Chapter 2

HYDROGRAPHY, SEDIMENT CHARACTERISTICS AND TOTAL MICROBIAL BIOMASS IN THE CONTINENTAL SHELF REGION OF SOUTH WESTERN BAY OF BENGAL

2.1 Introduction

The Bay of Bengal, the largest bay in the world, is an embayment of north eastern Indian Ocean. Roughly triangular in shape, it is bordered mostly by India and Sri Lanka to the west, Bangladesh to the north, and Burma and the Andaman and Nicobar Islands to the east. The Andaman and Nicobar groups are the only islands which separate the Bay from the Andaman Sea. This semi-enclosed basin has an area of about $2.2 \times 10^6$ km$^2$, which is 0.6% of the world ocean [La Fond 1966]. The Bay is about 1,000 miles (1,600 km) wide, with an average depth of more than 8,500 feet (2,600 metres). The maximum depth is 15,400 feet (4,694 metres). The topography is such that it is conical in shape with its wider and deeper end towards south and narrower and
shallower end towards north. Its zonal and meridional dimensions are comparable; each about 1500 km. The bathymetry of the open Bay shoals from 4 km at the southern end (approximately 5°N) to about 2 km near the northern end, at about 20°N [Muni Krishna 2008].

A number of large rivers – the Padma (a distributary of the Ganges), Meghna (a distributary of the Brahmaputra), Jamuna (a branch of the Brahmaputra), Irrawaddy, Godavari, Mahanadi, Krishna and Kaveri – flow into the Bay of Bengal. The uniqueness of Bay of Bengal results from these major rivers that flow through various geological formations of the Indian subcontinent. These rivers introduce $2.0 \times 10^{15}$ g suspended particulate matter annually into the Bay, which is approximately 15% of the contemporaneous global discharge of fluvial sediments into the world oceans [Rao 1985]. The Bay of Bengal is bordered in the north by a wide continental shelf that narrows to the south and by slopes of varying gradient on the northwest, north, and northeast, all cut by canyons from the rivers. Most imperative are the Ganges-Brahmaputra, Andhra, Mahadevan, Krishna, and Godavari canyons. Formerly these were estuaries when the shoreline was at the margin of the continental shelf during the Pleistocene epoch. The deep floor of the bay is occupied by a vast abyssal plain that slopes to the south. The main submarine features include the beginning of the long, seismically active Java Trench near the Nicobar-Sumatra mainland and of the aseismic Ninety East Ridge. The bay itself was formed as the Indian subcontinent collided with Asia within roughly the past 50 million years.
A unique feature of the Bay is the extreme variability of its physical properties. Temperature in the offshore areas, however, is warm and markedly uniform at all seasons, decreasing somewhat towards the north. During the inter monsoon season, sea surface temperature (SST) increases from 27.5 °C in the north to 30.5 °C in the central Bay. Surface salinity, normally measuring 33 to 34 parts per thousand, can fall to nearly half that level and can extend well to south of the Bay during the fall. Both river runoff and precipitation intensify during the southwest monsoon thereby, dropping the surface salinity 3 - 7 units lower in the Bay of Bengal throughout the year than in the adjacent basin, the Arabian Sea [Varkey et al. 1996], which leads to strong stratification [Shetye 1993]. Surface densities are considerably greater in spring than in fall, when river discharge is highest. Below the surface layer is an oxygen-poor intermediate layer that has high salinity and undergoes only weak circulation. Weak upwelling occurs in the northeast during the northeast monsoon. Surface movements of the waters change direction with the season; the northeast monsoon giving them a clockwise circulation and the southeast monsoon a counter clockwise circulation. Severe storms occur at the change of monsoon, particularly to the south in October. The sea presents alternately slick and ruffled surfaces over shallow internal waves all along the east-coast shelf.

Traditionally it has been considered that Bay of Bengal is poorer in biological productivity when compared to Arabian Sea. However being a cyclone-prone region certain episodic events are likely to chum-up the
area, injecting nutrients to the shallow euphotic zone and thereby enhancing production in upper layers. The biological productivity of any oceanic region is largely based on the organic production (primary production) of that region. Measurements of primary production in the Bay of Bengal were made for the first time during Galathea Expedition and subsequently, during International Indian Ocean Expedition (IIOE). Most of the studies depict Bay of Bengal as an oligotrophic system. Although, many major world river systems, bring in large quantities of suspended and dissolved substances, the narrow shelf, heavy cloud cover and less light penetration have been attributed as reasons for this [Qasim 1977; Gomes et al. 2000; Kumar et al. 2002 and Madhupratap et al. 2003].

The Bay experiences intense depletion of dissolved oxygen at intermediate depths [Wyrtki 1971]. The suboxic conditions may lead to important transformation in redox elements in the water column. An oxygen minimum zone between 100 and 500 m, less thick compared to Arabian Sea occurs in the Bay of Bengal [Olson et al. 1993]. Based on the data collected during International Indian Ocean Expedition (IIOE), Deuser [1975] reported that OMZ exists in the north eastern Bay and stressed on the possible occurrence of reducing conditions.

Sediments in the Bay of Bengal are dominated by terrigenous deposits from the rivers, derived mainly from the Indian subcontinent and from the Himalayas. The suspended sediment carried by river Ganges bypasses the bar and continues into the deep water through a
Hydrography, sediment characteristics and total microbial biomass in the continental shelf …

canyon called ‘swatch of no ground’. The heavy sediment load that is drained into the Bay of Bengal forms a wide sedimentary fall called the ‘Bengal fan’. It is about 1500 km wide and 3000 km long and encompasses the entire Bay of Bengal. The fan of sediments of the Ganges River is the widest - 5 to 7 miles (8 to 11 km) and thickest in the world. The river system transports major parts of its annual average sediment load \((1.1 \times 10^9\) tonnes) during the summer [Milliman and Syvitski 1992]. The fluvial inputs are the main source of nutrients to the Bay of Bengal. The annual supply of nutrients by the Ganges and Brahmaputra rivers to the Bay of Bengal is \(~2\%\) of the riverine input to the world ocean [Sarin et al. 1989].

