Chapter II

Review of literature

A thorough review of literature of deep-sea foraminiferal research is always next to impossible as there are innumerable publications in the form of research papers, atlases, monographs, articles, short communications and even queries and answers to published material. In this chapter, however, an attempt has been made to present at least some of the important contributions made by researchers on a global (post-1990) as well as national status as comprehensive as possible.

2.1 International scenario

The role of benthic foraminifera in deep-sea food webs and carbon cycling was investigated by Gooday et al. (1992), who opined that these micro-organisms play a largely unquantified but potentially significant role in deep-sea carbon cycling.

The distribution of Holocene benthic foraminiferal species in bottom sediments in the Izu-Bonin Arc region of the north-western Pacific Ocean was investigated by Kaiho and Nishimura (1992) on the basis of 23 samples recovered from water depths ranging between 1,100 and 4,100 m. They identified four species assemblages corresponding to four bathymetric zones: the abyssal zone (below 3,700 m water depth), lower bathyal zone (2,600–3,600 m), lower middle bathyal zone (1,600–2,300 m), and upper middle bathyal zone (above 1,300 m). They opined that to estimate Quaternary and Pliocene paleobathymetry in this region, three water-depth indexes would work well: 3,700 m for the CCD, 2,300 m and 1,600 m for the deepest habitat and shallowest habitats of B. aculeata.

According to Linke (1992), who analyzed adenosine tri-phosphate (ATP) content and metabolic activity of benthic foraminifera from deep-sea sediments of the Norwegian-Greenland Sea, such species as Cribrostomoides subglobosum, Pyrgo rotalaria and Rhabdammina abyssorum undergo large fluctuations in seasonal values of ATP and heat production, but retain a high, relatively constant ATP turnover rate, enabling these taxa to take quick advantage of sudden nutrient inputs. This state of readiness is, however, maintained at the cost of the protoplasm, which is metabolized during times of starvation.

Clarke et al. (1994) examined a suite of 62 surface and near surface samples collected from a water depth range of 110 to 8,900 m, and distributed across the tropical south-west Pacific Ocean, north and east of Australia for benthic foraminiferal faunas. They identified 606 species and recognized assemblages characteristic of different water masses in the region.

Smart et al. (1994) investigated a core retrieved from the northern edge of the Nazca Ridge in the Pacific Ocean at a water depth of 2,530 m, where the spring bloom of phytoplankton leads to a seasonal pulse of phytodetritus to the ocean floor. According to them, one of the opportunistic benthic foraminiferal species, Epistominella exigua exhibits periodic peaks in abundance in the fossil record at many open ocean locations. Although such peaks had been previously interpreted as a consequence of changes in physico-chemical properties of bottom water mass and deep-sea circulation, they proposed that E. exigua could be used as a proxy for pulsed organic matter inputs to the deep ocean and, thereby, as an indicator of relative changes in productivity.

Recent foraminifera from the continental shelf and slope off Kaikoura, New Zealand were studied by Cameron (1995), who observed that samples from relatively greater water depths ranging between 940 and 1,920 m contained the highest proportion of planktic foraminifera, whereas 80% of the total fauna was planktic in a water depth range of 2,152–2,155 m.
A comparative study was carried out between two planktic foraminiferal species – *Globorotalia tumida* and *Globigerinoides sacculifer* – in a depth transect on the Ontong Java Plateau in the western equatorial Pacific Ocean by Brown and Elderfield (1996). While *G. tumida* tests from core top sediments exhibited decreasing Mg/Ca and Sr/Ca ratios with increasing water depth (1,600–4,400 m), tests of *G. sacculifer* larger than 355 µm showed no variations. They opined that although *G. tumida* is considered as a dissolution-resistant form, majority of Mg/Ca and Sr/Ca depletion (and chamber loss) occurs above the lysocline.

Ishman and Foley (1996) identified distinct depth distribution of three dominant benthic foraminiferal assemblages: the *Textularia* spp.–*Spininctammina biformis*, *Cassidulina teretis* and *Oridorsalis tener–Eponides tumidulus* biofacies that were strongly controlled by the dominant water masses within the Canada Basin: the Arctic Surface Water, Arctic Intermediate Water and Canada Basin Deep Water. Their study was based on box core surface samples taken from a transect down the Northwind Ridge into the Canada Basin and onto the Beaufort Sea shelf (48 to 3,808 m water depth), during the U.S. Geological Survey 1992 (PI92-AR) and 1993 (PI93-AR) Arctic cruises aboard the U.S. Coast Guard Icebreaker *Polar Star*.

Whether δ¹³C of organic matter bound within the crystal lattice of foraminiferal calcite tests might provide a potential tracer of the isotopic composition of the surface water primary photosynthate was discussed by Maslin *et al.* (1996), who opined that it was theoretically possible to estimate paleo-surface water pCO₂. Their initial surface water pCO₂ estimates from a deep-sea core retrieved from a water depth of 3,547 m on the East Thulean Rise in the north-east Atlantic Ocean indicated that this region might have been a greater sink for CO₂ during the last glacial than during the Holocene.

A compilation on the reliability and trustworthiness of benthic foraminiferal proxies based on Recent and Late Quaternary samples material from the polar oceans collected from the sea floors of the Arctic Ocean, the Norwegian/Greenland seas and the North Atlantic Ocean as well as from the Weddell Sea and the South Atlantic Ocean was made by Mackensen (1997). He concluded that paleontological proxies could be quantitatively interpreted, but only under consideration and with knowledge of ecologically limiting threshold values.

Planktic foraminiferal census data were collected on 34 surficial sediment samples from east of New Zealand by Weaver *et al.* (1997), who compared sea surface temperature estimates derived from the data using the modern analogue technique (MAT), data from CLIMAP’s FA-20 equation, and data computed from oxygen isotope analyses of *Globigerina bulloides*. They noted that the temperature estimates compared well among the three methods and were found to correlate closely with the appropriate seasonal sea-surface temperature as measured by satellite. The foraminiferal assemblages and derivative temperatures clearly identified the major watermasses and oceanic fronts in the region, and thus can be applied to palaeoceanographic analysis of south-west Pacific sediments.

Chen and Prell (1998) examined faunal distribution patterns of planktic foraminifers in surface sediments (two core tops) of the low-latitude Pacifico to compare with direct observations of SST as well as the depth of thermocline (DOT), a primarily important variable for describing the vertical structure of upper-layer oceans at low latitudes. Results of their study indicated that the effect of DOT controls on faunal distributions of planktic foraminifers in this region is important and interpreting the DOT or other hydrographic variables of upper-layer oceans from planktic foraminifer faunal data would be more appropriate in future palaeoceanographic applications.

According to Gross (1998), benthic deep-sea foraminifera are largely fueled by organic matter arriving from the sea-surface and they respond rapidly to incoming phytodetritus. In order to study such a response, he conducted laboratory experiments with special microcosms and living foraminifera from down to 2,880 m water depth were successfully maintained and
observed. Results indicated that deep-sea foraminifers were not slower in their migration speeds than shallow water species; moreover, no differences in speed for epifaunal or infaunal foraminifera were observed. In contrast, factors such as temperature, food concentration and oxygen content clearly influenced the benthic foraminifera.

Bathymetric distribution and microhabitat partitioning of live (rose Bengal-stained) benthic foraminifera along a shelf to bathyal transect ranging in depth between 146 and 1,200 m in the southern Adriatic Sea were studied by de Stigter et al. (1998). They observed that total numbers of deposit-feeding foraminifers decreased on a fairly regular basis with increase in water depth, and attributed this to possible decrease in organic matter flux.

Eguchi et al. (1999) deployed three time series sediment traps in the central North Pacific Ocean along 175° E for about one year, at water depths of 1,412, 1,482 and 3,873 m, respectively, to study the seasonal response of planktic foraminifera to surface ocean conditions, and observed that both temporal and regional fluxes of planktic foraminifera showed large variations during the experiment. They noted that, in general, total foraminiferal fluxes (TFFs) showed positive correlation with organic matter fluxes (OMFs), suggesting that food availability is one of the factors controlling the production of planktic foraminifera in the region.

