Radiolarian abundance and geochemistry of the surface-sediments from the Central Indian Basin: Inferences to Antarctic bottom water current

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The distribution trend of numbers of radiolarian shells/gram dry sediment, biogenic silica, organic carbon, and the carbon/nitrogen ratios in the surface sediments of the Central Indian Basin is similar. Ratios of two suborders of radiolaria, i.e. the nassellaria (N) and spumellaria (S), show a trend opposite to the above parameters. Low values of organic carbon in the basin indicate that the basin is oxygenated and sedimentary organic carbon is oxidized. The higher N/S values coincide with the entrance of oxygen-rich Antarctic bottom water in the eastern side of the basin. As nassellarians are comparatively less susceptible to dissolution, their ratio with spumellarians indicates differential oxygen content in the sediments. Therefore, it is proposed that N/S ratio in the sediments may be considered as the index for the oxygen content and a proxy for Antarctic bottom water (AAWB) current within the Central Indian Basin.

SILICEOUS sediments are excellent indicators of overlying productivity in various degrees[1]. These sediments on the surface of the ocean floor reflect areas of high productivity with some bias due to the filtering process of overlying water column[2]. This bias has been documented by Takahashi[3] for Nassellarian and Spumellarian sub-orders of Radiolaria. Biogenic silica which is principally a reflection of organic production in the overlying water column was expected to retain more oceanic environmental records than any other sedimentary type such as carbonate, hence has long been proposed as a palaeoproductivity indicator[4]. Large amount of biologically produced silica gets dissolved into the water column and only a part (0.05–0.15%) of it gets incorporated into the underlying sediments[5]. The radiolaria account for 62 and 99 wt% of the biogenic silica suspension in the tropical Pacific[6]. The number of radiolarian shells/g of the dry sediment has been reported as a function of the differential dissolution of biogenic silica and the radiolarian flux from the plankton production in the water column[2,3,7,8]. Takahashi[9] reported that these two suborders, the nassellaria (silica content 98.4%) and spumellaria (silica content 90%), respond differently to dissolution owing to differences in their shell structure and silica content of their test.

Similarly, the settling flux of carbon decreases by a factor of ten for every 10-fold increase in water depth; i.e. approximately 10% of the given production rate at 400 m depth and only 1% at 4000 m depth[10]. The export of organic matter though is not a linear function of the production rate[11]. Keeping the above in view, it could be speculated that organic carbon should have some relation with abundance of radiolaria and biogenic silica in pelagic sediments. Differential dissolution of radiolarian shells should reflect sub-surface oceanographic conditions. In the present study we have tried to elucidate the surface distribution of radiolarians in relation to the organic carbon, carbonate carbon, biogenic silica and nassellarian (N) vs spumellarian (S) ratio in the surface sediments from the Central Indian Basin.

Materials and methods

Forty-two surface-sediment (approx. top 10 cm of seafloor) samples were collected using Pettersson and Van Veen Grab during the surveys to identify the Indian Mine-Site for polymetallic nodules in the Central Indian Ocean Basin. Locations of these samples are plotted in Figure 1. Total carbon and nitrogen (TC & TN) of these sediments were determined on a Carlo Erba 1106 elemental analyser as described by Patient *et al.*[12]. Total organic carbon (C_{org}) was calculated as the difference between total carbon and carbonate carbon, the latter was determined by using carbonate analyser. Radiolarian shells/g dry sediment (rads/g) was determined using random settling method for radiolarian slides as described by Moore[13]. The species belonging to radiolarian suborders nassellaria and spumellaria were counted separately to calculate their ratio in these samples. Biogenic silica of these samples determined by Pattan *et al.*[14] has been used in the present study for comparison.

