Indian Journal of Economics and Development, Vol 3(4), 226-233, April 2015 ISSN (online): 2320-9836

Foraminifera: Indicators of past environment; Key to future: A review

R. Gadgil [1], A. Viegas[2], D. Thulasimala[3]

[1, 2] *Department of Earth Science, Goa University, Taleigao Plateau, Goa-India.*
[3]*Bharathi Women's College, Chennai, India.*
[1]ragsraga@gmail.com, [2]aviegas@unigoa.ac.in, [3]thulasi_107@yahoo.com

Abstract

Background: In the very long history of the Earth, it has undergone through cyclic stage of warming and cooling which are geologically well documented. Foraminifera have emerged as in important tool to not only provide details of past climate and environment but also give an insight to what the future climate and environment holds forth.

Methods: The morphology of the foraminifer tests along with their oxygen isotope ratio, the proportion of the planktic specimens, species diversity and different shell type ratios are closely related to physico-chemical characteristics of ambient seawater. These characteristics of foraminifera, especially the capacity of equilibrium fractionation of oxygen, are extensively used in paleo-oceanographic studies, specifically paleosea surface temperature and pale salinity estimations based on whole test ICP-MS oxygen isotope analysis of planktic foraminifera.

Findings: A few species of foraminifera are unique in that their tests' coiling are a function of ocean temperature. Left handed coiled tests live in colder water while right handed coiled tests in warmer water. Paleo-environmental interpretations are made possible by recognizing several kinds of patterns in foraminiferal assemblages. Rise in sea-level and changes in monsoonal rainfall pattern are the significant consequences of warming due to greenhouse effect. Present-day responses of planktic foraminifera to anthropogenic change should provide a "living laboratory" for interpreting past responses that have been recorded in the sediments over geological times-scales. Understanding the drivers of the changes in foraminifer species assemblages, abundances, distributions and shell chemistry should lead to improved reconstructions of past climates. It has been observed that assemblages characterized by high proportions of agglutinated taxa dominate in intertidal marshes whereas those largely made up of porcelaneous species characterize shallow tropical environments. It can be thus concluded that a decrease in temperature in most cases results in size increase.

Applications/Improvements: Historical changes in foraminifer abundance have been shown to reflect anthropogenic climate change. Foraminifera are established proxies of past climatic change and, by corollary, should "record" future climate change.

Keywords: Foraminifera, Paleosalinity, Paleomonsoon, Sea-level changes, Future environment

1. Introduction

There is a general worldwide consensus that our planet is warming. Over the last century, the average temperature has risen to around 0.6°C around the world. Another notable observation is that there is more warming, at higher latitudes, where temperatures have risen to twice the global average. One school of thought is of the opinion that human interference with the climate system is occurring, and climate change poses risks for human and natural systems. While the other school of thought of Earth scientists, many of them, believe with hard evidence that global warming and climate change is just another event in the evolutionary history of the Earth.

One of the more relevant aspects of paleontology today is using microfossils as a tool to decipher paleo-environment. It shows how knowledge obtained via study of modern organisms can be used to infer environmental conditions in the past. It also demonstrates the predictive side of science [1]. Foraminifera and other micro- and macro-fossils provide a long-term record of global environmental and climatic change, including natural as well as anthropogenic global warming; and, importantly, they also provide pointers as to rates of change. For example, they indicate that the past natural global warming associated with events such as the Paleocene–Eocene Thermal Maximum (PETM) was relatively rapid, implying that the present anthropogenic global warming could be too, and with similarly widespread consequences [2-7].

Foraminifera which are unicellular microorganisms are essentially marine in nature. As regards their habitat they are both benthic as well as planktic with the latter contributing as much as 32%–80% to the global flux of calcium carbonate that reaches the seafloor [8], in-spite of their relatively sparse distribution throughout the world's oceans. They, along with coccolithophores and pteropodsrepresent planktic groups that dominate the oceanic carbonate flux. Indeed, much of the seafloor is covered by foraminifer tests [9]. They live in every ocean and are almost always part of the material included in deep sea sediment cores. A few species of foraminifera are unique in that their tests coil to the left or right depending on ocean temperature. Left handed coiling tests prefer to live in colder water and right handed coiling tests in warmer water, and thus providing a tool for climate interpretation of the past [10]. Paleo-environmental interpretations can be done by recognizing several kinds of patterns in foraminiferal assemblages [1]. The morphology along with oxygen isotopic ratio of calcareous tests secreted by foraminifera, is a function of physicochemical characteristics of ambient seawater [11].

