CHAPTER 3

3.0 PHYSIOGRAPHIC AND OCEANOGRAPHIC SETTINGS

In order to understand the spatial distribution of radiolaria in the surface sediments from the Central Indian Basin, the physiographic, oceanographic and environmental parameters of the northern Indian Ocean with special reference to the Central Indian Basin are summarized in this chapter.

3.1 INDIAN OCEAN

3.1.1 PHYSIOGRAPHY, REGIONAL SETTING AND SEDIMENT TYPES

Indian Ocean is bounded by the southern margin of Asia, eastern margin of Africa, western margin of Australia and northern limit of Antarctica, constituting world's third largest ocean. Indian Ocean, compared to the Pacific and Atlantic Oceans, is quite young and is the result of fragmentation of Gondwanaland. Displacement of India, Australia, Africa, and Antarctica from their original places (since <120 Ma) is due to the mid Indian Ocean Ridge, Carlsberg Ridge, SE Indian Ridge, Broken Ridge, 90°E Ridge, which constitute major physiographic features of the Indian Ocean (Fig. 2). This complex physiography plays a major role in the variation of surface and bottom water currents, and hydrographic
Figure. 2 Physiography and oceanographic settings of the Indian Ocean [compiled after Johnson and Nigrini, (1980, 1982)]. Contours are in km. Open arrows denote principal surface currents during NE monsoon; filled arrows indicate path of Antarctic Bottom Water (AAWB) Current (Warren, 1974, 1978; Johnson and Damuth, 1979). AABW enters in the Central Indian Basin through the deeper saddles in 90°E ridge near 3-5°S latitudes. Major frontal zones shown indicate south equatorial divergence, subtropical convergence in Indian Ocean. Bathymetric contours are in km.
fronts in the Indian Ocean. As this ocean is almost
land locked from three sides i.e. east, north and
west, it receives huge amount of terrigenous
sediments and have world's largest and thickest
sedimentary deposits i.e. Bengal and Indus fans, in
its NE and NW part north of equator (Fig. 3).
Influence of terrigenous material has also been
traced up to 8°S in the Central Indian Basin (Nath et
al. 1989). Ocean floor having depth less than
carbonate compensation depth (CCD 4.8 km) are covered
by the calcareous ooze (Kolla et al. 1976a), whereas
deeper areas are covered either by siliceous ooze or
by the pelagic clays.

3.1.2 OCEANOGRAPHY

Major oceanographic features of the equatorial Indian
Ocean are summarized below to have a better
understanding of the environmental characteristics
which may be controlling the spatial distribution of
the radiolarians.

3.1.2.1 SURFACE WATER CHARACTERISTICS

Surface Current

With the completion of International Indian Ocean
Expedition (IIOE), geographical and seasonal
variations of major oceanographic parameters are well
established (Wyrtki, 1971). The surface currents
Figure 3. Distribution of calcareous and siliceous ooze, pelagic red-brown clays and terrigenous sediments in the Indian Ocean (after Udintsev, 1976).
Figure 4. Seasonal surface circulation pattern in the northern Indian Ocean i.e. (a) during February, the peak of NE monsoon (Nov.-April). South equatorial current, north equatorial current, and equatorial counter current are separated by north and south equatorial divergence fronts; (b) during August, the peak of southwest monsoon (June-Sept.) [modified after Prell et al. 1980, based on data of Defant, 1961, and Wyrtki, 1973].
(Fig. 4) are chiefly governed by prevailing winds. The surface circulation pattern of the Indian Ocean is summarized in Figs. 2 & 4, with the details of two major seasonal current pattern indicating north and south equatorial currents, equatorial counter current, monsoonal and subtropical gyres.

North Equatorial Current flows in east-west course between 10°N and 2-3°S during north-east monsoon (Nov.-April, Fig. 4 a). It begins near Sumatra and Malaya, passes south of Sri Lanka and then expands to the northwest. Its water accumulates on Somali coast, from where it turns southward towards doldrums near 5°S. It then turns eastward between 3°S and 8-10°S to form the Equatorial Counter Current. South Equatorial Current originates between Australia and Java, between 8°S and 20°S and attains velocity of more than 1 knot. South Equatorial Current is strongest and closest to the equator (reaches up to 7°S) during southwest monsoon (July - August) period (Fig. 4 b).

