronological order i.e., in a geological time scale (Jurassic to Quaternary) framework.

Jurassic

Callovian age foraminiferal assemblages systematically described from Chari Formation, exposed at Fakirwari Dome in Kutch envisaged shallow water, near shore, open marine middle shelf environment with frequently fluctuating shoreline. The assemblage was assigned to Indo-East African Province, located at the southern margin of the Tethyan realm and transitional between the Tethyan

and the Antiboreal realms (Bhat *et al.* 2016). The other foraminiferal assemblage from the same region and time, described from Dharang Member of the Habo Formation, Habo Dome in Kutch suggesting that deposition took place in open marine conditions in a tectonically unstable middle to outer shelf, with a fluctuating shoreline (Talib *et al.* 2017). Riding *et al.* (2017) documented a well-preserved palynobiota including dinoflagellate cysts of Gondwanan (Australasian) affinity from the lowermost Patasar Shale Member of the Patasar Tank section, Wagad Uplift in the Kachchh Basin and dated Early Kimmeridgian age based on the Dingodinium swanense Interval Zone (Fig. 2).

Cretaceous

The foraminiferal study from Dherani Limestone Member, Ariyalur area in the Cauvery Basin proposed early Maastrichtian age based on the developmental

Fig. 3: Latest Maastrichtian calcareous nannofossil assemblage from Syndai Village, Meghalaya (after Singh 2018)

Fig. 4: Records of Orthophragminids in the Paleocene and Paleocene-Eocene boundary in Tethys and SE India (after Ozcan *et al.* 2018)

state of *Lepidorbitoides*, the occurrence of *Siderolites* and absence of typical Campanian Larger Benthic Foraminifera (LBF) (Malarkodi *et al.* 2017). The recorded data was also used to assess the phylogenetic stage of the genus by evaluating them with the evolutionary model of *Lepidorbitoides* from the Western Tethys and with Maastrichtian paleobiogeography of the genus.

In the northeastern region, Singh (2018) conducted a study from the outcrop section near Syndai Village, Meghalaya and recorded the latest Maastrichtian calcareous nannofossils belonging to *Micula prinsii* Zone. The distribution pattern of calcareous nannofossils (Fig. 3) has been linked to climatic variability within the *Micula prinsii* Zone and confirmed an additional warming pulse before K-Pg boundary in Tethyan province. The paleoenvironmental studies from the same region, in Um Sohryngkew River section, Meghalaya provided organo-chemical evidence of incidence of “regional fire” which was possibly responsible for stepwise disappearance of planktic foraminifers in upper Maastrichtian biozones (CF4-CF3) and migration of some forms out of warm

water environment (Pal *et al.* 2018). Among the various other causes of late Maastrichtian warming, they presumed the regional fires to be one of the factors.

From the western Indian region, Singh and Rai (2017) carried out calcareous nannofossil biostratigraphy from 795 m thick subsurface Cretaceous succession (depth range 1104-1899 m) from Tanot area, Jaisalmer Basin. Detailed systematic description of 222 nannofossil species belonging to Late Albian to Early Maastrichtian age has been produced in this study.

Timing of angiosperm diversification was addressed by Prasad *et al.* (2018) through a palynological study from borehole sediments of Infratrappean deposits in the Ashtona Village, Yeotmal District, Maharashtra. The Cretaceous paleovegetation, paleoecology, depositional environment and paleogeography of central India before Deccan volcanism has been discussed based on a rich assemblage of pollen-spore and dinoflagellate cysts. Furthermore, a shallow marine embayment in central India during the late Maastrichtian, which

Fig. 5: The foraminiferal assemblage from the Panandhro and Matanomadh lignite mines (after Khanolkar and Sharma 2019)

extended from the east coast through the Godavari rift zone, was envisaged. The study supported the Out-of-India hypothesis.

K/Pg Boundary

A planktic foraminiferal biostratigraphic study from the continuous upper Maastrichtian- middle Danian

shelf successions in Meghalaya have provided planktic foraminiferal biozones at a finer resolution (Mukhopadhyay 2016). The effect of basin instability on planktic foraminiferal successions and sea-level changes during the late Maastrichtian to early middle Danian (K-Pg transition) has been analyzed to delineate the depositional environment.

Fig. 6: Commonly occurring calcareous nannofossils and radiolarians from Kalapathar Section, Havelock Island (after Chakraborty *et al.* 2018)

Fig. 7: Benthic foraminiferal morpho-groups from the shelf and slope of the central-western Bay of Bengal (after Suokhrrie *et al.*, 2018)

Paleogene

Palynofacies analysis from two Lakadong Limestone sections, Dohnsiang (Kurtinsiang) (KPL) and Laitmowksing (LTL) from Khasi Hills (Meghalaya) showed a cyclic pattern in the organic matter types, linked to the higher-order sea-level changes. The sections were dated as late Paleocene based on the characteristic larger benthic foraminiferal assemblages belonging to the Tethyan Shallow Benthic Zones (SBZ) 3 (Gogoi *et al.* 2018). A multi-proxy study based on grain size, physical sedimentary structures, biogenic structures, palynological, geochemical and organic carbon isotopic analyses have been carried out on upper Paleocene-lower Eocene coal-bearing shallow-marine succession from Jathang, East Khasi Hills, Meghalaya (Prasad *et al.* 2018). The study envisaged that the succession was deposited in a low-energy, coastal marsh-bay complex with reduced duration of the dry period during the latest Paleocene-earliest Eocene, due to a more active hydrological cycle in the paleo-equatorial region. Özcan *et al.* (2018) established a systematic, biostratigraphic and paleobiogeographical framework for orthophragminids from late Paleocene Lakadong Limestone in Meghalaya (Fig. 4). The Paleocene and Eocene orthophragminids records from India and Pakistan suggested that *Orbitoclypeus* is the only orthophragminid in the Paleocene of the eastern Tethys whereas *Discocyclina* first appears in early Eocene times, being mainly represented by endemic taxa confined to the Indian subcontinent. Facies change in the Mawmluh Quarry Section from a marine to the continental setting within SBZ 4 corresponds to the oldest record from the Indian plate in the Paleogene, which may be linked to the flexural uplift of the passive margin of the Indian plate, marking the onset of the collision of the Indian and Eurasian plates.