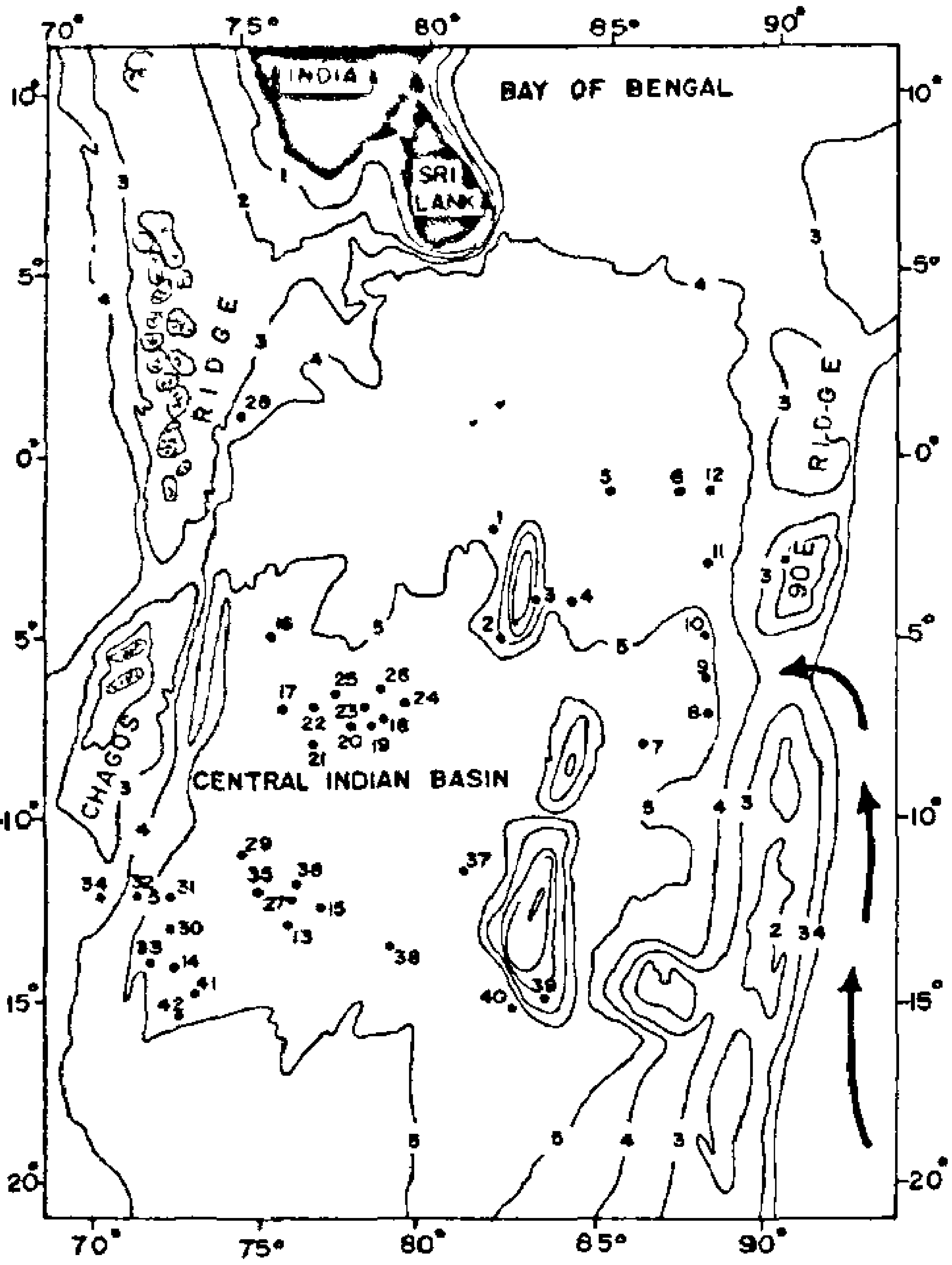

Figure 1. Location map of the surface sediments collected from the Central Indian Basin. Depth contours are in km. Arrow near the 90°E Ridge indicates entrance point of the Antarctic Bottom Water in the Basin (modified after, Udintsev[28], Johnson and Warren[29], Kolla *et al.*[30]).

Results and discussion

The distribution of rads/g, biogenic silica, C_{org}, and the C/N ratios (group A) show similar trend, whereas the $CaCO_3$, and N/S ratio (group B) show similarity in their trend (Figure 2 *a–f*) and a behaviour opposite to that of group A parameters (Table 1).