It is estimated that flow of this current is minimum (40X10⁶m³/s) during northeast monsoon (Dec.-February) and maximum (54X10⁶m³/s) during south-west monsoon (July-Aug.) exhibiting a strong seasonality (Tchernia, 1980).
**Sea Surface Temperature**

Indian Ocean witnesses strong seasonality in sea surface temperature (SST) which ultimately governs salinity and the primary productivity. Sea surface temperature varies from 26-29°C during northeast monsoon. Temperature variation is high and localized from region to region in the equatorial Indian Ocean (Fig. 5a). During southwest monsoon period temperature varies from 23-29°C, with a marked regional trend. From 10°N to 4°S temperature varies from 29-28°C, but south of 4°S to 20°S temperature gradient is very high 28°-23°C. Isotherms generally have latitudinal trend (Fig. 5b). South of 4°S to 20°S surface water is cooler compared to the northern part during southwest monsoon.

**Salinity**

Salinity has seasonal fluctuation and a marked east west zonality, a peculiarity of the equatorial Indian Ocean, is evident (Wyrtki, 1971). During northeast monsoon salinity varies from 32-34.5% and 34.5-35.5% in the east and west of 80°E, with minor fluctuations (Fig. 6a). During southwest monsoon salinity contrast is very prominent in the equatorial Indian Ocean. East of 80°E salinity is less than 34.5%, whereas west of 80°E, it is generally more than 34.5%. (Fig. 6b). The salinity contrast in the
Figure 5. Seasonal variation in sea surface temperature (SST °C) in the equatorial Indian Ocean during (a) December (NE monsoon) and (b) August (SW monsoon) [after Wyrtki, 1973].
Figure 6. Seasonal variation in salinity (%) in the equatorial Indian Ocean during (a) Nov.-Dec. (NE monsoon) and (b) July-August (SW monsoon) [after Wyrtki, 1971].
equatorial Indian Ocean is due to wast monsoonal precipitation and fresh water run off from the Bay of Bengal (Tchernia, 1980).

**Primary Productivity**

Primary productivity in surface water (0-75 m) varies from 1-3 MGC/m$^3$/d during northeast monsoon. High primary productivity cells are localized near regions off Sumatra at the western equatorial region (Fig. 7a). During southwest monsoon primary productivity is comparatively higher. Zone having primary productivity 2-5 MGC/m$^3$/d covers almost entire equatorial Indian Ocean (Fig. 7 b) with highest concentration at few regions between 0-10°N.

3.1.2.2 **SUB-SURFACE WATER CHARACTERISTICS**

A five layered vertical stratification of watermasses is described in the Indian Ocean. Tchernia (1980) characterized these watermasses as follows i.e. (i) surface water of variable regional characteristics; (ii) central water from 100-700 m depth with 15-10°C potential temperature (C$^o$), 35.60-34.70 $\%$ salinity, 5.5-5.0 ml/1 O$_2$, and 24-26 potential density; (iii) antarctic intermediate water near 1 km depth with 5.0°C potential temperature, 34.50%. salinity, 4.5 ml/1 O$_2$, and 27.30 potential density; (iv) deep water around 2.5-3.0 km depth with 2.0°C potential
Figure 7. Seasonal variation in surface primary productivity (MGC/m³/d) during (a) Nov-April (NE monsoon) and (b) May-Oct. (SW monsoon) [after Krey and Babenerd, 1976].
temperature, 34.74%. salinity, 4 ml/l O₂, and 27.70 potential density; (v) bottom water around 4 km depth with 0.5°C potential temperature, 34.70-34.72 %, salinity, 4.5-5.0 ml/l O₂, and 27.85 potential density. In northernmost Indian Ocean generally antarctic water characteristics are absent except at places where it has been traced with the help of potential temperature and other characteristics. These north south vertical water structures are separated by a vertical salinity minima from the surface to great depth around 10⁰S, which is generally termed as 10⁰S hydrographic front (Fig. 8).

