

Sedimentation of particulate material in stratified and nonstratified water columns in the Bombay High area of the Arabian Sea

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ABSTRACT: Sedimentation of particulate material at 22, 42 and 62 m was recorded at a station in the Bombay High area of the Arabian Sea from September 1985 to March 1986. Diatom numbers and physical structure, especially thermal stratification, played an important role in controlling both magnitude of total flux and nature of sedimented material. Changes in suspended diatom numbers were, with some exceptions, reflected in the sedimented material caught by the traps. From September to March, mean sedimentation of total particulate material (TPM) and particulate inorganic material (PIM) increased with depth. Up to December, particulate organic carbon (POC), particulate organic nitrogen (PON), particulate biogenic silica (PSi), chlorophyll *a* equivalents (Chl *a* equiv.), total particulate carbohydrates (TCHO) and the constituent fractions dilute alkali-soluble (AL-CHO) and residual carbohydrates (RS-CHO) increased and dilute acid-soluble carbohydrates (AC-CHO) decreased with depth. From January to March, however, mean sedimentation rates of POC, PON, PSi and Chl *a* equiv. generally decreased with depth, whereas sedimentation fluxes of TCHO, AC-CHO, AL-CHO and RS-CHO decreased between 22 and 42 m and increased again at 62 m. Low POC/Chl *a* equiv. and POC/PSi ratios indicate that fairly fresh biogenic material settled during January to March when the water column was more or less homogeneous, as compared to September to December when the water column was thermally stratified. Sedimentation of organic carbon was correlated with sedimentation of biogenic silica, especially during January to March. There were positive and highly significant relationships between the flux of TCHO and those of TPM, POC, Chl *a* equiv. and PSi. From the latter 2 relationships, it was deduced that diatoms were the major source of TCHO at this station. High sedimentation of TPM was associated with high flux of organic carbon and TCHO. This may have a stimulatory effect on benthic organisms and may also enhance the chances of burial of organic matter in sediments.

INTRODUCTION

Recently, there has been growing interest in the measurement of particle flux to the sea floor in order to improve understanding of biological and geochemical processes in marine environments. Sediment traps have been used widely to assess the flux of particles in various aquatic environments. Seasonal variability in total particle flux has been found to parallel the typical seasonal pattern of primary productivity in surface water (Deuser & Ross 1980, Deuser et al. 1981, Honjo 1982). Particle flux attains its maximum within days to weeks after surface phytoplankton blooms, suggesting rapid transport of particles. Large particles such as faecal matter, faecal pellets and amorphous aggregates of small particles including phytoplankton cells ('marine snow') have been implicated as important vehicles for the rapid transport of organic matter to the

sea floor (Deuser & Ross 1980, Deuser et al. 1981, Honjo 1982, Asper 1987). These rapidly sinking particles form an important source of supply of organic matter, produced in the upper sunlit waters, to marine sediments and benthic organisms. Seasonal supply of high nutritional quality organic matter has a profound effect on the growth and reproduction of shallow (Graf et al. 1982, 1983, Smetacek 1984) and deep water benthic organisms (Billett et al. 1983).

In the open ocean, the particle flux is often dominated by biogenic particles (Honjo 1978, Deuser & Ross 1980, Deuser et al. 1981). Terrestrial particles and resuspension of bottom sediments may influence the flux of particles in shallow coastal and shelf environments (Degens & Ittekkot 1985, Nelson et al. 1987). Rapid mass sedimentation of phytoplankton blooms has been reported for many coastal and shelf localities (Smetacek 1984, 1985, Skjoldal & Wassmann 1986,

