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Review Article

Non-Destructive Foraminiferal Paleoclimatic Proxies: A Brief Insight

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The knowledge of past climate can help us to understand imminent climatic changes. Oceans are the vast archives of past climate. Various indirect techniques termed as proxies are used to infer key components of the past climate from the marine sediments. The fossil remains of marine microorganism foraminifera, are widely used to reconstruct past climate from marine archives, as foraminifera are highly abundant and extensively present in almost all marine realms. Foraminiferal paleoclimatic proxies can be classified in two broad categories, viz. A) destructive (the stable isotopic and trace element composition of foraminifera), those wherein the foraminiferal remains are analyzed to measure its chemical composition and it leads to destruction of the foraminiferal test, and B) non-destructive, wherein changes in the abundance and morphology of foraminifera are used to reconstruct past climate. Here the non-destructive foraminiferal paleoclimatic proxies have been discussed with its recent developments as well as applications. Despite the extensive application of the stable isotopic and trace element composition of foraminifera to infer past climate, non-destructive techniques are still quite helpful to reconstruct past climate as well as to substantiate inferences drawn from destructive techniques.

Key Words: Foraminifera; Proxy; Morphology; Paleoclimate; Benthic; Planktic; Species

Introduction

Climate is one of the important factors that affect the fate of mankind on earth. Climate changes can lead to significant cultural shifts, large-scale migration or even demise of civilizations (Polyak and Asmerom, 2001; Haug *et al.*, 2003; Gupta, 2004; Robbins *et al.*, 2013). Therefore, precise information of imminent climatic variations is necessary to secure the fate of mankind on earth and for long and short-term policy planning. Continuous efforts are made to develop models to predict future climatic variations. The training and validation of climate prediction models requires knowledge of inter-relationship among various climatic parameters, as well as short and long-term changes in the climate. In view of the absence of written records of climate variations prior to the last ~100-150 yr, indirect techniques called proxies are used to infer past climate changes. An index sensitive to changes in the physico-chemical characteristics of the ambient environment and having good preservation potential (resistant to any pre- or post depositional change, especially the changes that can alter the signatures of environmental conditions) can be used to infer past climatic conditions.

The aquatic bodies, with continuous accumulation of sediments are among the ideal places to retrieve paleoclimatic proxies and records. The sediments accumulating at the bottom of aquatic bodies contain various indices that incorporate signatures of environmental conditions. In the aquatic bodies, the indices containing climatic signatures are immediately buried below subsequent sediments to be preserved for long time. Even though the characteristics of sediments, including its physical

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*Author for Correspondence: E-mail: rsaraswat@nio.org; Phone: +91-832-2450622/489 and chemical properties, have been used to infer past climate (Bassinot, 1993; Weber *et al.*, 1997), the variations in the characteristics of the biological component of the sediments have been used most extensively. The preferred application of biological components over the abiogenic remains arises due to the high sensitivity and enhanced response of biological components to the changes in ambient environment. Since marine sediments contain plenty of remains of marine microorganisms (like coccolithophores, radiolarians, pteropods, ostracodes, foraminifera, and others), such remains serve as potential proxy to infer past climatic conditions. Out of these remains of various marine microorganisms, the hard outer skeletal remains of foraminifera, termed as tests, are among the most widely used paleoclimatic proxy.

As foraminifera are extremely sensitive to ambient conditions, and ubiquitous in almost all the marine realms, they are extensively used to reconstruct past climate. Ever since their discovery, numerous characteristics of foraminifera have been used to infer different seawater parameters. The initially developed techniques made use of changes in abundance and morphology of foraminifera and thus were non-destructive. The stable isotopic analysis of foraminifera were initiated in the early fifties (Urey *et al*., 1951; Emiliani and Epstein, 1953; Emiliani, 1955), while the first successful attempts to analyze trace element ratio of foraminiferal tests were made in early eighties (Boyle, 1981; Boyle and Keigwin, 1985) leading to the development of destructive techniques to reconstruct past climate by using foraminiferal tests. Despite the growing application of stable isotopic and trace element ratio of foraminifera to reconstruct paleoclimate, non-destructive techniques are still extensively applied not only to independently infer past climate but also to substantiate inferences drawn from the stable isotopic and trace element ratio. In this review, the traditional non-destructive foraminiferal proxies are summarized.