It is concluded that the Bay of Bengal is a unique ocean with interrelated oceanographic, biological and sedimentary processes. The semi enclosed nature of the Bay and its proximity to the equator marks it exclusivity from other oceans.

Marine sediments are documented as important domicile for microbial activity [Danovaro et al. 2000] and are colonized intensively by microorganisms including bacteria, cyanobacteria, viruses, fungi, algae and protozoans. Ample oceanographic researches depicted the biomass present in the marine ecosystem especially that of microorganisms at the base of the food chain [Karl 1980; Harris and Kell 1985; Cragg et al. 1992; Contin et al. 2000; Koster and Meyer-Reil 2001; Mirto et al. 2004; Steward et al. 2007]. Reliable estimation of benthic biomass is essential to determine the quantitative importance of these groups in marine ecosystem. In sediments, they play a key role
in the disintegration, production as well as the consumption of organic matter and the release of inorganic nutrients to the environment [Meyer-Reil 1993].

The microbial biomass in sediments can be determined from cell constituents such as phospholipids, ATP, chlorophyll \( \alpha \) and bacterial number [White et al. 1979; Parkes 1987]. Of these, a compound fundamental to the energy metabolism of all living organisms, ATP (adenosine triphosphate) is considered to be a good indicator of the benthic biomass [Holm-Hansen and Booth 1966; Karl 1980; Egeberg 1995; Pryputniewicz et al. 2002; Nakamura and Takaya 2003], such as microbenthos and meiobenthos. Synthesis and degradation of ATP is continuous as long as these cells are alive and lost rapidly upon cell death [Pryputniewicz et al. 2002]. The amount of ATP thus found in sediments acts as an indicator of the biomass of live microorganisms. Today, the determination of ATP is considered as most convenient and reliable method for evaluating the living microbial biomass in most environmental samples.

Bacteria are accountable for most of the living benthic biomass [Danovaro et al. 1995; Gasol et al. 1997 and Polymenakou et al. 2009] and it is well known that they play significant ecological and biogeochemical processes in benthic ecosystems and form the basis of food webs. During the past two decades their importance in aquatic ecosystems has repeatedly been documented [Pomeroy 1974; Williams 1981; Azam et al. 1983; Sherr et al. 1988; 1993]. The quantification of bacterial roles requires precise measurements of their parameters.
Distribution of microbial biomass in marine sediments is determined by the availability of organic material to microbial assemblages [Nedwell and Gray 1987; Boetius et al. 1996]. The amount of organic matter present in the continental-shelf sediment of the northern part of the east coast is poor compared with the world’s average for near shore sediments. Benthic bacteria play a pivotal role in converting organic matter into their biomass which have been largely consumed by protozoa [Danovaro et al. 1999] and meiofauna [Danovaro 1996], thereby allowing the transfer of energy into higher trophic levels [Kemp 1988; Bak and Nieuwland 1989; Hondeveld et al. 1994]. Nevertheless, a gross measure of total organic matter content in sediment gives scant information on its actual availability to consumers [Fabiano et al. 1995]. It is the readily available fraction of the organic matter which is assumed as an important factor in regulating benthic community distribution in marine sediments. This can be accomplished by the determination of carbohydrates, lipids and proteins as indicators of the readily available (labile) fraction of organic matter, rather than with carbon or organic matter concentrations alone [Fabiano and Danovaro 1994; Danovaro 1996; Grémare et al. 1997; Dell’Anno et al. 2000; Medernach et al. 2001]. Thus, the biopolymeric fraction of sedimentary organic carbon, (the sum of the protein, carbohydrate and lipid carbon equivalents), as potential food supply is an efficient tool to provide insights in benthic fauna ecology (e.g., abundance, diversity, and activity) [Albertelli et al. 1999; Fabiano and Danovaro 1999; Grémare et al. 2002; Rossi et al. 2003]. Moreover, concentration and composition of the sedimentary organic
matter are important indicators of the trophic state of marine environments [Fabiano et al. 1995].

The nutritive value of the organic content of the sediment has been suggested as a key factor that may explain the extreme richness of the benthic biomass in this area [Gili et al. 2001]. With this perspective our main goal was to analyse the sediment characteristics and its availability as potential food supply to rich benthic communities inhabiting this environment. ATP estimation was also carried out as a proxy to microbial biomass in sediments.

2.2 Materials and Methods

2.2.1 Study Area

The study area was the continental shelf region of south western Bay of Bengal extending between latitude 10º 36’ 00” N to 15º 14’ 82” N and longitude 80º 07’ 06” E to 81º 35’ 09” E (Fig.2.1), covering 18 stations over 6 transects (Karaikal, Cuddalore, Cheyyur, Chennai, Thamminapatnam and Singarayakonda). Across the transects, 3 stations each at a depth of 50 m, 100 m and 200 m were sampled. Details of the stations are given in Table 2.1.
Table 2.1. Details of sample collection onboard FORV Sagar Sampada (Cruise No. 266)

<table>
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<tr>
<th>STATIONS</th>
<th>DATE OF SAMPLING</th>
<th>DEPTH (M)</th>
<th>LATITUDE (°N)</th>
<th>LONGITUDE (°E)</th>
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<td>3</td>
<td>5/5/2009</td>
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<td>10° 35' 38&quot;</td>
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<tr>
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<td>11° 34' 52&quot;</td>
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<td></td>
<td>7</td>
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<td>11° 32'93&quot;</td>
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<td>12° 31'35&quot;</td>
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<td>15° 14' 82&quot;</td>
</tr>
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</table>

2.2.2 Sample collection

Sediment samples for the present study were collected onboard Fisheries and Oceanographic Research Vessel (FORV) Sagar Sampada (Cruise No.266), Ministry of Earth Sciences, Govt. of India, during May 2009. Samples were collected using Smith McIntyre grab (0.2 m² area) from desired depths (Fig. 2.2). Hydrographical parameters of bottom water such as temperature, salinity and dissolved oxygen were recorded from each station using Niskin bottles mounted on a conductivity
temperature depth probe (CTD, Sea bird, USA) (Fig 2.3). pH of the sediment was noted using a portable pH meter.

