

## Role of Foraminifera in Oceanographic Events

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The earliest known description of foraminifera from the Northern Indian Ocean (Arabian Sea and the Red Sea) was given by Fichtel and Moll<sup>1</sup>. Later, d'Orbigny<sup>2</sup> described several species from the Indian Ocean region. HMS Challenger (1873-1876) undertook its first major scientific cruise in the Indian Ocean to collect the bottom samples systematically. Brady's monograph on the Indian Ocean foraminifera<sup>3</sup> was followed by the works of Chapman<sup>4</sup>, Heron Allen and Earland<sup>5</sup>, Hofker<sup>6</sup>, LeRoy<sup>7</sup> and Said<sup>8</sup>.

In subsequent oceanographic work, vessels like Albatross, Dana, Snellius, Atlantis, Siboga, Investigator, INS Kistna, INS Darshak, Meteor, Discovery, Pioneer, Eltanin, Oceanographer and Glomar Challenger were used.

The next phase in the study of the foraminifera of the Indian Ocean began with the International Indian Ocean Expedition (IIOE), sponsored by UNESCO (1962-1965). Using modern methods, studies were directed mostly towards ecological and paleontological aspects, distribution patterns and variability of planktonic species. Later, the faunal observations of the shelves of India were supplemented by the work of Indian scientists<sup>9-13</sup>.

Phillippi<sup>14</sup> in the Indian Ocean, and Schott<sup>15</sup> in the Atlantic, interpreted the globigerina oozes and the planktonic assemblages as glacial and post-glacial deposits. These expeditions confirmed the existence of only a few planktonic species in the present oceans; their distribution was differentiated as tropical, temperate and arctic-antarctic assemblages considering temperature as the major controlling factor. This was used to interpret the paleoclimatic changes in the world.

Through the use of improvised techniques, standardized methods and sophisticated instruments, living foraminifera from various depths in tows and dead assemblages in undisturbed long cores from various regions of the ocean were collected and studied.

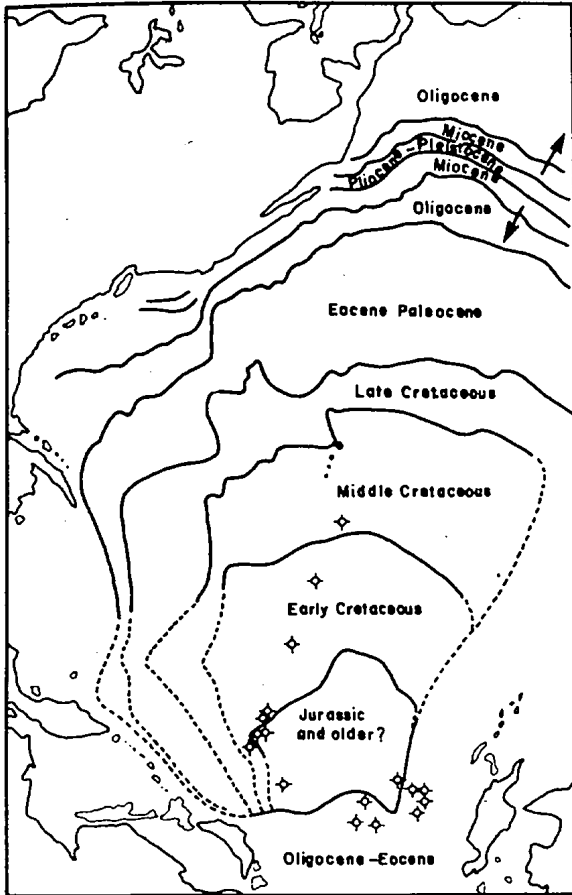
Following the success of the Mohole project in 1961, JOIDES undertook a programme called the Deep Sea Drilling Project using the R/V Glomar Challenger. Several hundreds of cores of hundreds of metres length were drilled, collected and studied from various points of view. The cores included sediments from the Cretaceous through the Recent.

The Indian Ocean cores are deposited with the Lamont-Doherty Geological Observatory of Columbia University at New York. Many of the over 1000 cores studied so far revealed that they represent sediment from Early Cretaceous to Holocene; Palaeocene and Oligocene sediments, though rare, have been recovered from all the three oceans. Miocene and Pliocene strata are found to be complex, whereas Quaternary is less than 10 m thick at most of the places. Cores recovered from the ridge areas are older, suggesting increasing age and indicating sea-floor spreading.

### Core Studies and Stratigraphy

(a) *Sea-floor spreading and stratigraphy*—According to the sea-floor spreading hypothesis of Hess<sup>16</sup>, new crustal material is being continuously formed and added along the narrow, linear mobile belts like the Mid-Oceanic Ridge and the Mid-Atlantic Ridge. The lateral movement required for spreading is attributed to the convection current in the mantle. As a result, the crustal material, including the overlying sedimentary strata and the continental masses attached to the oceanic plates, moves away from the ridge axis and their original junction. The validity of this theory was checked during the Deep Sea Drilling Project (DSDP) and it was found that the spreading rate of crustal plates is in the range 2-8 cm/yr; thus, Africa and South America were separated nearly 130 m yr ago. Since the sediments become older with distance away from the ridge axis, considering radiometric dating, the evaluation in mid-Atlantic indicates a drifting rate of 2.5-1.6 cm/yr. If this rate of drifting is assumed to be constant, Africa and South America were contiguous about  $1.6 \times 10^8$  years ago (somewhere in Jurassic time) (Fig. 1)<sup>17</sup>.

In 1966, during deep sea drilling aboard R/V VEMA, oceanographers discovered for the first time, Albian (lower Cretaceous) to Recent sediments from the Shatsky Rise, near Japan trench in the Pacific. Two hundred metres of unconsolidated sediment is found to overlie the consolidated sediment which forms the basement here. The sediment found immediately below this consolidated basement may be mid-Jurassic (172 m yr old)<sup>18</sup>. All the characteristic species of Albian like *Ticinella primula*, *Hedbergella planispira*, *Biglobigerinella cushmanii*, etc. are found.



◆ Drill site Leg VI

Fig. 1—Sea floor ages in North West Pacific defined as a result of studies carried out during the various legs of the Deep Sea Drilling Project. Drill site on Leg VI indicates a remnant of ocean floor of more than 140 m yr ago. Area line east of the Mariana-Bonin Islands (from Saito *et al.*<sup>17</sup>)

Sediment of late Paleocene to Middle Eocene (Thanetian to Ypresian) from the Vema Fracture zone in Mid-Atlantic Ridge (01° 23.5'S and 29° 12.0'W at a depth of 4,200-3,600 m from the wall of the fracture zone) was collected. The sample was an admixture of chalky friable ooze and sepiolitic material and contained typical specimens like *Globorotalia velasocensis*, *G. pseudomenardii* and *Pseudohastigerina eocenica*<sup>19</sup>. Normally, such sediments are found near or along the continental margins. Hence, the sea-floor spreading is considered to have taken place along the transverse fracture zones.

Two boulders of basalt dredged from the crests of Mid-Atlantic Ridge near 30°S at a depth of 4,280 m and from the Atlantic Fracture Zone were found to contain embedded in their vesicles the Lower to Middle Miocene foraminifers and Coccolith ooze which were found to be partly altered. The foraminifers were *Globorotalia fohsi fohsi*, *G. fohsi barisanensis* of Burdigalian (Low. Miocene) age, and *Globigerina concinna* and *Globorotalia conica* of Vindobanian (mid. Miocene) age (Fig. 2).

The age of this dredged basalt is found to be  $29 \pm 4$  m yr, which suggests that the crustal movement ceased at least 20 m yr ago<sup>17</sup>. These data rule out the possibility of large scale drifting of the sea-floor since Lower Miocene.

(b) *Biostratigraphy and cores*—The biostratigraphic principles and their application to marine and land sequences are the same, but there are marked differences in the kinds of fossils involved and the factors affecting their preservation. One of the outstanding characteristics of deep-sea sediments is their low rate of sediment accumulation, the highest being approx. 15 m per m yr and the lowest, one or less per million years for unfossiliferous red clays. These

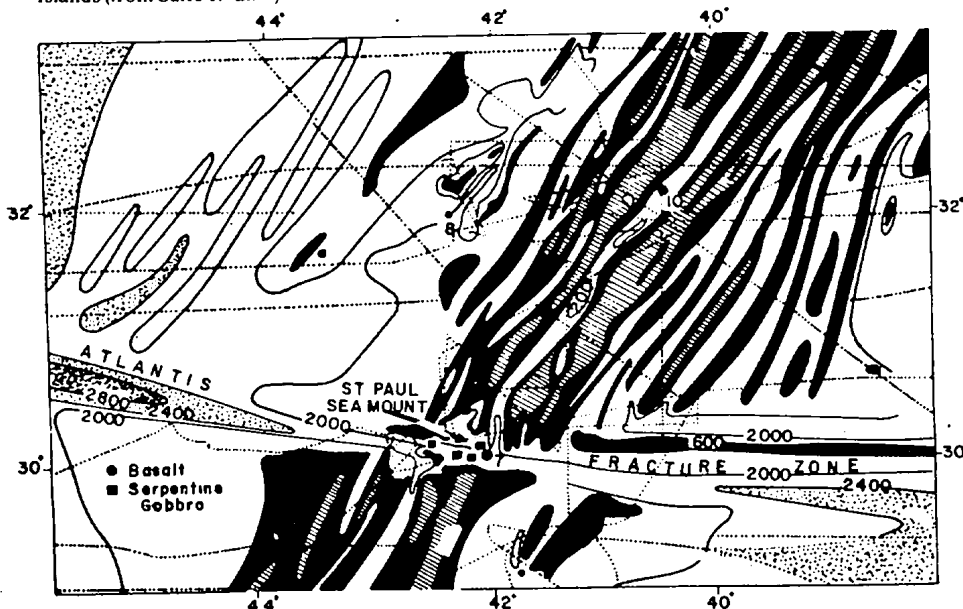


Fig. 2—Dredging on cruise A 150 near the Atlantis fracture zone. Numbers indicate dredging sites, Contour interval, 400 fathoms (732 m); dark area, 1,200-1,600 fathoms [After Heezen and Tharp, *Phil Trans. R. Soc.*, A258 (1965), 90]

are, as usual, subject to submarine erosion, admixture and the like<sup>20</sup>.

Planktonic foraminifera assumed considerable importance with the appearance of globigerina-like species in Early Cretaceous. Their importance increased further, since they showed rapid evolution and worldwide distribution. Though only about 60 genera and 500 species in all are known to date, they play an important role in biostratigraphy, paleoclimatology and geochronology.

Biocoenosis and thanatocoenosis differ considerably and the effects of preservation of various skeletal remains under different conditions become very important in their ecological interpretation. However, the oceanographer deals with well preserved microfauna and so develops, extends and relates the biostratigraphic zonation to offer a more secure and precise time correlation of world events through the study of the cores.

Several cores collected aboard R/V ELTANIN from Antarctica were studied. Fillon<sup>21</sup> reported widespread disconformity in the basins and ridges of the Ross Sea. It further indicated scouring action by high velocity currents, and the presence of thin, patchy layers of 20-30 cm thick Pleistocene sediments which indicated a slow sedimentation rate and extensive submarine erosion. *Neogloboquadrina pachyderma* is the overwhelmingly dominant foraminifer found here. Late Brunhes sediments contain exclusively agglutinated foraminifers at all depths, but in Recent sediments at 250 m and lower depths, the calcareous benthic foraminifers predominate.