3.1.2.3 BOTTOM WATER MOVEMENT

Sea water starts sinking due to extremely cold (T = -0.7°C), highly saline (34.66 %.), O₂ rich (6.0 ml/l), and highly dense (potential density 27.88) water in Weddell Sea, Antarctica (Tchernia, 1980). While spreading to east and north direction this antarctic bottom water penetrates into Indian Ocean between 4-5.5 km water depth. Its potential temperature is below 0°C near the Antarctic Ocean and it increases accordingly while travelling in different basins in the northern Indian Ocean. In the eastern Indian Ocean antarctic bottom water crosses SE Indian Ridge near 110-120⁰E where it enters into South Australian Basin and reaches into the Central Indian Basin.
Figure 8. Vertical stratified salinity structure of the Indian Ocean from Arabia in the north to Antarctica in the south. Monsoonal and subtropical gyres are distinctly separated by the hydrographic front at around 10°S (after Tchernia, 1980).
Evolution of Potential (≈ Antarctic Bottom water) at depth 400m after Tchernia, 1980

Figure 9. Movement of Antarctic Bottom Water (AABW) in different basins characterized by the potential temperature at 4 km depth in the Indian Ocean (after Tchernia, 1980).
through the deeper saddle of 90°E Ridge after crossing over the Wharton Basin. The potential temperature of the antarctic bottom water is 0.97°C in the Central Indian Basin (Fig. 9). Movement of antarctic bottom water is through SW Indian Ridge on the west from Crozet Basin towards Arabian Basin passing through Madagascar, Mascarene and Somali Basins.

3.2 CENTRAL INDIAN BASIN
Apart from the general oceanographic characteristics of the equatorial Indian Ocean, Central Indian Ocean has its own peculiarities which may also help in interpreting the spatial distribution of radiolarians in the basin. These characteristics are summarized below.

3.2.1 PHYSIOGRAPHY, REGIONAL SETTING AND SEDIMENT TYPES
Central Indian Basin is bounded by 90°E Ridge, SE Indian Ridge, Mid Indian Ridge and Chagos Ridge, and the equator as its eastern, southern, western and northern boundaries respectively (Fig. 10). The eastern boundary of the basin is the 90°E Ridge which is the longest known submarine linear physiographic feature on the ocean floor in the world along the 90°E longitude in the Indian Ocean. In general the
Figure 10. Physiography and sedimentary domains of the Central Indian Basin (Udintsev, 1976). Contours are in Km.
depth on the ridge varies from 2-4 km, but it has few
deepersaddlesnear5-6°S,wheredepthismorethan3
km. These saddles are supposed to be the entrance
point of the antarctic bottom water (AABW) in the
basin. The western boundary of the basin is Mid
Indian Ocean Ridge and Chagos Ridge on which depth
varies from 3-4 km in general and these ridges crop
out above the sea level as the coralline islands of
Chagos and Maldives archipelago. Northern side of the
basin is comparatively deeper (>4 km depth). Major
part of the basin is deeper than 5 km with a few
exception like Afrau-Nikitin sea-mounts and abyssal
hills. Northern part of the basin receives
terrigenous sediments of the distal part of Bengal
Fan. These sediment are rich in foraminifers and also
called as foraminiferal ooze. Radiolarian ooze and
pelagic red-brown clays are other twosedimentary
domains of the basin which have boundaries
approximately at 5°S and 15°S respectively (Udintsev,
1976). Bathymetric survey at 10 nautical miles
interval in the southwestern part of the basin
(between 8°-16°S and 71°-82°E) by the National
Institute of Oceanography Goa, has revealed few
seamountsand abyssal hills (Fig. 11) ranging from
200 to 1500 m height with a N-S trend on the sea-
floor (Kodagali, 1989 a,b; Kodagali, 1991 mss;
Figure 11. Bathymetric map of the southwestern part of the Central Indian Basin at close grid sounding (10 nm). Contours at 200 m interval. Several seamounts trending in NS directions and abyssal hills are characteristics of the basin floor (after Kodagali et al. mss.).
3.2.2 SURFACE CURRENTS

