

Particle Fluxes in the Bay of Bengal measured by Sediment Traps

V. RAMASWAMY and G. PARTHIBAN
National Institute of Oceanography, Goa

ABSTRACT

Particle fluxes were measured between October, 1987 and March, 1988 using six automated time series sediment traps at three locations in the northern, central and southern Bay of Bengal. The traps were deployed at depths of approximately 1000 and 2200 m below the sea surface and were programmed to collect samples every 9.5 days.

Particle fluxes varied between 16.8 and 345 mg m⁻² day⁻¹ with generally higher fluxes during December and January. Annual fluxes decreased from 41.2 g m⁻² y⁻¹ in the northern Bay of Bengal to 19.69 g m⁻² y⁻¹ in the southern Bay of Bengal. As compared to the Arabian Sea, the observed particle fluxes in the Bay of Bengal are higher by a factor of 1.5 despite the fact that the primary productivity here is lower. In the central and southern Bay of Bengal, the deeper traps show much higher fluxes compared to the shallow traps indicating significant lateral transport and scavenging of particles in the water column.

Carbonate percentages in the traps increased away from the mouths of the Ganges - Brahmaputra rivers from 29.1% in the northern Bay of Bengal to 46.8% in the southern Bay of Bengal. Conversely, lithogenic fluxes decreased towards the southern Bay of Bengal. Lithogenic fluxes account for more than a third of the particle fluxes in the northern Bay of Bengal while biogenic silica contributed about 20% of the total particle flux. Sedimentation rates in the Bay of Bengal, calculated from sediment trap data, range between 17 and 32 mm per thousand years. Factors controlling particle production and transport to the sea floor are also discussed.

INTRODUCTION

Marine sediments are mainly composed of terrigenous matter delivered by riverine and aeolian processes, and biogenic particles produced in the water column. The Stokesian settling velocity of most of these particles especially clays is less than a meter per day and it may take decades to sink through the water column and settle on the sea floor (McCave, 1975). However, clay mineral distribution as well as study of suspended particles in the water column shows that clays in fact settle rapidly through the water column by getting incorporated into the matrix of larger, faster sinking particles (Honjo, 1982; Deuser *et al.*, 1983).

Most of the carbonate, opal and organic matter in the sediments are biogenic in origin and are produced in the upper layers of the ocean. The production of these particles depends on biological processes which in turn depends on various physico-chemical processes

affecting the upper mixed layer, like availability of sufficient nutrients and light, *etc.* (Wefer, 1989). Sediment trap studies have given new insights into how these particles form and settle through the water column. With the advent of time-series sediment traps the seasonality in production and transport of these particles can be studied (Honjo and Doherty, 1988).

The Ganges and Brahmaputra together with peninsular Indian rivers contribute annually about 1300 km³ of fresh water and approximately 2000 million tonnes of suspended matter to the Bay of Bengal. (Holeman, 1968; Milliman and Meade, 1983). This tremendous freshwater influx together with monsoon winds strongly influences the circulation, stratification, productivity and sedimentation patterns in the Bay of Bengal (Rao, 1977). To study the influence of the major rivers on particle fluxes in the Bay of Bengal, six sediment traps have been deployed at three locations

in the northern, central and southern Bay of Bengal. In this paper, the characteristics of the collected particles and the factors controlling their production and transport to the sea floor are being discussed.

METHODS

Three mooring systems each consisting of two time-series sediment traps (Honjo and Doherty, 1988) were deployed in the northern, central and southern Bay of Bengal (Fig. 1). The sediment traps were pre-programmed to measure the flux of sinking particles at intervals of 9.5 days. Details of mooring configuration and sampling intervals are given in Table 1. Prior to deployment, the collecting cups were poisoned with mercuric chloride to inhibit microbial degradation of the samples.