### Ecology and Paleocology

The principle behind the role of foraminifers as environmental indicators involves a combination of basic concepts of sedimentology, ecology and oceanography. Hence, an interpretation of depositional environment or paleocology from microfossils depends mainly upon comparison of fossil assemblages to Recent foraminifers. Thus, foraminifers have been a subject of intensive study in the last two decades and their depth distribution is now well established<sup>22,25</sup>. The ecological study of foraminifers constitutes a dominating feature of oceanographic investigations.

Benthonic foraminifers are the chief indicators of temperature, density and bottom conditions, whereas planktonic foraminifers overlap a variety of sedimentary environments, indicating broad latitudinal boundaries of temperature and salinity of the overlying waters.

For a proper determination of an environmental condition, the foraminifers must be considered first as though they are particles of sediment and hence an integral part of lithology; and secondly as they are derived from the living and the dead alike, they involve both the biocoenosis and thanatocoenosis conditions.

The various features that determine their distribution and the environmental factors that govern

them are temperature, salinity, depth, density of the water, light penetration, character of the substrate, hydrogen ion concentration, oxygen and carbon dioxide contents in the water, organic carbon content, nutrients, the various water masses and their movement as currents, Eh, pH, pE (redox potential), distance from the shore, hydrostatic pressure, turbulence, turbidity and other biological factors. Some of the chief controlling factors are discussed below.

**Depth**—Phlegar<sup>22,26</sup> regarded depth as the most important and the major environmental factor. Hence, he proposed faunal depth boundaries on the continental shelf to slopes and basins, but studies of Cooper<sup>27</sup>, Funnell<sup>28</sup> and several other workers showed that depth is not the only controlling factor. Said<sup>8</sup>, in his study of the Red Sea foraminifers, considered that the depth zonation is controlled by organic content and substrate, but not by temperature. Foraminifers are known to build thicker shells and close up their pores as they descend to great depths as an influence of density of the water. Todd and Low<sup>29</sup> have observed that depth zonations of foraminifers are undoubtedly the result of a combination of many factors other than water depth alone, and probably some of these factors do exert more influence than depth in certain regions. Depth and access to the open ocean appear to be the chief ecologic factors affecting distribution and abundance.

**Temperature**—Laboratory studies have shown that minimum and maximum temperatures are directly related to the survival of a species as well as its reproduction. Some species show an adaptation to temperature variance, sometimes producing ecologically affected dwarfed fauna, while some others do not<sup>30</sup>. It is observed from laboratory cultures that larger specimens of the species may be expected in some unfavourable environments, but smaller specimens result under the most favourable conditions<sup>31</sup>. The surface layer of 200 m undergoes a seasonal variation, but in the range 200-1,000 m, which is the permanent thermocline, temperature decreases rapidly with depth (almost to 2°C at the bottom of the ocean).

**Salinity**—Extreme variations of high and low salinities affect the reproductive cycle of the species, resulting in the retardation of growth, size, thickness and ornamentation of the test. Species that can tolerate wide limits of salinity are found in marsh, brackish and hypersaline waters. Salinity is variable in surface waters up to 200 m depth and it may also show a variation up to 1,000-1,500 m depth, but below this depth, it is relatively constant. The high proportion of planktonics in chalk of Cretaceous is related more to high salinity and lack of turbidity than to greater depths<sup>28</sup>.

Low oxygen content leads to depauperation of benthic fauna below the sill depth in stagnant waters.

**Character of the substrate**—Said<sup>8</sup> noted that there is a direct proportional relationship between for-

aminifer number and the median diameter of the sediment in the Red Sea. It was also found that the coarser the sediment, the greater is the concentration of the benthonics in it. In Java Sea, it was found that each type of bottom sediment contained distinct population, large species occurring in sandy mud bottoms, flattened tests on heavy mud bottoms and relatively smaller species in the fine muds<sup>32</sup>. Thus, shifting sands produced the highest agglutinated forms, while compact organic rich argillaceous sediments had depauperate fauna; fine, clean sands had most abundant foraminifers. Cooper<sup>27</sup> showed that in Chuckchi Sea it was the sediment type that affected the species, and the fauna is mostly of circumpolar type.

**Water column**—Planktonic foraminifers are found at different depths within the water column and migrate up or down diurnally. They also live and grow at different depths in the standing waters and mature<sup>33</sup>. Collections by plankton tows revealed that high concentration of specimens is more common in the range 50-100 m than in the upper columns. Largest specimens of many species are found in the deepest samples. These are all subject to movement of water masses, currents and the like, which may move them to long distances and finally deposit them in sediments as a result of various causes, including upwelling<sup>34</sup>.

**Water masses**—Currents and movement of bodies of water masses help in the dispersal and transport, particularly of planktonics (either living and/or dead tests), to long distances, as noticed in the case of *Neogloboquadrina pachyderma*. The dextral forms of *N. pachyderma* are considered to be transported through Central and Equatorial Indian Ocean water masses flowing northwards and the sinistral forms through Antarctic bottom water mass which after mixing with the Indian deep water becomes the Indian Ocean bottom water mass and flows into the northern reaches of the northern Indian Ocean<sup>34</sup>. Quantitative determination of foraminifers from plankton tows in the Arabian Sea revealed three important characteristics: (1) *Globorotalia cultrata* dominates in an assemblage that lives in water which contains certain amount of Red Sea water in it, (2) *Globigerinoides ruber* is dominant in the water of the Arabian Sea which contains Persian Gulf waters in it, and (3) *Globigerinoides succulifer* and *Globigerinella siphonifera* are dominant in waters of the central and southern Arabian Sea that is not influenced by high salinity from the north<sup>35</sup>. The deduction seems to support Rochford's<sup>36</sup> postulation of migration of water masses from the north to the Arabian Sea and to the Indian Ocean, even though it is lately being disputed by some physical oceanographers.

**Turbidity**—The turbidity of the water becomes a limiting factor for light penetration. The photic zone differs in extent, but it extends up to 120 m in clear tropical waters, 40 m in shelf waters and 15 m or so in coastal waters of temperate latitudes<sup>28</sup>.

Turbulence may bury the benthonics and thus restrict their growth and development.

**Geochemical evidence**—In paleoecological investigations, it is of utmost importance to consider the geochemical evidence. Pyrites, galena and other sulphides present within the sediment indicate high reducing conditions, while glauconite indicates mild and localized reducing conditions. Pyrite and glauconite filled foraminifers indicate a non-depositional environment<sup>37</sup>. Ankerite and other carbonates indicate a positive pE (redox potential) and a pH near 8 or higher; but non-detrital silica and chamosite imply almost a neutral pH and moderate to low Eh; iron and manganese oxides favour a similar pH, but highest Eh<sup>38</sup>. Magnesium-containing calcareous forms suggest marine origin; when the proportion of magnesium falls, it suggests a decrease in temperature and an increase in latitude and depth<sup>39</sup>. Strontium in the test suggests specific salinity of the parent waters<sup>40</sup>.

### Distribution

The marsh fauna is dominated by simple agglutinated forms, while the beach fauna is often characterized by broken, coarsely perforate, calcareous forms where the environment is characterized by turbulence, temperature variation, evaporation, water seepage and run off and unstable substrate; of late, it is also being affected by pollution by man. The lagoonal facies is dominated by species like *Ammonia*, *Elphidium*, *Quinqueloculina* and is characterized by similar euryhaline fauna. *Ammonia*, a shallow water form, is an important ecologic factor for salinity and also organic matter content in the sediment<sup>41</sup>.

Brackish water foraminifers are generally cosmopolitan. According to Bandy<sup>42</sup>, Phlegar<sup>26</sup> and some other workers, the inner channel and bay regions are characterized by high frequencies of *Ammonia* and *Elphidium*; the lower reaches of rivers and inner shoals by *Ammonia* and *Ammobaculites*; the intermediate, harbour and bay areas by the above, together with abundant miliolids and other marine forms. Low pH values of river waters offer a restrictive factor to porcellaneous and hyaline species. A progressive increase in depth on the continental shelf results in increase in the population of planktonic species.

It is common knowledge that benthonic foraminifers are abundantly distributed on the shelf nearer to the coast and they decrease towards the slope and basins, whereas the planktonic specimens are highest on the outer shelf and in the upper bathyal zones and their number declines towards the more variable inshore waters. Thus, a predominance of planktonics over the benthonic populations (20:1 or so) indicates an area of not less than 200 m depth from the shore. In this way, a distribution of strata and their contained fauna can be judged. Thus, the foraminifer distribution pattern and the faunal trends are fairly standardized in various areas of marine environment in different parts of the world. Bandy<sup>43,44</sup>, Phlegar<sup>22-24,45</sup>, Cifelli<sup>46</sup>, Boltovskoy<sup>25</sup>, Murray<sup>47,48</sup> and some other workers gave the distribution of foraminifera with those species

which are characteristic of marsh, beach, channel, lagoon, inner and outer neritic, bathyal and abyssal regions.

In certain areas of the shelf, though depth, salinity and temperature restrict the number of species, the fauna appears to have been affected by the nature of the substrate. Cooper<sup>27</sup> found that *Eggerella advena*, which is a species of the inner shelf, can withstand variable conditions throughout the world, including very cold climate of the Chukchi Sea. Further, the general fauna is composed of species that are circumpolar and the calcareous assemblage is found on coarse sediment, while the arenaceous assemblage is in the fine sediment.

Akpati<sup>49</sup>, from his studies in long Island Sound, demonstrated that the bottom current is a major significant controlling factor in the distribution of fauna, even though the data revealed that there is a strong relationship between the grain size, organic carbon content and availability of nutrients in the region. Similarly, Stone<sup>50</sup> had earlier stated that the abundance and size of the foraminifers are closely related to the direct influence of currents. According to Bandy<sup>51</sup>, among the agglutinated foraminifers, the simple forms are characteristic of bays and lagoons, whereas labyrinthic forms with siphonate chambers are found in the central and outer shelves and bathyal areas. Similarly, diverse miliolids are abundant in bays and the inner shelf, but large biloculine types are from bathyal depths; also, calcareous perforate species occur in the inner shelf and those with coatae and striae are common in the outer shelf and bathyal depths. Further, coarser ornamentation, larger size and thicker tests are characteristic of deeper waters.

*Astrorhiza*, *Hyperammina* and *Harmosina* are common at depths of 3,000-6,000 m and calcareous species dominate up to 2,000 m. Benthic foraminiferal fauna is fairly homogeneous in the same environment and in the same depth zones throughout (e.g. Mediterranean). A few studies of deep sea trenches and their foraminiferal content by Brady<sup>3</sup> and Bandy and Rodolfo<sup>52</sup> revealed (e.g. from the Peru-Chile trench) that some foraminifera of 1-10 mm size are still found to be living in such great depths (e.g. *Bolivina costata* at 796 m, *Cassidulina neocarinata* at 1932 m, *Epistominella levicula* at 1932-5929 m, *Uvigerina proboscidea* at 4606 m and *Stilostomella antillea* at 6011 m). Saidova<sup>53</sup> recorded the occurrence of *Sorosphaera abyssorum* at a depth of 10,687 m from the Kuriel-Kamachatka trench. With the occurrence of such foraminifers at such great depths, it appears as though the compensation depth is not very active in the trench regions. But CCD prevents the accumulation of calcareous tests to a greater extent in the abyssal and hadal zones, where the agglutinated foraminifers are cosmopolitan, showing high diversity, since temperature and salinity are uniform and the rate of sedimentation is very low<sup>48</sup>.

In the pelagic sediments, the planktonic foraminifers give a clear indication of discontinuity by the presence

of turbidites. This is revealed by a change in abundance, size and assemblage of the species, their diversity and the mixed age displayed by the intervals<sup>54</sup>.