A review of temporal variability in living deep-sea benthic foraminifera by Gooday and Rathburn (1999) revealed that the population dynamics of deep-sea benthic foraminifera (total live populations and individual species) appeared to be controlled largely by two inversely-related parameters, the flux of organic matter to the seafloor and concentrations of oxygen in the sediment porewater. They opined that organic matter food inputs are most intense along bathyal continental margins, and their oxidation often leads to the depletion of oxygen in surface sediments, and under such conditions, foraminiferal faunas are dominated by low-oxygen tolerant, infaunal species, the abundance of which fluctuate in response to seasonally varying amounts of food and oxygen.

Benthic foraminifera in gravity and piston cores from two sites of the northern and southern slopes of the South China Sea (SCS) were analyzed by Jian et al. (1999) to evaluate changes in surface productivity and deep-water mass characteristics over the last 40,000 years. Their observations suggested that changes in organic carbon flux (food supply) and chemical and/or physical properties of the ambient water mass might be the two primary and inter-correlated factors controlling the distribution patterns of benthic foraminifera.

The wall structure and test morphology in three large deep-sea agglutinated foraminifers, Rhabdammina parabyssorum, R. Abyssorum and Astrorhiza granulosa, were studied by Gooday and Smart (2000), who described some novel test-wall features in two species, R. parabyssorum from the Arabian Sea and A. granulosa from the north-east Atlantic Ocean. They observed that these large, agglutinated foraminifers have tests which consist of a central inflated region giving rise to a variable number of radiating arms. Both species include two- and three-rayed morphotypes and both have a two-layered wall structure in which a thin inner layer is overlain by a thicker, outer, friable layer.

Schönfeld and Zahn (2000) used records of benthic foraminiferal assemblage variations and benthic δ^{13}C along 12 sediment cores from the western Iberian Margin, between 36° and 42° N at water depths from 820 to 3,580 m, to monitor fluctuations of the Mediterranean Outflow Water (MOW) during the past 30,000 years. They observed that increased abundances of suspension feeding benthic foraminifers closely match areas where the recent MOW core layers impinge on the continental slope at 800 and 1,300 m water depth, and near-bottom current velocities are enhanced.

Recent planktic foraminiferal analysis in 52 surface sediment samples collected from the Ryukyu Arc region in the north-west Pacific Ocean and the adjacent East China Sea yielded 39 species (Ujiie and Ujiie, 2000). They classified the Globigerinoides ruber species group and G.
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sacculifer to be susceptible to carbonate dissolution, the Pulleniatina group, Neogloboquadrina dutertrei, Globorotalia menardii and G. tumida to be dissolution-resistant, and Globigerina bulloides and Globigerinella calida to suggest the influence of cold water invasion.

Altenbach and Struck (2001) compiled a data set of 212 locations from 2 to 9,300 m water depth covering the Arctic, Atlantic, Indian and Pacific oceans to compare benthic foraminiferal biomass values with the annual flux rates of organic carbon to the sea floor. They estimated that a decrease of annual flux rates by a factor of ~10 causes a decrease in mean foraminiferal biomass by a factor of >100. They considered this to be an adaptation to lowered efficiency in gathering food and increased amount of biodegraded matter.

The distribution of living (rose Bengal-stained), dead and fossil benthic foraminifera was investigated by Edelman-Furstenberg et al. (2001) in six short cores retrieved from the central Red Sea at water depths ranging between 366 and 1,782 m. They observed that although the extremely high values of temperature and salinity were constant below ~200 m in the sea, the flux of organic matter to the sea floor varied considerably with bathymetry and appeared to be the principal factor controlling the distribution pattern of benthic foraminifera.

Havach et al. (2001) presented present the first trace metal partition coefficients obtained from reproducing cultures of deep-sea benthic foraminifera. Paleoceanographically important species, including juvenile Bulimina marginata, Cibicidoides pachyderma, and Uvigerina peregrina, were maintained in sediment microcosms at 10°C, 35 psu, and pH 8 for 1–3 years. They also measured Ba/Ca partition coefficients (D_Ba) in replicate for Bulimina marginata (0.24 ± 0.07) and Uvigerina peregrina (0.24 ± 0.06, and found them to closely match the ranges from the Ontong Java Plateau.

Analysis of material collected from the Laptev Sea in a wide water depth range of 8 to 3,171 m from six Arctic expeditions by Lukina (2001) yielded 130 foraminiferal species, of which 62 were arenaceous, agglutinated taxa. Though she observed changes in species composition with increasing depth, they were not as distinct as could be expected considering the abrupt variations in depths, and were attributed to strong currents and characteristic bottom relief features of the sea.

The depth distribution of Recent deep-sea benthic foraminifera east of New Zealand was studied by Hayward et al. (2001) for realizing their potential for improving paleobathymetric assessments of Neogene microfaunas. They opined that the upper depth limits of some benthic foraminiferal species (e.g., Fursenkoina complanata 200 m, Bulimina truncata 450 m, Melonis affinis 550 m, Eggerella bradyi 750 m, and Cassidulina norvangi 1,000 m) have potential to improve the precision of paleobathymetric estimates. On the other hand, they felt that taphonomic loss of most agglutinated tests, except for some textulariids, in the abyssal zone negates the potential usefulness of these taxa in paleobathymetric assessments.

Heinz et al. (2001) studied the response of deep-sea benthic foraminifera from the Mediterranean Sea to simulated phytoplankton pulses under laboratory conditions, and observed enhanced population densities when algae was added as food material. They also demonstrated that deep-sea benthic foraminifera developed a normal vertical distribution pattern, and comparisons of vertical distributions of individual species from laboratory cultures and field studies exhibited identical patterns.

Benthic foraminiferal thanatocoenoses were studied in 29 sediment surface samples off north-west Africa, between 19° and 27° N, and from water depths between 506 and 3,314 m (Morigi et al., 2001). They compared the results with estimated values of the downward organic flux and measured bottom water oxygen concentrations. On the basis of R-mode multi-variate statistical analysis, they recognized six species clusters that were separated geographically by differences in organic flux and water depth.
The depth distribution of living (rose Bengal-stained) benthic foraminifera in near-surface sediments was analyzed by Schönfeld (2001) along four short cores from the western Iberian Margin and Gulf of Cadiz at water depths from 800 to 1,920 m. They noted that more than 50% of the benthic species occupied extended sediment depth habitats and a wide range of oxygen levels among the sites studied. They also listed *Globobulimina affinis*, *Chilostomella ovoida* and *Bathysiphon capillare* as indicators of dysoxic conditions. Moreover, many species considered earlier to be sub-oxic indicators were actually ubiquitous or preferred microhabitats at oxic levels. Fontanier et al. (2002) selected five stations to compose a rather ideal SE-NW transect, ranging from the outer shelf to bathyal open slope environments at water depths ranging between 140 m and 1,993 m in the meso-oligotrophic Bay of Biscay. They observed that a diminishing downward organic matter flux with depth was accompanied by an important decrease of the live foraminiferal density. Although bottom water oxygenation was not directly influenced by organic matter input, the oxygenation of interstitial waters and the primary redox fronts did change in response to variations of the organic matter flux. They suggested that the occurrence of deep and intermediate infaunal taxa could be linked to fundamental redox fronts and putative associated bacterial consortia.