The samples recovered were immediately wet sieved using a 1 mm plastic sieve and split on board using a precision rotary splitter. One quarter of the < 1 mm fraction was filtered through a polycarbonate filter (0.4 μm), dried and analysed for total flux. First order components like carbonates, organic matter, opal and lithogenics were determined using methods described elsewhere (Honjo, 1980, Honjo *et al.*, 1987).

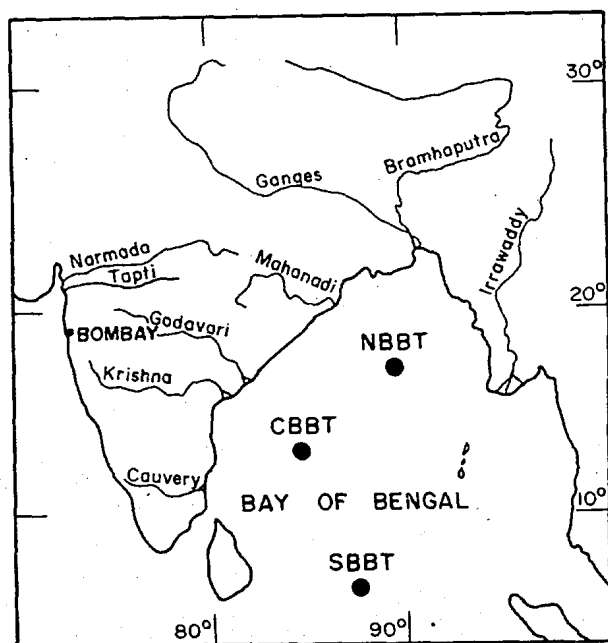


Fig. 1: Mooring locations in the northern (NBBT), central (CBBT) and southern (SBBT) Bay of Bengal.

RESULTS AND DISCUSSIONS

Total fluxes

The total fluxes in the Bay of Bengal (Figs. 2 a, b, c) range between 16.88 and 344.18 $\text{mg}^{-2} \text{day}^{-1}$. Total annual fluxes in the shallow traps decrease from 41.26 g in the northern Bay of Bengal to 21.33 g in the southern Bay of Bengal (Table 2). Peak fluxes of particles at all three stations are generally during December and January, when the influence of the NE monsoon is the strongest.

The annual flux in the Bay of Bengal range between 21 to 55 g (Table 2) and is much higher than generally reported for the open ocean including the Arabian Sea, even though the primary productivity here is not exceptionally high (Rao, 1977; Qasim, 1977). The high fluxes here points to higher new production in the surface layers, the mechanism of which will be discussed later on in this paper.

The annual fluxes in the shallow traps show a decreasing trend from north to south. The deeper traps, however, do not show this pattern. The anomalously high flux in the deeper traps especially in the central and southern sites point to significant lateral advection and or scavenging of particles in the water column.

Component fluxes

The principal components of particles in the sediment trap are carbonates, lithogenic matter, biogenic silica (opal) and organic matter in that order. Component flux patterns in general follow that of total flux, but percentage of components between the traps show spatial significant differences. Carbonate percentages are higher in the central and southern trap while lithogenic percentages are higher in the northern trap.

Carbonates

Carbonates are the most dominant component in the traps, with percentages ranging between 19 and 74%. They generally show a decrease with depth. Carbonates in the traps are mostly contributed by foraminifera, coccoliths and to a minor extent, pteropods. Sarin *et al.*, (1979) report that calcium carbonate distribution in the surface sediments increase from less than 10% in the northern Bay of Bengal to nearly 70% at the equator. Carbonates exhibit an opposite trend to primary productivity with abundance increasing towards the open sea where productivity is relatively less. According to them such a distribution is possible only if the detrital accumulation near river mouths overwhelms the effect