Sediment from the surface layer (top 5 cm) was aseptically transferred into sterile polythene bags and immediately subjected to Total bacterial Count (TC, Epifluorescence) and ATP analysis. Sediment samples were preserved at -20 °C in a deep freezer for organic matter and texture analysis.

Fig. 2.1. Location of sampling stations in the study area
Fig. 2.2. Smith McIntyre grab used for sediment sampling

Fig. 2.3. CTD Sampling device
2.2.3 Sediment Analysis

2.2.3.1 Grain size analysis

The sediment samples were dried overnight in a hot air oven at 60°C. About 10 g each of the dried sample was accurately weighed and dispersed using sodium hexametaphosphate (10%) and kept overnight. Grain size of the sediment was measured by separating the fine fraction (<180 µm) by wet sieving. Then the fine fraction of the sediment was determined using Particle Size Analyzer (SYMPA TECH, Germany). The fraction >180 µm was dried and weighed separately. After data processing the percentage of sand, silt and clay was plotted in ternary graph according to Shepard [1954].

2.2.3.2 Biochemical Analysis

2.2.3.2.1 Organic matter estimation

Sediment samples from each station were subjected to chemical analysis to determine the total organic carbon (TOC) as well as organic matter (TOM) content. The sediment samples were ground and powdered well after drying in hot air oven at 60°C. The organic carbon content of the sample was determined by wet oxidation method [El Wakeel and Riley 1957]. The cleaned powdered sediment sample was weighed into a glass test tube and 10 ml of chromic acid was added. The test tubes were shaken well and heated in a water bath for 2 hours until the sample was digested and then poured the contents into a conical flask containing 200 ml of distilled water. To this 2 drops of ferrous phenanthroline indicator was added and titrated against 0.2 N ferrous ammonium sulphate. The end point was brick red colour. The organic
carbon content obtained was multiplied by a factor of 1.72 [Wiseman and Bennette 1940] in order to get the total amount of the organic matter (TOM) in the sample and was expressed as percentage organic matter in sediment.

The labile organic matter was determined by estimating the amount of total protein, total carbohydrate and total lipid present in the shelf sediments.

2.2.3.2.2 Estimation of Protein

The protein content was estimated by the method of Lowry et al. [1951]. About 500 mg of sample was mixed well with 2 ml 1 N NaOH. Sample was vortexed and kept in boiling water bath for 5 minutes at 100 °C. The sample was then allowed to cool and centrifuged at 2500 rpm for 5 minutes. To 1 ml of the supernatant, Reagent C (Reagent A + B in 50:1; Reagent A - 2% Na₂CO₃ in 0.1 N NaOH and Reagent B - 0.5% CuSO₄ in 1% Na-K tartrate) was added and kept for 10 minutes in dark room. After incubation, 0.5 ml Folin-Ciocalteu reagent was added and again kept in dark for 20 minutes. The colour developed was measured at 750 nm in a UV-Vis Spectrophotometer (Hitachi, Japan). Bovine Serum Albumin was used as the standard.

2.2.3.2.3 Estimation of Lipids

The lipid content in the sediment was analysed by Phosphovanillin method following chloroform-methanol extraction of the samples [Barnes and Blackstock 1973]. About 500 mg of sample was mixed well with 10 ml of chloroform: methanol solution (2:1) in a homogenizer.
To the supernatant, 2 ml of 0.9 % NaCl was added and shaken well. The mixture was transferred to a separating funnel and allowed to stand overnight at 4 °C. The lower phase that contained all the lipids was removed and the volume was adjusted to 10 ml by the addition of chloroform. From this, 0.5 ml of the extract was taken in a clean tube and allowed to dry in vacuum desiccator over silica gel. Further it was dissolved in 0.5 ml of conc. H₂SO₄, mixed well, plugged and placed in a boiling water bath for 10 minutes and then cooled to room temperature. To 0.2 ml of the acid digest, 5 ml of vanillin reagent was added and incubated for 30 minutes and measured the colour at 520 nm. Cholesterol was used as standard.

2.2.3.2.4 Estimation of Carbohydrates

Total carbohydrates in the sediment were determined spectrophotometrically by Phenol sulphuric acid method [Kochert 1978]. About 500 mg of the sample was hydrolysed in a boiling water bath for 3 h with 1.5 ml of 5% TCA. It was then cooled and centrifuged at 5000 rpm for 5 min. Then, 1 ml of phenol reagent and 5 ml of conc. H₂SO₄ was added to 0.5 ml of the supernatant. It was incubated for 30 minutes and the colour developed was read at 480 nm. Glucose was used as the standard.

2.2.3.2.5 Biopolymeric Carbon

The biopolymeric (BPC) fraction of the organic carbon was calculated as the sum of protein, lipid and carbohydrate carbon [Fabiano et al. 1995]. To obtain these carbon equivalents, each fraction was multiplied by 0.49, 0.75 and 0.4 respectively and expressed as mg C/g sediment.
sample respectively [Pusceddu et al. 2000]. The protein to carbohydrate ratio (PRT: CHO) was calculated and used as indicator of the status of biochemical degradation processes [Galois et al. 2000]. Lipid to carbohydrate ratio (LPD: CHO) which can be used as a good index to describe the energetic (food) quality of the organic contents in the sediments was also calculated.

2.2.3.3 CHNS Analysis

The sediment samples were ground and powdered well after drying in hot air oven at 60 °C. Total Carbon, Hydrogen, Nitrogen and Sulphur present in the shelf sediments were determined using a CHN Analyzer at Sophisticated Test and Instrumentation Centre (STIC), CUSAT, Cochin. Carbon/Nitrogen (C/N) ratio was tabulated from the above mentioned data.