Environmental conditions and productivity changes in the south-eastern Okhotsk Sea were reconstructed for the last 20,000 years by Gorbarenko et al. (2002) using planktic and benthic foraminiferal oxygen isotope records and CaCO₃, organic carbon and opal content data from two sediment cores retrieved from water depths of 1,590 m and 1,175 m, respectively. Species variability in benthic foraminiferal and diatom assemblages provided them additional paleoceanographic evidence, and variations in benthic foraminiferal assemblages with time, helped them to recognize seven zones with different species composition. Hayward et al. (2002) analyzed the factors influencing the distribution patterns of Recent deep-sea benthic foraminifera, east of New Zealand, south-west Pacific Ocean, and concluded the following: (i) the occurrence of the bathyal associations (230–2,840 m), dominated by *Cassidulina carinata*, *Alabaminella weddellensis* and *Abditodentrix pseudothalmanni*, closely mirrors the distribution of Antarctic intermediate water within a region of variable food supply; and (ii) the sustainability of food supply combined with bottom water type and associated ventilation and dissolution strongly influence the composition of abyssal associations (1,200–4,700 m), mostly dominated by *Epistominella exigua* and *A. weddellensis*.

According to Gooday (2003), flux proxies are based on the benthic foraminiferal accumulation rate (BFAR) and multi-variate analyses of species data. Oxygen proxies utilize the relative proportions of epifaunal (oxyphilic) and deep infaunal (low-oxygen tolerant) species. He opined that many problems still remained, particularly those concerning the calibration of proxies, the closely inter-woven effects of oxygen and food availability, and the relationship between living assemblages and those preserved in the permanent sediment record.

Recent benthic foraminifera from offshore Taranaki, New Zealand, were studied by Hayward et al. (2003), who observed that the lower bathyal to upper abyssal (1,400–2,150) associations are dominated by *B. marginata f. aculeata* and *Globo cassidulina substubosa* (both) along with *Alabaminella weddellensis* in the >63 µm and *Uvigerina peregrina–Oridorsalis umbonatus* in the >150 µm fractions, respectively. However, they noted that species diversity measures did not show any useful pattern with depth.

Smith and Gallagher (2003) studied nine bathyal (reduced oxic) samples from depths between 995 and 2,980 m. This zone was classified as ‘reduced oxic’ due to the high percentage of *Rhabdammina* spp. and *Bulimina marginata*, and zone also corresponds with the OMZ of the data from Levitus (1982). They also studied seven middle to lower bathyal (oxic) samples come from depths ranging between 1,025 and 3,931 m, and suggested that increased dissolved oxygen
conditions exist compared to the ‘reduced oxic’ samples described earlier due to a decrease in abundance of the reduced oxygen indicators, such as *Rhabdammina* spp. and *Bulimina* spp.

Laboratory experiments were carried out by Geslin *et al.* (2004) to investigate the migratory responses of deep-sea benthic foraminifera to changing bottom and pore water oxygen concentrations under conditions of controlled temperature and salinity. Their results showed that some deep-sea species can actively migrate along the sediment column to reach their favorite microhabitat; they also suggested that changes in oxygen content are mainly responsible for those migrations.

Lithium/calcium ratios were measured in planktic and benthic foraminifera from a variety of hydrographic settings to investigate the factors influencing lithium incorporation into foraminiferal tests including temperature, dissolution, pressure, and inter-species differences (Hall and Chen, 2004). Down-core measurements of planktic (*Orbulina universa*, *Globigerinoides ruber*, and *G. sacculifer*) and benthic foraminifera (calcitic *Cibicides wuellerstorfi* and aragonitic *Hoeglundina elegans*) showed a systematic variation in Li/Ca with δ¹⁸O through the last glacial–interglacial transition.

Tachikawa and Elderfield (2004) analyzed Cd/Ca, δ¹³C and Mg/Ca of six species of benthic foraminifera with different microhabitats from throughout the sediment-mixed layer at three well-characterized sites in the north-eastern Atlantic: *Cibicidoides wuellerstorfi*, *Uvigerina peregrina*, *Cibicides bradyi*, *Melonis barleeanum*, *Bulimina striata* and *Hoeglundina elegans*. They compared δ¹³C in foraminifera with bottom water and pore waters to estimate average calcification depths within the sediment for each species and thereby determine D_Cd based on the Cd concentrations at different depths of the water column. They observed that D_Cd for *C. wuellerstorfi* was 3.2 ± 1.1 at 3,600 m water depth and 3.9 ± 1.3 at 1,900 m, in accordance with the D_Cd estimates from culture experiments.

The impact of late Quaternary environmental changes on deep-sea benthic foraminiferal faunas of the Red Sea was studied by Badawi *et al.* (2005), who observed that a comparison with recent faunas from the Red Sea and adjacent oceans allowed the reconstruction of temporal changes in deepwater ventilation, salinity and food availability at the seafloor. Generally, the abundance of infaunal and miliolid taxa increase during glacial intervals indicating increased organic matter fluxes, oxygen decrease and salinity increase in deep waters during these times.

The ash layer from the 1991 Mt. Pinatubo eruption provided a natural laboratory to assess mass mortality and the rates of recovery of deep marine ecosystems after a catastrophic event and to draw a parallel with the environmental impact of the K/T boundary event on deep-sea foraminiferal communities (Kuhnt *et al.*, 2005). According to them, the first re-colonization assemblages of benthic foraminifers after the Mt. Pinatubo ash fall exhibited surprising similarities with benthic foraminiferal communities established following the K/T boundary event, i.e., comparatively low abundance and diversity, absence of suspension feeders, dominance of mobile infaunal taxa and a high proportion of agglutinated foraminifers. They realized that the first foraminifers to re-colonize the deep-sea after both catastrophic events were opportunistic forms with high capability for rapid dispersal.

Hayward *et al.* (2006) investigated the ecologic distribution of Recent benthic foraminifera off north-east New Zealand, and concluded that the depth-stratified distribution of lower bathyal to abyssal (>1,000 m) associations accords well with the deep water masses, and attributed it partly to lower oxygen concentrations in the bottom waters. Canonical correspondence analysis showed that the associations correlated most strongly with factors related to water depth, especially decreasing food supply (organic carbon flux) with increasing depth.

In order to understand the distribution patterns of modern benthic foraminifers in bathyal and abyssal waters of south-western Gulf of Mexico, Machain-Castillo *et al.* (2006)
analyzed species data from twelve core-tops (water depth 960–3,255 m). Using multi-variate Q-mode factor analysis, they distinguished foraminiferal faunas of the North Atlantic Deep Water (NADW, deeper than ~2,000 m), dominated by *Nuttallides decorata*, *Alabaminella turgida*, *Ioanella tumidula*, and *Globocassidulina subglobosa*, from those of the shallower Subantarctic Intermediate Water (AAIW) and Caribbean Midwater (CMW), characterized by the association of *Bolivina lozanoi*, *Bulimina aculeata*, *Alabaminella turgida*, *Globocassidulina subglobosa*, *Epistominella exigua*, and *E. vitrea*.

Martinez et al. (2006) explored the responses of community assemblages of planktic and benthic foraminifera and coccolithophorids to transient climate change over the last ~40,000 years. Their study was based on analysis of the uppermost 2 m of two cores retrieved from the Panama Basin at water depths of 3,461 m and 2,200 m, respectively. According to them, the deglaciation interval was a period of enhanced productivity and major re-organization of planktic trophic webs. They also identified four periods of oceanographic change: advection (24,000–20,000 years), strong upwelling (20,000–15,000 years), weak upwelling (14,000–8,000 years), and oligotrophy (8,000 years to present).

The distribution of planktic foraminifera from the continental slope onto the shelf of the south-eastern Bay of Biscay was discussed in relation to environmental factors by Retailleau et al. (2006). Samples were obtained between March and November, 2006–2008, along a bathymetric transect from 145 to 2,000 m water depth, from 50 km off the shelf-break onto the outer shelf. They observed that chlorophyll-a concentration (i.e., food) and fresh water input were found to affect the abundance of planktic foraminifera; however, they did not find any influence of water depth or proximity to the shelf.