2. Climate change

Global warming, that is being experienced today, could be better appreciated in the context of the temperature changes over the last two centuries. Three distinct temperature record trends have been noticed. A warming trend of about 5^{o} C in the late 19th century has peaked around 1940. This was followed by a temperature decrease till the late 1970's and then a 3rd warming trend occurred from 1976. In the last decade, the hottest years recorded were 1998, 2001, 2002, 2003 and 2005 [10]. According to NOAA report of 2014,with records dating back to 1880, the global temperature averaged across the world's land and ocean surfaces for October 2014 was the highest on record for the month, at 0.74°C (1.33°F) above the 20th century average. This also marks the third consecutive month and fifth of the past six with a record high global temperature for its respective month (July was fourth highest).

The present global scenario poses multiple environmental problems such as greenhouse effect, ozone holes, global warming and consequential sea level rise, all being attributed to anthropogenic contributions. However, in recent years, awareness about climate, its variation, prediction and consequences therewith, has increased significantly, because of the potential impact of the climatic variations on ecological, economic systems and geopolitics. Climatic changes due to global warming associated with greenhouse effect can cause rapid sea-level rise, change in the intensity and frequency of monsoons and cyclones [12]. However, warming and cooling of the earth and associated sea-level rise has been known to occur even in geological past [10]. With rapid technological advances and industrialization, the rates of these processes are likely to change. Therefore the complex nature of human-climate interaction forms one of the most urgent matters of concern for the modern environment.

In recent years, however, with an increased awareness of how humans are affecting the natural world, in many cases for the worst, micropalaeontologists are increasingly studying the past to decipher key to the future [1]. Microfossils, especially foraminifera have been traditionally used for biostratigraphy with applications in petroleum industries. Rise in sea-level and changes in monsoonal rainfall pattern are the significant consequences of warming due to greenhouse effect. For India, it is more necessary to assess the impact of these changes as its largely agrarian economy depends on monsoonal rainfall. Similarly any accelerated rise in sea-level will affect large population living along its nearly 7000 km long coastline [13].

3. Foraminifers: Their significance

Foraminifera are single-celled organisms that are similar to amoebae and have a single nucleus, however, they differ from amoebae in that they possessgranulo-reticulose rather than filose or lobose pseudopodia; and also by their possession of an agglutinated or secreted shell or test, bearing an opening or aperture through which they can communicate with their external milieu. They are composed of protoplasm, which is capable of being formed into pseudopodia alluded to above, or, literally, 'false feet', for the purposes of attachment, locomotion or feeding [14].Living faunas contain numerous delicate, soft-bodied agglutinated forms which have virtually no fossilization potential, whereas fossil faunas usually consist of calcareous and more robust agglutinated taxa [15].

They commonly dominate ocean-floor eukaryotic communities. In the marine regime, they dwell in the ocean bottom: benthic, and the free floating: planktic and, among the benthic, both, epifaunal or surface-dwelling, and infaunal, or burrow-dwelling. Foraminifera are 'animal-like' protists or 'protozoans', constituting part of the zoobenthos or zooplankton, and as such are heterotrophs or consumers, as opposed to autotrophs or producers [15]. They typically eat bacteria, algae and organic detritus. Benthic foraminifera can be agglutinated or calcareous. Calcareous species are divided into those whose shells have a clear or translucent appearance (hyaline) with tiny perforations (pores) and those whose shells are white and opaque and have no perforations (porcelaneous).

They also are the most abundant benthic organisms to be preserved in the post-Paleozoic deep-sea fossil record. Recent observations have emphasized the important, often active role that foraminifera play in the dynamics and structuring of deep-sea benthic ecosystems.