Harding et al. 1987) and is generally related to low biomass of zooplankton (Smetacek 1984, Harding et al. 1987). Thus, in the absence of effective grazing by zooplankton, a large part of the phytoplankton bloom sinks out from the euphotic zone. The process of algal cell sinking is not well known, but nutrient starvation, light deficiency and a generally deteriorated physiological state are perhaps involved (Smetacek 1985, Skjoldal & Wassmann 1986). Furthermore, seasonal changes in physical properties such as temperature, water density, wind and currents are accompanied by alteration of mixed layer depth. Changes in mixed layer depth are expected to modify nutrient supply to the euphotic layer thereby controlling algal production and/or concentrations (Ryther et al. 1966, Banse 1984, 1986). Physical processes controlling phytoplankton development may also influence the magnitude of total mass flux and its nature in shallow marine environments (Hargrave & Taguchi 1978, Wassmann 1985, Harding et al. 1987).

To our knowledge, no data on sedimentation of particulate material in the coastal and shelf waters of the Arabian Sea has previously been available. In this paper, data on the sedimentation of particulate material in thermally stratified and non-stratified water columns at a station in the Arabian Sea are presented and discussed.

AREA OF INVESTIGATION

The study site ($19^{\circ} 20' N$, $71^{\circ} 20' E$) is located in the Bombay High region of the Arabian Sea, about 160 km off Bombay which is a highly industrialized and one of the most populous (8 million) cities in India (Fig. 1). This area has lately been subjected to intensive oil exploration and exploitation activities. The region experiences a slight excess of precipitation over evaporation (>20 cm) annually. Surface circulation is influenced by 2 monsoons. During the southwest (SW) summer monsoon (June to September) there is a clockwise current system, and during the northeast (NE) winter monsoon (October to May), an anti-clockwise system. The current system during the SW monsoon is reinforced by the stronger winds (25 to 30 knots). One of the most important features of the SW monsoon is the upwelling along the coasts of Somalia, Arabia and southwest India (Sastry & D'Souza 1972). Surface waters exhibit a bimodal temperature pattern over the year with lows in the winter and during the summer (SW) monsoon (Shetye 1986). Temperature changes are accompanied by alteration of mixed layer depth due to change of water density and/or wind action (Banse 1984, 1986). Upwelling along the coast may also influence the mixed layer depth. Seasonal variations in

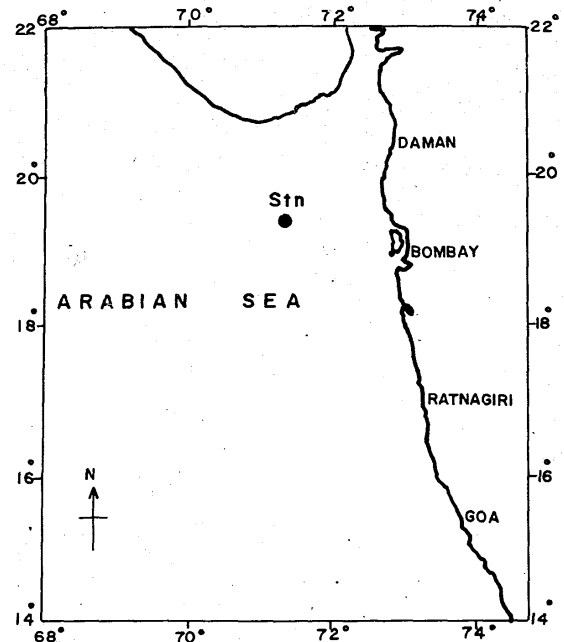


Fig. 1. Study area showing the location of the station in the Bombay High region of the Arabian Sea

the current, wind and mixed layer depth are expected to influence nutrient supply to the surface layer and may have direct implication on algal production and/or concentrations (Ryther et al. 1966, Banse 1984, 1986).

MATERIALS AND METHODS

The observations were carried out at a single sampling station (Fig. 1) with a water depth of about 78 m. Nansen and/or Niskin water samplers were used for discrete water sampling. Temperature was recorded with a reversing thermometer. Salinity and dissolved oxygen were determined by titration methods (Strickland & Parsons 1972).

