# Distribution of upwelling index planktonic foraminifera in the sediments of the Western continental margin of India

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ABSTRACT

Twenty-one surficial sediment samples were analysed for planktonic foraminifers, radiolarians, calcium carbonate and organic carbon. The distribution of these parameters suggests that the sediments record an upwelling signature. The relative abundance of planktonic foraminifers and radiolarians, and the concentration of calcium carbonate and organic carbon are higher in the upper slope region (< 1 000 m), and low in the lower slope region (> 1 000 m); this indicates that the intensity of upwelling is greater on the upper slope. The distribution patterns of planktonic foraminifera and radiolarians show a positive correlation.

Q-mode factor analysis of twenty-two planktonic foraminifera species reveals four assemblages accounting for 96% of the information given in the original data matrix. Based on the distribution of factor loadings, the frequency of *Globigerina bulloides* in the sediments can be used to reconstruct the intensity of past upwelling in the Arabian Sea.

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RÉSUMÉ

Répartition des foraminifères planctoniques dans les sédiments d'une zone d'upwelling, marge continentale de l'Inde

Les foraminifères planctoniques, radiolaires, carbonates et le carbone organique, ont été analysés dans vingt et un échantillons de sédiments. La répartition de ces paramètres révèle que les sédiments contiennent la signature d'un upwelling. L'abondance relative des foraminifères planctoniques, des radiolaires et les teneurs en carbonates et en carbone organique sont plus élevées sur la pente continentale, et faibles dans les zones profondes. La répartition des foraminifères planctoniques et celle des radiolaires présente une corrélation positive.

Les analyses factorielles (mode-Q) de vingt deux espèces de foraminifères indiquent quatre peuplements, tenant compte de 96 % de l'information dans la matrice de données. D'après la répartition des paramètres varimax, la fréquence de *Globigerina bulloides* dans les sédiments peut être utilisée pour déterminer l'intensité de l'upwelling dans le passé géologique de la Mer d'Arabie.

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## INTRODUCTION

Coastal upwelling is a dynamic process caused by the interaction of atmospheric circulation with the surface ocean and continental boundaries. Distinctive plankton flora and fauna thrive in the cool nutrient-rich waters. The accumulation of these plankton on the sea floor constitutes a record of temporal variations of the over-lying environment and consequently reflects variations in regional climate. Information on the intensity and extent of paleo-upwelling is recorded in deep-sea sediments in the form of sedimentary and biologic indices such as the foraminiferal (planktonic/benthic) ratios or/and radiolarian/planktonic foraminifera, organic carbon and opal content (Diester-Haass, 1977; 1978; Molina-Cruz, 1977). Assemblages of planktonic foram-

inifera, radiolaria, and diatoms have also been correlated to upwelling and used to estimate upwelling variations through time (Prell et al., 1980; Thiede, 1975; 1977).

The deep-sea stratigraphic record has shown that upwelling systems vary significantly during glacial and interglacial times (Duplessy, 1982; Prell, 1984). Thus, a detailed understanding of the modern sedimentary record of upwelling fauna is a prerequisite for use of the latter for the reconstruction and interpretation of paleo-upwelling and its climatic significance.

The surface oceanography of the Northern Indian Ocean is dominated by a seasonally changing monsoon gyre (Wyrtki, 1973). During the Southwest monsoon (May-October) surface circulation is dominated by a strong, wind-driven anticyclonic gyre which is characterized by the westward flowing South Equatorial Current, an eastward flowing Monsoon Current, and a strong western boundary current, the Somali Current (Fig. 1 A). Circulation during the Northeast monsoon (November-April) is relatively weak and is characterized by a North Equatorial Current, as an eastward flowing Equatorial Counter Current to the south, and a moderately developed anticyclonic gyre in the Bay of Bengal (Cullen and Prell, 1984; Fig. 1 B).
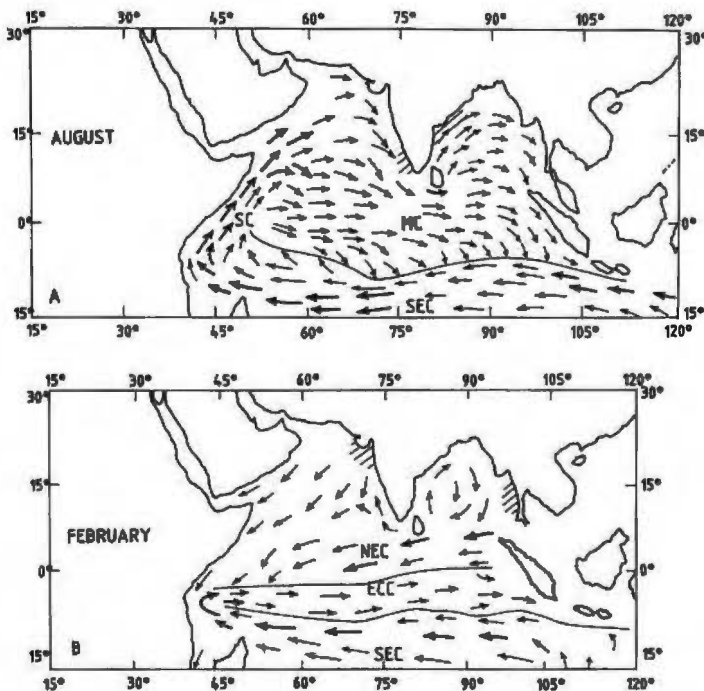