2.2.4 Estimation of total bacterial count (epifluorescence)

Total bacterial count in the shelf sediments was determined by the method of Hobbie et al. [1977]. One gram of the sediment sample was aseptically transferred into sterile slurry bottle. To the sample bottle, 50 ml autoclaved seawater was added and mixed well. From this, 5 ml were taken into clean vials. For total count, the samples were immediately fixed with 250 µl buffered formalin and stored at 4 °C. After vortexing, the samples in the vials were sonicated at 40 hertz for 10 seconds to separate the micro-organisms from sediment particles.

Then, 1 ml of supernatant was taken from the vortexed sample and 100 µl of acridine orange dye was added. After incubation the stained
samples were filtered through 0.2 µ polycarbonate filter paper and the filter paper was placed over a drop of non epifluorescent immersion oil on a clean slide. After keeping another drop of immersion oil over the filter paper and a cover slip, observation was made under 100 x magnifications in an epifluorescence light microscope. The bacteria present in the microscopic field were counted.

The counting was done for 10 different microscopic fields and an average was taken. From the average, total count was calculated by the formula i.e. Total Count = n × factor value/v, where n = Average No. in one square, volume = Volume of sample filtered.

2.2.5 ATP measurement for estimating active microbial biomass

ATP was extracted from the sediments on board immediately after sampling. Extraction was done using sterile, boiling Tris- HCl (0.02 M) buffer, pH 7.8 [Parsons et al. 1984]. Tris buffer was brought to boiling point in a beaker, covered by a watch glass. Sediment was added and after 5 min, the beaker was removed to a bath of crushed ice. After cooling, the supernatant was centrifuged at 1,500 g for 5 min. The supernatant thus obtained was then decanted into a graduated test tube and held at -20 °C until analysis. The ATP concentration was determined by the luciferin-luciferase reaction, using an ATP bioluminescent assay kit (Sigma chemicals, USA). Bioluminescence ATP assays were performed using a luminometer (Turner, Biosystems, USA). The generated light signal was measured after a 3 second delay time and a 14 second integration time. ATP (Sigma Chemicals, USA) at a concentration
of 10-50 ng/ml was used as the standard. Controls for background luminescence (Tris-HCl buffer) were run, and the readings were subtracted from readings for ATP concentration. ATP concentration was then converted to total microbial biomass carbon or dry mass (Microbial biomass C=ATP value × 250) [Holm-Hansen and Karl 1978; Karl 1980].

2.2.6 Statistical Analysis

Statistical softwares such as, PRIMER 6, SPSS 21, ORIGIN 8 and SURFER 8 were used for the data analysis and representation. For all the analysis, one way analysis of variance (ANOVA) using SPSS software was performed to test for significant differences in values between stations. In order to interpret statistically significant differences between respective depths and transects Tukey’s post-hoc test was carried out. Probabilities (p) of <0.05 were considered to be significant.

2.3 Results

2.3.1 Abiotic factors

The key hydrographical parameters such as temperature, salinity, dissolved oxygen and pH did not vary significantly between transects (Appendix Table 1).

2.3.1.1 Temperature

Temperature noticed from the shelf regions of south western Bay of Bengal ranged between 13.10 - 27.52 °C (Fig 2.4). A significant variation (p<0.05) was noticed with depth i.e., 50, 100 and 200 m (Fig. 2.5). Moreover, temperature profile slightly demarcated the southern latitudes; considerable increase in values was noticed towards the northern
latitudes (Fig. 2.6). At 50 m, temperature variations were in the range of 23.3 - 27.5 °C, at 100 m it varied from 18.1 - 23.4 °C and at 200 m values in the range of 13.1 - 17.2 °C was noticed. Highest temperature was noticed from the inner shelf regions of Cheyyur and lowest at the outer shelves of Karaikal.

Fig. 2.4. Transect wise temperature profile along the shelf sediments of south western Bay of Bengal

Fig. 2.5. Depth wise temperature profile along the shelf sediments of south western Bay of Bengal
2.3.1.2 Salinity

Salinity of the study area ranged between 34.41 - 34.95 psu (Fig. 2.7). Mean bottom water salinity was 34.78 ± 0.14 psu. A slight increase in salt concentration was observed towards higher depths (Fig. 2.8). Latitudinal shift was insignificant within the study area (Fig. 2.9).
Fig. 2.7. Transect wise salinity profile along the shelf sediments of south western Bay of Bengal

Fig. 2.8. Depth wise salinity profile along the shelf sediments of south western Bay of Bengal
2.3.1.3 Dissolved Oxygen

Dissolved Oxygen (D.O) value ranged from 0.07 – 3.63 ml/l (Fig.2.10) with an average of 0.89 ± 1.05 ml/l. D.O was considerably low at 200 m (0.07 – 1.02 ml/l) (Fig.2.11). At 50 m the value ranged between 0.85 – 3.63 ml/l, at 100 m the value was in between 0.11 – 0.95 ml/l and at 200 m values ranged from 0.07 – 1.02 ml/l. Northern transects however showed much increase in oxygen concentration thereby exhibiting an insignificant latitudinal alterations (Fig.2.12). At 50 m depth of Cheyyur
was reported to have highest oxygen availability while, least availability was off Singarayakonda.