Water samples (100 ml) of phytoplankton were preserved with 5 ml of Kieffer's solution (Carlberg 1972). Subsamples (10 to 50 ml) were transferred to sedimentation tubes for 24 h. The supernatant water was discarded and diatom cells were counted and identified using an inverted microscope (Parsons et al. 1984). Replicate analysis of samples gave a coefficient of variation of about 26 to 30 % for total diatom counts.

Settling particles were intercepted using PVC cylindrical sediment traps. Each trap had a diameter of ca 100 mm (height:diameter ratio, 3:1). The traps were deployed during 7 periods ranging from 25 to 36 d in September 1985 to March 1986. Generally duplicate or triplicate traps were used at the same depth to compare the variability between replicate traps (Table 1). A hexagonal steel frame with 2 or 3 traps (fixed using

Table 1. Sedimentation rates ($\text{mg m}^{-2} \text{d}^{-1}$) of total particulate matter (TPM) and their variability observed with replicate traps during various periods of deployment

Date	Exposure period (d)	22 m				42 m				62 m			
		Flux	X	SD	CV	Flux	X	SD	CV	Flux	X	SD	CV
30 Sep to 29 Oct 1985	29	2972	3304	332	10.0	4312	4572	260	5.6	3663	4460	797	17.8
		3636				4832				5257			
29 Oct to 23 Nov	25	2537	2325	272	11.7	6235	5377	612	11.3	7412	5336	1731	32.4
		2498				5052				3173			
		1940				4845				5423			
23 Nov to 31 Dec	38	1245	1396	151	10.8	1992	2062	104	5.0	3590	5037	1068	21.2
		1547				1985				6138			
						2211				5384			
31 Dec to 31 Jan 1986	31	5676	4311	1364	31.6	3065	2921	144	4.9	5103	6132	1029	16.7
		2947				2777				7162			
31 Jan to 1 Mar	29	11810	12208	398	3.2	7400	7881	481	6.1	9847	10835	988	9.1
		12606				8363				11823			
1 Mar to 6 Apr	36	3926	3563	363	10.2	2984	4193	1209	28.8	7467	7591	124	1.6
		3200				5402				7715			

X = mean, SD = standard deviation, CV = coefficient of variation (%)

clamps), was kept suspended at depths of 22, 42 and 62 m from an offshore oil production platform. Deployment and retrieval of the traps were carried out using a pneumatically operated winch. Chloroform was added to the traps beforehand to reduce decomposition of organic matter.

After retrieval, the material collected in each trap was passed through 300 μm gauze to remove larger zooplankton and then suspended in a known volume of filtered seawater and split for the analyses described below.

A known volume was filtered through ignited (450 °C, 3 h) and preweighed GF/C glass filters, desalted by repeated washing with distilled water, dried at 40 °C for 24 h and weighed to obtain total particulate material (TPM). The fraction of particulate organic material (POM) was determined by weight loss on ignition at 450 °C for 3 h (Dean 1974). The content of particulate inorganic material (PIM) was then calculated by difference ($\text{PIM} = \text{TPM} - \text{POM}$). Particulate organic carbon (POC) was analysed following the method of Strickland & Parsons (1972). Particulate organic nitrogen (PON) was determined following the method of Smart et al. (1983). Particulate biogenic silica (PSi) was extracted with 0.05 % Na_2CO_3 (Anderson 1986) and analysed as suggested by Strickland & Parsons (1972). Chlorophyll *a* and phaeopigments were extracted with 90 % acetone and determined spectrophotometrically (Strickland & Parsons 1972). Results are expressed as chlorophyll *a* equivalents (Chl *a* equiv.) as described by Smetacek (1980). Total particulate carbohydrates (TCHO) and the constituent frac-

tions dilute acid-soluble (AC-CHO), alkali-soluble (AL-CHO) and residual (RS-CHO) carbohydrates were analysed by the phenol-sulphuric acid method as described earlier (Bhosle & Dhople 1988, Bhosle & Wagh 1989). The coefficient of variation of the analytical methods used for PIM, POM, POC, PON, TCHO and PSi based on 6 replicate analyses was 0.49, 2.08, 2.40, 4.24, 4.90 and 6.50 %, respectively.