Extensive studies were made on the bathymetric distribution of planktonic tows in the equatorial Atlantic and in the Sargasso Sea<sup>55,56</sup>, in the vicinity of north Atlantic current<sup>54</sup> and from Cape Cod to the equatorial region near west Africa<sup>46</sup>; the results were compared with those for Pacific distribution<sup>57,58</sup>.

Among others, *Globorotalia menardii* showed a notable change in frequency<sup>46</sup>. North of 18°N, this species was found to be rare, but to the south of it, it was appreciable, common in the region of the South Equatorial Current, but increasingly abundant in the equatorial waters. *Globigerina bulloides* was dominant in slope waters, but was virtually absent in the Sargasso Sea and ubiquitous to the south of it. But the dominance of *G. bulloides* during the cooler months is replaced by that of *Globigerinoides ruber* during the warmer months<sup>59</sup>.

Thus, it is observed that the modern planktonic fauna occurring in the surface sediment of the topmost part (2.5 cm) of a core differs in the faunal constituents of the immediately lower part of the same core. This lower core fauna may be similar to the modern fauna of a higher latitude. Thus, 'cold water fauna' are recorded from several submarine cores of the present day 'warm water fauna' areas of Atlantic<sup>15,60</sup>, Gulf of Mexico<sup>45</sup>, the Mediterranean<sup>37</sup>, and the Arabian Sea<sup>61,9</sup>. Such foraminifers are considered paleoclimatic indicators or thermometers of past climates<sup>62</sup>.

The physical, chemical and biological parameters involving a seasonal cycle indicate that phytoplankton productivity acts as the controlling factor of the standing crop of planktonic foraminifera, but other factors, such as salinity, temperature, oxygen content, phosphates, etc. are secondary<sup>63</sup>. Further, the majority of the spinose species are surface dwellers or are present in the euphotic zone; the non-spinose species occur in the sub-surface depths or at 50-500 m depth with an early stage in the euphotic zone. While the shell thickening process is an adaptation to increasing depth habitats, the "bottom stage" of the planktonics is considered a gerontic feature<sup>33</sup>.

In recent years, living populations have been compared with the dead assemblages, because a relative ratio of this gives evidence of the rate of sedimentation in the region. Thus, a decrease in the relative number of living specimens indicates a decrease in the sedimentation rate. Similarly, the coiling direction ratio in foraminifers is considered to be a potentially important stratigraphic tool. This is because the left and right coiled forms of a species are identical in morphology and are extremely similar in size or shape, except in the coiling direction. Therefore, a change in the ratio of the coiling direction of a species from left to right or right to left represents only a gradient in a core and so represents a uniform change in population through time in a non-discontinuous sedimentary environment.

In India, foraminiferal distribution has been reported from the beach, inter-tidal, nearshore and offshore regions. Earlier, Brady<sup>3</sup> had studied the foraminifers from the *Challenger* expedition; later Chapman<sup>4</sup> studied the foraminifera from the Laccadive region, and Stubbings<sup>61</sup>, those from the John Murray expedition collections. In recent years, Choudhury and Biswas<sup>64</sup>, and Bhatia<sup>65</sup> studied the foraminifers of Juhu Beach, Bombay and Chatterji and Gururaja<sup>66</sup>, those from the Mangalore coast. The foraminifers from the shelf region off Kerala were studied by Setty<sup>9</sup>, those off Mangalore and Karwar by Setty and Guptha<sup>10</sup> and those off Bombay and Cambay region by Rao<sup>11,12</sup>. Setty and Almeida<sup>67</sup>, Almeida and Setty<sup>68</sup> and Bhatt<sup>69</sup> studied foraminifers from the shelf area of the east coast of India, while those of beach sands of Madras were studied by Bhalla<sup>70</sup>, those of Puri sands, Orissa by Bhatia and Bhalla<sup>71</sup> and of Vizag by Bhalla<sup>72</sup>. Biometric and zoogeographic relations and Indo-Pacific affinity of some of these species were discussed by Bhalla<sup>72</sup>. Speciation and subspeciation of *Neogloboquadrina pachyderma* (Ehrenberg) occurring in the northern Indian Ocean beyond the equator were proposed by Setty<sup>73</sup>.

#### Correlation

Sediment is deposited on the ocean floor slowly, particle by particle and in an uninterrupted manner, but at a variable rate in different regions. This may be interrupted locally by slumping and turbidites. A measure of matching between two or more regions of a succession, particularly in the case of cores, is two-dimensional, the time equivalence of various faunal zones and vertical deposition of the sediments. The two keystones of correlation by planktonic foraminifers are their (1) worldwide contemporaneous existence, and (2) their unchanging sequential relation to one another. While correlating the cores of Eniwetok and Bikini islands in the Pacific, Todd<sup>74</sup> noticed that the paleontologic affinities of the smaller foraminiferal species are equally divided between eastern and western hemispheres. In the Eocene, they are comparable with those of southeastern US, West Indies and also of Central Europe and Near East, while in the Oligocene, the major tie is with southeastern US, and in Miocene it is with Australia, New Zealand and Fiji, but less with US, West Indies and Europe.

Cifelli<sup>54</sup> observed, following a study of Mid-Atlantic Ridge sediments, that there was a period of tectonism and volcanism prior to late Miocene, then a period of pelagic deposition followed by another eruptive phase as late as the Quaternary. He further observed that vesicles of highly alkaline olivine basalt (in D43) dredged from a depth of 1,200 m were filled with indurated foraminiferal ooze which included *Globorotalia truncatulinoides*, thus giving an age of Quaternary for the sediment.

Pujo-Lamy<sup>75</sup> was able to demonstrate from a study of the bottom surface samples from the Bay of Biscay (560-4,450 m depth) that *Siphotextularia rolshauseni*

characterises the beginning of late Holocene; *Aderocotryma glomerata* now lives at depths exceeding 3,500 m, whereas up to Mid-Wurm they lived on the slope region; *Karreriella* sp. is represented only after Wurm II to Wurm III interstade; and *Eggerella* sp. had disappeared during Wurm III, but is present at least since the end of Riss, and some other genera have now invaded the abyssal plain.

In 1959, Hendrix<sup>76</sup> introduced a novel method of correlation which does not require any guide fossils. This method involves the complex interrelationships shown by overlapping patterns of individual species to develop time correlations instead of by matching of fauna. Somehow, this method did not become popular with stratigraphers.

In the Indo-Pacific, a 'letter classification of Tertiary sediments' was proposed by Van der Vlerk and Umbgrove<sup>77</sup> based upon larger foraminifers, as the fauna appeared to be constant over wide areas. Van der Vlerk<sup>78</sup> in 1968 introduced another system of worldwide correlation based on two different methods which are found to be supplementary to each other. This method introduces a new parameter known as 'the degree of curvature' of the lepidocyclines, the other being the usual method based on planktonic foraminifers. This 'degree of curvature' parameter is a modification of another earlier parameter (considered as an indicator of time) proposed by him and known as 'grade of enclosure' of the nucleocoenoch by the deuteroconch<sup>79</sup> of the Lepidocyclines.

Adams<sup>80</sup> emphasized the usefulness of the 'letter classification' for the Tertiary. Cole<sup>81-83</sup> found this system very useful and so he suggests reliance on inter regional correlations also. Considerable work has been done in India on larger foraminifers<sup>84-94</sup>. Correlations embracing the European and Indo-Pacific region have also been attempted.

To make such a correlation more effective, Cole<sup>83</sup> has emphasized that specific names may have to be reduced to the minimum by a process of elimination of synonyms and a reassignment may have to be adopted in terms of radiometric dating.

#### Paleontologic Zonation and Radiometric Dating

From the various contributions, it is clear that a sequence of stratigraphic events in time should be worked out on the basis of cross-correlation among paleontologic zones and radiometric dating. Changes in the earth's magnetic polarity provide yet another evidence. Bandy and Ingle<sup>95</sup> opined that good radiometric dates require good paleontological control both above and below the dated horizons. The problems affecting foraminiferal zonations are chiefly nonisochronous isomorphism of species like orbulines at different times; the necessity of relating planktonics to paleo-oceanography; radiometric dating at significant points; variations in the coiling ratios of significant foraminifers *Neogloboquadrina pachyderma*, *Globorotalia crassaformis* G. *truncatulinoides* etc.; paleoclimatic trends; and other environmental

factors<sup>96</sup>. Correlations derived by comparing the faunal zonation with faunal components between nearby sections are reasonably accurate, especially when planktonic foraminifers are employed. Berggren<sup>97</sup> proposed a refined radiometric time-scale for the Cenozoic to which planktonic zonations can be related. The letter number series developed by Blow<sup>98</sup> for the late middle Eocene to Holocene and by Bolli<sup>99</sup>, as modified by Berggren<sup>100,101</sup> for the remainder of the Paleocene, known later as the Blow-Berggren System, though unsatisfactory for a number of reasons, is adopted to a great extent in the DSDP core studies. Thus, the foraminiferal assemblages of Nishikurosawa formation of Japan are defined with the worldwide chrono-stratigraphic framework, and at the same time the Neogene transgression is dated<sup>102</sup>.

The radiometric dates of minerals from marine Neogene strata in California also suggested the need for a revision. When the base of the lower Miocene was approx. 24 m yr, the Miocene-Pliocene boundary dated back to approx. 9 m yr ago; the Pliocene-Pleistocene boundary was at about 3 m yr ago; and the Pleistocene-Holocene boundary was at 11,000 years ago<sup>95</sup>. According to paleontologic zonation, the upper Pliocene is marked by the first appearance (in California) of *Globorotalia truncatulinoides tosaensis* and the first appearance of *Globorotalia truncatulinoides truncatulinoides* (d'Orbigny) at the base of the Pleistocene in deep sea sediments. The Zemorrian-Saucesion boundary is thus equivalent to Oligocene boundary.

A planktonic-based paleontologic zonation shows that *Neogloboquadrina pachyderma* (*Globigerina pachyderma*) has dextral populations in Lower and Upper Pliocene and Holocene, whereas the sinistral populations dominate the Middle Pliocene and Pleistocene times. These changes in coiling directions of *N. pachyderma* are considered cyclic paleo-oceanographic events.

The evolutionary trends are fundamental in establishing the 40 odd planktonic foraminiferal zones currently used in inter-continental correlations of Cretaceous-Tertiary sequences. These zones are applied in the studies of cores drilled for DSDP, as they have wide applicability and validity of the established biostratigraphic zones. In the Indian Ocean, the Cretaceous sediments are encountered from the Agulhas Rise and the Eocene sediments from north of Madagascar<sup>103</sup>. Ericson *et al.*<sup>104</sup> established six faunal zones in Atlantic deep sea cores for the Quaternary and noticed an abrupt shift in the last zone at 11,000 years ago, which marks the glacial to present day interglacial climate.

### Magnetic Stratigraphy

The Cenozoic chronology was hitherto based mainly on biostratigraphy related to specific events, particularly of terrestrial mammalian evolution on the one hand and marine molluscan or foraminiferal events on the other. In recent years, the pelagic

foraminiferal record has been revised considerably taking into account the use of magnetic polarity stratigraphy as an accurate and absolute correlation tool<sup>105</sup>. The study of such geomagnetic polarity reversals which occurred during the past five million years has been useful in providing ages and also correlations between many deep sea cores, but it has rarely been applied to Cenozoic strata found on land, with the exception of New Zealand<sup>106</sup> (Fig. 3). With the close correlation of magnetic and planktonic events<sup>107-109</sup> it is clear that mutual corroboration of these two correlation methods does exist. There is no major contradiction between magnetic stratigraphy and planktonic events.