The response of planktic foraminifera needs to be projectedto highlight anthropogenic change. Foraminifera are useful biological indicators of anthropogenic climate change in the marine environment because:

- Foraminifera are established proxies of past climatic change and, by corollary, should "record" future climate change,
- The present day global distribution of foraminifera is one of the most well-known of all oceanic taxa and provides a useful baseline for measuring change, there are no known specific predators of foraminifera, so changes in foraminifer distributions are more likely to reflect environmental rather than ecological changes,
- The spatial distributions of pelagic organisms are expected to shift faster to climate change than demersal species [16],
- The growth rates and abundances of foraminifera are very responsive to changes in temperature, particularly at the limit of their temperature range [17]
- Historical changes in foraminifer abundance have been shown to reflect anthropogenic climate change [18], and
- Changes in the abundance and distribution of foraminifera are well preserved in ocean sediments, and can be measured from plankton tows and sediment traps.

Present-day responses of planktic foraminifera to anthropogenic change should provide a "living laboratory" for interpreting past responses that have been recorded in the sediments over geological times-scales. Understanding the drivers of the changes in foraminifer species assemblages, abundances, distributions and shell chemistry should lead to improved reconstructions of past climates [9].

3.1. Paleoecology and Paleobiogeography

As various species of foraminifera are found in different marine environments, they are used to determine past environments. Foraminifera have also been used to map past distributions of the tropics, locate ancient shorelines, and track global ocean temperature changes during the ice ages. In instances of fossil foraminifera containing many extant species, then the present-day distribution of those species are used to infer the environment at that site when the fossils were alive. While on the other hand, where samples contain all or mostly extinct species, then their past environment can be inferred by studying species diversity, the relative numbers of planktic and benthic species, the ratios of different shell types, and shell chemistry [1].

1) Species diversity:This accounts for the number of benthic species in a standard-sized sample. The general pattern recognizable in marine environments today is of increasing diversity away from shore with increasing water depth.
2) Percent planktics: The proportion of planktic specimens increases from 0 percent in shallow marine environments to more than 90 percent in deep marine environments. Modern plankticforams generally have

globular chambers, often with spines. Some plankticfossils, particularly in the Cretaceous, had a more flattened shape, sometimes with heavy keels running around the shell.

3) Shell-type ratios: Benthic foraminifera are either agglutinated or calcareous. Calcareous species are divided into those whose shells have a clear or translucent appearance (hyaline) with tiny perforations (pores) and those whose shells are white and opaque and have no perforations (porcelaneous). The proportions of these three types of walls (agglutinated, hyaline, porcelaneous) in a sample of foraminifera is also characteristic of particular environments in modern seas and oceans. It has been observed that assemblages characterized by high proportions of agglutinated taxa are found in intertidal marshes whereas those dominated by porcelaneous species characterize shallow tropical environments.
4) Shell chemistry: Foraminiferal abundances are closely linked to levels of organic matter input, and to dissolved oxygen concentrations in the near-bottom water which in part, are related inversely to the magnitude of organic fluxes. Food and oxygen requirements also control the microhabitat preferences of species, which are reflected in their test morphology. The chemistry of the shell is useful because it reflects the chemistry of the water in which it grew. Thus, the abundance of modern species, species assemblages, and test morphotypes can be related to regional organic carbon inputs and oxygen concentrations. The carbon and oxygen isotope signals preserved in calcareous benthic and plankticforaminiferal tests provide the most important method available to paleoceanographers for estimating long term fluctuations in polar ice volumes, carbon fluxes (paleoproductivity) and deep-ocean temperature and circulation in response to global climatic change [19]. The ratio of stable oxygen isotopes depends on the water temperature, because warmer water tends to evaporate off more of the lighter isotopes. Measurement of stable oxygen isotopes in planktic and benthic foraminifera shells from hundreds of deep-sea cores worldwide have been used to map past surface and bottom water temperatures. This data helps us understand how climate and ocean currents have changed in the past and may change in the future.

   Biological insights, particularly those regarding microhabitats and diets, provide the essential background for refining interpretation of the carbon isotope record in particular. The stable isotope chemistry of foraminiferal carbonate varies interspecifically as a result of the occupancy of different microhabitats. Sediment pore waters tend to become depleted in ^{13}C as a result of the oxidation of isotopically light (^{12}C enriched) organic matter [20]. This trend is reflected in the carbon isotope chemistry of tests which have grown at different depths within the sediment [21]. Epifaunal, shallow infaunal and deeper infaunal species tend to show progressively lower δ^{13}C values [22-25]. These trends provide a means of estimating δ^{13}C pore water gradients which are related to organic matter fluxes to the seafloor and to bottom water oxygen gradients in ancient sediments [26, 24].