A subsample was preserved with buffered formalin (5 %) (Wassmann 1983, Liebezeit & Bodungen 1987) for microscopic observation.

RESULTS

Hydrography

The euphotic zone was about 20 m and 16 m deep in the periods September to December and January to March, respectively (Venugopalan 1988). Temperature has a profound influence in controlling the vertical mixing of the water column (Fig. 2A). Temperature of the surface water was high and generally decreased with depth. From September to December, the water column was stratified, with homogeneous temperature in the upper 20 to 38 m. From December onward, with the development of cold and dry northeast winds (Antony pers. comm.), the surface water temperature declined. The effect of this winter cooling penetrated to 70 m, making the water column thermally homogeneous from January to March. Surface salinity was high during September and low in December and generally

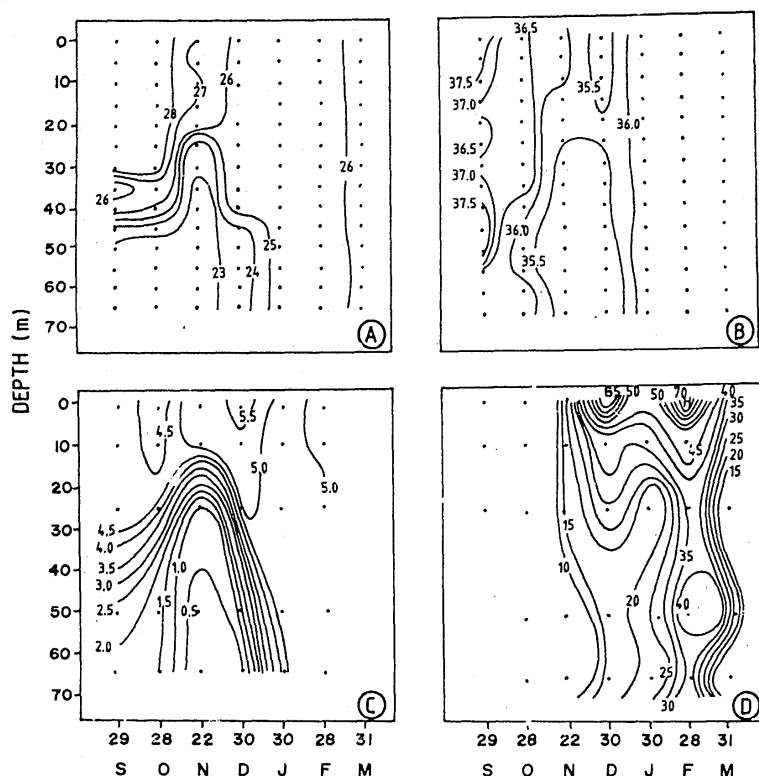


Fig. 2. Distribution of A: temperature (°C); B: salinity (‰); C: oxygen (ml l⁻¹); and D: diatom numbers (cells ml⁻¹) during September 1985 to March 1986

decreased with depth (Fig. 2B). Dissolved oxygen was high in the surface water and decreased with depth in the period September to December. Rather uniform high concentrations of dissolved oxygen in the water column were observed from January to March (Fig. 2C).

During the SW monsoon the coastal current runs clockwise and the deep subsurface water *upslopes* onto the shelf of Africa, Arabia and southwest India (Ryther et al. 1966, Banse 1984, 1986). The *upsloped* water persists on the shelf off Bombay well into November (the NE monsoon period) as was evident from the distribution of temperature and dissolved oxygen (Fig. 2A, C).