*Spheroidinella dehiscens* datum occurs at the Miocene-Pliocene boundary which is in the Gauss epoch. The appearance of *Globorotalia truncatulinoides* at the Pliocene-Pleistocene boundary (when the discosterids become extinct) is at or near the Gilsa event. The first of the three major cold cycles of the Pleistocene occur when *Neogloboquadrina pachyderma* shows sinistral coiling at the Gilbert a-c epoch, the second at the lower Matuyama epoch (Up. Pliocene), and the third at the Brunhes epoch. There was a long preglacial Pleistocene interval before the Gunz epoch glaciation<sup>110</sup>. Johnson *et al.*<sup>111</sup> studied the Pleistocene valley fill of San Pedro, Arizona, and noticed 12 superimposed magnetic polarity zones which ranged from upper Gilbert epoch through Brunhes. Based on mammalian fauna they erected four datum planes; the first of *Lepus* sp. is placed below the Olduvai Event.

Opdyke and Glass<sup>112</sup> examined several cores from the Indian Ocean for paleomagnetism and sedimentation rate and attempted to correlate the same with magnetic stratigraphy. It was noticed that the sedimentation rate ranged from 3 to 7 mm per 1,000 years. The sediment cover over the crest of the Mid-Oceanic ridge seems to be lacking in the northern parts, but it is somewhat considerable in the southern part. This appears to be in agreement with the sea-floor spreading hypothesis.

### Boundary Problems

(a) *Cretaceous-Tertiary boundary*—Various theories have been advanced in respect of animal and plant extinctions, faunal and floral changes, disappearance and appearance of several foraminiferal species and their diversification at the Cretaceous-Tertiary boundary.

Lipps, as quoted by Berggren<sup>100</sup>, presented a hypothesis for the extinction and later diversification of planktonic foraminifers. According to him, the warm high latitudinal seas eliminate horizontal and vertical habitats and barriers to competition, thus causing extinction, while cool high latitudinal seas create thermal or related barriers and increase ecological opportunities for speciation by horizontal and vertical isolation of populations. Therefore, it seems most appropriate to search for an explanation to this problem through the cores of the DSDP.

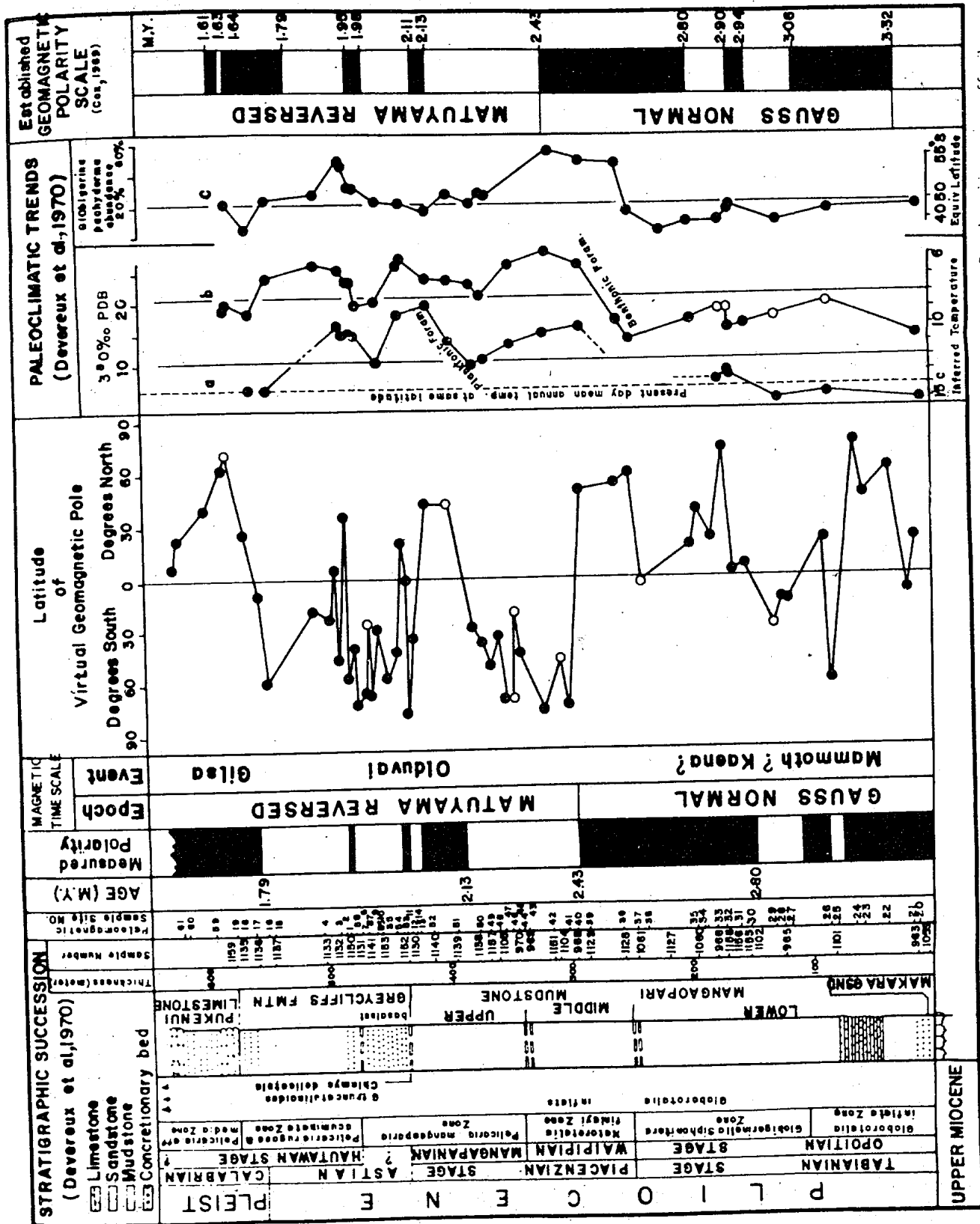


Fig. 3.—Paleomagnetic stratigraphy, stratigraphic succession and paleoclimatic trends at Mangopari stream-Makara river, New Zealand. Sample positions, ranges of fossils, local stratigraphic units and possible European correlations, magnetic polarity reversals are shown (After Kennett *et al.*, 1966.)



Recent oceanographic studies indicate that significant changes in the oceanic circulation patterns occurred in the early Cenozoic as a result of the opening of the North Atlantic along the Raykjanes Ridge<sup>13</sup>. On Leg 12, of DSDP, it was observed that the planktonic foraminifers increased in diversity, which is correlatable to the rising temperature.

For the first time, the Mesozoic/Cenozoic (or Cretaceous/Tertiary or Maestrichtian/Danian, or Maestrichtian/Lower Paleocene) boundary was crossed by DSDP coring at site 20 of Leg 3, in the south Atlantic at a depth of 4,484 m. At this boundary, the Danian was less than 1 m thick, and the entire Paleocene was only about 5 m thick. An extremely sudden or abrupt break in fauna and flora was visible at the boundary; a considerable reworking of Maestrichtian sediments in lower Middle Paleocene was also noticed. The sedimentation rate here is observed to be 5 mm/1,000 years.

(b) *Paleocene-Eocene boundary*—In India, well developed Paleocene-Eocene marine strata with their characteristic fauna are seen in the Cauvery basin and also in Meghalaya. In the Cauvery basin, this boundary (Upper Cretaceous/Lower Paleocene) is marked by the extinction of typical upper Cretaceous planktonic foraminifera like *Abathomphalus*, *Globotruncana*, *Hedbergella*, *Heterohelix* and *Rugoglobigerina*, and the sudden appearance of simple globular forms of *Globigerina*, *Globigerinoides* and *Globorotalia*<sup>14</sup>. Similarly, the Paleocene-Eocene boundary in the Cauvery basin is marked by the extinction of *Globorotalia velascoensis* and other angulocarinata, sharply-keeled forms, and the first appearance of *Hantkenina*, *Pseudohastigerina*, *Globigeropsis*, abundant large species of *Discocyclina*, *Assilina*, *Nummulites*, *Operculina*, etc. However, the extinction level of *Globorotalia pusilla* marks the Paleocene-Eocene boundary at the base of the Thanetian of Thanetian-Sparnacian boundary in Meghalaya<sup>15</sup>.

Leg 23 of DSDP in the Arabian Sea at site 220 and 6°30.97'N 70°59.02'E at a depth of 4,036 m on the Laccadive-Chagos Ridge shows basalt flows and the intertrappeans which are overlaid by chert and Middle Eocene to Holocene sediments, whereas on the Owen Ridge at 3,633 m depth, the volcanics are found to be overlaid by Upper Paleocene to Recent sediments.

Further, based on the occurrence of volcanics at depths ranging from 345 m at Padra to 3155 m at Sanand in the Cambay region, and the drilling operations conducted by the ONGC13, and cross-correlation, it is considered that this volcanism may be a part of the major Deccan Trap activity, which ranged between upper Jurassic to Eocene to Oligocene time.

(c) *Miocene-Pliocene boundary*—The overlap of *Globigerina nepenthes*, *Globoquadrina altispira* and *Spheroidinella seminulina* in range with *S. dehiscentis* in the cores of Mid-Atlantic Ridge sediments is indicative of a continued sedimentation to Lower Pliocene. The first appearance of *Globorotalia truncatulinoides* marks

the base of the Pleistocene<sup>54</sup>. Srinivasan and Srivastava<sup>116</sup> believe that *Spheroidinella dehiscentis* datum of Bandy<sup>43</sup> in the Philippines marking the base of Pliocene is significantly younger than the *Globorotalia margaritae* and *S. dehiscentis* datum in the Andaman strata.

In the tropical regions, the Miocene, according to Bandy and Ingle<sup>95</sup>, is divided into three equal important dates, the Lower Miocene beginning with *Globigerinoides trilobus* having a radiometric dating of 24.5 m yr B.P; (2) Middle Miocene with *Orbulina universa* at 19.25 m yr B.P; Upper Miocene with *Globorotalia menardii* at 14 m yr B.P; and (3) the Pliocene with *Spheroidinella dehiscentis* at 9 m yr B.P. (Gauss Magnetic epoch).

(d) *Pliocene-Pleistocene boundary*—The faunal evidence advanced by Ericson *et al.*<sup>117</sup>, Riedel *et al.*<sup>118</sup> and Berggren *et al.*<sup>119</sup> indicates that (1) the extinction of discoasterids and planktonic foraminifera like *Globigerinoides fistulosus*, *G. altispira*, *Spheroidinella multiloba* and dextral *Globorotalia menardii*, and (2) the first appearance of *Globorotalia truncatulinoides* and sinistral *G. menardii* mark the Pliocene-Pleistocene boundary. These Atlantic cores correlate well with those of Pacific cores, and are relatable to the holostatotype of Calabria in Italy (Fig. 4).

*Hyalinea balthica* is also another important indicator of Pliocene-Pleistocene boundary because of its first appearance at the base of the Pleistocene, as defined in the sections of Le Castalia, Calabria, Italy. Though Ericson *et al.*<sup>117</sup> considered this to be only a local feature, this species was recorded in the Gulf Coast region<sup>120</sup> and in the shelf sediments of Kerala coast<sup>73</sup>. This species is considered to be a cool water to cold water indicator.

According to magnetic stratigraphy, the Pliocene-Pleistocene boundary occurs within the Olduvai Normal Event and is dated at about 1.85 m yr. Kennett *et al.*<sup>106</sup> consider that the boundary is at the base of the Gilsa Event at about 1.79 m yr and at the first definite appearance of *Globorotalia truncatulinoides*. According to Berggren<sup>121</sup>, the major extinction of discoasterids takes place about 100 cm above the base of the Pleistocene and they briefly reappear in a sample within the Jaramillo Normal Event at about 0.9 m yr ago. A sharp reduction in *Pulleniatina obliqueloculata* and *S. dehiscentis* and a sharp increase in *Globorotalia inflata* and *G. hirsuta* in the Lower Pleistocene indicate a stronger cooling, which is related to the onset of Pleistocene continental glaciation. But Kennet *et al.*<sup>106</sup> consider that this cooling took place much earlier than the Gilsa Event, i.e. upper Gauss (Upper Pliocene) to Middle Matuyama (Early Pleistocene), which is about 2.43 m yr ago. This deduction is based upon a study of the abundance of *N. pachyderma* as a percentage of all planktonic tests and the paleoclimatic curves drawn using oxygen isotope ratio of planktonic and benthonic species. Therefore, it is suggested that this transition does not indicate any major environmental change of worldwide significance<sup>122</sup>.