Radiolaria/g

The number of rad/g of sediments in the basin varies from 2,434 in the northern part to 3,44,943 in the central part of the basin (Figure 2 *a*). The distribution of radiolarian abundance follows the same trends as biogenic silica, indicating their contribution ($r = 0.48$) in the preservation of biogenic silica. Less abundance of radiolaria in the northern part of the basin is related to dilution by terrigenous inputs derived from the Ganges and Brahmaputra rivers and the foraminiferal lysocline[15]. The radiolarian counts/g of sediments remarkably increase many folds (> 1,00,000/g) from 6°S to 13°S latitudes. Evidently in the same latitudinal belt over the Chagos Ridge the radiolarian counts are less due to shallower bathymetry and abundance of calcareous ooze (Figure 2 *c*). This indicates that the enrichment of radiolarian tests in the sediments depends on physio-chemical environment in the basin.

Biogenic silica

Biogenic silica is less in the northern part of the basin as compared to the central part (11°S–13°S lats.) where it is maximum (Figure 2 *b*). This effect is due to better preservation of radiolarian tests only in deeper central part of the basin compared to shallower northern part of the basin[14]. Cushing[16] reported variation in primary productivity of the surface waters in the basin from < 100 to 100–150 mg C m^{-2} d^{-1}. The primary productivity is generally higher in the central part (from 9°S to 14°S) but higher biogenic silica coincides more with the greater depth in this area. In the same latitudinal belt, biogenic silica content is higher in deeper areas compared to shallower area over the Chagos Ridge. This indicates the dilution of biogenic silica in shallower regions by the calcareous input in western side of the basin and by terrigenous input in the north; thus the preservation of biogenic shells is controlled topographically, which in turn controls the sedimentary facies in the basin. The dissolution of the biogenic silica depends on variation in pH, dissolved silica in the water column and surface area of radiolarian skeleton[17].

Organic carbon

The organic carbon content in the basin ranges from 0 to 1.3% (Figure 2 *c*). Its distribution in the sediments broadly follows the surface productivity trend. In western areas of calcareous ooze, the organic carbon percentage is less, whereas in the siliceous ooze sediment belt it is comparatively larger. Higher content of organic carbon coincides with the higher biogenic silica and better grade ferromanganese nodules. The southern and western part are less enriched in the organic carbon as compared to the central part. Though the general trend of organic carbon in the basin is the same like biogenic silica and the radiolaria, its low percentage in the basin indicates that the basin is oxygenated and sedimentary organic carbon is oxidized. Paropkari *et al.*[18] suggested that the influence of surface productivity on organic enrichment is of secondary importance, it is the bottom water anoxia with other depositional parameters which control the preservation of organic carbon. It can be surmised that differential values of organic carbon may be related to differential dissolution of radiolaria in the basin.

The organic carbon in the sediments, however, is mainly from the marine origin as indicated by the very