Diatoms

Observations carried out at this station since 1984 suggest that diatom numbers were generally low during September to November (Kelkar unpubl.). A many-fold increase in diatom numbers was observed in December to February (Fig. 2D). This was followed by a decrease in March to cell numbers fairly similar to those observed in September to November. The distribution of diatoms in the upper 10 m seems to parallel that of chlorophyll *a* (Venugopalan 1988). He observed low concentrations of chlorophyll *a* in September to November (ca 0.04 to 0.06 $\mu\text{g l}^{-1}$) and high concentrations in December to February (ca 0.30 to 0.50 $\mu\text{g l}^{-1}$).

Cell numbers generally decreased with depth in the September to December period. Also in January and February their numbers decreased in the upper 25 m, but below this depth they were rather homogeneous with a slight increase at 50 m.

The genera *Navicula*, *Rhizosolenia* and *Coscinodiscus* were most abundant in the water column during September to November. From December to February *Rhizosolenia*, *Nitzschia* and *Chaetoceros* were most abundant.

Sedimentation

Sedimentation in relation to depth

There were some differences in sedimentation in relation to depth. To illustrate this, we have divided the investigation into 2 periods, September to December when the water column was thermally stratified and January to March when the water column was more or less homogeneous or nonstratified (Fig. 2). Mean sedimentation of TPM, PIM, POC, PON and PSI increased with depth in the stratified period, whereas Chl *a* equiv., after an increase at 42 m, decreased below this depth (Fig. 3). In contrast, mean sedimentation rates were higher and generally decreased with increasing depth during the nonstratified period, except for TPM and PIM which increased (Fig. 3).

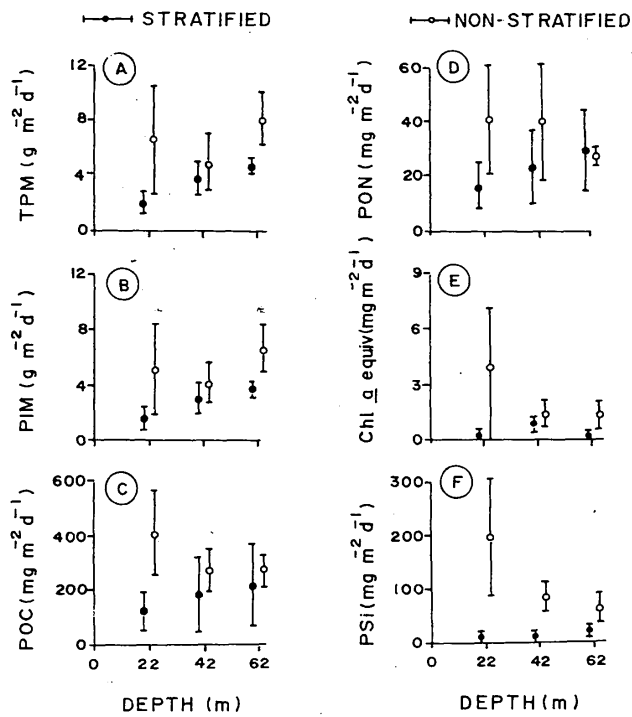


Fig. 3. Mean sedimentation rates of A: total particulate material (TPM); B: particulate inorganic material (PIM); C: particulate organic carbon (POC); D: particulate organic nitrogen (PON); E: chlorophyll *a* equivalents (Chl *a* equiv.); and F: particulate biogenic silica (PSi) in the stratified (●) and non stratified (○) periods. Bars represent 2 SD

During the stratified period the pattern of mean sedimentation fluxes of TCHO and the constituent fractions, except for AC-CHO (Table 2), was similar to that of TPM, PIM, POC, PON and PSl observed during this period. In contrast, mean fluxes of TCHO and the constituent fractions decreased between 22 and 42 m and increased again at 62 m during the nonstratified period.