3.2. Biostratigraphy

Foraminifers are found since Cambrian times, they are abundant and widespread in all marine environments, and they have a definite evolutionary trend. All these factors aid in biostratigraphic classification of marine rocks.The smaller species of Fusulinida, Miliolida and Globigerinida are extremely locally useful in biostratigraphy, while the larger representatives of the same are useful in correlating shallow water sediments of the Late Palaeozoic, Mesozoic-Cenozoic and Cretaceous-Cenozoic respectively of the Tethyan realm [14].

3.3. Oil exploration

Their known geological age and specific environment qualify them as an important tool in petroleum exploration. Stratigraphic control using foraminifera is so precise that these fossils are even used to direct sideways drilling within an oil-bearing horizon to increase well productivity.

3.4. Temperature

Carpenter [27] was the first to suggest that temperature can play an important role in the morphological variations of the foraminiferal test. Rhumbler [28] pointed out that the same species (e.g., *Triloculinatricarinata* and some Astrorhizidae) may be represented by larger specimens in cold waters than in warm. Temperature also appears to play a role in variability of test shapes. In this study no specific morphological trend is discernible, except that it appears that the number of varieties increases with increasing temperature. Although changing of coiling directions is well known for planktic foraminifers in relation to temperature, it is less well documented for benthic species.It can be thus concluded that a decrease in temperature in most cases results in size increase. It is quite probable, although the evidence is still tenuous and more study is required, that changes in temperature can also affect the sinistral/dextral ratio in some species [29].

3.5. Salinity

For survival, growth, and reproduction, each benthic foraminiferal species has specific limits of tolerance to salinity as well as other factors. If, for a given species, salinity is within the species' normal growth limits, it obviously has no special effect on the morphology of the test. Tappan [30] recorded that, in cultures of benthic foraminifers, on addition of distilled water, tests became thinner and transparent. According to Bradshaw [31], the presence of ammonia increases its size in low-salinity water.

Salinity within tolerance limit does not show any change in the morphology of the test. It is also known that salinity and $CaCO_3$ solubility are closely associated. If it is lower, many foraminiferal species become smaller, thin walled, and their ornamentation can decrease or even disappear altogether. The observations in this regard are numerous and have been made in various environments [32, 33].

These characteristics of foraminifers, especially the capacity of equilibrium fractionation of oxygen, are widely used in paleo-oceanographic studies, specifically paleosea surface temperature and paleosalinity estimations based on whole test ICP-MS oxygen isotope analysis of planktic foraminifers. The life spans of foraminifers spell out the duration for which the tests incorporate and represent the physicochemical conditions of ambient seawater [11].

3.6. Sea-level rise

To use foraminifers as a means for understanding rise in sea level, an understanding of the earlier inferred data of sea-level fluctuations is necessary. Sea-level rise can be conveniently inferred either by shoreline movement or through depth fluctuations at particular locations. Nigam and Henriques [34] have also developed a regional model for paleo-depth determination, which is based on planktic percentage of foraminiferal fauna in surface sediment of Arabian Sea. One of the main advantages of this model is that it requires no detailed taxonomic study of the fauna. Only separating the fauna into two groups is sufficient i.e. planktic and benthic.

Foraminifers present in the Lothal Dockyard (in Cambay, Gujarat) are discussed as case studies of high sea stand around 6000 years B.P. [35]. A significant application of foraminiferal studies towards getting an insight into marine archaeology was appreciated during the excavation for Harappan settlement at Lothal, where archaeologists stepped into a large rectangular structure and were perplexed about its actual usage. This controversy was finally put to rest with the help of foraminiferal studies. The presence of foraminifers in the sediments from the tank, suggested that the rectangular tank was a dockyard connected to the open marine environment with high tidal range.

3.7. Paleomonsoon

Paleomonsoon studies have been carried out with the aid of coiling direction [36, 37], and oxygen isotope ratios of foraminifers [38]. Nigam and Khare [39] established the significance of correspondence between river discharge and mean proloculus size of benthic foraminifera in paleo-monsoonal studies.

A clear understanding about future changes in rainfall pattern is very useful for long-term planning [40]. If natural calamities like floods or droughts can be anticipated well in time, the human life and livestock could be appropriately managed, thus alleviating the burden on state resources. The quantum of rainfall either way can go a long way to improve relationship betweenriparian states.