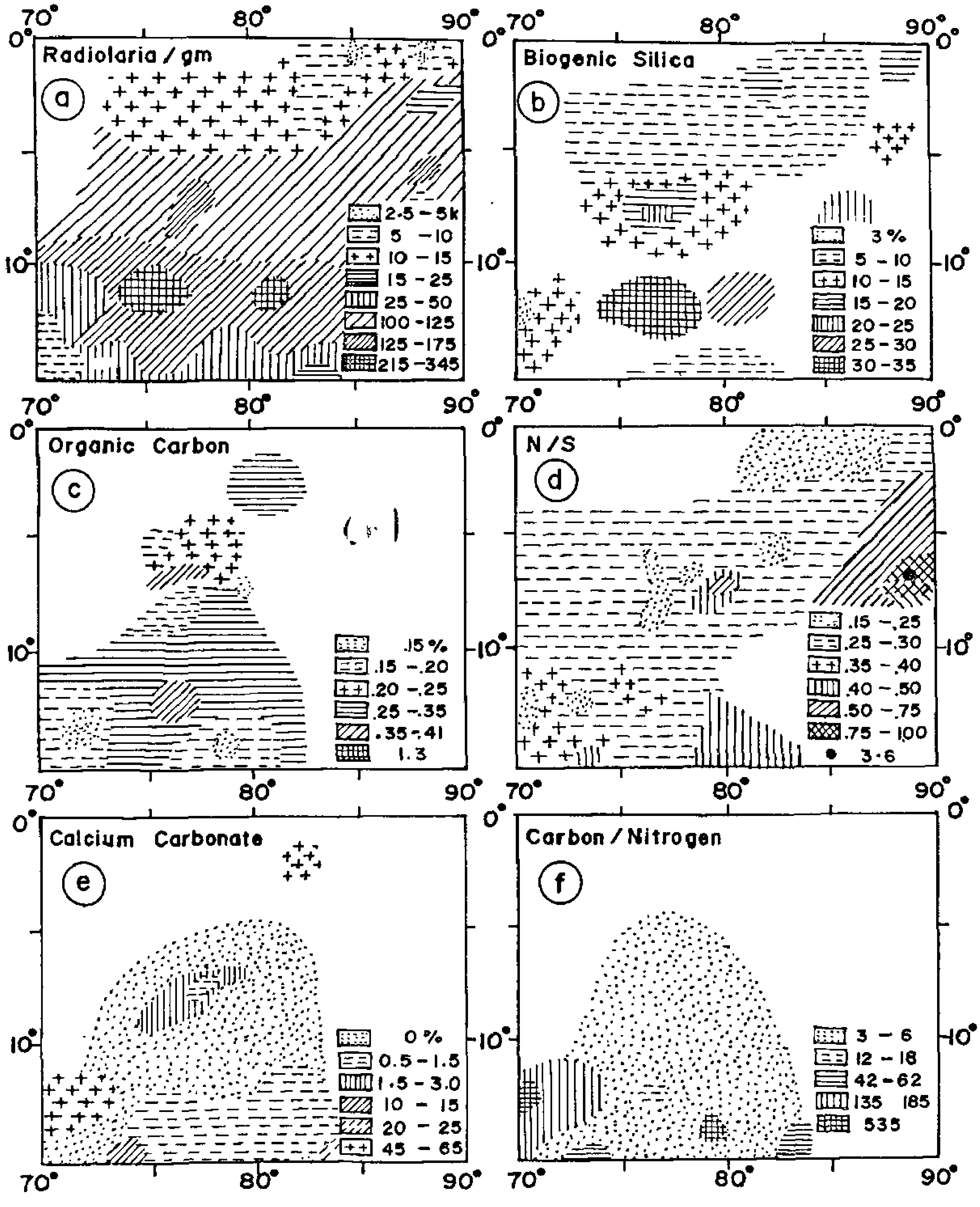

Figure 2. Distribution of the various parameters used in the present study. *a*, Radiolarian shells/g of dried sediment; *b*, Biogenic silica; *c*, organic carbon; *d*, N/S ratio; *e*, $CaCO_3$; *f*, carbon/nitrogen ratio.

low nitrogen values and C/N ratio, perhaps derived primarily from the flux of surface waters. Sedimentation of sinking organic matter at depth is known to cause a depletion of dissolved oxygen[19], which may enhance preservation of organic matter. However, the poor preservation of organic carbon in the basin indicates oxidation of the organic matter; therefore, the possible source of oxygen in the basin needs to be traced. Tchernia[20] summarized the entry of oxygen-rich Antarctic bottom water (O_2 = 4 ml l^{-1}, T° = 0.96, S = 34.71 k^{-1}, Ot = 27.84) into the Central Indian Basin, while passing from the south and northeast Australian and Wharton Basin and by crossing the deeper saddles of 90°E Ridge. Therefore, the northeastern part of the Central Indian Basin is influenced by the oxygen-rich Antarctic bottom water, which is reflected in poor content of organic carbon in

Table 1. Correlation matrix between various parameters used in the present study

	Rads/g	N/S ratio	$CaCO_3$	C_{org}	Bio-silica
Rads/g	1.000				
N/S ratio	−0.0122	1.000			
$CaCO_3$	−0.5273	0.2675	1.000		
C_{org}	0.6197	−0.0185	−0.2516	1.000	
Bio-silica	0.4788	0.1155	−0.2364	0.8896	1.000

the sediment in this region.

Nitrogen

The total nitrogen content in the sediments is insignificant as it is less than 0.1% in all the samples and may have been derived from organic source, produced in the basin itself. The C/N ratio, therefore, reflects only its association with the sedimentary facies in the Central Indian Basin (Figure 2*f*). There is only one analysis available in the north of the basin. Very high C/N ratio of this sample and the samples from western part reflects the total carbon enrichment in the samples by higher input of terrigenous sediments in the north and calcareous sediments in the west, where the carbon is mainly released by the biogenic shells. On an average 5 ratio in central and southern basin indicates its derivation from the organic carbon input.