Sedimentation of the measured components in the

nonstratified period, as a percentage of sedimentation during the total period, was high and varied from 63.9 to 91.7% at 22 m and from 38.7 to 71.1% at 62 m (Table 3). The percentage sedimentation in the nonstratified period was particularly high for PSl (64.1 to 91.7%) and Chl *a* equiv. (51.8 to 90.0%). The percentage sedimentation in the nonstratified period tended to decrease between 22 and 62 m.

The extent to which sedimentation differed vertically in the water column can be assessed by analysing the coherence between seasonal sedimentation rates at various depths expressed by the product moment correlation coefficient (Sokal & Rolf 1981, Wassmann 1985, Skjoldal & Wassmann 1986) (Table 4). Highly significant correlation coefficients were observed between 22 m and 42 and 62 m for TPM, PIM, POM, PSl, Chl *a* equiv. and TCHO. There was no significant correlation between 22 and 62 m for POC, nor between 22 and 62 m and 42 and 62 m for PON. This suggests that most of the sedimentation rates at succeeding depths were closely related. The observed insignificant correlations for POC and PON were probably due to sedimentation of resuspended organic matter.

Temporal pattern of sedimentation

Seasonality was observed in the sedimentation of TPM, POC, Chl *a* equiv., PSl, TCHO and its constituent fractions (Figs. 4 and 5). Sedimentation rates were relatively low in the stratified period. Thereafter, they generally increased during the nonstratified period and reached a maximum in February. An increase in sedimentation of POC and TCHO in November was observed. The pattern of sedimentation rates implies that the periods with stratified and nonstratified water columns (Fig. 2) were characterized by low and high rates, respectively.

Table 2. Sedimentation of carbohydrates and constituent fractions during stratified (September to December) and non-stratified (January to March) periods. TCHO: total particulate carbohydrates; AC-CHO: dilute acid-soluble carbohydrates; AL-CHO: dilute alkali-soluble carbohydrates; RS-CHO: residual carbohydrates; TPM: total particulate material; POC: particulate organic carbon. Mean values \pm SD

Parameter	Stratified period			Nonstratified period		
	22 m	42 m	62 m	22 m	42 m	62 m
TCHO ($\text{mgC m}^{-2} \text{d}^{-1}$)	18.68 \pm 12.36	19.88 \pm 10.64	25.76 \pm 7.56	61.72 \pm 33.76	37.96 \pm 13.24	58.36 \pm 13.28
AC-CHO ($\text{mgC m}^{-2} \text{d}^{-1}$)	4.40 \pm 3.16	4.28 \pm 1.96	3.88 \pm 1.04	13.44 \pm 7.28	7.48 \pm 4.00	10.92 \pm 2.00
AL-CHO ($\text{mgC m}^{-2} \text{d}^{-1}$)	3.60 \pm 4.04	3.92 \pm 3.28	4.28 \pm 0.80	15.64 \pm 12.00	10.88 \pm 5.28	13.16 \pm 3.92
RS-CHO ($\text{mgC m}^{-2} \text{d}^{-1}$)	10.65 \pm 5.48	11.66 \pm 7.18	17.60 \pm 6.49	32.65 \pm 14.62	19.52 \pm 4.06	34.24 \pm 7.52
TCHO-C/TPM (%)	1.00 \pm 0.48	0.53 \pm 0.20	0.52 \pm 0.12	0.92 \pm 0.08	0.76 \pm 0.08	0.72 \pm 0.02
TCHO-C/POC (%)	14.63 \pm 1.84	11.12 \pm 4.94	16.18 \pm 6.91	14.35 \pm 2.35	14.15 \pm 2.96	21.24 \pm 2.48
AC-CHO/TCHO (%)	23.55 \pm 5.40	21.52 \pm 12.82	15.60 \pm 10.64	21.77 \pm 3.41	19.70 \pm 3.92	18.71 \pm 1.50
AL-CHO/TCHO (%)	19.27 \pm 7.63	19.71 \pm 11.31	16.61 \pm 3.11	25.34 \pm 5.1	28.66 \pm 4.2	22.54 \pm 1.20
RS-CHO/TCHO (%)	57.01 \pm 9.59	58.65 \pm 11.73	72.47 \pm 6.24	52.90 \pm 6.06	51.42 \pm 6.49	58.67 \pm 1.96