In the same area, the dominance of Paleocene-Eocene coralline alga *Distichoplax* recorded from multiple carbonate sections outcropping in Mawmluh. The study suggested the intertidal to subtidal zones of the shallow-marine ecosystems about high hydrodynamic conditions in an oligo-mesotrophic nutrient regime. Their gradual extinction may be linked to the climate adversities like the Paleocene-Eocene Thermal Maximum (PETM) and biotic pressures like the Larger Foraminiferal Turnover (LFT) (Sarkar 2018). Sarkar (2019) studied paleoecological

characteristics of Late Thanetian (SBZ 4) benthic foraminifera *Haymanella elongata* and *Keramosphaera iranica* from the same successions and depicted that both the forms were sensitive to the hydrodynamics in shallow-marine environments. Sarkar and Rao (2018) studied coralline red algae and larger benthic foraminifera from Late Paleocene-earliest Eocene carbonate succession of Sylhet Limestone platform deposits outcropping on the Jowai-Badarpur Road in the Jaintia Hills Meghalaya and conceptual food web and trophic-level structure envisaged for the Lakadong Limestone Paleocommunity. The microfacies analysis of LBF from the Middle Eocene sediments of Prang Formation, Sylhet Limestone Group in Meghalaya suggested deposition in an oligotrophic nutrient regime from restricted lagoonal to proximal/ middle outer shelf environment. The reason for the dominance of LBF genera with the scarcity of corals has been attributed to the biotic response to events like MECO which triggered warming episodes (Sarkar 2017a).

A conceptual paleoenvironmental model based on early Eocene calcareous algae and benthic foraminifera from the Umlatdoh Limestone succession, Meghalaya has been showcased various facies gradients, bathymetry levels, and shelf zones (Sarkar 2016). Humane *et al.* (2017) reported early Eocene Halimedacean and Udoteacean algal assemblage from shallow marine subsurface Sylhet Limestone Formation of the Bengal Basin, India which is closely comparable to the Paleogene Halimedacean and Udoteacean algal elements of Morocco and Egypt. They also explained that the association of Halimedacean and Udoteacean algae with Dasycladalean elements indicates that the deposition took under shallow, warm, tropical, open lagoonal to shelf environment at a depth of 5-6 m below low tide level with Tethyan affinity. A brief overview of the fossil coralline red algae recorded from the different sedimentary basins of India, their paleoecological applications have been discussed by Sarkar (2017b). Emphasizing studies on coralline red algae, the drawbacks and prospects of paleoalgal studies in India pertinent to significant aspects such as paleoecology, paleoenvironmental reconstructions, climate dynamics and extinction episodes are also discussed.

Singh *et al.* (2016) reported well-preserved

Fig. 8: Light micrographs of *Thalassiosira lentiginosa* showing valve size variability (small to large-sized – A to H) from surface and down-core sediments from the southern ocean (after Shukla *et al.*, 2016)

Priabonian age calcareous nannofossils from the Rewak Formation exposed along the Siju-Rewak road section, West Garo Hills, Meghalaya. Based on the

assemblage, they suggested that the deposition took place in a hemipelagic, nearshore, warm water environment. Singh *et al.* (2018) highlighted

Fig. 9: *Cristadinium striatiserratum* reported from the modern sediments of the northern Indian Ocean (after Uddandam *et al.*, 2018)

Paleogene events in the Manipur region on the basis of fossil evidences and erected three biostratigraphic zones ranging in age from late Paleocene-early Eocene (Thanetian-Ypresian) and suggested shallowing up in depositional environment from Upper Disang Formation to Barail Group.

In the western Indian region, based on an integrated study of sedimentary structures (including paleokarst and paleosols), carbonate microfacies and micropaleontological characteristics, two depositional sequences (having cyclicity) were depicted in the Eocene succession of Kutch. The cycles of Sequence-I were of low amplitude, low frequency,

and limited to inner shelf having cyclicity of 1.2 Myr while Sequence-II comprises high frequency and higher amplitude cycles on mid-shelf settings having cyclicity of 77 Kyr (Saraswati *et al.* 2016a). Based on the biostratigraphy of planktic foraminifera and LBF from the Eocene succession of Kutch, Saraswati *et al.* (2016b) estimated hiatuses of ~7 Myr between the Deccan Traps and Naredi Formation, ~7 Myr between Naredi Formation and Harudi Formation and ~4 Myr between Fulra Limestone and Maniyara Fort Formation. They also reported no evidence of Paleocene marine sediments in on-land Kutch. The test morphological studies of Bartonian Orthophragminids of the Indian subcontinent facilitated the erection of two new species *Discocyclina kutchensis* and *D. sulaimanensis* possibly representing endemic foraminiferal fauna confined to Indo-Pakistan region and are important for Paleobiogeographic studies (Özcan *et al.* 2016). Khanolkar & Saraswati (2016) reported an atypical planktic foraminifer, bearing close resemblance with *Orbulinoides* from the restricted marine Middle Eocene (Bartonian) succession of Kutch, western India although taxon was still unnamed and open for nomenclature. Saraswati *et al.* (2017) examined the earliest reticulate *Nummulites* forms occurring in the Bartonian succession of Kutch and carried out a detailed biometric analysis to distinguish them and inferred that three reticulate species of *Nummulites* possibly evolved from *N. acutus* in Zone P14.