Calcium carbonate

The $CaCO_3$ content in the basin ranges from 0 to 85.63%. Figure 2*e* shows the highest percentages of $CaCO_3$ at station 34 followed by station 33 which are located over the Chagos Ridge, in the calcareous ooze areas with shallower water depth (< 4800 m). These stations fall above the foraminiferal compensation depth, hence foraminifers are responsible for the enrichment of calcium in this area. Higher content at station 39 explains its location at the summit of a seamount (at a shallower depth). Remaining samples show very little calcium carbonate varying from zero to > 1.5%. This lower percentage may occur due to alteration of feldspars and clay minerals. This indicates that due to the effect of carbonate compensation depth (CCD) most of the carbonate dissolved before reaching the deeper parts, especially in siliceous ooze area of the basin.

N/S ratio

The ratio of two suborders of radiolaria, i.e. nassellaria (N) and spumellaria (S), shows inverse relationship with the total number of radiolarian shells/g in the sediments. The ratio observed in the present study ranges from 0.1 to 0.76. It is least in the north, followed in the centre with a few pockets of high ratio, and higher towards south and southwestern parts. The northeastern part of the basin shows the highest ratio (Figure 2*d*). The general trend of highest N/S ratio is towards northeastern side (Figure 3*a*, *b*, *c*). N/S ratio has negative correlation with C_{org} in the basin. Takahashi[9] observed in the sediment trap experiments that the N/S ratio decreases three orders of magnitude from near surface trap to a few 1000 m deep traps. The ratio is lower in the sediments compared to the deepest trap, suggesting