Table 3. Sedimentation (g m^{-2}) during January to March as percentage of sedimentation from September to March. TPM: total particulate material; PIM: particulate inorganic material; POM: particulate organic material; POC and PON: particulate organic carbon and nitrogen; PSi: particulate biogenic silica; Chl a equiv.: chlorophyll a plus phaeopigments; TCHO: total particulate carbohydrates

Component	% Sedimentation (Jan-Mar / Sep-Mar)		
	22 m	42 m	62 m
TPM	71.2	49.5	55.5
PIM	70.5	48.2	55.6
POM	73.9	55.1	55.4
POC	71.2	53.1	48.9
PON	63.9	54.2	38.7
PSi	91.7	80.5	64.1
Chl a equiv.	90.0	51.8	71.1
TCHO	71.5	57.6	61.2

Table 4. Product moment correlation coefficients (r) comparing seasonal sedimentation rates of total particulate material (TPM); particulate inorganic material (PIM); particulate organic material (POM); particulate organic carbon (POC); particulate organic nitrogen (PON); particulate biogenic silica (PSi); chlorophyll a equivalents (Chl a equiv.); and total particulate carbohydrates (TCHO) at 22, 42 and 62 m depth (n = 7)

Component	Depth (m)	Depth (m)	
		42	62
TPM	22	0.82***	0.92****
	42		0.74**
PIM	22	0.82***	0.92****
	42		0.71*
POM	22	0.81***	0.90****
	42		0.84***
POC	22	0.70*	0.58
	42		0.97****
PON	22	0.91****	0.20
	42		0.54
PSi	22	0.90****	0.90****
	42		0.80***
Chl a equiv.	22	0.86***	0.89***
	42		0.92****
TCHO	22	0.89***	0.94****
	42		0.84***

* p < 0.05; ** p < 0.02; *** p < 0.01; **** p < 0.001

Nature of sedimented material

Microscopic examination (qualitative) revealed that most of the material collected in the sediment traps consisted of detrital material and a number of identifiable diatoms. Some copepod faecal pellets were also found in the traps in the stratified period, while they were rarely present during the nonstratified period. Diatoms such as *Chaetoceros*, *Coscinodiscus*, *Navicula*, *Nitzschia* and *Rhizosolenia*, which were most abundant