Central Indian Basin has three main surface currents i.e. (i) North Equatorial Current, flowing east to west between Sri Lanka and Equator; (ii) Equatorial Counter Current, flowing from west to east between equator to 10°S and (iii) South Equatorial Current, flowing east to west in southern part of the basin during NE monsoon period (Figs. 4 a, b). During southwest monsoon period (July-Aug.) North Equatorial Current and the Equatorial Counter Current of NW monsoon period are replaced by Summer Monsoon Current flowing mainly from west to east between south of Sri Lanka and 5-6°S, whereas South Equatorial Current is strongest and closest to the equator near 6-7°S. It is estimated that flow of South Equatorial Current is minimum (40X10^6 m^3/s) during north-east monsoon (Dec.-February) and maximum (54X10^6 m^3/s) during south-west monsoon (July-Aug.), exhibiting a strong seasonality (Tchernia, 1980).

3.2.3 BOTTOM WATER CURRENTS

During the GEOSECS observation Jacobs and Georgi (1977), Chung and Kim (1980) and Warren (1978) have reasonably well defined the deep water circulation of
the Indian Ocean. The abyssal path of bottom water has been traced by Kolla et al. (1976b, 1978). Johnson and Damuth (1979) have traced the abyssal current path in the Indian Ocean. Warren (1981, 1982) demonstrated a two layered structure of antarctic bottom water current i.e. (i) upper deep water (2000-3800 m) flowing directly from Antarctica along the eastern flank of the Central Indian Ridge; (ii) the lower deep water (>3800 m) derived from the boundary current in west Australian Basin and flowing across the 90°E Ridge. Whereas, antarctic bottom water (AABW) in the Central Indian Basin is characteristic at 5.0-5.5 km depth with 0.97°C potential temperature, 34.71‰ salinity, 4 ml/l O₂ content, and 27.85 potential density (Tchernia, 1980). In brief AABW crosses the southeast Indian Ridge and flows clockwise around the Black Plateau and Broken Ridge in south Australian Basin (Fig. 2, and Fig. 9) which continues northwards along the 90°E Ridge and some part of the Antarctic Bottom Water Current passes westward through deeper saddles in the 90°E Ridge entering into the Central Indian Basin. The oxygen content (4 ml/l) of the antarctic bottom water (Tchernia, 1980) is the prime source for the oxidizing sedimentary environment within the Central Indian Basin (Nath and Mudholkar, 1989; Pattan and Mudholkar, 1990; Banaker et al., 1991).
3.2.4 SURFACE WATER CHARACTERISTICS

The basin witnesses the strong seasonality in the surface-oceanographic parameters like sea surface temperature, surface currents, nutrient contents and primary productivity. Variation in sea surface temperature and the surface currents between two monsoonal seasons (NE and SW) is summarized in Figs. 12 a & b. Seasonality in sea surface temperature and current pattern is reflected in the nutrient contents like silicate and phosphate in the surface water (Figs. 12 c & d). Chlorophyll-a contents in the surface water show wide variations in the basin in both the monsoonal seasons (Figs. 12 g & h). Potential primary productivity varies in both the seasons and reaches a maximum around 0.5 MGC/m³/h. However, our study area (0-16°S) shows rather high concentration (0.2-0.5 MGC/m³/h) during SW monsoon. During NE monsoon concentration varies from 0.05-0.2 MGC/m³/h (Figs. 13 a & b).