Flint<sup>123</sup> had earlier suggested that a distinction between the Tertiary and Quaternary periods is artificial, since the world climate deteriorated gradually and glaciation had already begun in the high latitude several million years before it reached the temperate regions.

**Paleotemperature and Isotope Studies**

Emiliani<sup>124</sup> was the first to attempt quantitative determination of the range of oceanic temperature fluctuations. He introduced oxygen isotope analysis to deep-sea stratigraphy, in general, and to foraminiferal sequences, in particular. This study considers that in a state of thermodynamic equilibrium, calcite and sea water differ in their <sup>18</sup>O/<sup>16</sup>O ratios and this difference decreases with increase in temperature. Thus, shells formed in equilibrium with sea wafer are rich in <sup>18</sup>O

relative to sea water, but the <sup>18</sup>O content falls with increase in temperature. The empirical relationship between the temperature of precipitation and isotopic composition is<sup>125</sup>

$$T = k_1 - k_2 - (\delta - A) + k_3 (\delta - A)^2$$

where

$$\delta = \frac{{}^{18}\text{O}/{}^{16}\text{O}(\text{sample}) - {}^{18}\text{O}/{}^{16}\text{O}(\text{standard carbonate})}{{}^{18}\text{O}/{}^{16}\text{O}(\text{standard carbonate})} \cdot 10^3$$

and

$$A = \frac{{}^{18}\text{O}/{}^{16}\text{O}(\text{water}) - {}^{18}\text{O}/{}^{16}\text{O}(\text{standard water})}{{}^{18}\text{O}/{}^{16}\text{O}(\text{standard water})}$$

where  $k_1$  is 16.5;  $k_2$  is 4.3; and  $k_3$  is 0.14 (ref. 126). Oxygen isotope equilibrium denotes similar environmental conditions; hence, a difference in this ratio in different species means different temperatures during their growth<sup>127</sup>.

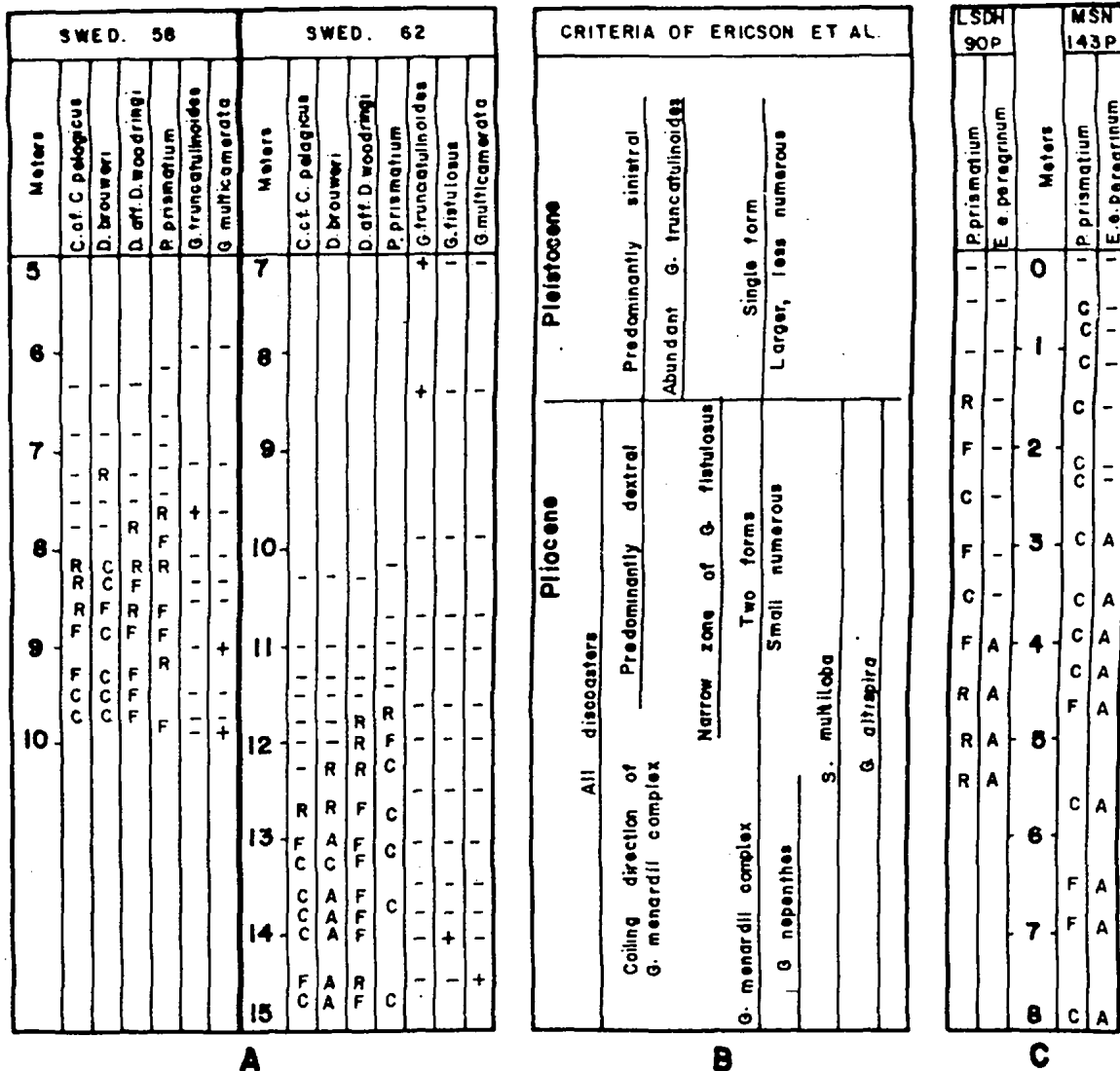


Fig. 4—A (left) Occurrence of some planktonic micro-fossils in two Swedish Deep Sea Expedition cores. A, abundant; C, common; F, few; R, rare; P, present; -, absent; B (middle). Summary of criteria used by Ericson et al. to distinguish the "Pliocene-Pleistocene" boundary. (After Riedel, W.R. et al.<sup>118</sup>)

Oxygen isotopic temperature is used to determine the ancient ocean currents and also the orientation of large crustal plates on the earth's surface relative to its rotational poles. Similarly, oxygen isotope studies confirm that the temperature declined very rapidly at the end of the Cretaceous and the bottom water temperature of the South Atlantic was about 10°C higher than today<sup>128</sup>. It was also found to be low, as in the present day, in Oligocene, as noticed in the DSDP cores collected near Mcquire Ridge near Antarctica; the Antarctic ice sheet was already present at its present dimensions in Pliocene<sup>129</sup>. Carbon isotope studies revealed that foraminifers with the highest carbon isotope values live closest to the surface and those with the lowest values live at great depths<sup>128</sup>. Further, all Recent planktonic foraminifers are heavier in <sup>13</sup>C by 1.5-2‰ compared to the Recent benthonics, because the dissolved inorganic carbon is richer in surface waters than in bottom waters. The carbon (<sup>13</sup>C/<sup>12</sup>C) isotope ratios of the tests correlate roughly with both salinity and temperature<sup>127</sup>.

Oxygen and carbon isotope studies on the DSDP samples collected from Campbell Plateau show that the surface temperature of Early Eocene was 19°C and it declined to 7°C in Oligocene, though separated by episodes of temperature stability<sup>129</sup>. The Pleistocene temperature is estimated by species composition by foraminiferal assemblage and the oxygen isotope composition of individual species. The isotopic composition depends upon temperature and the magnitude of glacial effect and the variables like vital effect, differential dissolution effect, evaporation precipitation pattern, etc.<sup>125</sup>.

Depth stratification is very clear in the <sup>18</sup>O/<sup>16</sup>O ratios of different species in a sediment assemblage. Oba<sup>130</sup> noticed that depth ranking based on isotopic data of deep-sea cores from the Indian Ocean are consistent with those of other oceans and are largely consistent with the stratification order worked out from plankton tows<sup>131</sup>.

#### Pleistocene Climate

Studies on cores of DSDP have shown that foraminifers are very good indicators of temperature changes in the levels of the seas during the Pleistocene and post-Pleistocene times. The relationship between the present day living and fossil populations and their temperature and depth environments appears to be the most important factor controlling their distribution. A lowering of the sea level was postulated for some of the substages and inter-substages of the Pleistocene by demarcating the sedimentary strata, the presence of cold water planktonics and the warm water benthonics overlying. Thus, planktonic foraminifers indicate the temperature of surface waters, while the benthonics refer to depth zones and the temperature variations.

Correlation between the cores in the North Atlantic showed changes in the composition of benthonic assemblages during the past 150,000 years. In the present day seas and oceans, the benthonic

foraminiferal faunal composition is dominated by a few species which indicate decreasing temperature with increasing depth, e.g. *Uvigerina hollicki*, which is today confined to 1,200 m depth and a temperature of 4°C in the North Atlantic, was a dominant species 150,000 years ago at 4,500 m depth and was present so far south as Cape Verde islands<sup>132</sup>.

Temperature influences the latitudinal depth and longitudinal distribution<sup>133</sup>. Temperature zones in space and time are inferred on the basis of variations in test size, coiling ratio and other ecological parameters. The planktonic foraminiferal assemblages also show effects of climatic control on water masses, as seen in DSDP cores from the north-eastern Pacific which indicated (1) a warm-cool-warm cycle marking the Pliocene, (2) a subtropical to a transitional water mass in lower Pleistocene, and (3) severe cooling, resulting in the Pleistocene glaciation. The inter-glacial stages in the upper Pleistocene are marked by abundant sinistral *Neogloboquadrina pachyderma* and *Globigerina bulloides*, followed by warm species increasing with the abundance of *Globorotalia inflata* and *G. crassaformis*<sup>134</sup>. *Globorotalia hirsuta* first appeared within the warm interglacial intervals. A study of the North Atlantic Equatorial cores revealed that the longest and most complex specimens appear during the temperature maxima and the smallest and simplest individuals appear during the glacial temperature minima. Lidz<sup>135</sup> showed that the environmentally induced variations in shell morphology are conditioned by temperature, resulting in temperature dependent and temperature independent species. The temperature dependent forms which are directly related to temperature variations are characterized by their abundance, test size, development of thin wall, translucent chambers, partially carinate tests and the presence or absence of an imperforate rim. The temperature independent forms are characterized by conical angle of the test and tightness of coiling, variation in size, shape and depth of the umbilical area, depth of the sutures, marked peripheral angularity and acuteness, the flare of the chamber and the degree of lateral compression.

Srinivasan and Kennett<sup>136</sup> noticed, from a study of a deep sea core from the South Pacific, that *Neogloboquadrina pachyderma*, which parallels paleoclimatic oscillations from upper Miocene to Recent, also exhibits oscillations in the ratio of calcification in its test. This secondary calcification is a useful parameter in interpreting the Cenozoic climates. Further, it is interesting to note that the warm episodes are marked by an abundance of reticulate forms or low frequencies of crystalline forms. Thus, this feature represents a climatic index.