3.8. Storms/Tsunamis:

In the recent past, there has been a worldwide increase in the frequency of tsunamis and storms which have been ascribed to the phenomena of global warming. The east coast of India due to its geographical disposition has been found to incur the wrath of nature more frequently than the west coast. At least one such finding [13] based on foraminiferal evidences show that during early Holocene, rapid sea level rise along with warming, left the imprints of powerful storms/tsunamis off Kachchh, Gujarat, India. Evidence for this is given by older sediments getting sandwiched between younger sediments in a sequence. It was hypothesized that the erosion of sediments from the deeper region, transportation of fine grained sediments against gravity and deposition in shallower regions is possible only under the influence of storms/tsunamis.

4. Key to future environment

Foraminifera were found to be one of the functional types that dominate the total planktic biomass of the ocean [41, 42] and they contribute to the mineral ballast that facilitates the vertical transport of organic matter in the ocean [43]. Thus, foraminifera are also expected to play a vital role in the organic carbon cycle. Under future scenarios of climate change, ocean acidification is predicted to reduce the global carbonate production by plankticcalcifiers by the end of the century and drive a small reduction in the atmospheric CO_2 concentration [44, 45]. The impacts of both climate change and ocean acidification on plankticcalcifiers are projected to drive a decrease in the fossil-fuel burden of the atmosphere [46, 47]. The strength of this future CO_2-calcification feedback is sensitive to which calcifying species are assumed to contribute to the carbonate production of the open ocean [45].

5. Summary

The known abundance of foraminifers coupled with no known record of their predators makes them a very stable and reliable environmental indicator. The fact that there is no existence of predators suggests that any change in their abundance/behavior is environmental rather than ecological. In comparison to demersal species, the pelagic foraminifers are known to have a rather faster shift in spatial distribution which again qualifies them for being a good environmental indicator. Temperature plays a vital role in their abundance as well as growth rate. Recent studies have shown that their abundance in temperate and sub-polar regions are believed to be affected by anthropogenic changes. Foraminifers have been established as proxies for climate change in the past and therefore could be used as proxies for future climate change. In this age where there is widespread alarm and anguish about global warming, foraminifers have indeed proved to be a very reliable indicator of past, present and future environmental change.

6. References

1. S.J.Culver. Foraminifera. In: T.W. Broadhead, Fossil Prokaryotes and Protists. Notes for a Short Course. Department of Geological Sciences,Studies in Geology, University of Tennessee: USA. 1987; 169-212.
2. M. P. Aubry,S. G. Lucas,W. A. Berggren. Late Paleocene-early eocene climatic and biotic events in the marine and terrestrial records. Columbia University Press: New York. 1998.
3. S. L. Wing, P. D. Gingerich, B. Schmitz, E. Thomas. Causes and consequences of globally warm climates in the Early Paleogene. *The Geological Society of America Publication: Boulder*. 2003; (Special Papers, No. 369).
4. A. Sluijs, G. J. Bowen, H. Brinkhuis, L. J. Lourens, E. Thomas. The Paleocene-Eocene thermal maximum super greenhouse: biotic and geochemical signatures, age models and mechanisms of global change. In: Deep-Time perspectives on climate change – marrying the signals from computer models and biological proxies,*The Geological Society*, London (for The Micropalaeontological Society). 2007; 323-349.
5. M. Williams, A. M. Haywood, F. J. Gregory, D. N. Schmidt. Deep-Time perspectives on climate change – marrying the signals from computer models and biological proxies. *The Geological Society*, London (for The Micropalaeontological Society). 2007.
6. T. Dunkley Jones,D. J. Lunt, D. N. Schmidt. A review of the Paleocene–Eocene thermal maximum temperature anomaly. Abstracts, *International Palaeontological Congress*. 2010; 153.
7. K. J. Whidden, R. W. Jones. Correlation of early Paleogene global diversity patterns of Large Benthic Foraminifera with Paleocene and Eocene climatic events. *Palaios.* 2012; 27(4), 235-251.