Several surface samples and cores from the western European and African continental shelf and slope, along with few from the abyssal plains were studied by Schönfeld (2006) to comprehend the taxonomy and distribution of *Uvigerina peregrina* in the tropical to north-eastern region of the Atlantic Ocean. A new species, *Uvigerina celtica* n. sp. was erected and the regional distribution and inferred population dynamics revealed that *Uvigerina peregrina*, *U. celtica* and *U. pigmea* were indeed different species. It was suggested that *U. peregrina parva* was most likely a subspecies of *U. peregrina* and not an ecophenotype.

Coxall et al. (2007) observed that digitate species of planktic foraminifera are usually rare in fossil and modern assemblages but show increased abundance and diversity at times during the Cretaceous and middle Eocene. They suggested that the primary function of digitate chambers was as a feeding specialization that increased effective shell size and food gathering efficiency, for survival in a usually food-poor environment, close to the oxygen minima zone (OMZ), and that episodes of increased digitate abundance and diversity indicate expansion of the deep-water ecologic opportunity under conditions that were unfavorable to other planktic species.

According to Diz et al. (2007), who investigated benthic foraminiferal assemblages and carbon isotope composition of the epifaunal benthic foraminiferal species, *Epistominella exigua* and *Fontbotia wuellerstorfi* from a core retrieved from the Agulhas Plateau at a water depth of 2,660 m, They opined that *E. exigua*, more faithfully records the amplitude of ambient bottom water δ¹³C DIC (dissolved inorganic carbon) changes than *F. wuellerstorfi*, notably in settings such as the Southern Ocean that experienced substantial changes through time in the organic carbon supply to the seafloor.

Live (rose Bengal stained) foraminiferal faunas were investigated in surficial sediment (0–1 cm) from mid-shelf to mid-slope environments in the Bay of Biscay, at water depths ranging from 80 to 2,000 m (Duchemin et al., 2007). They observed a bathymetric zonation of taxa on the continental slope from upper-slope sites (550–1,000 m) rich in *Epistominella exigua* and *Uvigerina peregrina* to mid-slope stations (1,600–2,000 m), where *Nuttallides pusilus* and *Gavelinopsis translucens* dominated the small-sized living fauna. They suggested that this bathymetric
foraminiferal zonation probably reflected a trophic gradient between upper-slope eutrophic stations and mid-slope, more oligotrophic sites.

Hayward et al. (2007) investigated the combination of environmental factors that influence the distribution patterns of benthic foraminiferal tests in a topographically varied region south-east of New Zealand in a water depth range of 50 to 5,000 m. They identified three mid-bathyal to upper abyssal associations (500–3,300 m), dominated by *Alabaminella weddellensis*, *Cassidulinacarinata*, and *Epistominella exigua*, occurring in biopelagic sandy mud, beneath a region of strongly seasonal food supply, with their composition influenced by total food flux, ventilation, and bottom current strength.

Relative abundances of benthic foraminifera in 57 core tops collected within a water depth range between 700 and 4,335 m from the eastern Indian Ocean (mostly between Australia and Indonesia) were investigated quantitatively using Detrended Correspondence Analysis (DCA) to analyze species spatial-distribution (Murgese and De Deckker, 2007). They also carried out Canonical Correspondence Analysis (CCA) and used correlation matrices to evaluate the relationships between the species distribution and such environmental variables as temperature, salinity, dissolved oxygen, nitrate and phosphate concentrations, and carbon-flux rate.

Ahmad et al. (2008) used stable carbon and oxygen isotopic records of *Globigerinoides ruber* and *Cibicidoides wuellerstorfi* from a deep-sea gravity core retrieved from the north-eastern part of the Indian Ocean at a water depth of 3,306 m to infer surface and deep water characteristics for the last ~60,000 years. They recorded significant variations in δ¹⁸O during the last 2,000–60,000 years that were suggestive of large variations in monsoonal precipitation. Large fluctuations in δ¹⁸O of *G. ruber* were attributed by them to variations in fresh water influx; in general, planktic δ¹⁸O values showed a combined effect of increased sea surface salinity and decreased sea surface temperature (SST) during the Last Glacial Maximum (LGM).

The response of benthic foraminifera to sea-level change in the mixed siliciclastic-carbonate system of southern Ashmore Trough in the Gulf of Papua was studied by Carson et al. (2008), who noted that benthic foraminiferal assemblages in the sediment sink of the trough probably respond to the amount and type of sediment supplied from the proximal outer Gulf of Papua shelf.

Fontanier et al. (2008) analyzed stable oxygen and carbon isotopes of living (rose Bengal-stained) benthic foraminifera from a 2,800 m water depth sampling station from the Cap-Ferret Canyon in the Bay of Biscay. They analyzed eight taxa: *Hoeglundina elegans*, *Cibicides wuellerstorfi*, *Uvigerina peregrina*, *Bulimina inflata*, *Melonis barkeanus*, *Pulmo na quoqueloba*, *Chilostomella oolina* and *Globobulimina affinis*. They concluded that the δ¹³C of *U. peregrina* and the Δδ¹³C between *U. peregrina* and *G. affinis* were definitively more sensitive to labile organic matter supplies rather than to the advection of low-quality organic matter.

Geochemical investigations of gametogenic calcite addition in the planktic foraminifera *Orbulina universa* were carried out by Hamilton et al. (2008), who presented present the results of carbon-13, oxygen-18 and thermal labeling experiments conducted under high (HL) and low light (LL) regimes that vary symbiont photosynthetic activity, which indicated that tests of this thin-walled species from deep sea sediments are composed of >80% ontogenetic calcite that is precipitated in the primary, near-surface habitat of this species.

Living (rose-Bengal-stained) foraminifera from different sites off the Pacific coast of Nicaragua and Costa Rica between 743 and 2,421 m water depth were analyzed by Heinz et al. (2008). Sampled stations included sediments from mud volcanoes and mounds, but those sediments. They recorded highest foraminiferal densities on the slope off Nicaragua, lowest on the continental margin off Costa Rica where the smooth Cocos Plate subducts and intermediate densities on the continental slope where the rough Cocos Plate subducts.
Lobegeier and Sen Gupta (2008) identified 183 species of benthic foraminifera in a study of sediment substrates and tubeworm surfaces in (a) the Green Canyon, Garden Banks and Mississippi Canyon (245–1,081 m) and (b) the Alaminos, Farnella and De Soto Canyons (1,848–2,918 m), Gulf of Mexico; the samples were obtained from submersibles in both seep and non-seep (control) areas. They observed that none of the species was endemic to seeps, but 20 taxa were previously unknown in the Gulf of Mexico. Furthermore, they noted that species of wide-ranging morphologic and taxonomic affinities were able to maintain sizeable populations at the sites of hydrocarbon seepage, and opined that high bacterial productivity could be a major factor in sustaining these populations.

The impact of intentionally injected CO$_2$ hydrate on deep-sea benthic foraminiferal survival was investigated by Bernhard et al. (2009), who determined the survival response of calcareous, agglutinated, and thecate foraminifera in two experiments at ~3,100 m and 3,300 m water depths in Monterey Bay (California, USA). Their observations suggested that, if large scale CO$_2$ sequestration was enacted on the deep-sea floor, survival of two major groups of this prevalent protistan taxon would not be severely impacted, while calcareous foraminifera might face considerable challenges to maintain their benthic populations in areas directly exposed to CO$_2$ hydrate.

Regenberg et al. (2009) used tests of the mixed layer-dwelling planktic foraminiferal species G. ruber (pink and white varieties) and G. sacculifer (without sac-like final chamber), the seasonal thermocline-dwelling Globorotalia menardii and Neogloboquadrina dutertrei, the (sub)thermocline-dwelling G. tumida, and the deep-dwelling G. truncatulinoides dextral and G. crassaformis (permanent thermocline) from surface sediment samples collected at water depth range of 888 to 4,587 m at 41 Caribbean and 35 tropical Atlantic sites to consistently approximate the thermal vertical structure of past upper water columns.