Foraminifera

Foraminifera are unicellular, preferentially marine microorganisms with the single cell encased by a hard outer covering, called test. The foraminiferal test is made up either of calcium carbonate secreted by the cell (Calcareous) or various sized sediments adhered together with cement (Agglutinated). Foraminifera inhabit both the sediments on the sea floor (benthic foraminifera) (Fig. 1) as well as the upper few hundred meters of the seawater column (planktic foraminifera) (Fig. 2). Benthic foraminifera live both on the seafloor (epifaunal) and up to a few cm in the upper sediments (infaunal). The epifaunal and infaunal benthic foraminifera have a distinct morphology. Most of the infaunal forms are rectilinear, as it aids in burrowing, while the epifaunal forms are round in shape (Boltovskoy and Wright, 1976; Murray, 2006). A few benthic foraminifera, belonging to the family Allogromidae, thrive in fresh water and do not have hard exoskeleton like their marine counterparts. By using molecular systematic

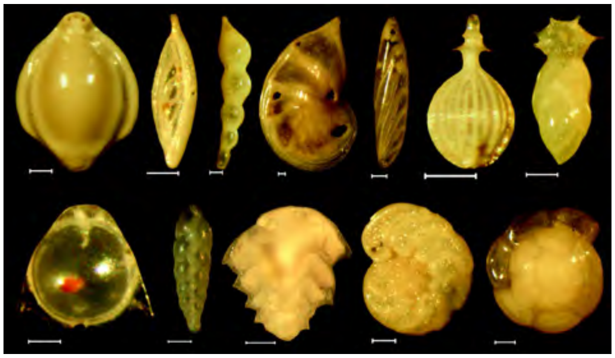

Fig. 1: Calcareous benthic foraminifera from the north-eastern Indian Ocean. The white scale bar at the base of each figure equals 100 µm

Fig. 2: Planktic foraminifera from the north-eastern Indian Ocean. A majority of planktic foraminiferal tests have globular chambers and are usually perforate. The white scale bar at the base of each figure equals 100 µm

analysis, foraminifera have also been reported in soils collected from different terrestrial regions (Lejzerowicz *et al*., 2010). The planktic foraminifera are depth stratified with a few species inhabiting the top mixed layer while a few others being abundant in the thermocline region. A vertical migration to cooler deep waters during the later phase of life for gametogenesis is reported in a few planktic foraminifera. The near coastal waters are almost exclusively inhabited by benthic foraminifera while both benthic and planktic foraminifera are found in oceanic regions deeper than ~75-100 m but above carbonate compensation depth (CCD). The agglutinated benthic foraminifera (Fig. 3) are abundant in regions where carbonate dissolution is prevalent, including marshes, deep shelves or below the carbonate compensation depth (Murray, 2006; Schröder-Adams and Rooyen, 2011). Even though the planktic foraminifera live in the surface water column in deeper oceanic regions, their tests almost completely dissolve, before reaching the seafloor due to over saturation of deeper oceanic waters by carbon dioxide (Berger, 1967).

While the benthic foraminifera are tremendously diverse with thousands of species reported from different parts of the world oceans, there are only ~40 species of planktic foraminifera found in modern world oceans. The tests of foraminifera, especially benthic foraminifera, show wide variations in size, ornamentation and shape, from being single chambered (unilocular) to chambers arranged in one, two or many linear rows (uniserial, biserial and multiserial, respectively) as well as chambers arranged in circular fashion (spiral forms). The planktic foraminiferal tests in general, have globular and highly perforated chambers and also comparatively large aperture.

Fig. 3: Agglutinated benthic foraminifera from the north-eastern Indian Ocean. The white scale bar at the base of each figure equals 100 µm

Foraminiferal Proxies

The variation in the abundance and morphology of the tests is an adaptive response of the foraminifera to the changes in environment inhabited by foraminifera. Thus the changes in the foraminiferal tests in response to climatic changes, makes it possible to apply various foraminiferal characteristics to infer past environmental conditions. Various non-destructive characteristics of the foraminiferal tests that have been used to infer past climatic variations include:

1. Total Foraminiferal Number
2. Benthic:Planktic Ratio
3. Foraminiferal Fragmentation index
4. Foraminiferal Size Fraction
5. Species Assemblages
6. Species Abundance
7. Test Size/Diameter
8. Coiling Direction
9. Average Number of Chambers
10. Proloculus Size
11. Test Abnormalities
12. Test Weight