Figure 1
*Surface circulation patterns in the northern Indian Ocean. A) August, the height of the southwest monsoon period (May-October). B) February, the height of the northeast monsoon period (November-April). Hatched pattern, areas of weak or sporadic upwelling. SC = Somali Current, MC = Monsoonal Current, SEC = South Equatorial Current, NEC = North Equatorial Current, ECC = Equatorial Counter-Current [adapted from Defant (1961), Prell et al. (1980) and Cullen and Prell (1984)].*

The study area is affected by both the northeast (November to April) and the southwest (May to October) Indian monsoons (Wyrtki, 1973; Couper, 1983). During the southwest monsoon, conditions consistent with weak and sporadic upwelling are observed in the Lacca-

dive Sea; during the northeast monsoon, upwelling sporadically occurs in the northeastern Arabian Sea (Colborn, 1975; Cullen and Prell, 1984). The current system of the area is shown in Figure 1. A strong northeast monsoon current carrying low-salinity waters from the Bay of Bengal turns north and flows up along the west coast of India, affecting the eastern Arabian Sea during the period from November to January (Wyrtki, 1973).

In the Arabian Sea, maximum primary production is found in the Gulf of Oman, around the mouth of the Indus river, in Saudi Arabian waters, and off Somalia and the southwest coast of India. The high production in these regions is due to upwelling. The study area productivity in the water column shows 200-300 t C/km$^2$/yr, whereas in the Somalia area it shows > 300 C/km$^2$/yr (Qasim, 1977).

The present investigation examines the intensity of upwelling and its influence on the sediments through the study of variations in abundance of planktonic foraminifera and radiolarians and the distribution of calcium carbonate and organic carbon in the sediments of the Eastern Arabian Sea.

## MATERIALS AND METHODS

The study incorporates 21 surficial sediment samples (Fig. 2) collected during the 191st cruise of R. V. Gaveshani, at depths ranging from 275 to 2050 m. The following findings indicate that the sediments are *in situ* and recent: *a)* the fauna is the same as that observed in plankton tow data (Zhang, 1985); *b)* there is no sign of relict fauna; and *c)* due to the absence of typical shallow-water benthic foraminifera they can not be considered as slumped material.

A known quantity of sediment sample was wet sieved (through 63 μm mesh); the dried coarse fraction was weighed; and 0.1 g of coarse fraction (> 63 μm) was scanned under stereobinocular microscope to identify and count planktonic foraminifers and radiolarians and estimate their relative abundance for one gram of sediment. The average numbers of specimens (planktonic foraminifera) counted per sample was 352. The planktonic foraminifera data were subjected to Q-mode factor analysis using the Fortran IV program package for factor analysis (Mahadevan and Fernandes, 1983) at the ND-100 computer centre of the National Institute of Oceanography, Goa. Calcium carbonate was determined using the carbonate bomb method (Muller and Gastner, 1971).