Deep-sea benthic foraminifera, planktic foraminifer Globigerina bulloides and pteropods were quantitatively analyzed in 451 samples from Ocean Drilling Program (ODP) Hole 716A by Sarkar and Gupta (2009) to understand both surface and deep-sea paleoceanographic changes in the equatorial Indian Ocean basin (Maldives Islands) during the late Quaternary. Their environmental interpretation of each species was based on the ecology of Recent deep-sea benthic foraminifera. From the faunal record, they inferred fluctuating deep-sea conditions including changes in surface productivity, organic food supply and deep-sea oxygenation linked to changing wind intensities.

Barras et al. (2010) investigated the importance of calibration of $\delta^{18}$O of laboratory-cultured deep-sea benthic foraminiferal shells in function of temperature. The results of their study opened new perspectives for future proxy calibrations in laboratory set-ups with deep-sea benthic foraminifera (e.g., quantification of the influence of the carbonate chemistry). Benthic foraminiferal and sediment biogeochemical data (total organic carbon, calcium carbonate and biogenic opal contents) in two cores (1,265 and 1,312 m water depths) from the south-eastern Sakhalin slope and one core (839 m water depth) from the south-western Kamchatka slope were investigated by Bubenshchikova et al. (2010) to reconstruct variations of the oxygen minimum zone during the last 50 ka in the Okhotsk Sea.

De and Gupta (2010) performed multi-variate analysis on percentages of 46 species of unstained benthic foraminifera from 131 core top to near core top samples collected at water depths ranging from 322 to 5,013 m in the Indian Ocean. They found a good correlation with surface productivity, organic flux to the sea floor, deep-sea ventilation and, to a less extent with bottom water temperature; no correlation was, however, observed with water depth. The foraminiferal census data combined with geochemical data has enabled them to divide the Indian Ocean into two faunal provinces, one with a pronounced OMZ, and the other which is well oxygenated with low and pulsed food supply.
Based on morphological and molecular characteristics, a remarkably new, monothalamous, agglutinated foraminiferal genus, *Capsammina patelliformis*, was described by Gooday et al. (2010), who recorded its occurrence mainly at bathyal (1,000–3,400 m) water depths in the Nazaré Canyon off Portugal. Analysis of a fragment of the SSUrDNA gene indicated that *C. patelliformis* belongs in a clade branching with *Crithionina delacai*, *C. granum* and an undetermined crithioninid species. They, however, observed that the divergences between the new species and *Crithionina* species ranged from 20–21%, and were, therefore, too high to classify it in the same genus. Furthermore, they noted that *C. patelliformis* occupies a shallow infaunal microhabitat, living mainly in the top 0.5 cm of the sediment.

Jayaraju et al. (2010) analyzed deep-sea benthic foraminiferal distribution in the southwest Indian Ocean at water depths ranging between 3,150 and 4,125 m and recorded 36 species belonging to 21 genera and 3 suborders. They observed that such species as *Epistominella exigua*, *Melonis sphaeroides*, *Oridorsalis umbonatus* and *Pullenia bulboides* occurred at both 3,150 m and 3,465 m depths indicating their depth persistence. They also observed the occurrence of species like *Gyroidina* sp., an indicator of low-oxygen environment and *Uvigerina hispida-costata* suggestive of high organic carbon at 3,150 m and 3,740 m, respectively.

Recent foraminiferal communities from the Makassar Strait off Indonesia were studied by Rositasari (2010), who found that five genera of planktic foraminifera formed the bulk of the sediment, and that the deep chlorophyll maximum in oceanic region of the strait was the prominent factor controlling living planktic foraminiferal populations. The benthic community consisted of 164 species belonging to 78 genera. *Uvigerinids* constituted 46–57% of the benthic fauna, and they opined that *Uvigerina asperula* might be considered as an indicator of the OMZ in Makassar Strait.

According to Nardelli et al. (2010), who examined living benthic foraminiferal assemblages along a latitudinal transect at 1,000-m depth off the Portuguese margin, foraminiferal abundance and species richness were related to the quantity and biochemical composition of the sedimentary organic matter, as well as to the stability of the sea floor. The rich fauna of Nazaré Canyon in this region is characterized by a strong dominance of intermediate and deep infaunal species such as *Melonis barleeanus* and *Chilostomella oolina* in superficial sediment layers, suggesting low bottom-water oxygen concentration and minimal oxygen penetration into the sediment.

Regenberg et al. (2010) analyzed surface sediment samples (0–1 cm) recovered from water depths <2,500 m using spade and giant box corers, wherein for size and weight measurements, coexisting *G. menardii* and *G. cultrata* were picked from four northern, central, and southern South China Sea samples, and additionally from two Timor Sea samples. Along with visual distinction, they encrusted distinguished *G. menardii* from the shiny *G. cultrata* by its on average doubled test weight, maximum diameter being equal. They noted that more elongated and flattened *G. cultrata* calcites within the deeper mixed layer, which applies also for the initial calcification of *G. menardii*. They also suggested that final encrustation of *G. menardii* after vertical migration takes place close to the bottom of the seasonal thermocline.

The response of Recent benthic foraminiferal assemblages to contrasting environments in Baffin Bay and the Northern Labrador Sea, north-west Atlantic Ocean was investigated by Schröder-Adams and van Rooyen (2011), who attributed the absence of benthic calcareous taxa in Baffin Bay attributed to cold, saline, CO₂-rich bottom waters related to the Baffin Bay Bottom Water and the Baffin Bay Atlantic Water. Modern foraminiferal assemblage distribution supports the model of increased organic flux under seasonal open-water conditions that feed a rich agglutinated assemblage, but lead to oxidation of organic matter and increased carbonate dissolution. They also observed that robust, tubular suspension feeders occupy regions under the influence of bottom currents that deliver nutrients.
Gooday et al. (2012) discussed the ecology and biogeography of *Disso spirina tenuissima* (Costa, 1856), a millilod foraminiferal species, in the Atlantic and Indian oceans, and provided the first records of this taxon from the Indian Ocean. They observed that this species occurred at bathyal depths in the north-west (1,980 m) and north-east (938 m) Arabian Sea, where bottom-water oxygen concentrations are depressed. They also noted that smaller, sessile organisms, including agglutinated foraminifera and occasional brachiopods use *D. tenuissima* tests as a substratum for attachment, and that in all areas, some tests were surrounded by a ring of sediment, presumably surface material collected by pseudopodia.

Living (rose Bengal stained) benthic foraminiferal faunas were investigated at 13 deep-sea stations sampled in the Cap-Ferret Canyon area at water depths ranging between 300 and 3,000 m in the north-east Atlantic Ocean, by Du ro et al. (2013), who observed that the faunal composition in the Cap-Ferret Canyon was different compared to the nearby Cap-Breton Canyon, where sediment gravity flows are active.

Marshall et al. (2013) used bi-weekly sediment trap samples and concurrent hydrographic measurements collected between March 2005 and October 2008 from the Cariaco Basin, Venezuela, to assess the relationship between [CO$_3^{2-}$] and the area densities ($\rho_A$) of two species of planktic foraminifers, *Globigerinoides ruber* (pink) and *G. sacculifer*. The results of their study showed a strong correlation between $\rho_A$ and ambient [CO$_3^{2-}$] for both *G. ruber* and *G. sacculifer* ($R^2 = 0.89$ and $0.86$, respectively), confirming that [CO$_3^{2-}$] has a pronounced effect on the calcification of these species.

### 2.2 National scenario

Studies on Recent foraminifers in the Indian region were initiated by Chapman (1895) who reported 274 species from the *Investigator* collections made off the Laccadives, in the Arabian Sea. Later, a monograph of foraminifers from the Arabian Sea was published by Hofker (1930). Setty and Guptha (1972) reported 15 species of planktic foraminifera from the sediments off Karwar and Mangalore. Kameswara Rao (1973) presented a quantitative distribution of planktic foraminifera in the south-west coast of India; he recorded 26 planktic foraminiferal taxa and concluded that the Arabian Sea has greater species diversity than the Bay of Bengal attributable, perhaps, to greater salinity in the former.