Total Foraminiferal Number

The total foraminiferal number (TFN) is defined as the number of intact foraminiferal tests in unit dry sediment. All the intact benthic and planktic foraminiferal tests are picked from a pre-weighed representative fraction and the TFN is calculated by extrapolating the foraminiferal number in unit gram of dry sediment. The representative fraction is taken either by quartering and coning the entire coarse fraction or by using a splitter. Although, initially it was proposed that the water depth or water mass characteristics are the major factors that control foraminiferal population, later it was realized that the food availability has the dominant control on the living benthic foraminiferal population (Jorissen *et al*., 2007). In addition to food, benthic foraminiferal population also depends on dissolved oxygen content of the water. The organic matter flux and dissolved oxygen content are inter-related and a model was proposed to infer the relative role of these factors on benthic foraminiferal population (Jorissen *et al*., 2007). Besides the food and dissolved oxygen, the foraminiferal population has definite environmental control, depending upon the water depth, turbidity, sediment characteristics, energy conditions in the region and other physico-chemical characteristics (Boltovskoy and Wright, 1976; Murray, 1991; Lee and Anderson, 1991). Dissolution during the sinking of planktic foraminiferal tests from the surface to the sea bottom as well as the post-depositional dissolution at the sea bottom, alters the foraminiferal population (Berger, 1967; 1968; Peterson and Prell, 1985; de Villiers, 2005). The agglutinated benthic foraminifera readily dissolve after death while a subsequent change in pore-water pH leads to partial or full dissolution of calcareous forms, thus altering the original foraminiferal population. Dissolution of calcareous foraminiferal tests also depends on the amount of organic matter settling in the sediments (Berkeley *et al*., 2007). Since the planktic and benthic foraminifera represent the top several hundred meters of the water column, and bottom water as well as sediment characteristics, respectively, separate estimates of changes in population of benthic and planktic foraminifera are more efficient proxy than the combined population, i.e. total foraminiferal number. The variations in planktic, benthic or total foraminiferal population have been used for stratigraphic correlation (Berggren and Boersma, 1969; Reiss *et al*., 1980), changes in the concentration of pollutants (see Nigam *et al*., 2006 for review), bathymetric changes (Bandy, 1956; Sharma and Takayanagi, 1982; Nigam and Henriques, 1992) and shifts in lysocline depth (Cullen and Prell, 1984).

Benthic: Planktic Ratio

Planktic foraminifera are rare in turbid shallow waters. Such regions also do not support vertical movement of planktic foraminifera, as required during gametogenesis in a few species, thus restricting their population. Therefore, the abundance of planktic foraminifera in general increases with depth away from the coast, till foraminiferal lysocline. Below the foraminiferal lysocline, significant dissolution of the foraminiferal tests leads to decreased foraminiferal abundance. Therefore, the changes in the relative abundance of benthic and planktic foraminifera indicate, changes in the bathymetry (Stehli and Creath, 1964; Wright, 1977), changes in the position of foraminiferal lysocline as well as carbonate compensation depth (Pinxian *et al*., 1995; Chen *et al*., 1997), and productivity changes (Berger and Diester-Haass, 1988). Although the planktic foraminiferal population in general decreases away from the coast in all world oceans, the exact relationship between changes in relative abundance of planktic foraminifera and water depth varies from region to region. A paleodepth model for the eastern Arabian Sea was suggested on the basis of study of planktic foraminiferal percentage in surface sediments collected from 13 m to 1050 m water depth, thus allowing prediction of paleodepth in samples with 5-93% planktic foraminifera (Nigam and Henriques, 1992). Benthic to planktic ratio can also be used as productivity proxy in deep-sea regions devoid of differential dissolution. The productivity in such pelagic conditions is the product of the benthic/planktic ratio in percent, and the depth of deposition, whereas in hemipelagic conditions, the index has to be corrected for the distance from the land by multiplying it by the square-root of its distance from the land (Berger and Diester-Haass, 1988).

Foraminiferal Fragmentation Index

The foraminiferal fragmentation index is defined as the number of fragments of foraminiferal tests per gram dry sediment. A part of the test which is less than two-thirds of the original test is defined as a foraminiferal fragment (Berger *et al*., 1982). The foraminiferal fragmentation index (FFI) can be calculated by several ways.

A simple foraminiferal fragmentation index is defined as

FFI (%) = [Foraminiferal Fragments/(Foraminiferal Fragments + Whole Tests)]*100

Here tests with more than 2/3rd portion intact are considered whole tests, while any test with less than 2/3rd part intact is counted as fragment (Berger, 1970; Berger *et al*., 1982).