## RESULTS AND DISCUSSIONS

### Planktonic foraminifera

The planktonic foraminiferal population varied from 140 to 8,238 tests per gram sediment, with 22 species: *Orbulina universa, Globigerinoides conglobatus, G. ruber (white), G. tenellus, G. sacculifer, Globigerinella aequilateralis, Globigerina calida, G. bulloides G. falconensis,*
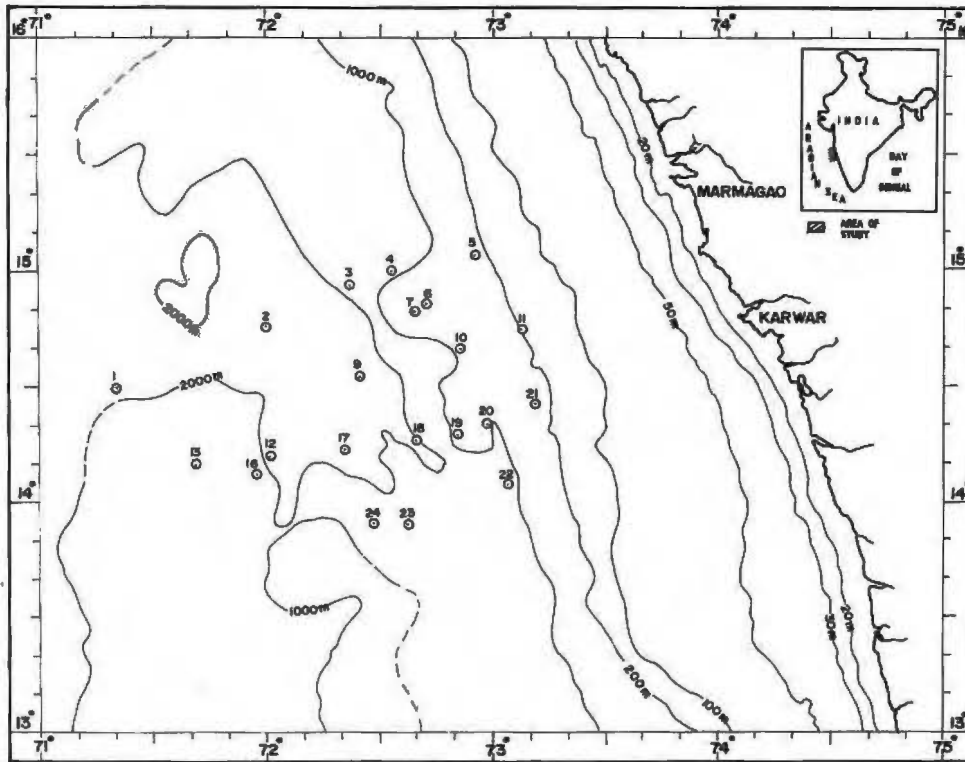
Figure 2
*Station location map.*

*G. rubescense, G. quinqueloba, Neogloboquadrina pachyderma (L), Neogloboquadrina pachyderma (R), Globoquadrina dutertrei, G. conglomerata, Pulleniatina obliquiloculata, Globorotalia crassaformis, G. hirsuta, G. menardii, G. menardii neoflexuosa, G. tumida* and *Globigerinita glutinata.* A few of these showed patchy and incoherent patterns of distribution; the number of variables was reduced by applying multivariate techniques (Imbrie and Andel, 1964).

The planktonic foraminifera found in 21 samples are resolved into four factors, which account for more than 96% of the total variance. Each factor variance, cumulative variance and assemblages are shown in Table 1. The important contributors to the four factors are given in Table 2.

Table 1
*Assemblages of four factors and their variance and cumulative variance.*

| Factor number | Variance | Cumulative variance | Assemblage |
|---|---|---|---|
| 1 | 86% | 86 | G. ruber G. sacculifer G. bulloides |
| 2 | 55% | 91 | G. bulloides |
| 3 | 3% | 94 | G. ruber |
| 4 | 2% | 96 | G. rubescens |