8. R. Schiebel. Planktic foraminiferal sedimentation and the marine calcite budget. *Global Biogeochemical Cycles*. 2002; 16(4), 1065.
9. T. Roy, F. Lombard, L. Bopp, M. Gehlen. Projected impacts of climate change and ocean acidification on the global biogeography of planktic foraminifera. *Biogeosciences Discussions*. 2014; 11, 10083-10121.
10. U. B. Mathur. Climate change: Past, Present and future. In: “Popularization of science series”. *Geological Society of India publication*. 2010.
11. R. Nigam, R. Saraswat, A. Mazumder. Life spans of planktic foraminifers: New insight through sediment traps. *Journal of the Paleontological Society of India.* 2003; 48, 129-133.
12. R. Nigam. Problems of global warming and role of micropaleontologists-presidential address. *Gondwana Geological Magazine*. 2003; 6, 1-3.
13. R. Nigam, S. Chaturvedi. Do inverted depositional sequences and allochthonus foraminifers in shelf sediments off Kachchh (Gujarat), India, indicate paleostorm and/or tsunami effects? *Geo-Marine letters.* 2006; 26(1), 42-50.
14. R. W. Jones. Foraminifera and their applications. Cambridge University Press: UK. 2014.
15. A. J. Gooday. The Biology of Deep-Sea Foraminifera: A Review of Some Advances and Their Applications in Paleoceanography. *Palaios.* 1994; 9(1), 14-31.
16. H. M. Pereira, P. W. Leadley, V. Proença, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarrés, M. B. Araújo, P. Balvanera, R. Biggs, W. W. L. Cheung, L. Chini, H. D. Cooper, E. L. Gilman, S. Guénette, G. C. Hurtt, H. P. Huntington, G. M. Mace, T. Oberdorff, C. Revenga, P. Rodrigues, R. J. Scholes,U. R. Sumaila, M. Walpole. Scenarios for global biodiversity in the 21st century. *Science*. 2010; 330, 1496-1501.
17. S. Rutherford, S. D’Hondt,W. Prell. Environmental controls on the geographic distribution of zooplankton diversity. *Nature*. 1999; 400, 749-753.
18. D. B. Field, T. R. Baumgartner, C. D. Charles, V. Ferreira-Bartrina, M. D. Ohman. Planktic foraminifera of the California Current reflect 20th-century warming.*Science*.2006; 311, 63-66.
19. E. L. Grossman. Stable isotopes in modern benthic foraminifera: A study of vital effect. *Journal of Foraminiferal Research*. 1987; 17(1), 48-61.
20. D. C. McCorkle, S. R. Emerson, P. D. Quay. Stable carbon isotopes in marine porewaters. *Earth and Planetary Science Letters*. 1985; 74(1), 13-26.
21. B. H. Corliss. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*. 1985; 314(6010), 435-438.
22. F. Woodruff,S. M. Savin. δ^{13}C values of Miocene Pacific benthic foraminifera: Correlations with sea levels and biological productivity. *Geology*. 1985; 13(2), 119-122.
23. A. Mackensen, R. Douglas. Down-core distribution of live and dead deep-water benthic foraminifera in box cores from the Weddell Sea and the California borderland. *Deep-Sea Research*. 1989; 36(6), 879-900.
24. D. C. McCorkle, L. D. Keigwin, B. H. Corliss, S. R Emerson. The influence of microhabitats on the carbon isotopic composition of deep-sea benthic foraminifera. *Paleoceanography*. 1990; 5(2), 161-185.
25. H. Oberhansli,E. Muller-Merz. Eocene paleoceanographic evolution at 20-30° S in the Atlantic Ocean.*Palaeogeography, Palaeoclimatology, Palaeoecology*. 1991; 83 (1-3), 173-215.
26. D. C. McCorkle,S. R. Emerson. The relationship between pore water carbon isotope composition and bottom water oxygen concentration.*GeochimicaetCosmochimicaActa*. 1988; 52(5), 1169-1178.
27. W. B. Carpenter. Researches on the Foraminifera, In Royal Society, London.*Philosophical Transactions*. 1856; 146, 547-569.
28. L. Rhumbler. Die foraminiferen (Thalamophoren) der plankton-expedition. Erg. Plank. Exp. Humboldt Stift., 3, L.C. 1911.
29. E. Boltovskoy, D. B. Scott, F. S. Medioli. Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters: A review. *Journal of Paleontology*. 1991; 65(2), 175-185.