According to Williams *et al*. (1985) and Malmgren (1987) the FFI can be calculated by the following equation

FFI = (F/8)/[(F/8) + Whole Planktic Foraminifera]

where F is number of fragments. As a foraminiferal test on an average usually breaks into 8 fragments and the number of fragments with respect to intact tests provides a better idea about dissolution, the number of fragments is divided by 8 plus the number of intact foraminiferal tests (Le and Shackleton, 1992). As the benthic foraminifera are more resistant to dissolution their tests are not included in the whole foraminifer count to assess changes in dissolution susceptibility.

Stuut *et al*. (2002) proposed carbonate fragmentation index (CFI) based on grain size distributions of the bulk calcareous ooze. It is defined as the ratio of the 25-90 μm and >90 μm fractions. The CFI relies on the fact that the complete shells and fragments of juvenile foraminiferal shells dominate the 25-90 μm of the bulk sediments, while >90 μm fraction primarily consists of adult foraminifera shells and fragments. The ratio of the 25-90 μm and >90 μm fractions is suggested as a measure of the extent of carbonate dissolution induced fragmentation of the foraminifera shells (Stuut *et al*., 2002).

A few foraminiferal dissolution indices make use of relative ranking of species in order of their dissolution susceptibility as inferred from both the field samples as well as controlled experiments, while a few others make use of dissolution resistance of benthic foraminifera as compared to dissolution susceptibility of planktic foraminiferal tests (Conan *et al*., 2002).

The fragmentation of the foraminiferal tests increases under high-energy conditions (increased turbidity) or increased dissolution susceptibility due to shoaling of lysocline or carbonate compensation depth. The variation in the amount of dissolved carbon-dioxide and carbonate ions also affects the rate of fragmentation of foraminiferal tests. Thus the foraminiferal fragmentation index provides information about turbidity currents as well as changes in the concentration of dissolved CO_2 and carbonate ions (Peterson and Prell, 1985; Pinxian *et al*., 1995; Chen *et al*., 1997). Dittert and Henrich (2000) proposed, ultrastructure breakdown in *Globigerina bulloides* as proxy to infer the position of lysocline and carbonate compensation depth. Similarly, the degree of attrition of tests of planktic foraminiferal species *Globorotalia menardii* and *Globorotalia tumida* has been applied to estimate amount of calcium carbonate dissolved from the sediments (Ku and Oba, 1978).

Foraminiferal Size Fraction

The foraminiferal tests, especially the planktic foraminiferal tests of different species fall within a particular size range. Thus the sediments of different size fractions are dominated by different species (Bé and Hutson, 1977; Peeters *et al*., 1999; Kandiano and Bauch, 2002). The total planktic foraminiferal composition tremendously changes with size; the species richness and diversity increases with decreasing sieve size (Peeters *et al*., 1999). The foraminiferal composition in different size fractions, of the water and sediment samples, differs significantly, suggesting large scale modulation of foraminiferal population during its post mortem settling on the sea floor (Peeters *et al*., 1999). Therefore, the variation in weight of different sized foraminiferal tests in the sediments where sand fraction (>63 μm) consists almost entirely of foraminiferal tests can be applied to document past variation in relative abundance of different species and to infer past climatic variations. However, while applying the test size/diameter to reconstruct past climate, the evolutionary changes in size of certain foraminiferal tests must also be considered, especially in studies including long time frame of several million years.

Species Assemblages

Certain foraminiferal species prefer similar restricted environmental conditions, while a few others dwell in a wide range of seawater conditions. The group of species that inhabit similar and restricted environment is referred to as species assemblage. The species assemblages are often identified with cluster analysis and the characteristic species of an assemblage representing a particular environmental parameter like organic matter flux, dissolved oxygen, grain-size, water depth, may vary from region to region. Such species assemblages are thus representative of specific environmental conditions in a region (Murray, 1973; SenGupta, 1977; Lutze and Coulbourn, 1984; SenGupta *et al*., 1993; Gooday, 1994; Mackensen *et al*., 1995; Jorissen *et al*., 1998; Loubere and Fariduddin, 1999; Gooday, 2003; Jorissen *et al*., 2007; Kirci-Elmas, 2013). Therefore, temporal variation in such species assemblages is applied to infer variation in environmental conditions and is one of the most extensively used foraminiferal proxies to infer paleoclimatic variations (Nigam *et al*., 1992; Mackensen *et al*., 1994; Gupta *et al*., 2001a; Gupta and Thomas, 2003). Application of species assemblages is preferred over that of the relative abundance of individual species due to a usually statistically significant number of individuals representing a species assemblage than individual species.