Fig. 2.10. Transect wise dissolved oxygen profile along the shelf sediments of south western Bay of Bengal

Fig. 2.11. Depth wise dissolved oxygen profile along the shelf sediments of south western Bay of Bengal
2.3.1.4 pH

Mean pH of the sediment was 7.71 ± 0.36 (range: 7.3 - 8.7; Fig.2.13). Variation in pH within the respective depths and transects were meagre (Fig.2.14 and 2.15). At 50 m depth, pH was in the range of 7.5 – 7.9, at 100 m 6.9 – 8.7 and at 200 m depth it ranged between 7.2 – 7.9.
Fig. 2.13. Transect wise pH profile along the shelf sediments of south western Bay of Bengal

Fig. 2.14. Depth wise pH profile along the shelf sediments of south western Bay of Bengal
2.3.2 Sediment characteristics

2.3.2.1 Sediment texture

Sediment was olive green to grey in colour and the sediment types ranged from clayey silt to fine sand. From the ternary plot it was evident that the sediment was sandy at 50 m and 100 m and was clayey silt at 200 m depth (Fig.2.19). The percentage of sand decreases as it moves.
towards the southern latitudes. The percentage of silt in the shelf sediments varied from 0.52 – 61.05%, sand fraction in the sediment was in the range of 1.19 – 97.98% and that of clay ranged between 1.49 – 57.89% (Appendix Table 2). Maximum silt content was reported from the 200 m depth of Cheyyur and minimum from 100 m depth of Karaikal. Percentage of sand predominates at 100 m depth of Karaikal and drops at 200 m depth of Singarayakonda. Highest clay content in the shelf sediment was reported from the 200 m depth of Singarayakonda and least was from 100 m depth of Karaikal. Sediment texture representing various depths is shown in the figure 2.16, 2.17 and 2.18.

![Diagram showing sediment texture at various depths](image)

**Fig. 2.16.** Sediment texture at the 50 m depth of the shelf sediments of south western Bay of Bengal
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Fig. 2.17. Sediment texture at the 100 m depth of the shelf sediments of south western Bay of Bengal

Fig. 2.18. Sediment texture at the 200 m depth of the shelf sediments of south western Bay of Bengal
Fig. 2.19. Ternary plots showing the distribution of silt, clay and sand at 50, 100 and 200 m depth regions in the shelf sediments of south western Bay of Bengal.
2.3.2.2 Sediment organic matter

Organic matter present in the shelf sediments did not show any significant (p>0.05) spatial variation between transects, though it was slightly greater towards northern latitudes of the study area. Organic matter ranged from 0.95 - 3.76% of dry wt. and was found to be maximum at 200 m depth (mean ± SD: 1.53 ± 0.53) followed by 100 m (mean ± SD: 1.53 ± 0.29) and 50 m (mean ± SD: 2.49 ± 0.65). Total organic carbon (TOC) (Fig.2.20 and 2.21) constituted only 36.22% of Total Carbon (TC) indicating the dominance of inorganic carbon fractions in the shelf sediments. However deeper shelf sediments (200 m) had an average of 59.87% TOC. Organic rich sediments were identified from the 200 m depth of Cheyyur and least concentration was from 50 m depth of Karaikal (Fig.2.22). At 50 m depth total organic matter content ranged between 0.95 – 2.45%, at 100 m the concentration varied from 1.03 – 1.94% and at 200 m the value was in the range of 1.74 – 3.76% (Fig. 2.23; Appendix Table 4). Latitudinal variation in organic matter concentration is shown in Fig. 2.24.
Fig. 2.20. Distribution of organic carbon along the shelf sediments of south western Bay of Bengal

Fig. 2.21. Distribution of organic carbon at various depths along the shelf sediments of south western Bay of Bengal
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Fig. 2.22. Distribution of organic matter along the shelf sediments of south western Bay of Bengal

Fig. 2.23. Distribution of organic matter at various depths along the shelf sediments of south western Bay of Bengal
2.3.2.3 CHNS Analysis

Average Total Carbon (TC), Total Hydrogen (TH), Total Nitrogen (TN) and Total Sulphur (TS) in the shelf sediments were 4.86 ± 2.83%, 0.72 ± 0.34%, 0.08 ± 0.04% and 0.08 ± 0.04% respectively. At 50 m depth, TC ranged between 1.17 – 5.16%, at 100 m depth, 1.67 - 6.88% and at 200 m depth values ranged between 6.4 – 11.05% (Fig.2.25). TH concentration at 50 m depth ranged between 0.12 – 1.57%, at 100 m

Fig. 2.24. Map showing the distribution of organic matter along the shelf sediments of south western Bay of Bengal
between 0.2 – 0.73% and at 200 m depth it ranged from 0.77 – 1.73% (Fig. 2.26). Concentration of TN at 50 m was in a range of 0.02 – 0.1%, at 100 m, 0.02 – 0.09 and at 200 m, 0.09 – 0.18% (Fig. 2.27). At 50 m the TS ranged between 0 – 0.1%, at 100 m depth range was in between 0 – 0.14 and 200 m the values ranged from 0.77 – 1.73% (Fig. 2.26). It was interesting to note that throughout the depth the concentration of TC, TH, TN and TS were much higher as we move towards the greater depth (200 m). Organic matter quality as measured by molar Carbon/Nitrogen (C/N) ratio was found to be 14.28 ± 5.47 (range: 8.44 – 28.38). Significantly low values (p<0.05) were sited at 200 m depth regions (9.64 ± 0.92) (Appendix Table 3).

**Fig. 2.25.** Percentage of Total Carbon (TC) present in the shelf sediments of south western Bay of Bengal
Fig. 2.26. Percentage of Total Hydrogen (TH) present in the shelf sediments of south western Bay of Bengal

Fig. 2.27. Percentage of Total Nitrogen (TN) present in the shelf sediments of south western Bay of Bengal
2.3.2.4 Biochemical composition (labile fractions) of sedimentary organic matter

A significant (p<0.05) difference in total protein and total carbohydrate concentration between the inner and outer shelf was evident from the study area. Total lipid and biopolymeric carbon did not show any significant (p>0.05) bathymetric variation though they varied significantly (p<0.05) between the northern and southern latitudes.

Total protein concentration ranged from 0.09 to 3.08 mg/g (mean ± SD: 1.14 ± 0.87 mg/g). Protein concentration did not show any significant (p>0.05) depth wise and latitudinal variation (Fig.2.30). However, the concentrations were found to be higher at 200 m depth regions along the shelf sediment (Fig.2.29). Concentration of total carbohydrate in the shelf ranged from 0.62 to 2.55 mg/g (mean ± SD:
1.24 ± 0.59 mg/g). Total carbohydrate concentration did not showed any significant (p>0.05) latitudinal variation (Fig. 2.32). Moreover, the concentrations were found to be higher at 200 m depth regions along the shelf sediment (Fig. 2.31). At 50 m depth the value was in the range of 0.81 – 1.14 mg/g, at 100 m; 0.62 – 1.51 mg/g and at 200 depth the concentration of total carbohydrate ranges from 1.17 – 2.55 mg/g.