A combined palynological and stable carbon isotope ($\delta^{13}\text{C}$) investigation from the lignite sequence at Panandhro, Kutch assigns an early Eocene (Ypresian) age to the lignitic succession based on dinoflagellate cysts and associated spore-pollen assemblage. Furthermore, a pronounced negative Carbon Isotope Excursion (CIE) of about 2.7‰, correlatable to the Second Eocene Thermal Maximum (53.7 Ma) hyperthermal event, has been noticed. It was concluded that there is no significant age difference between the lignite deposits of the Kutch and Cambay basins Agrawal *et al.* (2017). Saraswati *et al.* (2018) thoroughly reviewed the foraminiferal biostratigraphy of the Paleogene successions of Kutch and discussed the development in the stratigraphy of Kutch considering taxonomic revisions of the LBF and the refined shallow benthic zonations (SBZ). It is suggested that climate played a major role in building up the Paleogene stratigraphic succession of Kutch,

the carbonates formed during the warming intervals and the stratigraphic gaps were in the intervening cooling periods. Khanolkar *et al.* (2017) discussed the ecological response of foraminifera across the Middle Eocene Climatic Optimum (MECO) warming event from carbonate samples from Harudi and Fulra Limestone formations of Kutch. The study reveals that warming in middle Eocene commenced with high precipitation and eutrophy, but soon warmer and oligotrophic conditions prevailed that provided an optimum environment for larger benthic foraminifera to flourish and form the major carbonate platform. Khanolkar and Sharma (2019) have addressed the similarities and differences observed in the paleodepositional and paleovegetational conditions from the Cambay, Kutch and Barmer basins during the tropical climate of the Early and Middle Eocene (Fig. 5). For this, they have used an integrated approach by quantitatively analyzing various microfossil groups (foraminifera, spores- pollen, dinoflagellate cysts and fungi). Their results suggested the presence of overall tropical vegetation during Early and Middle Eocene in western India.

Furthermore, rainforest elements along with mangrove vegetation have recorded from Cambay and Barmer basins which were deposited in the marginal marine setting. In the Kutch mine sections, the bloom in triserial planktic foram and RBFs, low diversity and the presence of atypical planktic foraminifera are indicative of eutrophic and stressed conditions of deposition. In the same area, Khanolkar and Saraswati (2019) investigated the foraminiferal biofacies of shallow marine successions from a paleotropical site in western India (Kutch Basin) to understand the paleoclimate and its impact on the ecology of foraminifera. The results indicated that EECO and MECO did not harm shallow marine foraminifera, and mainly the larger benthic foraminifera attained high diversity, high abundance, larger size and broader latitudinal distribution in the middle Eocene.

Banerjee *et al.* (2018) presented paleodepositional and paleobathymetric interpretations for Middle Eocene Fulra Limestone and Oligocene Maniyara Fort formations of Kutch using benthic foraminifera in combination with a lithological association, sedimentary structures, and early diagenetic features. They erected six carbonate facies

from the Fulra Limestone indicate a depositional spectrum ranging from bar-lagoon to mid-ramp depositional conditions and four carbonate facies of the Maniyara Fort Formation represents deposition within the inner ramp setting in bar-lagoon and patch-reef environment. Broadly, the depositional setting of the Paleogene carbonate in Kutch resembles Eocene platform deposits in the circum-Tethys belt.

The global distribution pattern of Oligocene times corals from Maniyara Fort Formation, Kutch, and other records of the world had suggested strong specific endemism whereas large generic panendemism and had climatically controlled circumtropical distribution more or less similar to present day. The paleobiogeographical analysis revealed a strong Tethyan affinity of most of the province, suggesting a trans-Atlantic surface current and passages through the sea between the two American continents in Oligocene times (Sinha and Halder 2018). Less *et al.* (2018) performed a morphometric analysis of the nummulitids and lepidocyclinids from the Oligocene succession (Maniyara Fort Formation) of Kutch and compared them with the assemblages of Western Tethys. In the absence of planktonic foraminifera and calcareous nannoplankton data, Sr-isotope stratigraphy was applied as an independent tool for correlation and chronostratigraphic calibration between the Kutch and Western Tethyan Oligocene larger benthic foraminifera assemblages. Lumpy Clay Member of Maniyara Fort Formation is considered as unfossiliferous in terms of foraminifers and was dated on the basis of foraminiferal assemblages of underlying Basal and overlying Coral Limestone members. Verma and Singh (2019) conducted a study to resolve the discrepancy in the precise age of this strata and assigned Middle Rupelian (~31 Ma) age for the Lumpy Clay Member exposed at Bermoti Village, in Kutch based on dinoflagellate cysts and calcareous nannofossils.

Late middle Eocene-early Oligocene planktonic foraminifera was documented by Kalia and Sahu (2018) from the DSDP Sites 219 in the Arabian Sea, and site 237 in the western tropical Indian Ocean. MECO event was recorded at the Site 237. Sudden warming was reported in the Zone E12 with the extinction of *Acarinina bullbrooki* and *A. topilensis*. Whereas, a drop in temperature close to the end of MECO was marked by extinction of

Globigerinatheka kugleri, *G. euganea*, *Morozovelloides coronatus*, *M. lehneri*, and *O. beckmanni*. The change from the greenhouse to the icehouse world have been expressed by the composition and pattern of change in the planktonic foraminiferal assemblages of the zones E13 to O2 from both the sites.

Further from southern India, Mukhopadhyay (2018) recorded conjoined and aberrant test of *Nummulites* aff. *N. acutus* with minute biotic bodies from the subsurface middle Eocene sediments of South Pondicherry, Cauvery Basin. The study indicates gamontogamy of plastogamy type of sexual reproduction by the adult individuals of *Nummulites* aff. *N. acutus* to generate offspring as microspheric forms. Two distinct foraminiferal assemblages were recorded from the basal and top part of the Paleocene sequences in Andaman Islands by Koley *et al.* (2018). They suggested deep water depositional environment prevailed during the Lower Paleocene and shallow marine high energy condition thrived during the Upper Paleocene period.

Rai (2018) summarizes available records of nannofossils in Paleogene sedimentary successions from several sedimentary basins of India and also pointed out the gaps which can be taken into account in the near future. Raju (2018) presented an overview of the Paleogene stratigraphy of India with special emphasis on deposits and major geological events that occurred during Paleogene time in different basins of India viz. Himalayan foreland, NE Region, Andaman, West Bengal, Mumbai offshore, Cambay, Kutch and Jaisalmer.