Zhang (1985) opined that living planktic foraminifera are governed by upwelling seasonally and spatially than by sea temperature and latitude in the eastern Arabian Sea. The ecologic distribution of four abundant species of planktic foraminifers – *Globigerina bulloides*, *Globigerinoides ruber*, *Globigerinoides triloba* and *Neogloboquadrina dutertrei* – from the bottom sediments of the north-western part of the Bay of Bengal was studied by Elonee Pal (1988).

Divakar Naidu and Guptha (1989) analyzed a set of seven core tops from the western equatorial Indian Ocean for planktic foraminifera, and recorded 20 species, among which *Globorotalia menardii*, *Globigerinoides sacculifer* and *G. ruber* constituted the majority of the population. From the distribution of foraminifera, they observed that the tropical fauna gradually and progressively decreased from 6° N latitude to 21° S latitude from 98.9 to 58.2%, while the subpolar fauna showed upward trend in its abundance from 38% at 21° S latitude to 0.8% at 6° N latitude. Three warm and two cold episodes were identified by Divakar Naidu et al. (1989) based on an investigation on planktic foraminifera and CaCO$_3$ content of a box core collected at a depth of 2,556 m from the southern part of the Arabian Sea, indicating faunal changes depicting Quaternary climatic fluctuations.

Twenty-one surficial sediment samples were analyzed for planktic foraminifera, radiolarians, CaCO$_3$ and organic carbon by Divakar Naidu (1990), who suggested that the
sediments recorded an upwelling signature. Based on the relative abundance of planktic foraminifera and radiolarians, and the concentration of CaCO₃ and organic carbon, he concluded that the intensity of upwelling was greater on the upper slope (>1,000 m) than on the lower slope region (<1,000 m). Gupta et al. (1990) examined 39 vertical zooplankton hauls from the southeast Arabian Sea for living planktic foraminifera and reported 28 species, with the standing crop being highest off the Cape Comorin coast. They observed the presence of two assemblages indicative of upwelling off the Kerala coast and south of Cape Comorin, respectively.

Two cores collected in the eastern Arabian Sea at water depths of 1,750 m and 2,550 m, respectively, were studied for coarse fraction, CaCO₃ content and Globorotalia menardii complex abundance (Divakar Naidu, 1991). Based on the latter two parameters, he was able to place the Holocene/Pleistocene boundary at the 50-cm level and the LGM at 80-cm level from the top of the northern core, and at 40 cm and 65 cm, respectively for the southern core. He concluded that carbonate maxima with less abundance of G. menardii complex reflected glacial periods, while carbonate minima with high abundance of the menardii complex indicated the inter-glacials.

The ecology and distribution of Recent planktic foraminifera in the eastern part of the Arabian Sea were studied by Kameswara Rao et al. (1991); they recorded 30 living planktic foraminiferal taxa from 97 plankton tow samples. Analysis of 63 sediment samples from the western continental margin of India for planktic foraminifera, organic carbon, biogenic silica and calcium carbonate content showed higher frequency (30–40%) of Globigerina bulloides and high organic carbon (3%) coinciding with higher primary productivity (1 g C m⁻² day⁻¹) in the south compared to lesser (20–30%) abundance of G. bulloides and organic carbon (1–2%) and moderate productivity (0.5–0.75 g C m⁻² day⁻¹) in the north (Divakar Naidu et al., 1992).

Borole (1992) examined estimates of δ¹⁸O from the planktic foraminifer, Globigerinoides ruber (white) collected at fortnightly intervals using deep-sea sediment traps moored at water depths of 1,000 m and 2,787 m in the eastern Arabian Sea, and observed very little variations between May and October 1987, which is the period of intense south-west monsoon activity over the north Indian Ocean and the adjoining landmass. He underlined the use of seasonal variability in planktic foraminifera as proxy for monsoonal variations. According to Curry et al. (1992), planktic foraminifera collected in sediment traps in the Arabian Sea during 1986 and 1987 responded to the southern Asian monsoon in the form of changes in productivity, relative abundance of species and isotopic shell chemistry. They observed that most of the species increased in flux shortly after the advent of the south-west monsoon.

Analysis of 63 sediment samples from the western continental margin of India for planktic foraminifera, organic carbon, biogenic silica and calcium carbonate content showed higher frequency (30–40%) of Globigerina bulloides and high organic carbon (3%) coinciding with higher primary productivity (1 g C m⁻² day⁻¹) in the south compared to lesser (20–30%) abundance of G. bulloides and organic carbon (1–2%) and moderate productivity (0.5–0.75 g C m⁻² day⁻¹) in the north (Divakar Naidu et al., 1992). Kameswara Rao et al. (1992) recorded 25 planktic foraminiferal taxa from 36 plankton tows in the Arabian Sea, and observed that the fauna has, in general, a close affinity with that of equatorial waters of the world.

Distribution patterns of Recent planktic foraminifera in surface sediments of the western continental margin of India collected at water depths ranging from 25–3,679 m were studied by Divakar Naidu (1993), who observed that higher absolute abundance of planktic foraminifers in the offshore associated with lower frequencies of the productivity indicator, Globigerinoides bulloides, and inversion of these two parameters in the nearshore suggested that productivity did not control the absolute abundance of planktic foraminifera.

Divakar Naidu and Malmgren (1995) discussed the possibility of whether benthic foraminiferal records represent a productivity index in OMZ areas. They demonstrated that benthic foraminifer accumulation rates (BFAR) and benthic to planktic foraminifer ratios (B/P)
did not record surface-water productivity signal in the intense upwelling and OMZ along the Oman Margin. They speculated that dissolved oxygen concentrations might instead be controlling the benthic foraminifer abundance.

The relationship between late Quaternary upwelling history and coiling properties of *Neogloboquadrina pachyderma* and *Globigerina bulloides* in the Arabian Sea was explored by Divakar Naidu and Malmgren (1996), who established that enhanced flux of the sinistral morphotypes of *N. pachyderma* and *G. bulloides* during intensified upwelling suggested that the sinistral morphotypes of both taxa were more productive than the dextral morphotypes in the nutrient-rich upwelling waters. They suggested that these patterns indicated that surface-water temperature might not be the only factor controlling coiling directions of *N. pachyderma* and *G. bulloides*.

Guptha *et al.* (1997) analyzed particulate flux from two sediment trap mooring stations in the central and northern Bay of Bengal for planktic foraminiferal abundance and identified 26 species of which 8 accounted for >90% of the total planktic foraminiferal flux. The highest fluxes were recorded by them during the southwest monsoon with *Globigerinoides bulloides* being predominant and indicating upwelling in the region.

Twenty-eight species of planktic foraminifera were recorded from 46 samples collected at 27 stations along 5 transects off the Kerala Coast by Kameswara Rao and Jayalakshmy (1997). They identified two distinct assemblages in the fauna – first a summer tropical assemblage typified by *Globigerinella aequilateralis*, *Globigerinoides conglobatus*, *G. ruber*, and *G. sacculifer*, and a second summer tropical upwelling assemblage characterized by *Globigerina bulloides* and *Neogloboquadrina dutertrei*. Kameswara Rao *et al.* (1997) analyzed two pelagic cores retrieved from the Arabian Sea at water depths of 2,240 m and 800 m, respectively, to determine climatic changes during the last 30,000 years. They opined that the *Globorotalia menardii* complex (warm water group) and *Neogloboquadrina pachyderma* (cool water species) were reliable as climate indicators. According to Divakar Naidu *et al.* (1999), variations in the abundances of *Globigerina bulloides* and *Neogloboquadrina dutertrei* in the sediment cores of Arabian Sea and Bay of Bengal can trace the intensity of paleoupwelling and river discharge and thereby associated summer monsoon intensity and productivity changes in the northern Indian Ocean.