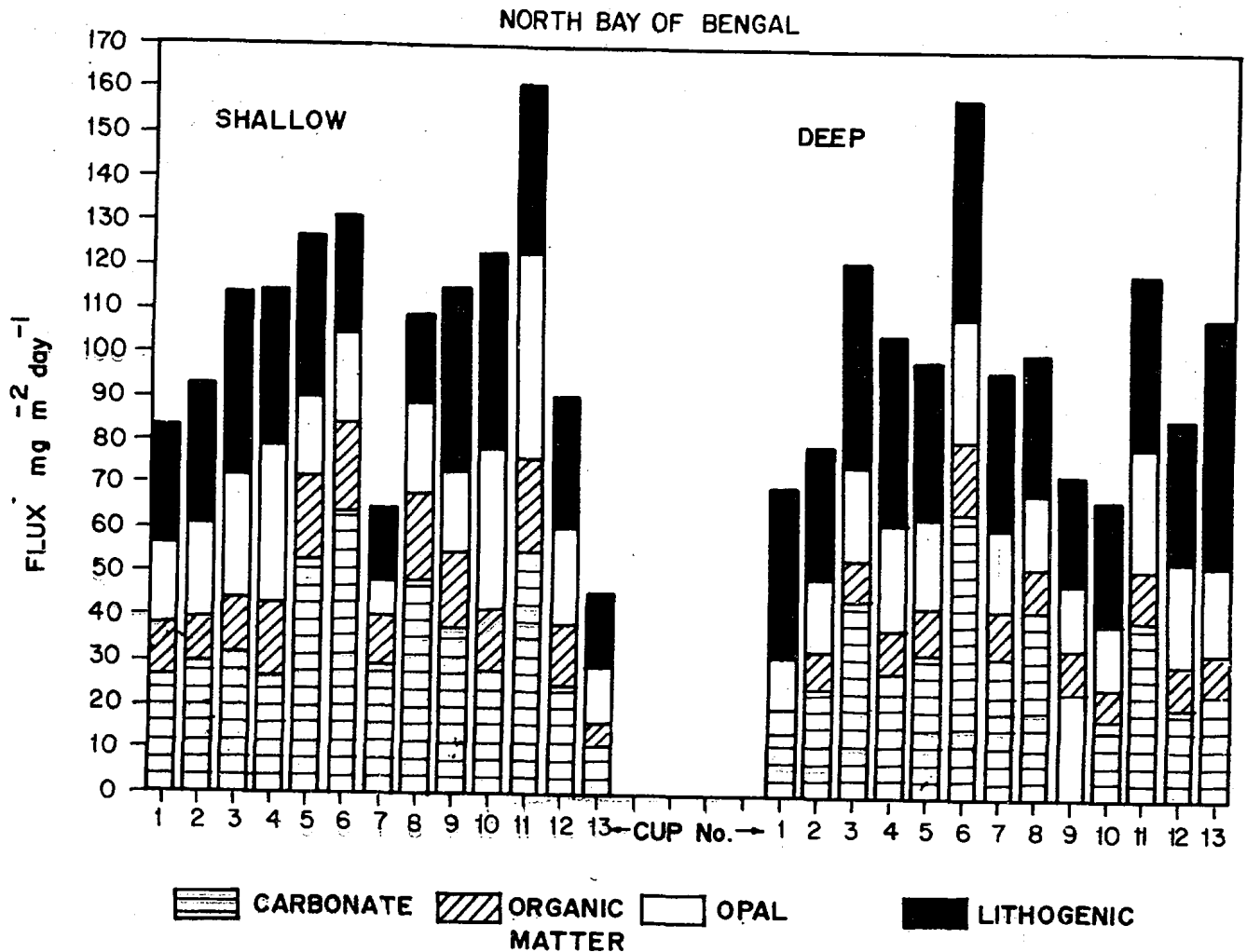


Fig. 2a: Total and component fluxes in the shallow and deep traps in the northern Bay of Bengal.

of productivity in the water column. Another reason could be the increasing influence of river discharge towards the northern Bay of Bengal. The salinity of the Bay of Bengal drops from normal value of about 35‰ at 13° N to about 20‰ in the northernmost part of the Bay (Rao, 1977). This sharp reduction of salinity may not have much effect on coccolith flux as they can tolerate a wide range in salinity (Haq, 1978). However, foraminifera react strongly to even minor changes in salinity. With reduction in salinity, foraminifera show a decrease in number and reduction in size. Confirmation of this comes from the fact that annual carbonate flux in the deep southern Bay of Bengal is 15.31 g while during the same period in the deep northern Bay of Bengal the annual flux is only 11.48 g (Table 2).