Neogene

Banerjee *et al.* (2017) presented the first detailed $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records of surface and deep-dwelling foraminifera from ODP site 758 in the Northeast Indian Ocean. A series of climatic events including (a) Mid Miocene Climatic Optimum (17-15 Ma), (b) Monterey excursion (17-14 Ma), (c) East Antarctica Ice sheet formation (13.8 Ma), (d) Initiation of Indian Summer Monsoon with waning of Antarctica Ice sheet (12.3-10.4 Ma), and (e) evidence of a cooling event (10.2-9.6 Ma) have been depicted in the study. A significant decrease in $\delta^{13}\text{C}$ at ~10.2 Ma was indicative of a complete re-adjustment of the carbon cycle after the Monterey excursion and export of the North

Atlantic Deep Water (NADW) towards the southern Ocean giving rise to Circumpolar Deep Water (CDW). A good correlation between the South Pacific, Indo Pacific, and Northeast Indian Ocean cores suggests that the strong westerly Indian Ocean current (MIOjet) linked these Oceans from 14 Ma.

Singh and Raju (2018) presented a study based on the phylogenetic evolution of miogypsinids of Burdigalian age from Bombay offshore. They used morphometric characters together with their biostratigraphic ranges and facies relationships as a vibrant tool for the study of shallow-water carbonate deposits, which are essential for a hydrocarbon exploration point of view. Integrated biostratigraphy from the Havelock Island was carried out by Chakraborty *et al.* (2018) based on multiple microfossils (diatoms, calcareous nannofossils, radiolarians) from the outcrop exposed in Vijaynagar Village near Kalapathar Beach. The recorded microfossils suggested an age range of ~16.4 to ~15.0 Ma (early-middle Miocene) and the deposition took place in a deepwater environment under the influence of MMCO event. Biofacies analysis was performed on late middle Miocene (Serravallian) algal-foraminiferal assemblages and carbonate deposition from the Hut Bay section of the Little Andaman Island. The biogenic assemblages indicate meso-oligotrophic, tropical shelf environmental settings with shallow to mildly deeper bathymetric levels (Sarkar *et al.* 2016).

Rai *et al.* (2017) used different indices of the diversity of planktic foraminifera to demonstrate the Pliocene Indonesian Through Flow (ITF) changes in the eastern subtropical Indian Ocean. The strong influence of warm ITF waters due to broad and open seaway until the end of early Pliocene increased the SST and depth of thermocline in the Leeuwin current area. The significant decline in faunal diversity between ~3.5 and 3 Ma is suggested to be in response to the fall in SST and increased surface water productivity due to reduced influence of ITF demarks the constriction of Indonesian seaway.

Quaternary

Several new proxies have been used in micropaleontology from different regimes for Quaternary studies by Indian Scientists to understand the paleomonsoonal and paleoclimatic changes over time. Kiran Kumar & Ramesh (2017) compiled recent

high resolution foraminiferal $\delta^{18}\text{O}$ data from the eastern Arabian Sea cores and adopted the explanation of steady strengthening of the summer monsoon during the Holocene. Naik *et al.* (2017) report enhanced productivity in the south-eastern Arabian Sea during MIS 3 whereas the Last Glacial maxima (LGM) are characterized by an abrupt fall in productivity, with oxygen-depleted waters. A variable relationship between the south-eastern Arabian Sea and the North Atlantic interventions through oceanic or atmospheric circulation account for the contrasting productivity during Heinrich stadial (HS) event 1 and 2. The global $\delta^{13}\text{C}$ minimum during the last deglaciation was associated with the weak monsoon interval during HS-1 and reduced productivity. Saraswat *et al.* (2016), reported Mid-Holocene Climate Transition based on a major shift in evaporation-precipitation (E-P), accompanied by a net cooling of SST synchronous with a change in surface productivity during the mid-Holocene. The MHCT coincides with decreasing low-latitude summer insolation, perturbations in total solar intensity and an increase in atmospheric CO_2 . Naik (2016) also reconstructed SST in core AAS9/21 from the eastern Arabian Sea on two sets of planktonic foraminifera. The Mg/Ca values using *G. ruber sensu-stricto* are seen to be higher during the Holocene whereas during the deglaciation, reconstructed SST from *G. ruber sensu-stricto* and *sensu-lato* accounts for stronger upwelling. Singh *et al.* (2016) presented a multi-proxy record from a gravity core from the ocean upwelling area in the western Arabian Sea. Based on the analysis, three intervals of increased Southwest Monsoon Mode (SWM) were inferred at ~16 to 12 ka (SWMI-I), ~10 ka (SWMI-II) and ~8.2-8.0 ka (SWMI-III). Two intervals of increased Northeast Monsoon Mode (NEM-winter monsoon) have also observed around 19-17 ka and NEMI-II (~8.0-5.4 ka).

Das *et al.* (2017) discussed the development and intensification of the oxygen minimum zone (OMZ) in the north-western Arabian Sea during the Holocene from records on benthic foraminifera and suggested replacement by oxygenated southern sourced Sub-Antarctic Mode and Antarctic Intermediate Waters, with oxygen-deficient Red Sea Water from the north during the middle Holocene. Naik and Naik (2018) suggest that the CO_2 outgassing noticed during deglaciation makes the Arabian Sea, an interesting region to understand if the outgassing

occurred from the deeper waters and hence led to any rise in deepwater $[\text{CO}_3^{2-}]$. The study from Verma *et al.* (2018) includes the cores from the lower boundary of the present-day OMZ offshore Goa. This study reports the abundance of benthic foraminifera with planoconvex tests during the cold HS, with oxygenated sea bottom due to better ventilation and weaker OMZ. Simultaneously, the benthic foraminifera having tapered/cylindrical tests dominate during the LGM and the Holocene (5–8 ka BP), suggests an oxygen-depleted benthic environment. Singh *et al.* (2018) published a planktic foraminifera abundance and SST based record to decipher past changes in sea-surface hydrographic conditions from the southeastern Arabian Sea core. The study suggests that intensified winter winds during 17.5–23.5 ka BP, resulted in nutrient injection into surface waters and eutrophic conditions, mainly through deep vertical mixing and moderate upwelling; and reduction in winter wind intensity caused stratification characterized by the high tropical SST since 17.5 ka BP.