Species Abundance

The relative abundance of any species can be counted by picking a minimum of ~300 specimens of foraminifera from a representative sample and then by dividing the number of specimens of the species by the total number of foraminiferal tests picked from the entire representative fraction. The relative abundance of benthic foraminiferal species is counted in fraction >63 μm, while that of planktic foraminiferal species in either >125 μm or >150 μm fraction. A relatively coarser fraction is taken to count the relative abundance of planktic foraminifera as the species identification is possible in only these coarser fractions. The juveniles of several planktic foraminifera are similar until they attain maturity and an average size of usually >125 μm. The foraminiferal studies from the surface sediments and sediment traps show significant changes in the abundance of foraminiferal species with changing ambient environmental conditions (Bé and Tolderlund, 1971; Boltovskoy and Wright, 1976; Bé and Hutson, 1977; Corliss, 1985; Thunnel and Honjo, 1987; Murray, 1973; Murray, 1991; Lee and Anderson, 1991; Naidu, 1993; Guptha *et al*., 1997; Kawahata *et al*., 2002; Fraile *et al*., 2008; Panchang and Nigam, 2012; Rao *et al*., 2013). Therefore, the fact that the abundance of certain planktic as well as benthic foraminiferal species changes with a change in physico-chemical conditions, has been applied to infer paleoclimatic changes. Besides the use in paleoclimatic reconstruction, appearance and disappearance of foraminiferal species, termed as ‘first appearance datum’ and ‘last appearance datum’ are widely used to assign stratigraphy of a marine sedimentary sequence. Benthic foraminifera *Asterorotalia trispinosa*, is abundant in fine grained low salinity regions of the Bay of Bengal (Panchang and Nigam, 2012; Rao *et al*., 2013) and thus its relative abundance has been used to reconstruct late Holocene monsoon changes (Panchang and Nigam, 2012). The variation in the abundance of benthic foraminiferal species *Epistominella exigua* has been applied to infer past changes in organic matter production (Gupta and Melice, 2003; Saraswat *et al*., 2005). Among the planktic foraminifera, the temporal variation in the abundance of *Globigerina bulloides* has very often been used to infer past upwelling/productivity changes from the Indian Ocean (Prell and Curry, 1981; Naidu and Malmgren, 1996; Anderson *et al*., 2002; Bassinot *et al*., 2011; Naik *et al*., 2014). The abundance and diameter of planktic foraminiferal species *Orbulina universa* is influenced by the ambient seawater temperature and salinity and thus, has been used to infer past temperature and salinity from the Indian Ocean (Colombo and Cita, 1980;

Haenel, 1987; Nigam, 1990). The disappearance of pink variety of *Globigerinoides ruber* from the Indian and Pacific Ocean at 120,000 yr B.P. has been used as a biostratigraphic datum (Thompson *et al*., 1979). While applying the relative abundance of species to reconstruct past climate or oceanography, it should however be kept in mind that its depth habitat may vary latitudinally (Saraswat and Khare, 2010). Additionally, the species abundance also depends on the size fraction taken for picking foraminifera. In the polar north Atlantic region, polar species *Neogloboquadrina pachyderma* (s) forms almost monospecific assemblages in larger size fractions (125-250 μm, >150 μm) of MIS 8 to 7 whereas, the smaller size fractions (100-150 μm, 80-150 μm) are dominated by the subpolar species *Turborotalita quinqueloba* (Kandiano and Bauch, 2002).