Organic matter

Organic matter fluxes in the Bay of Bengal traps are among the highest reported for the open ocean so far. Comparable flux rates of organic matter can be found in the southern oceans and in the Panama basin (Honjo, 1982). The high organic matter flux in the Bay of Bengal is not related to any plankton bloom, rather, it may be due to the nature of particles present in the water column. Due to the availability of a high amount of lithogenic matter in the water column, organic matter can easily form aggregates having a high lithogenic content. Higher lithogenic percentages in aggregates can make the particles denser increasing their settling velocities thus leading to more organic matter escaping the upper mixed layer (Haake and Ittekkot, 1990).

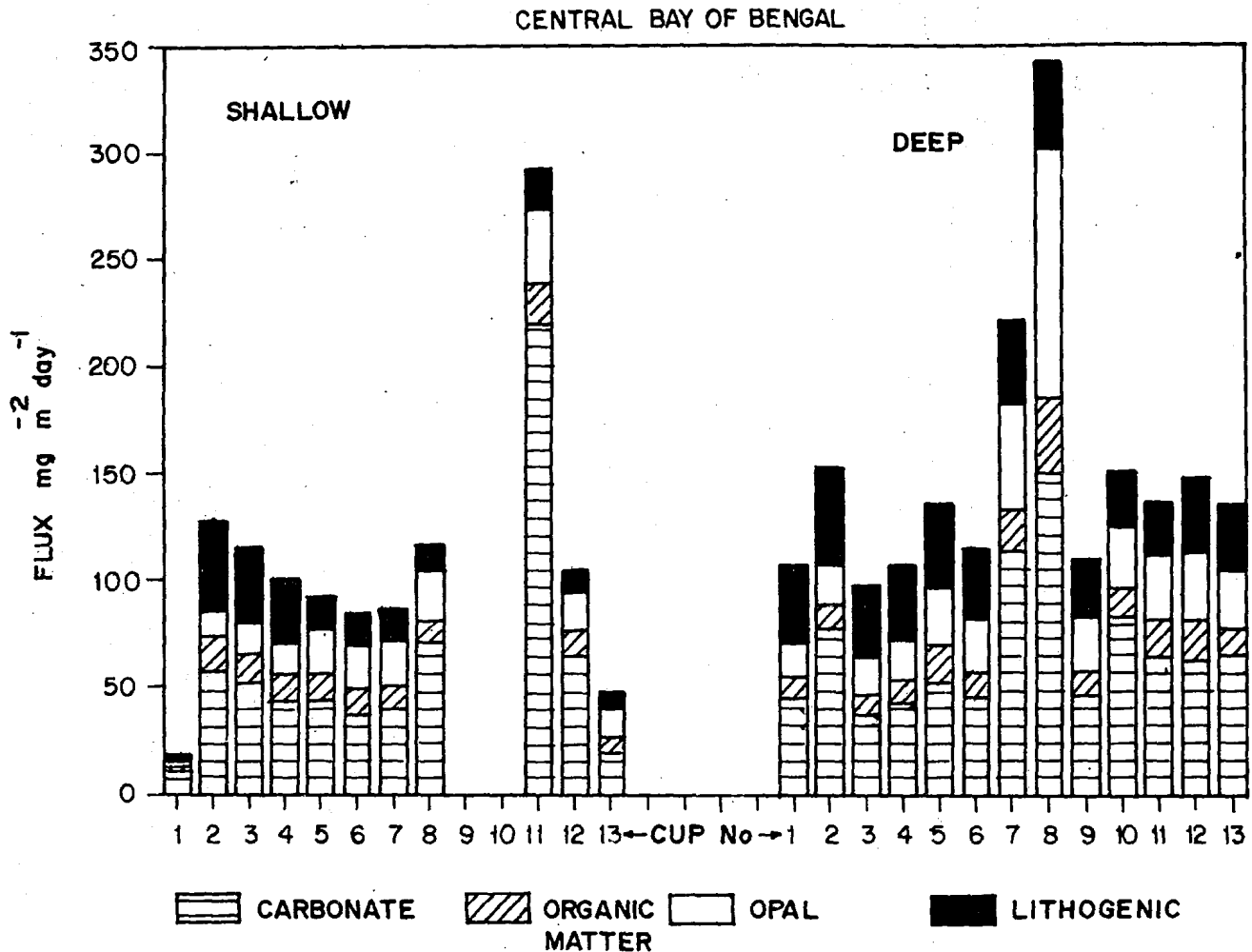


Fig. 2b: Total and component fluxes in the shallow and deep traps in the central Bay of Bengal.

Compared to an average of about 10% organic matter in the traps the sediments have less than 0.5% organic matter (Lisitzin, 1975). This shows that a major portion of the organic matter escaping the euphotic zone degrades at the sediment water interface.

Opal

Opal fluxes range between 1.54 and 94.3 mg m⁻² day⁻¹ and is mostly contributed by diatoms and silicoflagellates, with minor contribution by radiolarians. Silica percentages generally decrease with depth except in the southern Bay of Bengal where the flux in the deeper trap is higher. As this station is not close to any land mass the only explanation can be that the sediment trap is close to, but not directly under a high productive

area. The low opal content in the sediment (>0.5%) compared to about 21% in the bottom traps is due to dissolution of the opal at the sediment water interface. Another reason for low opal content in the sediment is due to the size of the biogenic silica particles. Diatoms, which have thin tests, are the main contributors of opal. These thin tests dissolve easily in the water column and are not easily preserved in the sediment.

Lithogenic flux

Lithogenic fluxes range between 1.85 and 56.4 mg m⁻² day⁻¹ and show an increase with depth at all stations. This is due to scavenging of the standing stock of lithogenic particles in the water column by marine snow (Honjo, 1982; Deuser *et al.*, 1983); Ramaswamy