Table 2
*Varimax factor score matrix.*

| Species | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Orbulina universa | − 0.097 64 | − 0.32 75 | 0.067 39 | 0.101 64 |
| Globigernoides conglobatus | − 0.043 57 | − 0.032 30 | − 0.131 09 | 0.045 88 |
| G. ruber (white) | 0.586 61 | 0.165 42 | − 0.701 63 | 0.154 38 |
| G. tenellus | − 0.085 49 | 0.068 60 | − 0.032 34 | − 0.022 22 |
| G. sacculifer | 0.511 10 | − 0.512 40 | 0.219 24 | − 0.202 54 |
| Globigerinella aequilateralis | 0.002 23 | − 0.060 93 | 0.074 32 | 0.064 73 |
| G. calida | − 0.032 49 | 0.070 51 | − 0.071 78 | 0.073 44 |
| G. bulloides | 0.410 13 | 0.617 66 | 0.583 18 | 0.141 18 |
| G. falconensis | − 0.115 76 | 0.076 42 | − 0.011 88 | 0.019 63 |
| G. rubescens | − 0.058 06 | 0.258 71 | − 0.088 66 | − 0.890 29 |
| G. quinqueloba | − 0.151 38 | 0.050 27 | − 0.017 53 | 0.053 41 |
| N. pachyderma (L) | − 0.148 85 | 0.079 41 | − 0.063 15 | 0.185 03 |
| N. pachyderma (R) | − 0.129 05 | 0.078 94 | − 0.041 93 | − 0.037 08 |
| Globoquadrina dutertrei | 0.101 79 | − 0.142 05 | 0.034 27 | − 0.002 53 |
| G. conglomerata | − 0.085 84 | − 0.101 91 | − 0.063 69 | 0.065 55 |
| Pulleniatina obliquiloculata | − 0.039 69 | − 0.189 28 | 0.162 67 | 0.024 31 |
| Globorotalia crassaformis | − 0.162 83 | 0.018 79 | − 0.046 19 | 0.018 37 |
| G. hirsuta | − 0.154 46 | − 0.013 61 | − 0.068 98 | 0.042 39 |
| G. menardii | 0.082 36 | − 0.388 53 | 0.163 59 | − 0.003 01 |
| G. menardii flexuosa | − 0.113 45 | 0.043 42 | 0.072 54 | 0.223 01 |
| G. tumida | − 0.117 31 | − 0.065 45 | − 0.000 39 | 0.066 32 |
| Globigerinita glutinata | − 0.158 35 | 0.021 06 | − 0.037 95 | 0.007 86 |
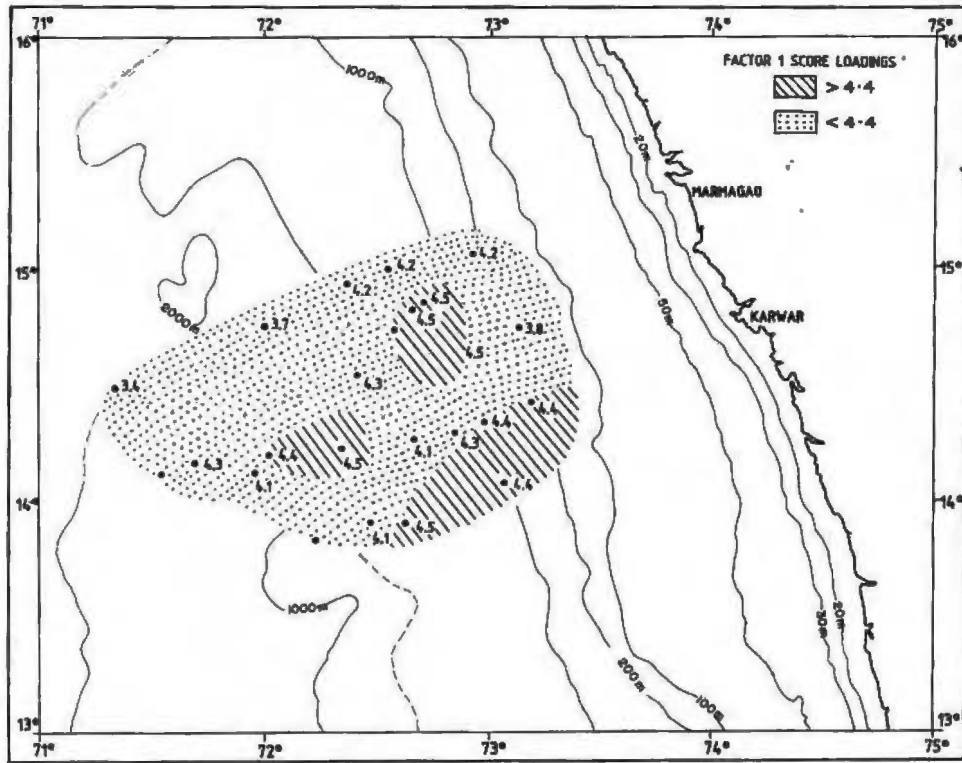
FIG. 3 A