No significant (p>0.05) depth wise variation in the concentration of lipid was noticed in this shelf (Fig.2.33). Compared to total protein and total carbohydrate, total lipid exhibited higher values ranging from 4.64 to 9.83 mg/g (mean ± SD: 7.17 ± 1.73 mg/g) (Fig.2.35, 2.36 and 2.37). Concentration of lipid was lowest along the Karaikal and Cuddalore transects and there after it increased towards the northern latitudes (Fig.2.34).

The sum of protein, carbohydrate and lipid carbon (Biopolymeric carbon, BPC) was determined as a relative measure of the amount of food potentially available for heterotrophic metabolism. BPC ranged from 4.10 to 9.64 mg C/g (mean ± SD: 6.43 ± 1.75 mg C/g). Highest BPC was observed in Chennai and lowest in Cuddalore (Fig.2.38) No significant depth wise variation was noticed (Fig.2.39). Lipids represented the main biochemical class of organic compounds. About 83.56% of BPC was costituted by lipid followed by protein (8.68%) and carbohydrates (7.74%).

Total organic carbon constituted a mean of 36.22 ± 9.34% of total carbon. Biopolymeric carbon fraction in total organic carbon was an average of 62.64 ± 12.32%. Protein to carbohydrate ratio (PRT: CHO)
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ranged from 0.14 – 1.59 and was found to be increasing when moving from 50 m to 200 m depth. LPD: CHO ratio ranged from 3.52 to 11.11 (Appendix Table 4).

![Fig. 2.29. Concentration of total protein present in the shelf sediments of south western Bay of Bengal](image)

![Fig. 2.30. Three dimensional plot showing the distribution of total protein present in the shelf sediments of south western Bay of Bengal](image)
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Fig. 2.31. Concentration of total carbohydrates present in the shelf sediments of south western Bay of Bengal

Fig. 2.32. Three dimensional plot showing the distribution of total carbohydrates present in the shelf sediments of south western Bay of Bengal
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Fig. 2.33. Concentration of total lipid present in the shelf sediments of south western Bay of Bengal

Fig. 2.34. Three dimensional plot showing the distribution of total lipid present in the shelf sediments of south western Bay of Bengal
Fig. 2.35. Concentration of total protein, carbohydrate and lipid present in the 50 m depth of shelf sediments of south western Bay of Bengal

Fig. 2.36. Concentration of total protein, carbohydrate and lipid present in the 100 m depth of shelf sediments of south western Bay of Bengal
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Fig. 2.37. Concentration of total protein, carbohydrate and lipid present in the 200 m depth of shelf sediments of south western Bay of Bengal

Fig. 2.38. Concentration of biopolymeric carbon fraction along the shelf sediments of south western Bay of Bengal
2.3.3 Total bacterial Count

Total bacterial count (epifluorescence; Plate 2.1) did not display any significant (p>0.05) latitudinal variations (Fig.2.40) though they exhibited significant (p<0.05) depth wise variation. Bacterial density was found to be higher in 200 m depth when compared to other depth regions (Fig.2.41). Total bacterial count in the shelf sediment ranged from $1.17 \times 10^8$ to $1.1 \times 10^9$ cells g$^{-1}$ dry wt. with its maximum off Thamminapatnam and minimum off Karaikal. At 50 m depth, the number varied from $1.17 - 5.16 \times 10^8$ cells g$^{-1}$ dry wt., 100 m; $1.67 - 6.88 \times 10^8$ cells g$^{-1}$ dry wt. and at 200 m depth it ranges between $6.41 \times 10^8 - 1.1 \times 10^9$ cells g$^{-1}$ dry wt. (Appendix Table 5).
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Fig. 2.40. Bacterial density (total count) in the shelf sediments of south western Bay of Bengal

Fig. 2.41. Bacterial density (total count) at different depth regions in the shelf sediments of south western Bay of Bengal
2.3.4 Living microbial biomass and spatial distribution of ATP

ATP concentration was used as an indicator of living microbial biomass. Concentrations were very low and ranges from 196.80 to 840.27 ng/g (mean ± SD: 445.26 ± 216.74 ng/g). Significant (p<0.05) differences in ATP concentrations between latitudes was observed. ATP was found to be significantly higher towards the northern latitudes (Fig. 2.42). Bathymetric variation in ATP concentration was not significant (Fig.2.43). Total living microbial biomass (MBB) estimated from the concentration of ATP ranges from 49.20 to 210.06 µg C/g (mean ± SD: 111.31 ± 54.18 µg C/g) and followed the same distribution trend as that of ATP (Appendix Table 5). Total microbial contribution to organic
carbon pool (MBB/BPC) in the shelf sediment was very low ranging from 0.72 to 2.85%.

Fig. 2.42. ATP (microbial biomass proxy) in the shelf sediments of south western Bay of Bengal

Fig. 2.43. ATP (microbial biomass proxy) in the shelf sediments of south western Bay of Bengal
2.4 Discussion

Seasonally reverting atmospheric forcing, limited northern extent and a large and seasonal freshwater pulse is characteristic to Bay of Bengal [Kumar and Ramesh 2005]. Most of the information on the hydrography of this Bay is derived from the surveys that have documented the seasonal variability in the salinity and temperature distribution in the area. Salinity of the Bay of Bengal is highly heterogeneous; both on the horizontal and vertical profile [Benshila et al. 2014]. Though not significant, the present study substantiated the fact that, horizontally it is characterized by fresh waters in the North and North-Eastern parts due to the excess freshwater supply from both continental rivers and from oceanic precipitation, and in the South-central Bay it is saltier waters. The fresh waters spread as a thin cap (10 to 20 m thick), and invade the northern half of the bay [Vinayachandran and Kurian 2007]. Vertically, over the upper 20 m of the water column, a downward increase of 5 units is quiet common in the open Bay [Vinayachandran and Kurian 2007].