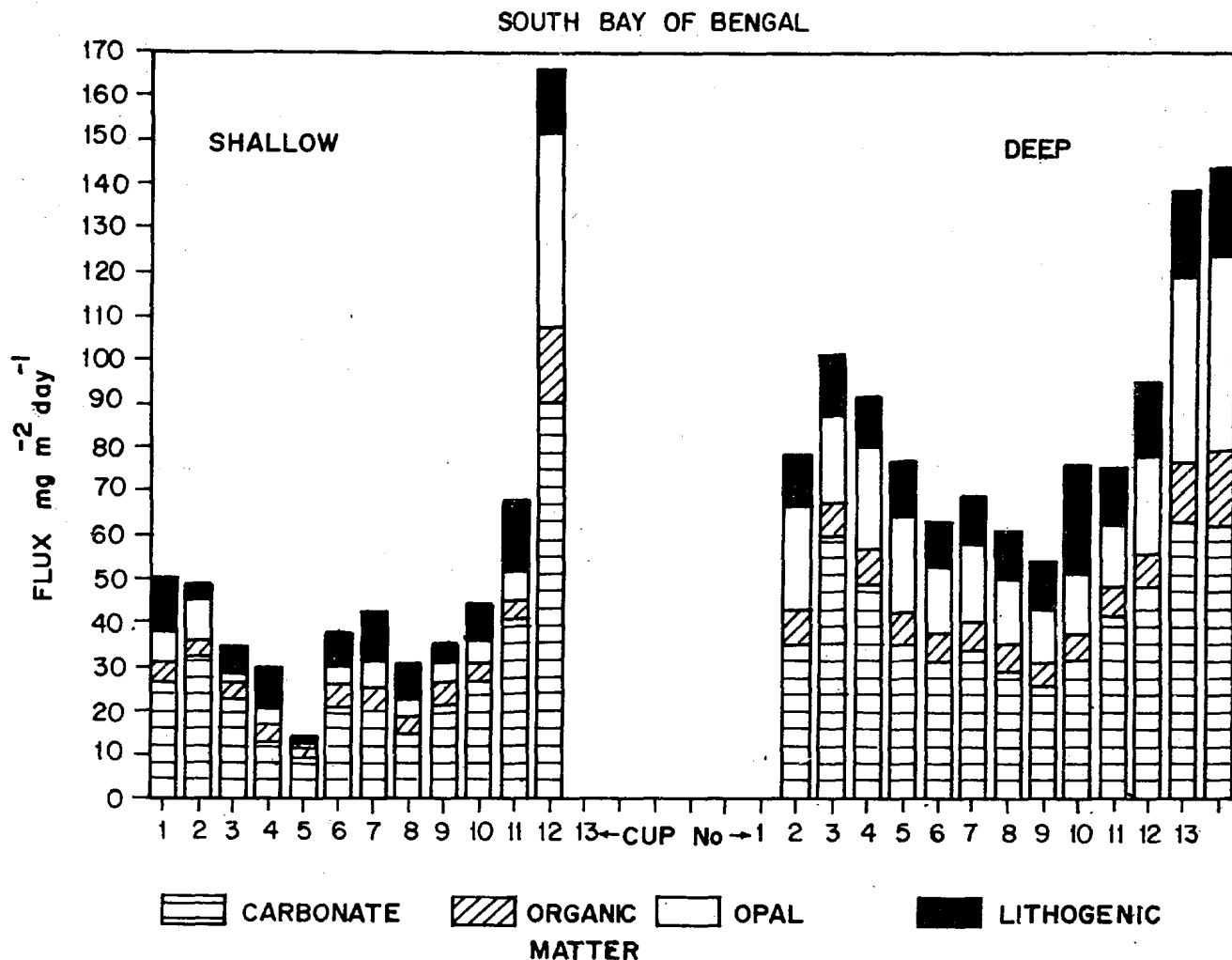


Fig. 2c: Total and component fluxes in the shallow and deep traps in the southern Bay of Bengal.

et al., in press). The lithogenic percentages also is one of the highest reported in sediment trap experiments in the world oceans so far. This is not surprising as over 2000 million tonnes of suspended sediments are discharged into the Bay of Bengal (Milliman and Meade, 1983). Most of the lithogenic flux is from rivers with minor contributions from aeolian sources (Goldberg and Griffin, 1970). Consequently, the lithogenic percentages decrease with increasing distance from the Ganges-Brahmaputra river systems.

Factors controlling particle fluxes

The main factors controlling particle fluxes in the Bay of Bengal are upwelling, mixed layer deepening due to wind stress and influence of river discharge.

Only weak upwelling has been noticed along the east coast of India even though the coast is favourably oriented in relation to wind pattern (Rao, 1977). During the SW monsoon period wind intensities are strong, but since river discharge is high during this period the offshore displacement of surficial waters is compensated by low saline waters rather than nutrient rich deeper waters. During the NE monsoon period the wind intensities are not strong enough to cause upwelling (Murthy *et al.*, 1990).

High wind speeds have been shown to affect productivity in monsoon dominated oceans by deepening the mixed layer and introduction of nutrient rich waters into the euphotic zone (Nair *et al.*, 1989). A similar process may play an important role here

mainly during the NE monsoon period when fresh water discharge by rivers is not very high. Peak fluxes in the traps are during December and January when wind speeds are strongest. The degree of stratification during winter is not as high compared to the SW monsoon period. The northeast monsoon winds can lower the mixed layer, and bring up nutrients from the deeper layers, thus enhancing primary productivity.