Paleoclimatic studies using multi-proxy records from the NE Arabian Sea revealed the variations in the shelf environment of the western continental margin of India (Azharuddin *et al.*, 2017; 2019). The periodicities in the multi-proxy record consisted of similar cycles, which also match with previously reported solar insolation influenced SWM and other global and regional cycles. The observations suggested that the solar insolation has been a leading factor responsible for the SWM trends during the Holocene, which may have further influenced the productivity, regional sea-level fluctuations and depositional conditions in the north-east Arabian Sea. In the western Arabian Sea oxygen isotopes data from planktic foraminiferal species (*G. sacculifer*) studied by Naidu *et al.* (2019) documented an increase in deglacial sea surface salinity seasonality attributed to the increase in winter evaporation and reduced monsoonal rainfall in contrast to the Holocene. Results shows a common winter-dominated SST signal in the Arabian Sea and Greenland during the last glacial period and the North Atlantic link to the Indian Ocean SST. Satpathy *et al.* (2019) from the eastern Arabian Sea (IODP site U1457) reported two distinct regimes of monsoon-induced changes in upper water structure. The period 1.85–2.7 Ma was attributed to an overall weaker South Asian/Indian winter and summer

monsoon circulations and the period between 1.55 Ma and 1.65 Ma was characterized by enhanced eutrophication of the mixed layer triggered by intensified winter monsoonal winds.

Khare *et al.* (2017) performed cluster analysis on benthic foraminiferal assemblage from 32 stations off the Mangalore-Cochin sector to study the ecological preferences and effect of depth on external test morphology. They grouped the foraminiferal distribution into three clusters and attributed the observed morphological changes to the sediment turbulence. Singh *et al.* (2018) document the vertical distribution of living benthic foraminifera along a depth gradient (58–2750 m) in the Gulf of Mannar to understand the sediment depth containing representative living assemblages of foraminifera populations and associated ecological parameters for their abundance. Singh *et al.* 2017 published a pteropod based record of factors affecting the Aragonite Compensation Depth (ACD) in the Arabian Sea. The study suggests that the ACD in the eastern Arabian Sea lies at ≤ 525 m water depth. The study also infers that the low dissolved oxygen coupled with the organic matter content in the sediments appears to favour better pteropod preservation in the eastern Arabian Sea.

Gebregiorgis *et al.* (2016) discuss the south Asian summer monsoon variability during the last ~54 kyrs inferred from $\delta^{18}\text{O}$ of seawater ($\text{D}\delta^{18}\text{Osw}$), sea surface salinity and Ba/Ca in *G. sacculifer* in the Andaman Sea. This study suggests that the South Asian Summer Monsoon (SAM) over the Irrawaddy strengthened gradually after the LGM begins at ~18 ka. Early to mid-Holocene SAM variability is characterized by a gradual intensification of monsoon rainfall with constant upper-ocean stratification. Peak monsoon strength during the mid-Holocene in the Andaman Sea is likely to be linked with combined precession and obliquity forcing. Sijinkumar *et al.* (2016a) reported rapid refreshing of the Andaman Sea during the LGM and sea-level low stand resulting in reduced surface water mixing with the open Bay of Bengal (BoB). $\delta^{18}\text{O}$ data of both surface and thermocline-dwelling species in the Andaman and northern BoB indicate colder and/or more saline conditions within the Younger Dryas. Sijinkumar *et al.* (2016b) adopted an abundance variation of *N. dutertrei*, *G. rubescens*, and benthic foraminifera to

demonstrate abrupt changes in the climate and oceanography related to Dansgaard-Oeschger (D/O) events and HS of the North Atlantic documented in the Andaman Sea. The lower abundance of *N. dutertrei* (corresponds to *G. rubescens* maxima) during HS, deglacial, YD and mid- to late-Holocene suggests reduced freshwater influx from the Irrawaddy and precipitation as a result of the weakening of summer monsoon driven by the teleconnection between North Atlantic climate and Indian monsoon. Another study from Neil Island, Andaman, and the Nicobar Islands by Chakraborty and Ghosh, (2016) document a strong monsoonal system with relatively weaker intermittent monsoonal activity. The dominance of diatom *Thalassionema nitzschioides* confirms the strong monsoonal activity and upwelling during the late Miocene in the study area.

Panmei et al. (2017) investigated the response of tropical Indian Ocean sea surface temperature (SST) to events such as the younger dryas (YD). SST reconstruction from the western BoB exhibits overall warming of 1.88°C during the YD. No significant negative SST anomalies in both the Arabian Sea and the BoB compared to pre- and post-YD suggests that no apparent cooling occurred during the YD in the Northern Indian Ocean. In contrast, most part of the YD exhibits positive SST anomalies in the Northern Indian Ocean that coincide with the slowdown of the Atlantic Meridional Overturning Circulation during this period. Kiran Kumar et al. (2017) demonstrate that there is no evidence to believe that the south Asian summer monsoon steadily declined during the Holocene, as reported in the earlier papers from the Western Arabian Sea. Kiran Kumar et al. (2018) inferred summer monsoon was weaker during MIS-3 than the early Holocene but was stronger than during MIS-2 from the $\delta^{18}\text{O}$ records of planktonic foraminifera. The $\delta^{18}\text{O}$ of *G. ruber* in the Andaman Sea is more depleted than that from southern BoB but more enriched in $\delta^{18}\text{O}$ in comparison with northern and western BoB core records during early Holocene. Sarathchandraprasad & Banakar (2018) studied the last 42 kyr sediment chemistry of oxygen-deficient coastal region (upper slope off Chennai) of the BoB. The $\delta^{18}\text{O}$ *G. sacculifer* time-series exhibits distinct enrichment ($\sim 0.4\%$) during the last glacial period (30-18 ka), and depletion ($\sim 2.2\%$) during the Holocene, suggesting a significant shift in ISM

intensity.