#### Case Studies

Case history studies of a few important species which played an important role in oceanographic events are considered useful and beneficial. They are presented below.

(1) *Orbulina universa* d'Orbigny—This species has been studied in considerable detail from various points of view, such as test size, porosity, developmental stages, variations, etc. and its strong inverse relationship to latitudinal occurrence, temperature, salinity, density of the water, living and dead assemblage differences and other environmental factors. Be' *et al.*<sup>137</sup> gave a statistical account of this species from the Indian Ocean, and revealed that large tests (600-800  $\mu$ ) are found in tropical and subtropical areas (highest in the Arabian Sea and the Bay of Bengal), whereas those smaller than 450  $\mu$  size are confined within the Subtropical-Subantarctic transition zone, and those of 550-450  $\mu$  are found in the mid-latitudes. The living forms are characterized by thinner tests and long spines, while the dead ones in sediments are thicker and are without spines. The pore diameter, test porosity and number of pores increase with test size, whereas smaller pore diameter is found in forms of higher latitudes; thus, a direct correlation can be drawn between surface water temperature and the species. According to Boltovskoy<sup>138</sup>, the thickening of the wall, lacking in the trochospiral spinose test inside, is due to resorption during the thickening of the outer wall.

Test porosity in planktonic foraminifers differs with latitude, which is considered a major environmental factor. Porosity is directly related to buoyancy. Tests with higher porosity are from lower density surface waters; thus, it is evident that test porosity and test density are indicative of surface water temperature, salinity and density. The highest test porosities in *O. universa* are observed in tropical areas and the lowest porosities are in temperate and subantarctic regions. Though test porosity and test size reach their maximum values in warm water regions, *O. universa* is abundant in relatively cool, subtropical waters. Similarly, specimens like *Globigerinoides succulifer*, *Globorotalia menardii* and *Neogloboquadrina dutertrei* collected from the Indian Ocean show decrease in pore density away from the equator, but *Globigerinella siphonifera* and *Globorotalia tumida* show decrease in test porosity<sup>139</sup>. Scott<sup>140</sup>, while studying the pustulose and honeycomb topography in *Globigerinoides trilobus altiaptura*, recognized that the depressions on the crests of some pustules (spine bases) provide a clue to the original occurrence of spines in fossil foraminifers.

Several other workers, including Parker<sup>141</sup> and Bandy<sup>142</sup>, have referred to various other characteristics of this species in terms of environment.

(2) *Neogloboquadrina pachyderma* (*Globigerina pachyderma* (Ehrenberg)—*N. pachyderma*, a bipolar species, has been studied by several workers from the morphological, distributional, ecological and climatic points of view. Its coiling direction and a change in it are directly related to temperature, salinity and density, while its test (thin or thick), number of chambers and nature of aperture are related to water masses. The arctic forms are thinner and smaller, while the antarctic species are thicker and larger<sup>56</sup> (Fig. 5).

The early stages of this species are confused by many authors with the juvenile forms of *Globigerina bulloides* and *G. eggeri*, because mature forms of *G. bulloides* and *G. eggeri* are not found in Arctic bottom sediments and the final stage forms are not found in plankton tows, and the transformation of the early stage to the final stage takes place at depths greater than 200 m. This led various authors to suggest different names for this species; thus, *Globigerina pachyderma incompta* Cifelli, and *G. inflata* are synonymous with *N. pachyderma*. Smith<sup>143</sup> considered *G. eggeri*, *G. quadrilatera* and *G. bulloides* as morphologic variants of *G. pachyderma*, i.e. *N. pachyderma*, but Boltovskoy<sup>138</sup> and Kennett<sup>144</sup> have sorted out the differences between the two.

Though Parker<sup>145</sup> had observed that *G. pachyderma* is 'occasionally observed beyond the equator', Setty<sup>73</sup> recorded its occurrence in 9, 12, 14, 19 and 23° north latitude in the Arabian Sea, and Bhatt<sup>69</sup> at 18°N latitude in the Bay of Bengal. After considering various factors, such as coiling direction, abundance of occurrence, temperature, world distribution and the T-S relationship of water masses, their movement in the Indian Ocean, and upwelling, etc., Setty<sup>73</sup> proposed that forms which occur in the low latitudes in the northern Indian Ocean be henceforth referred to as (1) *Neogloboquadrina pachyderma forma dextralis typica* Setty n. subsp. (s.s.), (2) *Neogloboquadrina pachyderma forma sinistralis typica* n. subsp. (s.s.), (3) those which occur in the mid-latitudes as *Neogloboquadrina pachyderma forma dextralis* Setty n. subsp. (s.s.), and (4) those which occur in the high latitudes as *Neogloboquadrina pachyderma* (Ehrenberg) (s.s.). This speciation and subspeciation into definite latitudinal zones in the Indian Ocean helps greatly in the standardization of this species.

(3) *Globorotalia menardii neoflexuosa*—Srinivasan *et al.*<sup>136</sup> renamed *G. menardii flexuosa* as *G. menardii neoflexuosa* as a new subspecies, because of its characteristic flexed final chamber, absence from the Atlantic, and occurrence in the present day Arabian Sea. It became extinct in the Atlantic near the end of the X-climatic episode, approx. 80,000 years ago. Rao<sup>12</sup> also observed its presence in his samples collected off

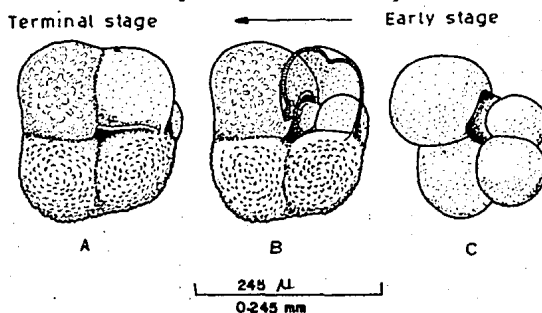


Fig. 5—Morphological variations in the ontogeny of *Globigerina pachyderma* (Ehrenberg). A, typical final stage specimen from Arctic bottom sediments; B, same specimen with final chamber broken off; C, modern specimen in early developmental stage from plankton-tow sample. Note the thickened tests of A and B and the similarity between B and C (After Be'<sup>53</sup>).

Bombay. Earlier workers must have dismissed this flexed nature of *G. menardii* as only an ecological variant and, therefore, considered that it did not warrant erection into a new species or subspecies. Be' and McIntyre<sup>146</sup> had earlier erected this variant into a new subspecies which is now differentiated from *G. tumida flexuosa* (Koch).

(4) *Globigerinoides obliquus* Bolli—*G. obliquus* has been reported as a fossil only and as a good marker species from Miocene and Pliocene of Trinidad<sup>147</sup>, Venezuela<sup>148</sup>, Spain<sup>149</sup> and Equatorial Pacific<sup>150</sup>, but Boltovskoy and Watanabe<sup>151</sup> reported its occurrence in the Recent bottom sediment of the South Pacific from 40°S 101°20'W from a depth of 3,240 m; hence it is of great significance. The assemblage containing *G. obliquus* is typically post-Pleistocene and is associated with *Globorotalia truncatulinoides*, but not with *G. tosaensis*. Thus, it may be noted that *G. obliquus* did not become extinct in the Pleistocene, but ranged through the Recent, at least in some restricted areas<sup>151</sup>. Tunyow Huang<sup>152</sup> reported the occurrence of *G. obliquus* from Yonahoma and Nagama assemblages containing *G. tosaensis* from Miyako-jima, Ryukyu, Japan. Srinivasan and Srivastava<sup>116</sup> noticed the occurrence of *G. obliquus* in the lower Pliocene of Chowra island, Andamans.

(5) *Neocarinina blowi* n. sp. and *Globorotalia crozetensis* n. sp.—These two are described as new species from the late Pleistocene from location 42°53'S 42°21'E at a depth of 4,330 m. In view of their rare occurrence, restricted appearance in the 20-30 cm layer and their association with *G. truncatulinoides*, they are useful biostratigraphic indicators for the Pleistocene-Holocene boundary here<sup>153</sup>.

(6) *Neogloboquadrina atlantica*—Poore and Burgren<sup>154</sup> re-examined *Neogloboquadrina atlantica* on its gross morphologic variation, test surface, ultrastructure related to secondary calcification, and its probable phylogenetic relationship. It shows a change in coiling direction at a level close to the Miocene/Pliocene boundary, but it becomes extinct in the Pleistocene; thus, it is useful in Neogene biostratigraphic studies of the North Atlantic.

(7) *Aberrant forms*—Reports of abnormal specimens of various species are found in the literature. Brady<sup>3</sup> reported the occurrence of an abnormal *Quinqueloculina* sp. from Recent sediments of North Pacific; Hooper<sup>155</sup> reported an abnormal *Miliolinella* sp. from the New Foundland, Grand Banks; Dhillon<sup>156,157</sup> referred to an abnormal *Astacolus reniformis* from the Holocene of Gantheame Bay, and to a double apertured *Ammotium salsum* from West Malaysia. Setty and Almeida<sup>67</sup> reported the occurrence of *Uvigerina* sp. having two terminal apertures with parallel necks and phialine lips; a twinned case of another *Uvigerina* sp., and *Siphonoperta* showing two end chambers as last chambers instead of the usual one only; and a 'bent' *Nodosaria* sp. from the Holocene shelf sediments of Bay of Bengal. It is observed that the two apertural

*Uvigerina* sp. and the finally terminated two-chambered *Siphonoperta* sp. are cases of phylogerontism showing overspecialization; the twinning in *Uvigerina* sp. as due to an accidental coalescence in early stages of growth after damage and recalcification with the terminal aperture shifting to an angle. Recently, Willems<sup>158</sup> also reported a *Uvigerina* sp. with two apertures, as reported by Setty<sup>9</sup> from the Lower Eocene of Belgium.

(8) *Spheroidinella dehiscens*—*S. dehiscens* is a very important taxon which indicates, by its appearance, at the base of the Pliocene and marked as *S. dehiscens* datum line and represents Miocene/Pliocene boundary.

Based upon its morphological and ecological evidences, Be'<sup>159</sup> suggested that *S. dehiscens* is an aberrant ecophenotypic variant of *Globigerinoides succulifer*. According to Bandy *et al.*<sup>160</sup>, *Globigerinoides* under bathyal habitat grows into *Spheroidinella* and *Spheroidinellopsis* in Miocene as an isomorphic derivative. Considering Blow's<sup>98</sup> arguments, Kumar and Mehrotra<sup>161</sup>, from their study in the Andamans, stated that *S. dehiscens* is a definite taxa evolved from *Spheroidinellopsis subdehiscens penedehiscens*.

(9) *Large-sized foraminifera*—While examining samples from the basins and deeper waters of the shelf of Southern California, Bandy<sup>43</sup> noticed some really large sized living foraminifers (exceeding 1 mm in diameter). *Pyrgoella sphaera* particularly occurs in more than twice its largest size known in deep well oxygenated waters, as in shallower bathyal waters; *Cyclammina cancellata* and some other species show a marked increase in maximum diameter with depth, temperature and dissolved oxygen in water. Similarly, deep water forms of *Glandulina laevigata* are found to develop an apical spine. Hence, it is concluded that oxygen content and temperature are important factors in determining the size and amount of secondary deposits in foraminifers.

*Globoquadrina conglomerata*, *G. hexagona*, *Globorotalia menardii neoflexuosa* are present today only in the Indo-Pacific region, whereas they disappeared from the Atlantic after the last glacial stage<sup>9,55</sup>. *Pulleniatina obliqueloculata* is extinct today in the Atlantic, but is found there only in its cores, while it is living today in the Indo-Pacific and Mediterranean regions<sup>145</sup>. Similarly, it is noticed that *Hastigerina pelagica* and *G. quinqueloba* are present in the Mediterranean, but are absent in the Atlantic. *Globoquadrina pseudofoliata* became extinct at about 222,000 years B.P. in the Pacific. It is also not found in the Atlantic today; hence, it can be used as a suitable datum.