Benthic foraminifera were quantified by den Dulk *et al.* (2000) in two sediment cores from a topographic high (Murray Ridge) in the northern Arabian Sea. One core was from a station within the present-day OMZ, while the other was from a station below the OMZ. They suggested that percentages of miliolids could be used for rapid reconstruction of periods of increased ventilation in the northern Arabian Sea and are a promising proxy for tracing changes in bottom and pore water oxygenation in general. However, they opined that that benthic foraminiferal accumulation rates cannot be used as a proxy for surface water productivity under the prevalence of severe dysoxia.

Divakar Naidu and Niitsuma (2003) performed oxygen and carbon isotopic analyses on the tests of *Globigerina bulloides* and *Pulleniatina obliquiloculata* to study the evolution of surface and bottom water hydrographic changes associated with summer monsoon upwelling process at the Oman Margin over the last 19,000 years. Ivanova *et al.* (2003) reconstructed variations in primary productivity in eutrophic, mesotrophic and oligotrophic parts of the Arabian Sea over the past 135,000 years applying principal component analysis and transfer function to planktic foraminiferal assemblages. They concluded that temporal variation in paleoproductivity was most pronounced in the mesotrophic northern and oligotrophic eastern Arabian Sea, but was relatively weak in the western site in the upwelling area off Oman.

A total of 128 surface sediment samples [76 grab and 52 core top samples] were analyzed for benthic foraminiferal contents from the region off Goa in the eastern Arabian Sea up to a water depth of 3,300 m by Mazumder *et al.* (2003), who identified 195 species. Species belonging
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Bolivina, Cassidulina, Lernula, Uvigerina and Eponides were found to be the most abundant within the depth zone of 150 to 1,500 m, a zone considered to be the OMZ for the Arabian Sea. A comparison of benthic foraminiferal species abundance in the OMZ of Arabian Sea with other parts of the world oceans revealed that Bulimina marginata, reported to be present in considerable numbers within the OMZ in other regions of the world oceans, accounted for only about 2% of the total benthic foraminiferal population in this region. On the contrary, Bulimina costata constituted >15% of the total populations, confirming the characteristic nature of the OMZ in the eastern Arabian Sea.

According to Nigam et al. (2003), the life spans of planktic foraminifera are vital in view of their increasing use for paleoclimatic studies. They proposed the use of sediment trap technique to get better estimates of life spans of planktic foraminifers and, on the basis of sediment trap results, they observed the life spans of planktic foraminiferal species to be of the order of few months instead of few days to few weeks, as reported earlier. Similar analyses were performed by Divakar Naidu (2004) on the tests of Globigerina bulloides, Globigerinoides sacculifer, Neogloboquadrina dutertrei and Pseudovolviatina obliquiloculata to study $^{18}$O and $^{13}$C of shallow and deeper-living planktic foraminifer species. He suggested that both $^{18}$O and $^{13}$C of surface and subsurface living foraminifera could be used as isotope indices of upwelling in the Arabian Sea.

Ammolagena clavata (Jones and Parker, 1860), an agglutinated benthic foraminiferal species, was reported for the first time from Recent sediments of the Arabian Sea by Nigam et al. (2004). They recorded its occurrence in the depth range of 1,650–2,050 m, compared to the depth range of 684–2,503 m in the Pacific Ocean and 553–4,500 m in the Atlantic regions. Although earlier reports had indicated its presence as attached specimens, either on large quartz grains or on some other larger benthic foraminiferal species, they found this taxon to be attached to tests of the planktic foraminifer, Globorotalia menardii.

According to Rai and Srinivasan (1994), who made an attempt to understand the Pleistocene bottom water history in response to paleoclimatic changes in the in the northern Indian Ocean using quantitative analyses of deep-sea benthic foraminifera at two DSDP sites, Uvigerina proboscidea was the most dominant species during the Pleistocene at both sites. They also stated that the lower depth range for the occurrence of Bulimina aculeata in the Indian Ocean is ~2,300 m, similar to that of many other areas.

Divakar Naidu and Malmgren (2005) reconstructed the annual, summer, and winter sea surface temperatures (SSTs) in the western Arabian Sea over the last 22,000 years using artificial neural networks (ANNs) based on quantitative analyses of planktic foraminifera. Down-core SST estimates revealed that annual, summer, and winter SSTs were 2.0, 1.2, and 2.6°C cooler, respectively, during the last glacial period than in the Holocene.

Planktic foraminiferal studies from the southern Bay of Bengal (SBBT) revealed the presence of corroded specimens of Globorotalia menardii in the deep trap at a depth of 3,011 m during February–March 1992 (Mohan and Guptha, 2006). Strangely, all the other spinose and less resistant spinose foraminiferal species were devoid of any signs of dissolution in association with these. As the trap depth was well above the lysocline, they postulated that the corroded specimens of G. menardii tests could have been supplied by lateral advection and got mixed up with the settling particles at SBBT.

Heinz and Hemleben (2006) investigated the response of deep-sea benthic foraminifera to the north-east monsoon in the western and southern regions of the Arabian Sea, and obtained contrasting results. They attributed steady, increased foraminiferal numbers between March and the beginning of May, deepening of the foraminiferal living horizon, variable diversity and rapid variations between dominant foraminiferal communities to enhanced organic carbon fluxes during and after the monsoon in the western Arabian Sea. In the southern Arabian Sea, however, they did not find any significant influence of the monsoon on benthic foraminifera.
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Divakar Naidu (2007a) summarized the influence of monsoon-driven upwelling on the planktic foraminiferal species abundances, coiling directions of *Globigerinoides bulloides* and *Neogloboquadrina pachyderma* and size variations of selected planktic foraminiferal species, and carbon isotopic composition of *G. bulloides*. Calcite dissolution in marine sediments is known to be driven by the degree of saturation state with respect to CaCO₃, of overlying bottom waters. According to Divakar Naidu (2007b), oxygen isotopic ratios (δ¹⁸O) of *Globigeroides ruber* in the northern Indian Ocean reveal a pattern similar to that of salinity conditions. In the Bay of Bengal, the δ¹⁸O values decrease progressively toward the mouth of the Ganges-Brahmaputra-Irrawaddy River system, clearly reflecting the salinity pattern. The general north-south δ¹⁸O increase in the Arabian Sea also fits the salinity pattern and reflects the strong evaporation excess in this basin.

Three paleocarbonate ion proxies – size index, planktic foraminiferal shell weight, and calcite crystallinity were employed by Naik and Divakar Naidu (2007, 2008) to a set of core top samples from the western tropical Indian Ocean in the water depth range of 1,086 to 4,730 m. All three proxies complemented each other well and revealed that calcite dissolution starts to affect planktic foraminifera from 2,250 m depth onward, and intense calcite dissolution begins around 3,900 m depth in this sector of the tropical Indian Ocean. The possibility of benthic foraminifera as proxy for oxygen-depleted conditions off the central west coast of India was examined by Nigam et al. (2007), who identified 65 species of rectilinear bi- and tri-serial species belonging to 18 genera. Their study was based on 103 surface sediment samples collected at water depths ranging from 15–3,300 m. The good correlation between this group of taxa and dysoxic/suboxic conditions in the Arabian Sea prompted them to suggest that these species groups could be utilized as a reliable proxy for paleo OMZ reconstructions.

Anand et al. (2008) studied two sedimentary cores from the western (water depth of 1,586 m) and eastern Arabian Sea (840 mm) to study past (SSTs) and seawater δ¹⁸O (δ¹⁸Ow) variations for the past 35,000 years by coupling Mg/Ca-δ¹⁸O calcite variability in two planktic foraminiferal species: *Globigerinoides ruber*, which thrives throughout the year, and *Globigerina bulloides*, which occurs mainly when surface waters contain high nutrients during upwelling or convective mixing. Based on Mg/Ca in *G. ruber*, they inferred that SSTs in both areas were 3 to 4° C lower during the Last Glacial Maximum (~21,000 years ago) than today and the Holocene period. The SST records based on *G. bulloides* also indicated general cooling, down to 18° C in both areas. Moreover, the SSTs in the western Arabian Sea based on *G. bulloides* were always lower than those based on *G. ruber*, indicating the presence of strong seasonal temperature contrast during the Holocene and LGM.