Soukhire et al. (2018) assessed the applicability of temporal changes in living benthic foraminiferal morpho-groups (Fig. 7) from the shelf and slope of the central-western BoB to reconstruct past monsoon changes in the last 2000 years. These authors reported an increased monsoon discharge during the Medieval Warm Period (MWP) and lowered during the Little Ice Age (LIA) and described a close relationship between the Monsoon and the solar activity. Shrivastav et al. (2016) discussed the problem arising from the use of several variants of *Globigerina bulloides* by different authors, particularly in the light of extensive use of a relative abundance of *G. bulloides* and stable isotopic analyses of its test as proxy indicator of paleomonsoon. This study illustrates that the picking up of a single morphotype of *G. bulloides* for isotopic analyses and advocates for a detailed genetic study of various morphotypes to get an enlightened picture of the species concept. Manasa et al. (2016) discuss the ecological preferences of two benthic foraminiferal morpho-groups namely rounded symmetrical and angular asymmetrical benthic foraminifera to reconstruct paleomonsoon from continental shelf region of the northwestern BoB. Saraswat et al. (2017) studied the abundance and Ecology of Endemic *Asterorotalia trispinosa* from the Western BoB. The spatial variation of *Asterorotalia trispinosa* abundance suggested for paleomonsoon reconstructions based on their ecological preferences.

Naidu and Govil (2017) used $\delta^{18}\text{O}$ and Mg/Ca ratio of planktonic foraminifera *G. ruber* from the BoB. The study suggests that the monsoon could kick the start of millennial-scale abrupt climate changes through the shifts of the Intertropical Convergence Zone (ITCZ) and associated convection, water vapour supply to the tropical troposphere and latent heat penetration. Raza et al. (2017) published an $\delta^{18}\text{O}$ and Mg/Ca ratio based SST record of northern Indian Ocean using two sediment cores from NE Arabian Sea and southern BoB. The study suggests significant changes in SST and $\delta^{18}\text{O}_{\text{sw}}$ since last glacial period. The glacial SSTs in the BOB and the NE Arabian Sea were lower by $\sim 2\text{--}2.5^\circ\text{C}$ relative to the Holocene. The SST time series in both these regions indicates a sudden and abrupt increase in temperature at the end of LGM. The SST time series in the NEAS core SK 148-21 reveals an intensification of the northeast

monsoon during the LGM. Study on both living (rose-Bengal stained) as well as dead agglutinated benthic foraminifera by Saalim *et al.*, (2019) assess the ecological preferences in the western BoB. Morphogroups from the fresh-water influx dominates western BoB and exceptionally high agglutinated benthic foraminiferal are abundant on the slope of the western BoB. A comprehensive study by Uddandam *et al.*, (2017) showed the spatial distribution of organic-walled dinoflagellates cyst in surface sediment samples from self and upper to middle slope in western BoB. Distribution of protoperidinioides in the upper-middle slope region in BoB indicted high nutrients and reducing environmental conditions for growth and preservation. Further, a new organic-walled dinoflagellate cyst *Cristadinium striatiserratum* sp. nov. has been reported from the modern sediments of the northern Indian Ocean (Uddandam *et al.*, 2018) (Fig. 9).

Few studies carried In the Vestfold Hill region of Antarctica, Raaza *et al.* (2018) reported two past storm-cyclone events based on two sets of inverted sediments sections from the core. The past storm-cyclone events based on the increased abundance of marine microfossils (foraminifera and diatoms in inverted layers) are suggestive of sediments transportation from the adjacent shelf. Saraswat *et al.* (2018) documented the spatial distribution of benthic foraminiferal morpho-groups from the Kongsfjorden-Krossfjorden and assessed its environmental significance. The significant correlation between foraminiferal parameters and water depth suggests that meltwater and glacial calving, as well as associated changes in the sedimentation rate, grain size, pH and organic carbon, affect benthic foraminifera in high latitudinal fjords.

The Southern Ocean is the least understood of the world's oceans, despite its vital role in the present climate system. Recent advances in the field of Southern Ocean paleoceanography by the Indian researchers have taken us a step closer to understanding the past climate variability at millennial and glacial-interglacial timescale. Nair and Mohan. (2017) reviewed in detail the paleoclimatic signals from the proxy records of the Southern Ocean to understand the past latitudinal variability of the Southern Ocean frontal systems and Antarctic sea-ice extent based on a multi-proxy approach. The multi-proxy approach

includes diatom size and productivity, magnetic, geochemical, and sedimentological parameters. The high-resolution records of diatom frustules from the Southern Ocean sediment cores revealed the control of iron availability or by other environmental conditions such as SST and/or sea ice presence on the morphometric variation of different diatom species. Shukla *et al.* (2016) reported the first study on modern sediments from the Southern Ocean to explore the variability of the mean valve area of *T. lentiginosa* in relation to productivity and modern environmental conditions (Fig. 8). *T. lentiginosa* means valve area variations in four deep-sea cores across the frontal zones in the Atlantic and Indian sectors of the Southern Ocean resulted from changes in SST and sea-ice presence modulating the species ability to make use of nutrient stocks and controlling the length of its growing season, respectively. Shukla and Crosta (2017) suggested that more favourable SST, within the *F. kerguelensis* ecological range, during the Last Glacial period may have enabled *F. kerguelensis* to make better use of the low silica stocks prevailing in the subtropical zone leading to larger valves. Shukla and Romero (2018) studied the *F. kerguelensis* size variation in core GeoB3606-1 collected in the Benguela Upwelling System, where *F. kerguelensis* valves were preserved during the glacial period (68–30/ ka) as a consequence of silicic acid leakage from polar to mid-latitudes. The altered growth rates of *F. kerguelensis* cells are attributed to the availability of iron through increased dust flux during the interglacial and glacial periods (MIS3 and MIS4).