#### Carbonate Compensation Depth and Lysocline

Calcium carbonate is one of the major constituents of the ocean water as well as its bottom sediments. Its production and solution (either by precipitation and removal by secretion or dissolution respectively) in the

ocean waters is one of the major problems of oceanography.

Arrhenius<sup>162</sup> postulated that the original distribution of calcium carbonate in the oceans is modified by the post-depositional dissolution of carbonate from the sediments, which is accelerated by low temperature, and high pressure of carbon dioxide formed by the oxidation of organic matter, and finally by rapid removal. However, dissolution of carbonate is effective at a depth of 4,000-5,000 m in the Pacific, and at a little greater depth in the Atlantic. This varies with latitude as a function of temperature and becomes very shallow at high latitudes<sup>163</sup>. This depth level is known as the carbonate compensation depth/level/horizon (CCD). The compensation depth for calcite is a little greater than that for aragonite.

Ruddiman and Heezen<sup>164</sup> and Berger<sup>165</sup> introduced the term 'Lysocline' which refers to the depth at which the dissolution of carbonate becomes apparent and thus is different from the compensation depth, the depth at which the dissolution is total; the lysocline lies a little higher than the carbonate compensation depth. The ultimate reason for the dissolution of tests, according to Berger<sup>166</sup>, is that the organisms supply more calcium carbonate to the ocean floor than through other sources, leading this excess supply to undersaturation, which, in turn, maintains a geochemical balance.

The dissolution effects in foraminifera are noticed in the fragmentation of tests, development of vesicles in the tests, superficial decalcification (primarily ornamentation, coatae, spines, etc.), evidence of corrosion, and also a reduction in the planktonic/benthonic ratio.

Planktonic foraminifera are more susceptible to solution than the benthonics. But among the planktonics, some are solution resistant. The solution sensitive species of the Pliocene of the Indo-Pacific region<sup>109</sup> are *Globigerina nepenthes*, *Globorotalia margaritae*, *G. miocenica*, *G. exilis*, *Globoquadrina altispira* and *Globigerinoides fistulosus*; and the solution resistant species are *Spheroidinella* sp., *Spheroidinellopsis* sp. and *Pulleniatina* sp.

According to Berger<sup>167</sup>, shallower dwelling species are generally more susceptible to dissolution than the deeper dwelling species, but those from warmer, shallower waters are the first to be destroyed when dissolution begins than those from the cooler, deeper waters.

The DSDP cores demonstrate that the selectivity in pre-Pliocene times is very similar to the Present<sup>168</sup>. However, lack of dissolution effect was observed in the case of *Neogloquadrina pachyderma* (collected from the South Pacific, Core 284, depth 1068 m) throughout from Upper Miocene to the Recent. This suggests that the changing ratio of reticulate to crystalline form is not controlled by selective dissolution<sup>169</sup>.

Dissolution was more intense during the interglacial period than during the glacial time and, therefore, the compensation depth was more during this period than

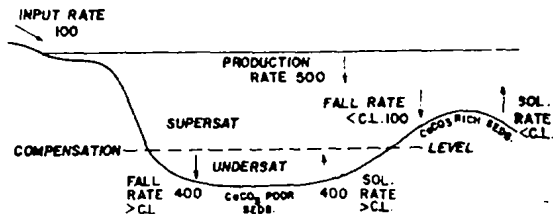


Fig. 6—Cycle of carbon "destined" to be lost from the sea as  $\text{CaCO}_3$ . The fivefold overproduction of  $\text{CaCO}_3$  by organisms is compensated by dissolution of  $\text{CaCO}_3$  in the deep sea. The boundary between undersaturated and supersaturated waters assumes a level such that only a quantity of  $\text{CaCO}_3$  equal to that supplied by rivers reaches sediments bathed in supersaturated waters. Positive feedback between the input loss difference and the carbonate ion content of the sea drives the compensation level towards that level yielding material balance (After Broecker and Broecker<sup>170</sup>)

during the interglacial time, thus resulting in lower dissolution and high sedimentation of both solution susceptible and solution resistant forms and vice versa<sup>170</sup> (Fig. 6). This periodicity of faunal fluctuation in a cyclic manner and its synchronous development with glacial-interglacial events suggests a causal relationship between the solution cycles and the Pleistocene climatic change, as seen in the Pacific Pleistocene sediments<sup>168</sup>.

Further, sediments can be correlated by the relative ratios of solution susceptible and solution resistant planktonic forms. This provides a criterion for a biostratigraphic sub-division or correlation. Although similar assemblages occur in all the oceans, the factors that control the distribution vary from one ocean to the other, finally resulting in the absence of less tolerant species. Thus, *Globoquadrina pseudofoliata* (Parker) became extinct about 222,000 years B.P. in the Pacific and it is not found in the Atlantic<sup>171</sup>.

### Species Diversity

Dissolution of foraminifera is more pronounced in the more productive equatorial areas of the oceans than in the adjacent tropical regions, resulting in the minimum species diversity.

The diversity of a planktonic assemblage depends chiefly upon the state of preservation of the specimens. In view of the wide distribution of planktonic foraminifers, their diversity patterns are valuable in the reconstruction of latitudinal positions and circulation patterns of water masses of the past ages.

As dissolution progresses, the species diversity decreases, but compound diversity based upon relative species abundance first increases and then decreases; on the other hand, the species dominance first decreases and then increases<sup>172</sup>.

The species diversity depends upon the distribution of individuals among the species. A sample constituting three species in equal proportions is considered to have a higher diversity than the one with 99% of one species and 1% of the others. Therefore, according to Gibson<sup>173</sup>, species diversity is inversely proportional to environmental variability, whereas

low diversity is related to high wave or current action or conditions in which salinity, temperature and turbidity remain unstable. The species diversity can be measured as follows:

$$(1) D_s = S$$

where species diversity is the number of species found in a sample.

$$(2) D_L \sim S/\log N$$

where the number of species ( $S$ ) found in a sample tends to be proportional to the log of the number of specimens ( $N$ ) counted.  $D_s$  is proportional to  $D_L$ .

(3) The species dominance is given as

$$D_D = P_{\max}$$

where  $P_{\max}$  is the maximum proportion of any one species in a given sample. The dominance is the simplest of the indices that make use of species proportion to define its diversity.

The Simpson's index<sup>174</sup> and Shannon's function<sup>175</sup> may be modified to show the species proportion, as

(4) Simpson's index

$$D_p = 1 - \sum_1^s p_i^2$$

measures the probability that two specimens picked randomly from a sample of infinite size belong to different species. This probability may be taken as a measure of the species diversity of an assemblage.

(5) Shannon's function:

$$D_H = \sum_1^s p_i \ln p_i$$

is a measure of the information necessary to specify as assemblage. All these indices are interrelated.

High shell output or species resistance to dissolution reflects a low diversity, e.g. in the tropics, *Globigerinoides ruber*, *Globigerinita glutinata* and *Globigerinoides succulifer* have high shell output, while *Globorotalia turnida*, *Pulleniatina obliqueloculata* and *Globoquadrina dutertrei* have considerable resistance to dissolution; hence, low diversity is noticed.

### Variation Studies

Variation in foraminifers is described as a tendency to deviate from the normal typical form. Though it is a well-known fact that two individual forms belonging to the same species are alike, they differ in some ways. This character leads to the erection of species to subspecies and varieties.

The variability parameters in species are many and they vary from one species to another. They are width-length ratio, length of costae, length of basal spine, number of pairs of chambers covered with ribs which increase or decrease, as seen in *Bolivina argentea* Cushman<sup>176</sup> coiling, uncoiling, and variation in the shape and arrangement of chambers, as seen in *Lenticulina subalata* (Reuss)<sup>177</sup>. Such changes are chiefly phenotypic variations and are controlled mostly by factors like low/high oxygen content in bottom waters, less secretion of calcium carbonate, resulting in slower growth and smaller chamber size and displacement from one environment (characterized by a certain temperature, depth, oxygen content,

salinity, nutrients, redox potential, pH, Eh, etc.) to another, so that the equilibrium is disturbed, as noticed in slope biotope to basin biotope in Santa Barbara basin off California<sup>178</sup>.

Sometimes, in addition to phenotypic variation, corresponding mutations may also occur due to low oxygen, H<sub>2</sub>S environment, etc., resulting in genotypic forms. However, these variant populations are connected by a complete linkage of transitional populations (a complete gradation from one end to the other) even though they appear to belong to different species, e.g. *Pararotalia ozawaii* represents one of the ontogenetic developments. *P. nipponica* (Asano) and *P. taiwanica* are a megalospheric generation of *P. nipponica*<sup>179</sup>.

As a word of caution, it may be suggested that before new foraminiferal species are erected, the variation scale of the populations must be studied besides investigating several samples from different localities to see the total variability of that species. In the opinion of the author, the erection of *Discocyclina remaraoi* by Samanta as a new species could have been avoided when the same trigonal species from the same locality was earlier recorded, described and identified as having an affinity to *Lepidocyclina boetonensis* Van der Vlerk from Indonesia, and *Discocyclina cristensis* Vaughan from North America by Setty<sup>93,94</sup>. Therefore, *D. remaraoi* should be treated as a synonym of *D. boetonensis*. Cole (personal communication) was also of the opinion that it does not warrant erection into a new species.

### Taxonomic Classification

The general classification of microfossils is based upon gross test morphology. As a result, artificial generic lumping and artificial splitting of species are reportedly numerous. Investigations in the internal morphology and wall structure of foraminifers have been made by many workers in recent years. The taxonomic wall structure is very important, because the rest of the foraminifera is to be regarded as a metabolic product of the living organism, which is determined by the stereochemistry of organic matrices<sup>180-182</sup>. The wall structure is a character of vast taxonomic importance, as it is not adaptive. Recent work has suggested that symbiosis and radial hyaline wall structure are interconnected, which may be related to the rise in rotalid groups and modifications seen in the chamber shape<sup>183</sup>. McGowan<sup>184</sup> mentions that all the discussions on classifications indicate that foraminiferal taxonomy is not evolutionary, but is only *a priori* and deductive. Parker<sup>145</sup> had earlier separated Globigerinidae and Globorotalidae based on wall structure and the development of spines, while *Globigerina* and *Globoquadrina* are separated on the basis of apertural character, pitted walls and spinosity.

While discussing the previous classifications and pointing out the inconsistencies, El-Naggar<sup>185</sup> proposed a new classification for Globigerinacea using



gross morphology of the test, its phylogenetic relationship, stratigraphic distribution, evolutionary trends and development. While the basic subdivisions are followed strictly, this classification is presented in the form of a periodic table, leaving gaps for characters not represented by known genera. The resulting classification includes 51 genera, 16 subgenera in 5 families: The Gumbelitridae, Globotruncanidae (including Globotruncaninae, Rotaliporinae and Planomalinae), the Globigerinidae (including Globigerininae, Globorotaliinae and Hantkenininae), the Heterohelicidae and the Chilogumbelinidae. Four genera and one subgenus are introduced here, *Gumbelitroides* gen. nov., *Claviticinella* gen. nov., *Globigerinoidesella* gen. nov., *Chilogumbelinella* gen. nov. and *Plummerita* (Ratotruncana) subgen. nov. Gumbelitridae is considered as the ancestral stock from which all other Globigerinaceae have evolved. This is supported by both morphologic and stratigraphic distribution of the known genera and their evolutionary trends.