Figure 3 A
*Distribution of factor 1 score loadings. Stippled pattern denotes highest loadings (> 4.4); dotted pattern shows relatively lower loadings (< 4.4) [factor loadings have been scaled on the assumption of the sum of their squares being equal to the variance corresponding to the factor].*
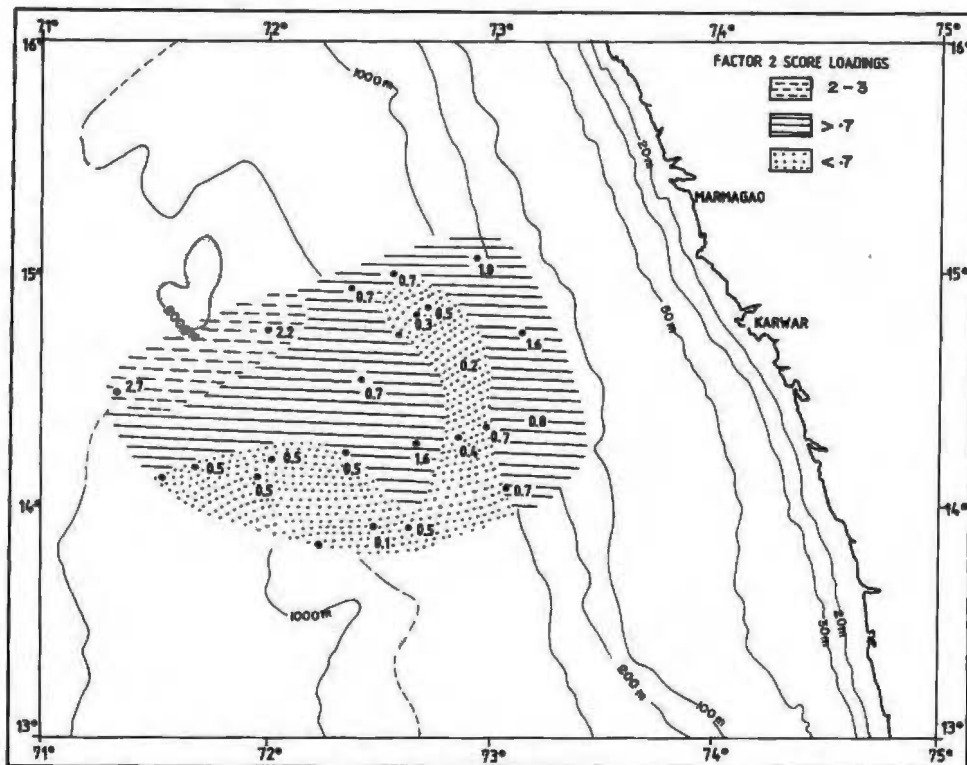


Figure 3 B
*Distribution of factor 2 score loadings. Highest loadings are seen on the northwest side and moderate loadings on the northern and eastern sides (factor loadings have been scaled on the assumption of the sum of their squares being equal to the variance corresponding to the factor).*

*Factor* 1 (*86% variance*)

The important species within this factor are *G. ruber* (0.58), *G. sacculifer* (0.51) and *G. bulloides* (0.41). Maximum loadings of this factor are noticed as three patches in the Southeast, Northeast and Southwest parts of the area, the remainder of which shows minimum loadings (Fig. 3 A).

*Factor* 2 (*5% variance*)

This is dominated by *G. bulloides* and the absence of *G. sacculifer* and *G. bulloides*. This factor shows maximum loadings on the northwest side and moderate loadings on the northern and eastern sides of the area (Fig. 3 B).

The two remaining factors (factor 3 accounting for 3%, and factor 4 for 2% of the variance) are not significant; hence they are not discussed.