Test Size/Diameter

The morphological changes, especially the variation in size (Fig. 4), in response to the changes in the physico-chemical conditions like temperature, salinity, upwelling intensity, have long been recorded from both field as well as laboratory culture studies of foraminifera (Bé *et al*., 1973; Hecht, 1976; Caron *et al*., 1987a; Caren *et al*., 1987b; Bijma *et al*., 1990; Naidu and Malmgren, 1996; Schmidt *et al*., 2004). Bé *et al*. (1973) showed that the test diameter of *Orbulina universa* from tropical and subtropical Indian Ocean shows a latitudinal variation and that the mean diameter of the test of *O. universa* in surface sediments and surface waters is strongly associated with the distribution of water masses in the southern Indian Ocean and northern Atlantic Ocean. Other than physico-chemical controls on the size of foraminifera, evolutionary changes have also been reported to result in an increase in the size of planktic foraminifera (Arnold *et al*., 1995). A concurrent change in test diameter of several dominant deep-sea benthic foraminifera and dissolved oxygen content of the seawater, during the last 120 m year, suggests a dominant control of climatic changes on benthic foraminiferal test diameter (Kaiho, 1999). The size and abundance of planktic foraminifera fluctuates with environmental factors such as temperature, primary productivity, and environmental variability and is maximum at optimum conditions suggesting a prominent effect of climatic conditions on planktic foraminiferal test size (Schmidt *et al*., 2003; Schmidt *et al*., 2004). Abundance of *Epistominella exigua* is inversely related to its size suggesting increased instances of asexual reproduction during favourable conditions (Saraswat *et al*., 2011). Thus, the temporal changes in foraminiferal test dimensions have been applied to infer past variations in physico-chemical parameters as well as in evolutionary studies (Naidu and Malmgren, 1996; Arnold *et al*., 1995; Kaiho, 1999; Schmidt *et al*., 2004). It should however be kept in mind that the close correspondence between planktic foraminiferal test size and climatic parameters is confined only to the regions of large climate variability like frontal systems and upwelling zones, whereas such a relationship is obscure in regions with relatively stable climate (Schmidt *et al*., 2004).

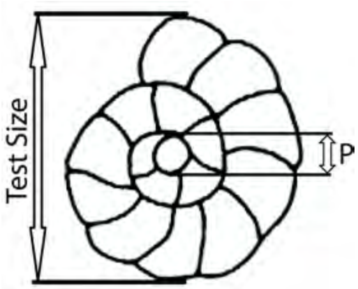

Fig. 4: A schematic of measuring the test size as well as the size of the proloculus. 'P' indicates the maximum diameter of the proloculus or the first formed chamber. The foraminiferal test should be kept in spiral view to measure the maximum diameter of the proloculus

Coiling Pattern

The foraminiferal tests, especially those of benthic foraminifera, show a wide variation in the number and arrangement of chambers. Out of several thousands of species of foraminifera, chambers are arranged trochospirally in a few foraminiferal species. In the species belonging to this group, the chambers may be arranged either in dextral (clockwise) or sinistral (anticlockwise) manner (Fig. 5). The coiling direction is determined by placing the tests in spiral view and following the direction of addition of chambers beginning from the proloculus and moving towards the last added chamber. If possible, a

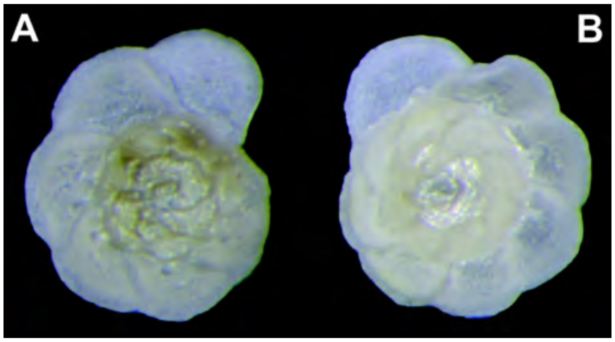

Fig. 5: Dextral (A) and sinistral (B) coiling in a trochospirally coiled foraminifera

minimum of 50 specimens of a species should be picked from each interval while assessing temporal changes in coiling direction, in order to arrive at a statistically significant interpretation. Various studies have shown that the ambient environmental conditions influence the direction in which the chambers are arranged in certain species of foraminifera (Bolli, 1950; Ericson, 1959; Nigam and Khare, 1992; Naidu and Malmgren, 1996). This preferred coiling pattern of both benthic and planktic foraminiferal species has been applied to infer past climatic conditions (Ericson *et al*., 1954; Bé, 1960; Thiede, 1971; Keany and Kennett, 1972; Williams, 1976; Nigam and Khare, 1992; West *et al*., 2004). The dextral *Rotalidium annectens* are preferentially microspheric suggesting that the mode of reproduction influences the coiling pattern (Nigam and Khare, 1992). The relative abundance of dextral and sinistral forms of planktic foraminifera *Neogloboquadrina pachyderma* was frequently used to reconstruct past seawater temperature, with the sinistral form being dominant in colder waters (Bandy, 1960; Keany and Kennett, 1972; Naik *et al*., 2013). Even though a similar possible control of regional seawater properties on the coiling direction of *Globorotalia menardii* was suggested by Bolli (1971), but no such relationship between coiling direction and sea water properties during the late Quaternary was found in the northern Indian Ocean, wherein only an insignificant percentage of specimens were dextrally coiled (Bhonsale and Saraswat, 2012). However, of late, with the application of molecular biology techniques, it has been established that the differently coiled specimens, formerly considered to belong to the same species, are, in fact, different species (Bauch *et al*., 2003; Darling *et al*., 2006).