It is generally agreed that the limiting nutrient in the Bay of Bengal is nitrogen (Anon, 1990). Nutrient concentrations in the Bay of Bengal increase sharply below the surface layer in the mass discontinuity layer (at 100 to 200 m depth) and is comparable to that of the Arabian Sea (Rao, 1977). According to Rao (1977), the renewal of nutrient in the surface layers of the Bay of Bengal is not affected by wind mixing, but, depends more on vertical advection and diffusion. The thickness of the surface layer appears to be governed more by near surface circulation rather than by wind stress.

Nitrogen derived from rivers can increase the productivity of coastal sea. In the case of large rivers their influence can extend for a considerable distance. Exceptionally high values of nitrate nitrogen has been recorded in the Bay of Bengal which is thought to have been derived from the rivers (Qasim, 1977). Values normally range from 200 to 500 $\mu\text{g. at. l}^{-1}$ but up to 1000 to 1500 $\mu\text{g. at. l}^{-1}$ were recorded in the northern Bay of Bengal. However, distribution of nitrate during the SW monsoon period shows a decreasing trend towards the mouths of the Ganges. There is no outflow of inorganic N, P and Si from the Ganges river, most of it being retained in the estuarine region due to precipitation and biological assimilation (Anon, 1990). Renewal of nutrients in the Bay of Bengal is probably from nitrogen in humus and urea associated with particulate organic matter in the river waters. The annual flux of particulate nitrogen from world rivers is in the order of 32×10^{12} g of which 70% is from rivers draining the Himalayas (Ittekkot, 1990). The particulate organic nitrogen can be directly assimilated by marine plankton or it can degrade slowly into inorganic forms.

Sedimentation rates

The present day sedimentation rates in the Bay of Bengal calculated from the total annual flux and lithogenic flux are shown in Table 2. The greater than 1 mm fraction was not taken into account as they are mostly composed of zooplankton remains, colonial radiolarians and pteropods. These particles rapidly decompose and dissolve in the water column at the benthic transition layer, and only a fraction of their

fluxes are preserved in the sediment column (Cole *et al.*, 1987). For similar reasons, organic matter and opaline silica in the less than 1 mm fraction was also ignored. Aragonite also dissolves rapidly on the sea floor. Aragonite in our traps is contributed mainly by large tests of pteropods, most of which is retained in the greater than 1 mm fraction. Hence, we have not made any corrections for aragonite. We have used a packing density of 1.15 g cm^{-3} for conversion of accumulation rates (fluxes as measured with sediment traps) to sedimentation rates (Honjo, 1986).

From the present study sedimentation rates show a narrow range between 17.88 and 32.53 mm/ky in spite of large variations in surface productivity and distance from river mouths. These rates are higher than those reported by Sarin *et al.*, who used ^{230}Th and ^{210}Pb to measure sedimentation rates. Sarin *et al.*, (1979) reported that unambiguous signals of ^{230}Th excess could be measured only in sediments south of 13° N . The mean clay accumulation rates in cores in the latitudinal belt 13° N to 2° S range between 1.3 to 7.4 mm/1000 yrs. In the northern Bay of Bengal sedimentation rates from the present study show a fairly good agreement with a nearby core (30P) of Sarin *et al.*, (1979). However, in the central and southern Bay of Bengal the rates calculated from sediment trap data is considerably higher. Sarin *et al.*, (1979) have not discussed the reasons for the low sedimentation rates south of 13° N . The difference cannot be explained by dissolution of carbonates as the sediments are well above the calcium carbonate compensation depth. The sedimentation rate reported by Sarin *et al.*, is definitely an underestimation, as Lisitzin (1975) reports sediment accumulation rates of 10 to 30 mm per thousand years in this area. Prell *et al.*, (1980) report that sedimentation in the central and southern Bay of Bengal range between 2 and 4 cm/ky. Further, sedimentation rates as low as 2 mm/ky is generally reported in extremely low productive areas and at depths well below the calcium carbonate compensation depth.