Results of Q-mode factor analysis show that *G. ruber*, *G. sacculifer* and *G. bulloides* are the significant species contributing to factors 1 and 2. The distribution of these factors and the occurrence of radiolarians and high organic carbon in all the sediment samples high in these factors indicate that the dominant species of these two factors are representative of the tropical Arabian Sea upwelling assemblage (*G. bulloides, G. ruber* and *G. sacculifer*). Separate loadings on *G. bulloides* in factor 2 in addition to factor 1 indicate the importance of the latter as an indicator of upwelling. *G. bulloides* occurs abundantly in the upwelling region off Somalia (Bé and Hutson, 1977). Preliminary work by Prell (1978) shows that the distribution of *G. bulloides* in the Arabian Sea is highly correlated with upwelling indicators such as sea-surface temperature and phosphorus content. Bé and Hutson (1977) reported that *G. sacculifer* and *G. ruber* shows highest abundance in the tropical and subtropical areas of the Indian Ocean. Since the investigated samples are from a tropical region, it is reasonable to expect tropical species such as *G. ruber* and *G. sacculifer* to be domi-

nant in the Arabian Sea in comparison with the upwelling indicator species *G. bulloides*. Hence the frequency of *G. bulloides* on the seafloor can be used as a measure of Paleo-upwelling in the eastern Arabian Sea. The individual percentage distribution of upwelling indicator species *G. bulloides* (Tab. 4) in the study area is in agreement with the earlier reports of Cullen and Prell (1984) and Zhang (1985). The upwelling indicator species *G. bulloides* is the lone significant contributor of factor 2, in the same factor, *G. sacculifer* and *G. menardii* are also grouped showing negative signs. This indicates that factor 2 loadings are characterized by an abundance of *G. bulloides* and the specific absence of *G. sacculifer* and *G. menardii*.

**Abundance of radiolarians (Tab. 3)**

The distribution of radiolarians in sediments has long been related to oceanic divergences, and radiolarian

Table 4

*Individual percentage distribution of* G. bulloides, G. ruber *and* G. sacculifer.

| Samples Nos. | G. bulloides | G. ruber | G. sacculifer |
|---|---|---|---|
| 1 | 15.0 | 16.0 | 27.6 |
| 2 | 28.0 | 26.0 | 10.0 |
| 3 | 14.3 | 21.0 | 15.3 |
| 4 | 20.0 | 17.4 | 11.7 |
| 5 | 18.1 | 32.9 | 16.5 |
| 6 | 13.9 | 23.0 | 22.8 |
| 7 | 12.8 | 21.0 | 18.0 |
| 9 | 23.3 | 16.3 | 19.0 |
| 10 | 16.7 | 19.9 | 18.2 |
| 11 | 21.2 | 18.6 | 15.5 |
| 12 | 15.0 | 23.9 | 13.7 |
| 13 | 11.6 | 15.5 | 17.1 |
| 16 | 13.4 | 33.2 | 20.0 |
| 17 | 17.7 | 20.5 | 16.4 |
| 18 | 13.9 | 11.7 | 23.0 |
| 19 | 15.0 | 18.6 | 16.7 |
| 20 | 21.2 | 23.2 | 20.2 |
| 21 | 15.0 | 20.6 | 25.2 |
| 22 | 14.4 | 21.2 | 19.3 |
| 23 | 16.0 | 22.2 | 20.3 |
| 24 | 19.6 | 11.2 | 18.4 |

Table 3

*Sample location, total planktic forams and radiolarians and percentages of calcium carbonate and organic carbon*