Average Number of Chambers

Many species of foraminifera have bimodal reproduction with morphologically distinct sexual and asexual phases. The tests belonging to offsprings of sexual and asexual mode of reproduction have several differences, including different number of chambers. The environmental conditions influence the mode of reproduction in foraminifera (Boltovskoy and Wright, 1976; Nigam and Rao, 1987; Nigam and Caron, 2000) and thus the number of chambers in the individuals belonging to the same foraminiferal species. This distinctive variation in average number of chambers, in certain foraminiferal species as a result of changing mode of reproduction under different environmental conditions, has been used to understand ecology of foraminifera and further proposed as a tool to infer paleoclimatic variations. The number of chambers in a test is counted starting from the proloculus and moving along the direction of addition of chambers till the last formed chamber (Fig. 6). On the basis of inverse relationship between *Epistominella exigua* abundance and the number of chambers, it was inferred that *E. exigua* prefers an asexual mode of reproduction during favorable conditions (Saraswat *et al*., 2011).

Proloculus Size

Cushman (1905) coined the term proloculus to represent the first formed chamber of the foraminiferal test. The changing mode of reproduction as discussed in the previous section, also influences the size of the proloculus (Fig. 4) with

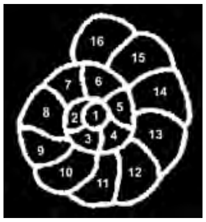

Fig. 6: A schematic of counting the total number of chambers in a test. The foraminiferal test should be kept in spiral view to count the total number of chambers

megalospheric specimens having larger proloculus as compared to microspheric specimens (Boltovskoy and Wright, 1976). The microspheric and megalospheric forms of a few benthic foraminiferal species cannot be clearly differentiated from the size of the proloculus. In such cases, the number of chambers (more in microspheric forms as compared to megalospheric forms) and the size of the tests (microspheric being larger than megalospheric) can help substantiate the differentiation between the two forms. The mean proloculus size of benthic foraminifera *Cavarotalia annectens*, calculated as the ratio of microspheric to megalospheric forms is inversely proportional to salinity and temperature in the shallow water regions of the eastern Arabian Sea (Nigam and Rao, 1987). As mentioned above, since the mode of reproduction in foraminifera is environmentally controlled, the mean proloculus size of selected foraminiferal species have been used to infer past climatic variations (Nigam and Rao, 1987; Nigam and Sarkar, 1993; Nigam and Khare, 1995; Saraswat *et al*., 2005).

Test Abnormalities

Majority of the foraminifera follow a well defined pattern to add chambers during its growth till it reaches maturity. This normal course of addition of chambers for any species, can be assessed by looking at the general population of that particular species in a region. Any deviation from this normal course of addition of chambers is termed as abnormality. The regions where deformed tests comprise upto 1% of the total population, are termed as normal while locations with >1% abnormal tests are termed as stressed (Alve, 1991). A comparatively large number of abnormal foraminiferal tests have been reported in sediments collected from ecologically stressed (both naturally as well as anthropogenically) environments (such as very high or low salinity, temperature, pH, or high concentration of pollutants like heavy metal, sewage) as well as in laboratory culture experiments wherein foraminifera were subjected to pollutants (Boltovskoy *et al*., 1991; Yanko *et al*., 1998; Alve, 1995; Stouff *et al*., 1999; Scott *et al*., 2001; Saraswat *et al*., 2004; Nigam *et al*., 2006a; 2006b; Nigam *et al*., 2009; Caruso *et al*., 2011). The abnormalities in foraminiferal tests from ecologically stressed environments include stunted tests, comparatively smaller or bigger chambers, chambers oriented away from the normal plane of addition of chambers and tests with regressed or completely absent ornamentation. Thus the unusual presence of abnormal foraminiferal tests is applied as a proxy to infer ecologically-stressed environmental conditions (Nagy and Alve, 1987; Schafer *et al*., 1991; Scott *et al*., 1995; Panchang *et al*., 2005). However, the application of test abnormalities to infer 'specific' ecologically-stressed environment is hampered due to the report of nearly similar test abnormalities from differently stressed environments and further by no correlation between abundance of deformed tests and known sources of pollution (Cosentino *et al*., 2013).