30. H. Tappan. Northern Alaska index Foraminifera. *Contributions from the Cushman Foundation of Foraminiferal Research*. 1951; 2(1), 1-8.
31. J. S. Bradshaw. Laboratory experiments on the ecology of foraminifera. *Contributions from the Cushman Foundation of Foraminiferal Research*. 1961; 12, 87-106.
32. M. Morishima. Deposits of foraminiferal tests in the Tokyo Bay, Japan. University of Kyoto, College of Science, Memoirs, B. 1955; 22, 213-222.
33. I. R. S. Forti, E. Rottger. Further observations on the seasonal variations of mixohaline foraminifers from the Patos Lagoon, Southern Brazil. *Archivio di Oceanografia e Limnologia*. 1967; 15(1), 55-61.
34. R. Nigam,P. J. Henriques. Planktic percentage of foraminiferal fauna in surface sediments of the Arabian Sea (Indian Ocean) and a regional model for paleopath determination. *Paleogeography, Palaeoclimatology, Palaeoecology*. 1992; 91(1-2), 89-98.
35. R. Nigam.Was the large rectangular structure at Lothal (Harrapan settlement) a "Dockyard" or an "Irrigation Tank"? *Proceedings 1st Indian Conference on Marine Archaeology of Indian Ocean Countries*,1988, 20-22.
36. R. Nigam, A. S. Rao. Proloculussize variation in recent benthic Foraminifera: Implications for paleoclimatic studies. *Estuarine, Coastal and Shelf Science*. 1987; 24(5), 649-655.
37. R. Nigam, N. Khare. Oceanographic evidences of the great floods at 2000 and 1500 BC documented in Archaeological records.*National Institute of Oceanography*. 1992; 2, 517-522.
38. R. Nigam, A. Sarkar. Mean Proloculus Size,^{13}C &^{18}O variation in benthic foraminifera from the west coast of India and their climatic implications. *Indian Journal Earth Sciences*. 1993; 20(1), 1-6.
39. R. Nigam, N. Khare. Significance of correspondence between river discharge and mean proloculus size in Paleomonsoon studies. *Geomarine Letters*. 1995; 15(1), 45-50.
40. R. Nigam. Addressing environmental issues through foraminifera: Case studies from the Arabian Sea. *Journal of the Paleontological Society of India*. 2005;50(2), 25-36.
41. E. T. Buitenhuis, M. Vogt, R. Moriarty, N. Bednaršek, S. C. Doney, K. Leblanc, C. Le Quéré, Y. W. Luo, C. O'Brien, T. O'Brien, J. Peloquin, R. Schiebel, C. Swan. MAREDAT: towards a World Ocean Atlas of MARine Ecosystem DATa.*Earth System Science Data Discussions*. 2012; 5, 1077-1106.
42. R. Schiebel, A. Movellan. First-order estimate of the planktic foraminifer biomass in the modern ocean. *Earth System Science Data*. 2012; 4, 75-89.
43. C. L. De La Rocha, U. Passow. Factors influencing the sinking of POC and the efficiency of the biological carbon pump.*Deep-Sea Research Part II – Topical studies in Oceanography*. 2007; 54(5-7), 639-658.
44. A. Schmittner, A. Oschlies, H. D. Matthews, E. D. Galbraith. Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO_2 emission scenario until year 4000 AD.*Global Biogeochemical Cycles*. 2008; 22, 1-21.
45. R. Gangstø, F. Joos, M. Gehlen. Sensitivity of pelagic calcification to ocean acidification.*Biogeosciences*. 2011; 8, 433-458.
46. A. Ridgwell, I. Zondervan, J. C. Hargreaves, J. Bijma, T. M. Lenton. Assessing the potential long-term increase of oceanic fossil fuel CO_2 uptake due to CO_2 -calcification feedback. *Biogeosciences*. 2007; 4, 481-492.
47. A. J. Pinsonneault, H. D. Matthews, E. D. Galbraith, A. Schmittner. Calcium carbonate production response to future ocean warming and acidification. *Biogeosciences*. 2012; 9, 2351-2364.

The Publication fee is defrayed by Indian Society for Education and Environment (www.iseeadyar.org)

***Cite this article as**:*

R. Gadgil, A. Viegas, D. Thulasimala. Foraminifera: Indicators of past environment; Key to future: A review. *Indian Journal of Economics and Development*. Vol 3 (4), 226-233, April 2015.