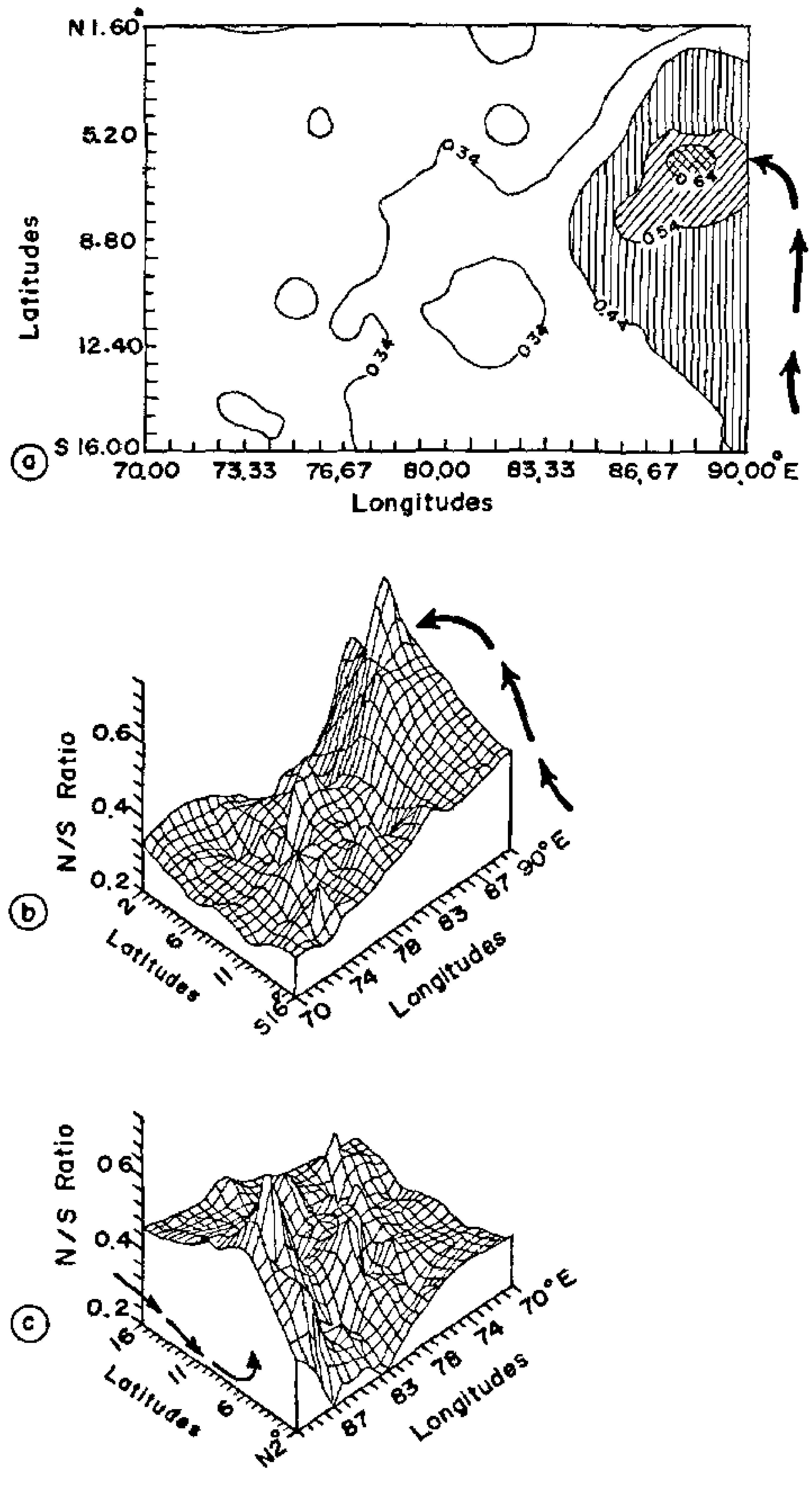

Figure 3. *a*, Contour map of N/S ratio; *b*, 3-D views at 245°/45° rotation and *c*, 45°/45° rotation of perspective axis of the Central Indian Basin. Arrows depict movement of Antarctic bottom water along 90°E Ridge and its entry near 6°S into the basin.

poorer preservation of N than S in the sediments or a possibility of *in-situ* dissolution.

As dissolution of radiolarian shells depends on subsurface water hydrographic parameters like temperature, Eh (oxygen content) and pH condition (alkalinity) and amount of dissolved silicate in the water column[21], GEOSECS (Geochemical Ocean Sections) vertical hydrographic profiles of dissolved oxygen, silicate and alkalinity of the water column near the locations studied would help in understanding the distribution of N/S ratio in the basin. The dissolved oxygen, silicate and alkalinity varies from 150 to 180 $\mu m\,kg^{-1}$, 110 to 130 $\mu m\,kg^{-1}$, and 2390 to 2420 $\mu Eq\,kg^{-1}$ respectively at GEOSECS stations numbers 449 to 452 along 85°E longitude, whereas they vary from 170 to 200 $\mu m\,kg^{-1}$, 120 to 140 $\mu m\,kg^{-1}$, and 2390 to 2420 $\mu Eq\,kg^{-1}$ respectively at stations 440 to 442 near the 90°E ridge in the deeper water mass (2–5 km) in the basin[22]. The differential values of these variables result in differential dissolution of radiolarian shells.

Takahashi[3] observed that owing to differences between shell structures, spumellarians tend to sink slower (57 $m\,d^{-1}$) compared to nassellarians (175 $m\,d^{-1}$). Spumellarians have larger tests which are made of several spherical slender and spongy shells, resulting in larger specific surface area exposed to corrosive action of the water for dissolution 3 times longer compared to nassellarians. Moreover, the skeletal silica content of nassellarians (@ 98%) and spumellarians (@ 90%) is different, which also makes nassellarians comparatively less susceptible to dissolution than spumellarians[9] apart from the differences in their shell geometry[23, 24]. Therefore, comparatively lesser spumellarians survive and reach the ocean floor than the nassellarians, which results in different N/S ratio in the basin. Therefore, it seems that N/S ratio reflects the oxygen content which is governed by the Eh–pH condition of the vertical water mass in the Central Indian Basin.

The higher N/S ratio coincides with the entrance of Antarctic bottom water (AABW) current in the eastern part of the basin. AABW enters through the deeper saddles of the 90° E Ridge (Figure 1) and its effect is indicated in more pronounced dissolution of spumellarian suborder than the nassellarian suborder. A three-dimensional view of the contour plot of this ratio is presented in Figure 3 *a–c*. This clearly indicates higher N/S ratio in the eastern side of the basin which also happens to be the entrance of Antarctic bottom water into the basin. Therefore, N/S ratio in the basin could be considered as an index for the oxygen content in this marine domain and thus a proxy for the presence of the Antarctic bottom water current in the Central Indian Basin[25, 26, 27]

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