Test Weight

A majority of the foraminiferal tests are calcareous. This shell calcite is a mixture of primary calcite and secondary calcite. Most of the planktic foraminifera grow in size by adding chambers secreted from primary calcite. In contrast, secondary calcification thickens existing chamber walls, which can double a shell's mass without significantly affecting its size (Lohmann, 1995). The different effect that primary and secondary calcification has on shell size, allow their relative proportions to be estimated. The secondary calcite is added to the shell when there is excess $[CO_3^{2-}]$ available, *i.e.*, the more the $[CO_3^{2-}]$ concentration, more the secondary calcification will occur (Broecker and Clark, 1999). Laboratory culture studies under controlled conditions indicate that an increase in ambient $[CO_3^{2-}]$ increases the calcification rates and size-normalized weight (SNW) of planktic foraminifera suggesting a dominant control of carbonate ions which are two orders of magnitude smaller than that of calcium ions in seawater, during the calcification (Bijma *et al*., 2002). Hence, if we can determine the secondary calcite amount then we can infer the $[CO_3^{2-}]$ concentration of the seawater. Therefore, the species in which secondary calcification changes only shell mass (e.g. *Pulleniatina obliquiloculata* and *Globoquadrina dutertrei*) and not the size, the amount of secondary calcite added to a shell reflects the change in the $[CO_3^{2-}]$ concentration of the seawater.

The size normalized weight of a foraminiferal species can be determined either by taking the average weight of specimens (with a precision of 1 µg) picked from a narrow size range (usually 50 µm) obtained by sieving the coarse fraction (Broecker and Clark, 2001) or by measuring the diameter of individual tests and by dividing the weight of the tests by the average measured size (Barker and Elderfield, 2002). Prior to weighing, the specimens should be thoroughly cleaned to remove organic matter/clay adhering to the tests. The changes in shell weight have been used to infer decrease in biogenic marine carbon sequestration due to increasing ocean acidification as a result of high atmospheric green-house gas concentration (de Moel *et al*., 2009). The shell weight is often used to assess the degree of dissolution and its potential effect on the trace element composition of the tests (Naik *et al*., 2014).

The use of shell weight as carbonate ion proxy however has a few potential problems. The shell weight may not always increase or decrease due to change in the carbonate ion concentration of sediment pore water. Additionally, the shell weight can also vary due to changes in environmental factors unrelated to carbonate ion concentration (Broecker and Clark, 2001). Only a weak covariance of shell weight with climate indicators and a smaller than expected offset between down-core records at a shallow and deeper sites in the Ontong-Java Plateau, suggests that the controls on shell weight are more complicated and also raises questions about the use of shell weight to reconstruct past carbonate saturation and carbon dioxide levels (de Villiers, 2003; de Villiers, 2005). Large interspecies- and intraspecies-specific variations were reported not only in the strength and gradient of the relationship between $[CO_3^{2-}]$ and the shell weight but also the sign of this relationship, suggesting that shell weight is not a reliable proxy to determine past $[CO_3^{2-}]$ changes (Beer *et al*., 2010). A few other studies reported a dominant control of phosphate ion concentration in seawater on shell weight in addition to $[CO_3^{2-}]$ and seawater temperature and minimal effect of optimum growth conditions, thus implying that further work is required before the shell weight can be used as a reliable proxy for $[CO_3^{2-}]$ (Aldridge *et al*., 2012).

Conclusions

Reconstructing the past climate is important and characteristics of marine microfossils, foraminifera offer a wealth of information about past climate. Changes in abundance, morphology and chemical composition of the foraminiferal tests are used to reconstruct past climate. The non-destructive foraminiferal proxies help in understanding seawater temperature, salinity, productivity, dissolved oxygen content, lysocline movement, sea level changes, organic matter flux, monsoon changes, circulation and several others. The non-destructive foraminiferal proxies not only help to reconstruct qualitative changes in past climate but are also effective to quantify a few parameters like paleodepth and temperature. The foraminiferal proxies are region specific and work best if calibrated regionally.

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