| Sample Nos. | Water depth (m) | Latitude (North) | Longitude (East) | Total planktic forams (per gm dry sediment) | Total radiolarians | CaCO₃ (%) | Organic carbon (%) |
|---|---|---|---|---|---|---|---|
| 1 | 1 900 | 14°29.0 | 71°20.0 | 380 | 4 | 53.6 | 0.79 |
| 2 | 2 050 | 14°46.7 | 72°00.4 | 140 | 12 | 35.7 | 1.01 |
| 3 | 1 850 | 14°56.3 | 72°21.9 | 1 022 | 16 | 46.4 | 0.95 |
| 4 | 1 350 | 14°59.5 | 72°33.5 | 634 | 18 | 42.8 | 1.95 |
| 5 | 275 | 15°04.1 | 72°56.0 | 4 475 | 14 | 85.7 | 1.26 |
| 6 | 975 | 14°51.0 | 72°42.8 | 3 053 | 48 | 42.8 | 3.81 |
| 7 | 325 | 14°49.6 | 72°39.4 | 4 077 | 29 | 64.2 | 5.00 |
| 9 | 2 050 | 14°32.7 | 72°24.3 | 287 | 2 | 5.7 | 1.40 |
| 10 | 1 200 | 14°40.2 | 72°52.0 | 873 | 4 | 35.7 | 3.84 |
| 11 | 250 | 14°45.5 | 73°08.0 | 4 174 | 45 | 64.2 | 2.51 |
| 12 | 1 520 | 14°11.8 | 72°01.4 | 1 051 | 10 | 57.1 | 1.05 |
| 13 | 1 600 | 14°10.4 | 71°42.9 | 620 | – | 64.2 | 1.27 |
| 16 | 1 700 | 14°08.4 | 71°57.4 | 1 960 | 26 | 57.1 | 0.98 |
| 17 | 2 050 | 14°13.4 | 72°20.6 | 444 | 10 | 35.7 | 1.46 |
| 18 | 2 000 | 14°16.8 | 72°40.9 | 362 | 15 | 35.7 | 1.55 |
| 19 | 325 | 14°18.0 | 72°51.0 | 8 238 | 51 | 57.1 | 5.00 |
| 20 | 900 | 14°20.4 | 72°58.5 | 1 923 | 16 | 50.0 | 4.30 |
| 21 | 320 | 14°26.3 | 73°11.0 | 5 443 | 20 | 71.4 | 3.40 |
| 22 | 1 150 | 14°04.8 | 73°03.7 | 661 | 5 | 35.7 | 0.26 |
| 23 | 1 100 | 13°53.9 | 72°38.1 | 3 941 | 2 | 57.1 | 2.42 |
| 24 | 2 050 | 13°54.7 | 72°28.8 | 405 | 15 | 35.1 | 1.37 |

abundance has been used as measure of upwelling. The abundance of radiolarians constitutes a valuable indicator of fertility changes because it reflect the opal input by diatoms (Berger *et al.*, 1978).

In the present study, the total number of radiolarians (for 1 g sediment) is higher in the upper slope region (275-700 m) of the area (> 30 tests), and decreases drastically in the lower slope region (> 1 000 m) (< 15 tests). This pattern is tentatively interpreted as the product of increased upwelling influence in the upper slope region. However, less oxygen in the upper slope region leads to less bioturbation and consequently to better preservation of radiolarians in the upper slope region.

The abundance of radiolarians in this region is less when compared with other upwelling regions of the Somalia area, where it varies from 50 to 100 tests per gram sediment (Petrushevskaya, 1971). Radiolarian concentrations are low in the area despite the expected high productivity, and may be to some extent due to dissolution of radiolarian tests. In the study area, higher values of silica (250 μg-at/l) are observed in the interstitial waters of sediments (Rao, pers. comm.). This further confirms that the dissolution of radiolarians occurs on the upper as well as on the lower slope. However, the chemical and sedimentological factors determining the rate of dissolution of siliceous microfossils are not well understood.

**Nutrients**

The area shows high dissolved phosphate (> 2.6 μg-at/l) at 200 m water level on the upper slope; its concentration varies on the lower slope (further offshore) from 2.4-2.6 μg-at/l. Nitrate concentration varies from 9.0-13.0 μg-at/l on the upper and 5.0-9.0 μg-at/l on the lower slope. Unlike dissolved phosphate and nitrates, dissolved silicates do not show variations between the upper and lower slopes, the concentration varying from 21-25 μg-at/l in the area (Sarupriya *et al.*, 1988).

The high nutrient values on the upper slope and low values on the lower slope thus correlate with the high abundance of planktons (foraminifera and radiolarians) on the upper slope and their low abundance on the lower slope. This points to a difference in productivity between the upper and lower slopes which can be explained by differences in upwelling intensity. Similar type of correlation between accumulation rate of radiolarians and planktonic foraminifers in the sediments and fertility in surface waters has been found by Diester-Haass (1976) in the region of Cape Barbas, Northwestern Africa, where upwelling occurs throughout the year.

The correlation coefficient values for planktonic foraminifera with radiolarians shows a positive correlation: $r = 0.67$ (Fig. 4). This indicates that planktonic foraminifers and radiolarians increase and decrease simultaneously.