Nair *et al.* (2019) documented the interactions between Southern Hemisphere high-latitude (Antarctica & Southern Ocean), southern Indian Ocean subtropics (Agulhas leakage) and Asian summer monsoon. Khare (2017) establish an interdependence of $\delta^{13}\text{C}$ values of planktic species *Globigerina bulloides* and the overall size of planktic foraminiferal population linked with the generation of food/nutritive in the sector (between 9.69°N and 55.01°S latitude and 80°E and 40°E longitude). Patil *et al.* (2017) studied the coccolithophore diversity in the Southern Ocean and suggested a direct correlation of temperature and nutrient concentration in water and sea surface samples collected from in Indian Southern Ocean Expedition. Mishra *et al.* (2017) investigated the variability of chlorophyll-*a* (*Chl-a*) and diatoms in the frontal ecosystems of the Indian

sector of SO. The maximum concentration of *Chl-a* and diatoms commonly observed in the SAF region are probably due to the moderate PAR, SST, and wind. The dominance of diatoms at the PF may be attributed to their adaptability for low light conditions. Hendrizan *et al.* (2016) studied the sediment core from the Andaman Sea which yielded 11 nannoplankton genus and discussed the importance of SEM images in nannofossil study. Taxonomy and detailed morphological description of calcareous nannoplankton from the Andaman Sea were explained in this study.

The systematic paleontology of textulariid, and miliolid foraminifera from the Arabian Sea has been carried out by Nimmy *et al.*, (2018). Also, miliolid foraminifera from shallow waters off the rocky island of Andamans has reported by Rajeshwara Rao *et al.* (2018). A sediment core was studied to infer the paleoecological characteristics of Pichavaram mangrove ecosystem, foraminifera distribution, percentage of CaCO_3 and organic matter content in the sediments (Jeyabal *et al.* 2016). Kannappan *et al.* (2016) studied community composition, density, richness, evenness, and diversity of meiobenthic fauna from Manakudy estuary, west coast of India. To investigate the rate of sedimentation and eutrophication processes in the Pulicat lagoon, Fulmali *et al.* (2017) studied a short core from the lake. The results suggest that bottom of core was dominated by the brackish water diatom species in hypertrophic conditions and top of the core was dominated by marine diatom species under the oligotrophic condition. The marine, as well as brackish water diatoms species, also show their tolerance towards pollutant which is caused by the anthropogenic activity. Studies on foraminifera distribution, ecology, sediment characteristics and its implication environmental changes in offshore region, river, and beach around Palk Strait, Tamil Nadu was studied (Suresh Gandhi *et al.*, 2017; 2018, Kasilingam *et al.*, 2019). Estuaries form Nellore coast, East India studied by Reddy *et al.* (2016) and reported foraminiferal test abnormalities in presence of heavy metal concentrations. Because of the effect of heavy metal pollution in these estuaries, drastic changes in the number of species and diversity of foraminifera were observed. Jeshma *et al.* (2017) studied the foraminiferal species to determine the environmental conditions in the Puravadaianar and Vettar estuary, Karaikal, along the southeast coast of

India. It has also reported that the impact of heavy metal pollution on benthic foraminifera was very less in the study area.

Gangadhara Rao & Kumar (2016) have studied a rich assemblage of foraminifera for ecological interpretations from the east coast of India (Gosthani River Estuary, Andhra Pradesh). Rajeshwara Rao (2016) presented a thorough review of foraminifera studies from the Muthupet Lagoon and also studied three cores to elaborate infaunal characteristics of benthic foraminifera from Muthupet Lagoon. Bhaumik *et al.*, (2017) discussed the habitat-wise isotopic variation and estimation of isotopic correction factors for the paired species benthic foraminifera from the Krishna– Godavari basin and Peru offshores. Tripathi *et al.*, (2018a) report the basin submergence in part of Sundarban mangrove delta with evidence from benthonic foraminiferal assemblages. The peculiar presence of intertidal assemblage above the upper marshes assemblages in recent sediment points towards the theory of submergence due to relative rise in the sea level. To understand the submarine behavior of these channels and associated meiobenthos, benthic foraminifera were studied from off Bakkhali, West Bengal, India (Tripathi *et al.*, 2018b). The study reveals that a total of fifteen species of recent present and their distribution mainly controlled by channel morphology and sediment character. In a case study from the Zuari estuary, Goa (Saalim *et al.*, 2017) reported the response of benthic foraminifera to changes in mining pattern and discussed the use of benthic foraminifera as an effective tool to monitor the impact of mining. They further suggest that the potential counter effect of terrigenous dilution on total and living benthic foraminiferal population should be considered while interpreting temporal variations in foraminiferal abundance in marginal marine settings. Dubey *et al.*, (2018) studied seasonal foraminiferal distribution in the Mudbank formation to understand the foraminiferal response to Physico-chemical changes associated with mudbank formation off Alleppey, Kerala and found low diversity of benthic foraminifera in the mudbank during both pre-monsoon and monsoon season which suggests a stressed environment.

A comprehensive review of the occurrence and implications of Ostracodes is presented by Hussain (2017) from the east and west coast of India. A fair