In the present study, salinity ranged between 34.41 - 34.95 psu and showed least variation, latitudinal as well as depth-wise. However, studies have shown that Bay of Bengal has relatively low salinity due to high runoff [Subramanian 1993] and precipitation [Kumar and Ramesh 2005]. The Bay receives immense fresh water runoff from major rivers, such as the Ganges, Brahmaputra, Godavari, Mahanadi, Cauvery, Irrawaddy, and Krishna. Both river runoff and precipitation intensifies during the southwest monsoon; June to September [Unger et al. 2003] thereby decreasing the salinity of the surface waters to 3 - 7 units lower
in the Bay of Bengal throughout the year than in the adjacent basin, the Arabian Sea [Varkey et al. 1996], which leads to strong stratification [Shetye et al. 1991; Shetye 1993].

Occurrence of oxygen minimum zone (OMZ) in the Bay of Bengal is well debated. Intense depletion of dissolved oxygen (DO) at intermediate depths of Bay of Bengal was reported by Wyrtki [1971]. Based on the data collected during International Indian Ocean Expedition (IIOE), Deuser [1975] reported that OMZ exists in the north eastern Bay. In the present study, dissolved oxygen values was observed below 0.5 ml/l at 200 m depth which can be due to the existence of oxygen minimum layer (O$_2$ concentrations < 0.5 ml/l) at that region. Gordon et al. [2002] suggested that the bottom water in Bay of Bengal is exposed to the waters derived from the West Australian which is nutrient-rich but oxygen-poor. Such low oxygen water pockets can cause advection of water from close to sediment where intense decomposition of organic matter or diffusion of oxygen into the pore waters thereby, leading to the decrease in oxygen levels. Madhu et al. [2006] observed that <20 μmol kg$^{-1}$ of DO was found between 100 and 150 m during summer. Further, Sardessai et al. [2007] also observed concentration close to ~10 μmol kg$^{-1}$ between 100 and 150 m in the near shore waters during summer. Edmond et al. [1979] and Broecker et al. [1980] described a nutrient-rich benthic layer within the Bay of Bengal and noted a sharp decrease in oxygen concentration at the sediment–water interface and a deep oxygen maximum layer is produced by spreading of slightly better ventilated West Australian Basin water over the denser nutrient-rich benthic layer.
Similar level of salinity and dissolved oxygen as that of the present study were reported from Bay of Bengal [Shetty 1978; Naqvi et al. 1979; Shirodkar and Jayakumar 1990; Vijayakumar et al. 1991; Gordon et al. 2002; Madhupratap et al. 2003; Saravanane et al. 2004] and other parts of the world [Mayer 1994; Hensen et al. 1997; Cowie et al. 1999; Alperin et al. 2002; Sauter et al. 2001]. Temperature of the sediment samples was directly influenced by the depth of the station. It showed a regular trend of decreasing from 50 to 200 m depth stations. The observed variation in temperature was due to the variable intensities of prevailing currents and the consequent mixing of water. The pH of bottom water ranged from 7.3 to 8.7 similar to that reported for tropical Ocean waters [Cavallo et al. 1999]. In the marine environment, near neutral to alkaline pH is quite common and Gallizia et al. [2004] reported the sediment pH in the same range with no significant relationship with depth.

The main parameter that limits the density, distribution and diversity of benthic community in sediment is the grain-size and organic matter [Sestanovic et al. 2005]. Factors such as the tectonic setting, river input of sediment and transport by waves and currents governs the sediment type of the continental shelf [Soetaert 2005]. Several studies have shown an inverse relationship between the particle size of marine sediments and various measures of 'nutritional quality' such as organic matter concentration or bacterial abundance [Meyer-Reil 1986]. Our study also presented a highly significant (p<0.001; Table 7.2) and negative correlation between bacterial abundance and mean grain size. Fine grained sediments carried high organic matter content and supported
a higher bacterial number as compared to coarse sediments. Percentage of fine grain sediments significantly correlated with depth ($r = 0.595$, $p < 0.01$; Table 7.2). In the shelf sediments of south east coast of India at 50 m and 100 m depth, the sediment was sandy and at 200 m depth it was clayey silt. This is in agreement with the report that sandy sediments dominate the continental shelves [de Haas et al. 2002]. The organic contents in the sandy sediments were 1–2 orders of magnitude lower than those of muddy sediments [Rusch et al. 2003] which support less surface area for bacterial attachment compared to clayey sediments. Benthic bacteria which signify a key step in the benthic food web play a predominant role in the early diagenesis of organic material in marine environments [Deming and Baross 1993]. But the benthic responses vary from place to place depending on the quantity and quality of the sedimenting particulate organic matter [Pfannkuche 1992]. Mean concentration of organic matter present in the eastern shelf sediment was $1.85 \pm 0.67\%$ which was lower than its western counterpart, Arabian Sea [Sajan et al. 2010]. But the values were comparable to that of north western Black Sea shelf [Wijsman et al. 1999], Great Barrier Reef shelf [Lourey et al. 2001], South Atlantic Bight continental shelf sediments [Jahnke et al. 2005], and the shelf sediments of China Sea [Xing et al. 2011]. In shelf sediments, concentration of organic matter reflects the productivity in overlying waters and shallow depth. The primary productivity in Bay of Bengal is relatively low due to narrow continental shelf and heavy cloud cover combined with high quantity of terrigenous organic matter which affects light penetration [Madhupratap et al. 2003]. Due to high terrigenous input, the organic carbon flux to this Bay is much
reduced [Ittekkot et al. 1991] which leads to the lower concentration of organic matter along the shelf sediments. Though the riverine flux may bring in nutrients, they are thought to be lost to the deep because of its narrow shelf [Sen Gupta et al. 1977].