Thus, the available information on radiolarian and planktonic foraminifera supply indicate – as expected – that production and preservation of both groups is dependent on nutrient content in the water column and depositional environment.
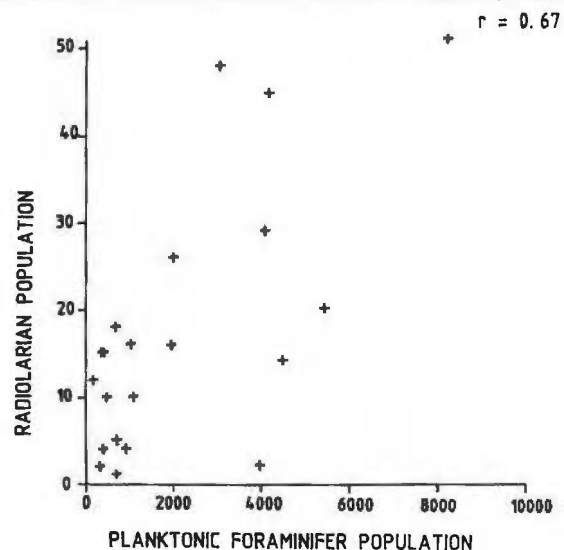


Figure 4
*Relationship between planktonic foraminifera and radiolarian populations.*

**Calcium carbonate (Tab. 3)**

The calcium carbonate content of deep-sea sediments is controlled by three separate factors: *a*) productivity of carbonate secreting organisms; *b*) dissolution of calcareous tests during and after deposition; *c*) dilution by non-calcareous material. In the upwelling regions, a relatively higher concentration of $CaCO_3$ is observed due to high productivity. The study area shows a variation of $CaCO_3$ from 35-85%, higher values being noticed on the upper slope (< 1 000 m; *i.e.* 50-85% whereas on the lower slope (> 1 000 m) it varies from < 50 to 30 %.

All the samples of the present investigation are above the calcium carbonate compensation depth (CCD); most sensitive species for dissolution, such as *G. ruber* (11.2-33.2%), *Orbulina universa* (0.5-5%) and *G. aequilateralis* (1.5-8%) are encountered and foraminiferal fragmentation is not observed. These findings indicate that there is no dissolution in the area. The higher concentration of calcium carbonate in the upper slope region may be due to high productivity as a result of upwelling (Qasim, 1977). Comparatively low concentration in the lower slope region may be due either to low productivity or to dilution by terrigenous input derived through the river Indus (Kolla *et al.*, 1981).

**Organic carbon content (Tab. 3)**

High accumulations of organic matter are known to occur on the sea floor beneath the highly productive upwelled surface waters. High values of organic carbon (> 3%) are observed in the sediments of upper slope; values decrease (< 1.5%) in the lower slope sediments (> 1 000 m; Rao, unpublished data).

In the continental slope region, fine-grained sediments (clayey silt and sandy clays) are encountered; they are olive-grey to green in colour, and extend to a depth of 1 500 m, beyond which brown muds occur (Stackelberg, 1972). The green muds present in the slope region are a consequence of oxygen – deficient conditions in

the depth range of 150-1 500 m, leading to reducing conditions in the northern Arabian Sea (Sengupta and Naqvi, 1984). Thus, the slope sediments are predominantly in contact with oxygen-poor water.

The high organic carbon values observed on the upper slope are probably due to two causes: 1) High productivity in surface water as a result of upwelling (Qasim, 1977). 2) Impingement of the oxygen minimum layer on the sea floor, which prevents the destruction of organic matter through oxidation. Low organic carbon values on the lower slope are due both to low productivity and to the low degree of preservation (Kolla *et al.*, 1981).

## CONCLUSIONS

1) The distribution of *G. bulloides*, the occurrence of abundant planktonic foraminifera and radiolarians, and the high calcium carbonate and organic carbon values found in all these samples clearly show the record of upwelling in the sediments.

2) As regards the significant contribution of *G. bulloides* in factors 1 and 2, the factor-loading distribution (Fig. 3 A and B) and individual percentage distribution pattern of *G. bulloides* (Tab. 4) in the study area match with the high productivity caused by upwelling. The relative abundance of *G. bulloides* in the sediments can therefore be used as a gradient in understanding paleo-upwelling in the Eastern Arabian Sea.

3) The fact that the relatively high abundance of planktonic foraminifera coincides with the higher concentrations of calcium carbonate and organic carbon in the upper slope suggests a greater intensity of upwelling in the upper slope region.

4) The distribution pattern of radiolarian and planktonic foraminiferal abundance reflects a positive correlation in the slope of Eastern Arabian Sea.

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