assemblage of foraminifera and ostracods were recorded by Hussain and Casey (2016) from the North Chennai Coast, Tamil Nadu. Identified species of foraminifera and ostracods are characteristics of the benthic, shallow, inner shelf (inner neritic) to marginal marine, tropical and distributed in intertidal sediments due to tides as well as longshore currents. They have also reported one endemic ostracoda species namely *Basslerites liebau*. Again fair population of foraminifera and ostracoda were recorded by Hussain *et al.* (2016) from the Kovalam beach, Thiruvananthapuram, Kerala. The distribution pattern of the individual taxon was examined, and their sediment relationship was determined for environmental interpretation. Hussain *et al.* (2017) studied foraminifera and ostracoda for ecological implications from the beach sands of Tuticorin Coast, Tamil Nadu and found that sand substrate was congenial for the population abundance. Predation marks on foraminiferal tests and change in their color have also noticed in few species with few broken and abraded tests which indicates the high amplitude of tidal agitation and comparatively low deposition of sand in the beach environment of Tuticorin coast. Hussain *et al.* (2018) studied the systematic and distribution of recent brackish water Ostracoda from the Pulicat lagoon, Tamil Nadu. An attempt has also been made to bring out the relation between the sediment characteristics and the Ostracoda population and to evaluate the favourable substrate for the population abundance in Pulicat Lagoon. From the study, it was inferred that the sandy substrate is congenial sediment type for the population abundance and distribution of ostracoda. Nazeer *et al.* (2018) carried out a preliminary study on marine ostracoda from BoB core. Depth-related distribution of ostracod fauna was reported from the seven transects of Sagar Kanya, SK 308 Leg-1, off central BoB (Nishath *et al.* 2017). The study displayed the maximum diversity of ostracods in shallower water rather than in the deeper water, which may be due to the optimum temperature, pH salinity, and substrate. It also provides a detailed account of bathymetry and associated changes in ostracod biodiversity.

Nigam *et al.* 2016 published a study from Dholavira, Gujarat India, suggesting that the ancient Indians (Harappan settlements) were aware of Tsunami/storm protection measures. They built fortification of maximum wall thickness up to 18 m,

which is extraordinary. Sreenivasulu *et al.* (2017a) presented a review of field and laboratory methods that have been used in recent foraminiferal studies (between 2000 and 2015) in the Indian coastal regions. Also, they attempted to quantify the organic matter using Fourier Transform Infrared Spectroscopy (FTIR) in benthic foraminifera shell from the Tupilipalem coast, BoB, Southeast coast of India (Sreenivasulu *et al.* 2017b). Their study suggests both a shift to a higher frequency and an increase in absorption strength for the band were observed from the beach and brackish environments. It indicates that the biological activity for brackish water is modified significantly due to its higher nutrient concentration. Sreenivasulu *et al.* (2019) used benthic foraminifera as a bio-indicator for assessing the environmental stress in the Beypore estuary. They computed the benthic foraminiferal diversity index and inferred that the estuary was dominated by stress-tolerant taxa due to the prevalence of hypoxic (low-oxygen) conditions.

Kurtarkar *et al.* (2017) reviewed the recent experimental research on foraminifera regarding factors that bring about changes in benthic foraminiferal abundance, diversity, morphology, the isotopic and chemical composition of the test. Also, they conducted a laboratory culture experiment on *Cymbaloporella plana* to understand the coupled effect of temperature and food (Kurtarkar *et al.*, 2019). From the experiments, they reported that at all temperatures, growth increased with an increase in food. They suggest warming, coupled with decreasing productivity is likely to affect the growth and abundance of shallow-water benthic foraminifera severely.

A textbook on “Micropaleontology and Its Applications” authored by the Kathal P K, Nigam R and Talib A (2017). This book is useful for the young researchers and students to understand the processes of micropaleontology and broader application.

Summary

The utility of foraminifera, nannoplankton, dinoflagellate, ostracod, diatoms, coralline algae, and radiolarian, etc. in the sediments has been well established in the recent decades for the paleoceanographic and paleoclimatologic studies. In this article, the authors describe the applicability of different microfossil proxies in ocean/marginal marine

regimes to understand the paleoclimatic, paleoceanographic and environmental changes. We identify and highlight the significant on-going discussions and gaps in knowledge which we expect to define the next decade of multiple disciplinary research into past palaeoenvironmental, paleoceanographic and paleoclimatic reconstruction. Few contributions span from extant to extinct (Permian–Pliocene) microfossil research with an emphasis on ecology, biofacies, and paleoecology in the Indian subcontinent as well as those working throughout the Indian Ocean region and beyond (Kathal *et al.*, 2017). One report published on the deeper time scale (Paleozoic era: late Ordovician–early Silurian) record of calcareous green algae from Tethyan Himalaya of India (Shabbar *et al.* 2019). Recent studies from the Callovian age sediments of Fakirwari and Habo domes (Kutch Basin) were deposited in open marine middle and middle to outer shelf respectively with the fluctuating shoreline. The foraminiferal assemblages of these two domes show connectivity with Indo-East African Province while the Kimmeridgian age dinoflagellate cyst recorded from Wagad Uplift situated towards the east of Kutch Basin show Gondwanan (Australasian) affinity. More studies on this aspect are required (based on different marine microfossils) to give a better picture of the paleogeographical position of the Indian subcontinent in Jurassic time. The succession deposited during the K-Pg transition from Central India has provided a remarkable study related to the timing of angiosperm diversification. In another study from NE India, a pulse of warming superimposed on global cooling has been recorded just before the K-Pg transition.

From the Paleogene period of India, work

has been done from NE and western India using several biotic proxies for a systematic, biostratigraphic and paleobiogeographical framework. In recent years the abiotic proxies such as geochemical characterization including stable isotope studies, facilitated better identification of signals of paleoenvironmental variability even up to demarcation of the global climate events of Paleogene times. Neogene marine microfossil studies enhanced understanding of their biostratigraphic ranges and facies relationships as a tool for the study of shallow-water carbonate deposits.

Quantification of the past climate change is necessary for the reconstruction of reliable models to understand the present and/or future predictions. Excellent studies have been carried out in the Quaternary period by Indian scientists to understand the paleoclimatic, paleoenvironmental and paleoceanographic changes in the Indian Ocean (including the Arabian Sea and Bay of Bengal), Southern Ocean, coastal and estuarine regions (SW and SE coast, India). These high-resolution studies provided both short-term and long-term changes in the Indian monsoon system, land-sea interaction, oceanic teleconnections, etc. Still, few gaps exist in our knowledge of the robustness of different proxies used in providing quantitative and qualitative insight into past and present climatic conditions. It is crucial to understand that these proxy parameters can be universal and the proper use of these records is necessary for a comprehensive perspective on past environments. The increasing participation in the ongoing global scientific programs and active involvement can fill the gap and augurs well for the future progress of geoscience studies in India.

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