The carbon/nitrogen ratio (C/N) has been used to highlight the quality of organic matter and influence of terrestrial environment in marine sediments [Middelburg et al. 1996]. Low values of C/N (< 10) indicate presence of relatively fresh and easily degradable organic matter of high nutritional quality, whilst high C/N ratio (> 10) indicates the presence of more refractory organic matter of continental origin [Köster and Meyer-Reil 2001]. In the present study average C/N ratio at 200 m depth regions were 9.64 ± 0.92 denoting the presence of high nutritional quality organic matter in the deeper fractions of the sediment. Organic matter at 50 and 100 m was more refractory in nature, with C/N ratio greater than 10. C/N ratio obtained in this study was comparable with that of north western Black Sea shelf (8.79 – 15.36) [Wijsman et al. 1999] and Pereque Beach, Brazil (6.08 – 22.6) [de Oliveira et al. 2007]. Total Nitrogen (TN) in the marine sediments plays an important role as a source of nutrients [Fütterer 2000] and was found to be more at 200 m depth.

Sedimentary variables such as protein, carbohydrate, lipid and biopolymeric carbon displayed increasing values when moving from the inner to the outer shelf. Such variances indicate that different depth regions are characterised by different organic matter loads which points to an assumption that the composition and concentration of sedimentary
organic matter are important indicators of the trophic state of the marine environments [Fabiano et al. 1995]. Bay of Bengal is characterised by a narrow shelf [Sen Gupta et al. 1977], permitting the nutrients that drain from the top, lost to the deep. This leads to the increase of organic matter, particularly labile fractions in the outer shelf. In the present study, PRT: CHO ratio in the inner shelf was < 1 and in outer shelf it was > 1. PRT: CHO can be used as an index to determine the origin of material present in sediments and to determine the age of sedimentary organic matter [Danovaro et al. 1993]. PRT: CHO ratio > 1 indicates living organic matter or ‘newly generated’ organic matter formed after the deposition of freshly produced phytoplankton [Pusceddu et al. 2003] or microphytobenthic bloom [Fabiano et al. 1995]. On the other hand, low PRT: CHO ratios suggest the presence of aged or more degraded organic matter [Danovaro et al. 1993]. Moreover, sediments with PRT: CHO ratios < 1 are considered to be representative of nitrogen deficiency [Mayzaud et al. 1989], as witnessed from the low protein nitrogen values along the inner shelf.

Concentration of carbohydrate present in the inner shelf sediments was comparatively higher than protein suggesting that carbohydrate accumulation in oligotrophic environments is not unusual [Danovaro et al. 1993]. This component may be largely composed of refractory compounds which are characterised by low degradation rates. Therefore carbohydrate seems to behave as a reservoir of non-utilised organic carbon in oligotrophic sediments [Danovaro et al. 1999].
Lipids outline the main biochemical component in the shelf sediment (83.56% of BPC). This is in contrast with most of the marine ecosystems where protein or carbohydrate dominates. The higher lipid content in this region may be ascribed by the flux of phytoplankton [Neira et al. 2001]. Diatoms and faecal pellets of zooplankton are assumed to be important carriers of lipids to marine sediments [Baldi et al. 2010]. The lipid content and lipid to carbohydrate ratio (LPD: CHO) have been used as good indices to describe the energetic (food) quality of the organic contents in the sediments [Grémare et al. 2002]. LPD: CHO ratio ranged from 3.52 to 11.11 and these higher values are characterized by organic matter with a high energy value. The energy content per unit carbon of LPD is 1.4 times higher than that of CHO and 1.2 times higher than that of PRT [Salonen et al., 1976].

Biopolymeric carbon (BPC) another relative measure of potentially available food [Dell’Anno et al. 2000], displayed higher values along the outer shelf sediments. Such variations between the inner and outer shelf sediments characterised by different BPC loads, displayed different trophic conditions. As specified by Vezzulli and Fabiano [2006] this was also evidenced in terms of biopolymeric composition of sedimentary organic matter as an increase in protein and a decrease in the carbohydrate contributions to total BPC. Higher lipid concentration in the shelf sediments results in larger amounts of BPC and, consequently, increased its contribution to TOC. The contribution of BPC to TOC was an average of 62.64 ± 12.32%, confirming that a less fraction of TOC is represented by refractory material. The high contribution of BPC to
TOC further suggests that the origin of TOC is autochthonous and that almost the entire organic carbon pool was represented by food material [Danovaro et al. 2000].

In the present study we used ATP as a global measure for calculating living microbial biomass [Karl 1993] as exocellular ATP has a half-life of less than 1 hour [Contin et al. 2001]. Exclusion of meiofauna and macrofauna was done by sieving the sediment through 1mm sieve there by assuming that ATP represents only the living fractions of bacteria, fungi, yeasts and actinomycetes. ATP obtained from the outer shelf sediments was higher than that from inner shelf sediments. It has been demonstrated that the availability of organic material to microbial assemblages is one of the key parameters for the distribution of microbial biomass in the sediments [Boetius et al. 1996]. The different organic matter concentrations at the two sites were reflected by ATP concentrations which displayed significant differences between sites. Bacteria accountable for most of the benthic biomass [Sestanovic et al. 2005] in marine ecosystems can contribute significantly to the heterotrophic activity in the system.

Bacteria alone contributed significantly to the total microbenthic biomass and were analogous to that found in the Yellow Sea [Meng et al. 2011]. Previous studies have indicated that marine sediments support a remarkably constant bacterial density (approximately $10^9$ cells/g), regardless of ocean depth [Schmidt et al. 1998]. Total bacterial count in the shelf sediment ranged from $1.17 \times 10^8$ to $1.1 \times 10^9$ cells g$^{-1}$ dry wt. These counts are comparable with those reported from the marine
sediments of Eastern Mediterranean Sea [Danovaro et al., 1998] and Botany bay, Australia [Lee and Patterson, 2002].

Thus it is concluded that benthic biomass of the shelf sediments was dominated more by bacteria than other microbenthos, and it is reasonable to assume that benthic microbial loop which controls the biological dynamics of Bay of Bengal shelf sediments, mostly hinge on the sediment bacteria.