Loeblich and Tappan<sup>30</sup>, in their treatise, have covered 8 families, 13 sub-families and 60 genera.

In recent years, extensive work has been done on the wall structure and ultrastructure of the test wall using scanning electron microscope.

Other lines of study are the amino acid composition of Recent and fossil foraminiferal tests which reflect the genotypes of living and dead foraminifers. This method may be useful in distinguishing between species, subspecies and the phenotypic variants. The amino acid patterns also suggest that protozoans and metazoan invertebrates have a common calcification mechanism. Secondly, evolutionary lineages could be traced paleontologically by studying both morphological and biochemical variations and phylogenetic relationships<sup>186</sup>. It is almost impossible nowadays to give a proper explanation for the similarity between Recent infrapopulational, ecophenotypic variation and the fossil morphogenetic lineages interpreted as a result of orthogenesis through orthoselection<sup>187</sup>.

Another aspect is the macromolecular chemical study of layering and laminations of foraminiferal tests which seem to be genetically stable and hence are of considerable taxonomic value<sup>188</sup>. These features are mostly the various projections and corrugations, such as double septa, septula, secondary septa, subepidermal partitions, alveoli, etc., which are directly related to layering, while inflational ornamentation of various types, formation of grooves, marginal cord, gradual constriction and deflection of pores, lateral chamberlets, umbilical and intramural cavities, etc. are consequential to laminations, irrespective of the biological factors causing their formation<sup>182,189,190</sup>. These features are of considerable taxonomic value.

In the search for a more natural classification, greater taxonomic value is currently attributed to the chemistry, mineralogy, micro- and ultrastructure of the test and to various other internal characters. The

importance of some of these characters in the classification and interpretation of evolutionary patterns seems to be generally accepted<sup>190</sup>.

### Pollution

In recent years, the most important problem affecting the modern foraminifera, their existence, abundance, distribution and the natural environment, and in the long run, the taxonomic classification of species, is pollution. Large scale pollution, creating imbalance in the natural environment and thus producing a cause-effect relationship resulting in the modification of the foraminiferal assemblage, is caused mostly by man himself.

Watkins<sup>191</sup>, Bandy<sup>192</sup>, Harman<sup>178</sup>, Sieglie<sup>193,194</sup>, Schafer<sup>195</sup> and Schafer *et al.*<sup>196,197</sup> studied the benthic foraminifers and the effect of pollutants on them. At the National Institute of Oceanography, Goa, Setty and his group have, for the first time, initiated a project to study the effects of pollution in selected areas along the West Coast of India. Earlier, some work was undertaken on this aspect by Sieglie<sup>193</sup> and others mostly in the Shelf Regions of Caribbean, Venezuela and Puerto Rico by Bandy *et al.*<sup>198</sup>, Bandy<sup>142,192</sup> and Harman<sup>178</sup> in Southern California, Pacific margin off Panama and Mississippi delta, and by Watkins<sup>191</sup> in Orange county, Huntington and Newport beaches.

Pollution is of different kinds: it may be due to enormous discharge of sewage into the sea, discharge of toxic effluents by industries located along the coasts, or dumping of highly toxic nuclear waste without pretreatment, and even hot water and nonrecycled water rich in ammonia, arsenic, etc. into the sea. causing widespread fish mortality, imbalances in heat budget and water masses, etc., thus affecting the natural environment.

When the natural balance of an environment is disturbed by the introduction of pollutants, an ecological shift in the biotic set-up takes place, resulting in a 'modified' environment known as pollution. This pollution or environmental stress gradient thus caused may be measured by monitoring the relative sensitivity of tolerance of the biota-benthic foraminifera as indicator species.

This sensitivity is highly variable and is controlled by the nature of the pollutants. It may cause abiotic conditions at the site of discharge, thus causing a total destruction of the biota or become hypertrophic, resulting in high productivity. When quantitative faunal data are compared with the time-integrated data of the most recent top layer of the sediment, an estimation of the degree of pollution can be made. Thus, the live/dead ratio of the benthic fauna establishes the zones of effects of pollution.

Usually the foraminiferal abundance trends are parallel to the shoreline, but this situation gets altered at the discharge site of pollutants. In the region of sewage outfall areas, according to Bandy *et al.*<sup>142,192</sup>, both living planktonic and benthonic foraminifers are several times more abundant. The living calcareous



perforate foraminifers are nearly eight times more abundant, but in the dead assemblage, it is the agglutinated foraminifers that predominate and increase by 5-20 times compared to the normal. This suggests that calcareous forms are undergoing post-depositional changes in the shelf region.

According to Bandy<sup>142</sup>, Murray<sup>48</sup> and Sieglie<sup>193</sup>, the characteristic foraminifers in such polluted areas are *Buliminella elegantissima*, which constitute more than 50% of the assemblage; *Trochammina pacifica*, *Eggerella advena*; and *Florilus grateloupi* which are more numerous in dead assemblage than in the living; and *Nonionella basispinata*, *N. miocenica stella*, and *Elphidium opima* which develop abnormalities. *Florilus grateloupi* and *Fursenkoina pontoni* are abundant in the polluted waters.

In the Greater Antilles, *Florilus grateloupi* occurs in smaller, thicker and deformed forms. These morphologic variations and deformities also prove to be diagnostic of the degree of pollution or modification of the environment.

In the polluted waters, the abundance of agglutinated species increases abnormally; in the case of *Bolivina* sp., their population increases by 8 times compared to the normal, of *Eggerella advena* by 5-300 times; of *Trochammina pacifica* by 2-1600 times or 10%; of hyaline species, as in the case of *B. elegantissima*, by 5-500 times (30-50%); and of *B. marginata denudata* by 10-900 times (50-100% in living assemblages). Thus, some species are impoverished in certain zones, while others are enriched in other zones. Bandy<sup>43,44</sup> observed that species like *Cylammina cancellata*, *Lenticulina thalmanii*, *Pyrgo* sp. *Pyrgoella sphaera*, *Glandulina laevigata* and others develop large sized forms, more than 1 mm in diameter.

The adversely affected species in the polluted waters are *Bucella frigida*, *Cibicides fletcheri*, *Quinqueloculina* sp., *Discorbis columbiensis*, *Rotarbinella lomaensis* and a few others.

The percentage of organic matter/carbon in the sediment acts as an influential variable in the distribution of benthic forms, thus indicating a cause-effect relationship. *B. elegantissima* and *B. sylviae* also become abundant when the organic carbon content is high (up to 5-10%), as noticed in the Venezuelan shelf sediments<sup>193</sup>. But under conditions of low organic carbon content (0.1-1.3%) and highly abundant nutrients, resulting in high productivity of the biomass, there appears in the clayey silt sediments and also off deltaic marine environments<sup>48</sup> species like *B. tenuata*, *Nonionella opima*, *Bolivina lowmanii* and *Epistominella vitrae*<sup>41,199</sup>. The organic carbon / foraminiferal abundance in the sediment is inversely proportional to each other. Harman<sup>178</sup> observed, from his study of Santa Barbara basin, that oxygen depleted environment lowers the ability of the foraminifer to secrete calcium carbonate from the waters, as seen in foraminifers like *Suggrunda eckesi*, *Bolivina seminuda* and *B. advena*.

*Bulimina*, *Bolivina*, *Guttulina* and *Uvigerina* form part of the deeper water assemblages and are closely associated with very high organic carbon content in the fine sediment, as seen in Naples Bay (Schmidt, as quoted by Boltovskoy<sup>25</sup>), Cariaco tench region and the Carrupano depression in the Venezuelan shelf<sup>200</sup>. The abundant occurrence of *Bolivina* and *Suggrundina* in sediments, ascribed to high organic carbon content, depletion of oxygen and their presence in greater abundance in the producing wells as well as in modern sediments, is considered to be a habitat of oil<sup>23,192,200</sup>.

These species have been encountered in the fossil assemblages of the oil basins of Miocene in California, and eastern Venezuela, Trinidad (Cruse and Forest formation), indicating in the sediment a high organic content, low oxygen content and possibly pollution in the waters during this time<sup>193</sup>. Thus, present day studies can throw light on conditions of the past.

In the recent sediments, some foraminifers show infillings of pyrites or pyritisation, which indicates oxygen deficit conditions, reducing environment and high organic content in the sediment. Pathy<sup>201</sup> observed pyritisation of foraminifers from bore holes collected off Mangalore harbour. The glauconite filled foraminifers and also the pyritized specimens in a sediment suggest non-depositional environment<sup>145</sup>. Recently, Setty<sup>202</sup> observed that the total foraminiferal number (TFN) and the total species number (TSN) represent the abundance, and the index of diversity besides spatial heterogeneity; but if TSN is more than TFN, it presupposes high local productivity, and hypertrophic conditions also. Therefore, it can be stated that the relative sensitivity of foraminifera to pollution is reflected in their abundance of populations, distribution patterns of species, and the live/dead ratio<sup>202</sup>.

It is hoped that the project initiated at the National Institute of Oceanography will throw more light on various other parameters in addition to those already discussed.

### Summary

Foraminiferal studies on deep sea cores have revealed that they represent sediments from the Early Cretaceous to the Present, but the cores from the ridge areas are older in age, indicating sea floor spreading along transverse fracture zones; however, large scale drifting does not seem to have occurred since the Lower Miocene.

The chief parameters that determine the distribution of foraminifera are depth, salinity, temperature, character of the substrate and water masses in the depositional environment; coarser ornamentation, larger size and thicker tests are characteristic of deeper water habitat. Species like *Epistominella laevicula*, *Uvigerina probosidea*, *Stilostomella antillea* and *Sorosphaera abyssorum* are found to be living in the hadal zone. The fact that the stratigraphic events are closely linked with the paleontologic zones and radiometric dating has been confirmed with the use of

magnetic polarity stratigraphy as an accurate and absolute correlation tool. Major boundary problems like the Cretaceous-Tertiary, Paleocene-Eocene, Miocene-Pliocene and Pliocene-Pleistocene boundaries with the characteristic foraminiferal datum lines emphasize the importance of and the major role played by these planktonic foraminifera in their determination.

The inter-relationship of paleotemperature and isotopes of  $^{18}\text{O}/^{16}\text{O}$ ,  $^{13}\text{C}/^{12}\text{C}$  with salinity, temperature and depth stratification of the ancient seas assists in the correlation with foraminifera as indicators. The planktonic assemblages also show effects of climatic control on water masses as seen in some deep sea cores. Species like *Orbulina universa*, *Neogloboquadrina pachyderma*, *Globorotalia menardii neoflexuosa*, *Globigerinoides obliquus* and *Spheroidinella dehiscens* play an important role in stratigraphic, climatic, evolutionary and several other oceanographic studies.

Calcium carbonate compensation depth is one of the major factors that determine the dissolution, fragmentation, decalcification and even corrosion of foraminifera at 400-5000 m depth, thus creating an imbalance in the planktonic/benthonic ratio. This is one of the major problems in oceanography today. The diversity pattern of planktonics is a valuable tool in the reconstruction of latitudinal positions and circulation patterns of water masses of the past ages. Thus, species diversity is a consideration of the distribution of individuals among the species. But variability in foraminifera is a tendency to deviate from the normal form which may lead to erection of species into subspecies.

Recent trends in taxonomic classification are based on the wall structure, surface ultrastructures and amino acid compositions of Recent and fossil foraminifera which reflect upon the genotypes of living and dead foraminifera. The importance of some of these parameters in the classification and interpretation of evolutionary patterns is generally accepted.

Various kinds of pollutants change the normal ecophenotypic system that exists in a regime. This is continuously being altered nowadays mostly by man. The alteration, modification and tolerance or destruction of foraminifera in the altered environment are being evaluated. Such an assessment becomes valuable in the understanding of similar events in the geological past.

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