Naik and Divakar Naidu (2010) carried out CaCO₃ analyses on two size fractions (<63 μm and >63 μm) from core sediment samples collected from above the lysocline depth in the Indian Ocean, to evaluate the CaCO₃ size index as paleocarbonate ion proxy in these cores. Their study demonstrated that apart from factors such as breakage of shells after burial due to organic matter respiration and dilution due to terrigenous material, changes in surface water productivity and coccolithophores might be a constraint to use size index as a paleocarbonate ion proxy for sediments from above the lysocline. Shell weights of *Globigerinoides sacculifer* and Mg/Ca ratios in *G. ruber* were measured from an Arabian Sea sediment core by Naik et al. (2010), who recorded an inverse relationship between the two parameters. The results revealed that shell weights are mainly controlled by surface water [CO₂] rather than calcification temperature. Based on the excellent correspondence between shell weight and CO₂ concentrations in an Antarctic ice core, they suggested that shell weights of *G. sacculifer* could be used as a proxy to reconstruct atmospheric CO₂ concentrations in the past.

Saraswat and Khare (2010) carried out stable isotopic analysis on 8–10 tests of *Globigerina bulloides* in the 250–355 mm size range (sieve size) picked from 19 surface sediment samples.
collected using gravity and piston corers and grab samplers at water depths ranging from 1,423–4,377 m in the south-western Indian Ocean. A comparison of seawater salinity and temperature estimated from *G. bulloides* δ¹⁸O, with the measured seawater salinity and temperature at different water depths, showed that the calcification depth of this planktic foraminifer varies from ~75 m from the equator to 15° S to ~200 m between 15° and 43° S latitudes.

Based on census counts of planktic foraminifers by using the ANN technique, Godad *et al.* (2011) estimated downcore variations in SST during May and August in a core, and showed that the timing of intense upwelling in the western Arabian Sea has varied over the last 22,000 years. Govil *et al.* (2011) reconstructed δ¹⁸O, sea surface salinity and SST changes in the Bay of Bengal by using paired measurements of δ¹⁸O and Mg/Ca in a planktic foraminiferal species, *Globigerinoides ruber*, from a core retrieved from the western Bay of Bengal at a water depth of 3,307 m in order to understand the rainfall variability associated with south-west monsoon over the past 32,000 years. Their SST reconstructions revealed that Bay of Bengal was ~3.2° C cooler during the LGM as compared to present-day temperature.

Paired measurements of δ¹⁸O and SST utilizing *Globigerinoides sacculifer*, an upper mixed layer dwelling foraminifer, were used by Mahesh *et al.* (2011) to report changes during the last 32,000 years in the Lakshadweep Sea (south-eastern Arabian Sea). The 552 cm long core was retrieved at a water depth of 2,300 m, and the upper 150 cm of it was studied by them. Naik *et al.* (2011) utilized shell weights of *Globigerina bulloides* and *Globigerinoides ruber* in the size range of 300–355 μm from a sediment core recovered from above the lysocline in the upwelling region of western Arabian Sea. Shell weights of *G. ruber* and *G. bulloides* showed significant correlation with their shell size from Recent to 16,000 years B.P., suggesting shell calcification under optimum growth conditions. On the other hand, during 22,000–16,000 years B.P., there was no correlation between shell weights and shell size. However, shell weights of *G. bulloides* exhibited significant negative correlation with annual SST implying that *G. bulloides* calcification might have been controlled by surface water [CO³⁻]. Therefore, they opined that shell weights of *G. ruber* and *G. bulloides* cannot be utilized to reconstruct surface water [CO³⁻] in this region.

The late Quaternary record of *Pulleniatina obliquiloculata* was investigated by Sijinkumar *et al.* (2011) from two well-dated sediment cores from the Andaman Sea (north-east Indian Ocean) retrieved at water depths of 2,064 m, 2,909 m, respectively, to examine its paleoceanographic significance and the presence of the *Pulleniatina* Minimum Events (PME) in the western North Pacific. As in the Pacific, their study showed that PMEs exist in the Indian Ocean albeit with a lower intensity. They concluded that the PMEs of the Andaman Sea were not current-driven events as in the western Pacific margin either by the weakening of the Kuroshio Current or reduced winter SSTs.

Tiwari *et al.* (2011) investigated the effect of varying frontal systems on stable oxygen and carbon isotopic compositions of modern planktic foraminifera of Southern Ocean. Samples from both plankton nets as well as core top sediments from five gravity and piston cores collected at water depths ranging from 2,256–4,389 m were analyzed for their isotopic compositions (δ¹⁸O and δ¹³C of planktic foraminifera). They observed the values to be significantly similar implying that planktic foraminifera secrete their shells in isotopic equilibrium with seawater and that planktic foraminifera preserved in sediments record overlying seawater signatures in this region.

Paleoproductivity records from a composite sediment core at the millennial scale during the last 80,000 years B.P., based on relative abundance counts of planktic foraminifera and organic carbon contents, were presented by Singh *et al.* (2011), who inferred that the eastern Arabian Sea upwelling-induced productivity was higher in the glacial period than in the Holocene, but fell repeatedly on millennial timescales. These productivity declines occurred during cold events in the North Atlantic region, with the most pronounced changes prevailing.
during the Heinrich events. They concluded that seasonal monsoon winds that drive upwelling-induced productivity in the east were weak when the North Atlantic was cold.

Bharti and Singh (2013) studied a 30,000-year record of benthic foraminiferal assemblages in a sediment core retrieved from the base of the OMZ off Goa (eastern Arabian Sea) at a water depth of 1,230 m. During the course of this study, they discovered a new species, *Bulimina arabiensis*, which dominated the benthic foraminiferal assemblage in the fine size fraction (63–125 µm). They opined that the morphological characteristics of this species suggested its preference for infaunal microhabitat and low-oxygen concentrations of bottom water.

Naik et al. (2013) estimated the shell weights of *Globigerinoides ruber* in the size range of 300–355 µm from sediment traps in the western and eastern Arabian Sea, which represent upwelling and non-upwelling conditions, respectively. Their results revealed that shell weights of *G. ruber* versus flux showed significant correlation at both the sites, implying that shell calcification mainly depends on optimal growth conditions.

The bathymetric preference of four major genera of rectilinear benthic foraminifera within the OMZ in the Arabian Sea off the central west coast of India was discussed by Mazumder and Nigam (2014). Their study was based on 52 surface sediment samples collected from the region off Goa, from water depths of 15–3,300 m were analyzed with special emphasis on foraminiferal content. They observed *Furukawina* to predominate at the shallow water OMZ, within the water depth zone of 50–60 m. Within 150–1,500 m water depth, which is considered as intermediate to deep water OMZ in this region, *Uvigerina* showed highest abundance >1,000 m water depth, whereas genus *Bulimina* displayed its affinity with >1,000 m water depth.

Recently, specimens of *G. ruber* from the last 22,000 years have been analyzed by Naik and Divakar Naidu (2014) for B/Ca, δ18O and Mg/Ca. B/Ca was compared to reconstructed salinity and sea surface temperature (SST) records, to gain insight into the processes controlling the incorporation of boron. They have concluded that that temperature governs the incorporation of boron in *G. ruber* to some extent, but have seriously doubted utility of B/Ca ratio as a pH or CO2 proxy. In another recent study, Naik et al. (2014) have reported coeval increase in productivity and denitrification from ~7 to 0 kyr in the eastern Arabian Sea, coinciding with minimum dissolved O2 levels in bottom waters, increased CaCO3 dissolution, diminishing shell weights of *G. ruber* with well-marked dissolution features on its tests. Based on their results, they emphasized the role of OMZ in governing CaCO3 dissolution and contributing to an increase in atmospheric CO2.