3.2.5 SUB-SURFACE WATER CHARACTERISTICS

As majority of the radiolarians inhabit in the upper 300 m water (Kling, 1979), the variations in physiochemical parameters in 0-300 m water column of the Central Indian Basin are considered in the present study. Subsurface hydrographic characteristics are very seasonal in the basin.
Figure 12. Seasonal variation in oceanographic parameters in the Central Indian Basin i.e. a = surface current and isotherms during January (northeast monsoon = NEM); b = surface current and isotherms during July (southwest monsoon = SWM); c = silicate (µg-atoms/l) in surface water during May-Oct. (SWM); d = silicate (µg-atoms/l) in surface water during Nov.-April (NEM); e = phosphate (µg-atoms/l) in surface water during May-Oct. (SWM); f = phosphate (µg-atoms/l) in surface water during Nov.-April (NEM); g = chlorophyll-a (mg/m³) in upper 75 m water during May-Oct. (SWM); h = chlorophyll-a (mg/m³) in upper 75 m water during Nov.-April (NEM) [after Krey and Babenerd, 1976].
Figure 13. Seasonal variation in potential primary productivity (MGC/m²/h) in the Central Indian Basin during (a) May-Oct. and (b) Nov.-April [after Kery and Babenerd, 1976].
Wyrtki (1971) reported seasonal variations (IIOE, profiles 36 and 37 at 0°S between 70-90°E) in potential temperature from 28°C to 15°C, and in salinity (Fig. 14 a) from 34.3% to 35.2% at the equator within 0-50 m and 100-200 m depth zone during northeast monsoon. During southwest monsoon potential T° varies from 26°C (at 0-50 m) to 14°C (at 100-200 m), whereas salinity varies from 34.2-34.8 % (0-50 m) to 34.7-35.2% (100-200 m, Fig. 14 b). During NE monsoon oxygen content in 0-100 m water varies from 2-4.5 ml/1, whereas it is less than 2 ml/1 in 100-300 m water depth (Fig. 14 c). During SW monsoon, oxygen content is >3 ml/1 in 0-100 m water column, whereas it varies from 1.5-2 ml/1 between 100-300 m water column (Fig. 14 d). An oxygen minima layer (<1.5 ml/1) is pronounced between the depth range of 100-200 m water column during southwest monsoon, in an area between 77-90°E (Fig. 14 d). Seasonal variations in vertical hydrographic parameters (IIOE, profiles, 29 at 75°E and 34 at 92°E) of salinity and oxygen contents are also prominent as one traverses from equator to 20°S and reflect the effect of hydrographic front at 10°S (Figs. 14 e, f, g, h).
Sub surface hydrography of Central Indian Basin
IIOE, Vertical profiles.
(aft. Wyrtki, 1971)

Figure 14. Seasonal variation in subsurface hydrographic parameters in upper 300 m of water column within the Central Indian Basin i.e. salinity structure during (a) March-April and (b) July; oxygen content during (c) March-April and (d) July (IIOE data of vertical profiles at section 36 and 37); salinity structure during (e) April and (f) Aug.-Sept.; oxygen content during (g) April and (h) Aug.-Sept. (IIOE data along profiles 29 and 34, after Wyrtki, 1971).
3.2.6 HYDROGRAPHIC FRONT AT 10°S

Monsoonal gyre is separated from the hydrographic front near 10°S by a remarkable salinity minima (Fig. 8) in the surface water extending from Sumatra to Africa and is the result of advection of low salinity water by south equatorial current from the Australia and Indonesian region coupled with Ganges-Bramhaputra fresh water discharge (Wyrtki, 1973; Johnson and Nigrini, 1980). During GEOSECS observations variations were recorded in potential temperature, salinity, oxygen content, silicate, phosphate and nitrate contents in the vertical hydrographic profile along 80°E longitude, which passes from the center of the Central Indian Basin (Fig. 15). In this data set the 10°S hydrographic front is also characterized by sharp gradient in the distribution of potential temperature, salinity, oxygen, phosphate, and nitrate contents (Spencer et al., 1982) in vertical hydrographic profile along 80°E longitude (Fig. 15). It inclines and slopes from 100 m depth at 10-12°S to 800 m at 16-18°S (Wyrtki, 1973).

Physical, chemical, and hydrological parameters described above provide general idea that how important is the monsoon system to understand the distribution pattern of the radiolarians within the basin.
Figure 15. Subsurface variation in upper 1000 m water column of the Central Indian Basin along 80°E longitude i.e., (a) potential temperature, (b) salinity, (c) oxygen content, (d) silicate, (e) phosphate and (f) nitrate (unit MM/Kg; GESECS, IIOE, Spencer et al. 1982). Note the changes in vertical profiles of hydrochemical parameters near 10°S, which is known as hydrographic front at 10°S.