It is estimated that presently about 70 million tonnes of hemi-pelagic sediments, including carbonates and lithogenics, are being deposited in the deeper parts of the Bay of Bengal each year. More than 2000 million tonnes of suspended material is discharged into the Bay of Bengal each year but only about 35 million tonnes reach the deeper part of the Bay, the rest being trapped in estuaries, deltas and continental shelves. This means that less than 5% of the lithogenic input is able to cross the coastal barrier and get deposited in the deep sea. Sediment traps moored 1000 m above the sea floor

measure mostly the vertical flux of particles, and the above estimates do not include transport by turbidity currents or other near bottom sediment transport processes. The numerous deep sea turbidite channels in the Bay of Bengal Fan can serve as conduits for transport of significant amounts of terrigenous material to the distal parts of the Bay of Bengal Fan.

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TABLE 1: LOCATION OF SEDIMENT TRAP MOORINGS AND SAMPLING INTERVALS IN THE BAY OF BENGAL

Station	Position		Water depth (m)	Sediment trap depth (m)	Sampling interval for all traps	
	Latitude (N)	Longitude (E)			Cup No.	Sampling Period From To
North Bay of Bengal	17°26.6'	89°35.6'	2263	809	1	Oct 28 - Nov 06 1987
				1727	2	Nov 06 - Nov 16 1987
					3	Nov 16 - Nov 25 1987
					4	Nov 25 - Dec 05 1987
Central Bay of Bengal	13°09.3'	84°21.5'	3259	906	5	Dec 05 - Dec 14 1987
				2282	6	Dec 14 - Dec 24 1987
					7	Dec 24 - Jan 02 1988
					8	Jan 02 - Jan 12 1988
South Bay of Bengal	04°27.6'	87°18.9'	4017	1040	9	Jan 12 - Jan 21 1988
				3006	10	Jan 21 - Jan 31 1988
					11	Jan 31 - Feb 09 1988
					12	Feb 09 - Feb 19 1988
					13	Feb 19 - Feb 28 1988

TABLE 2: ANNUAL FLUXES OF TOTAL PARTICULATE MATTER AND MAJOR COMPONENTS IN THE NORTHERN, CENTRAL AND SOUTHERN BAY OF BENGAL

Station	Carbonates		Organic matter		Opal		Lithogenic		Total
	mg m ⁻² %		mg m ⁻² %		mg m ⁻² %		mg m ⁻² %		
NBB SHALLOW	13.06	31.7	5.35	13.0	8.67	21.0	11.46	27.8	41.26
NBB DEEP	11.48	30.1	3.60	9.4	7.24	19.0	13.83	36.2	38.20
CBB SHALLOW	18.57	53.9	3.51	10.2	5.48	15.9	5.68	16.5	34.48
CBB DEEP	24.95	45.2	5.47	9.9	12.10	21.9	12.47	22.6	55.23
SBB SHALLOW	9.49	48.2	1.82	9.2	2.71	13.8	2.83	14.4	19.69
SBB DEEP	15.34	46.9	2.94	9.0	8.04	24.6	5.22	16.0	32.69

TABLE 3: PRESENT DAY SEDIMENTATION RATES IN THE BAY OF BENGAL COMPARED TO HOLOCENE SEDIMENTATION RATES

Station No.	Lat (N)	Long (E)	Depth in m	Carbonate percentage	Sedimentation rates in mm/1000y	
					Total	Lithogenic
Present day sedimentation rates						
NBOB	17.20	89.35	1727	30.1	22.01	12.02
CBOB	13.10	84.20	2282	45.2	32.53	10.84
SBOB	06.40	87.35	3006	46.9	17.88	4.54
Holocene sedimentation rates						
30P	17	93	2403	<5.0	30.0	
38G	13	87	3076	22.2	2.0	
22PG	11	84	3456	28.2	5.6	
42G	07	89	3714	65.0	7.2	
44G	04	89	4057	60.2	5.1	

Holocene sedimentation rates from Sarin *et al.*, 1979.