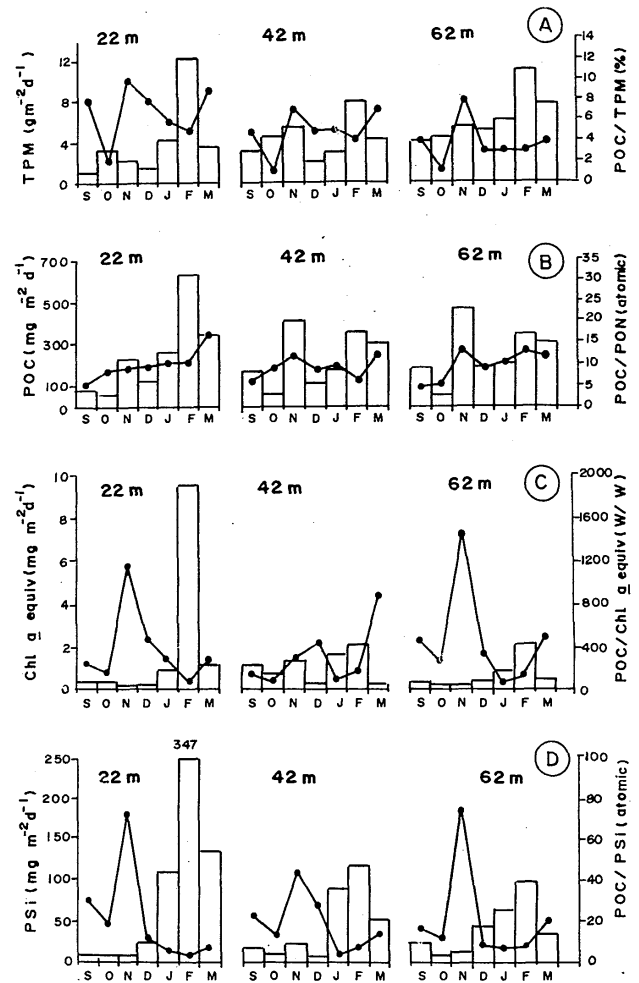


Fig. 4. Sedimentation rates of (left axis, bars) A: total particulate material (TPM); B: particulate organic carbon (POC); C: chlorophyll a equivalents (Chl a equiv.); D: particulate biogenic silica (PSi); and (right axis, line graphs) A: POC/TPM (%); B: POC/PON (atomic); C: POC/Chl a equiv. (wt/wt); D: POC/PSi (atomic) ratios of the sedimented material at 22, 42 and 62 m from September 1985 to March 1986

in the water column, were also generally found in the traps at all the depths. Amongst these, *Rhizosolenia*, *Coscinodiscus* and *Navicula* in the stratified period, and *Chaetoceros* and *Nitzschia* in the nonstratified period, were most predominant in the sedimented material.

Although sedimentation rates of PIM were lower during the period of stratification (Fig. 3B), the relative PIM contents of the TPM were quite similar during the 2 periods and varied from 76 to 82 % (Fig. 6A, B). The PIM/TPM ratio tended to increase with depth. The relative POC content of the TPM showed seasonal variation and ranged from 1 to 10 % (Fig. 4A). The POC content of the TPM showed a general decrease with increasing depth (Fig. 6A, B). The mean POC content of the TPM was 4 to 7 % and 3 to 5 % in the stratified and nonstratified periods, respectively.

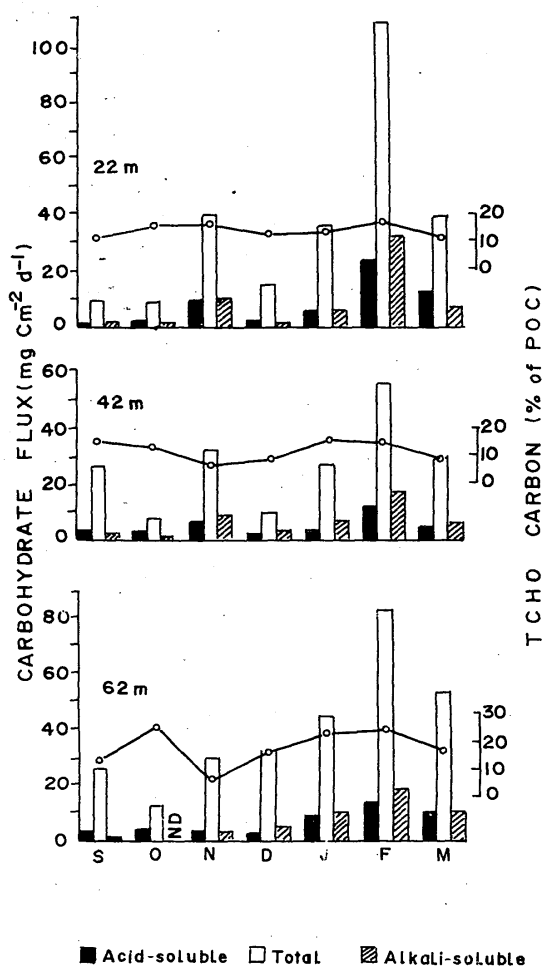


Fig. 5. Sedimentation rates of total particulate, dilute acid-soluble, alkali-soluble, carbohydrates, and the total particulate carbohydrates (TCHO-C)/particulate organic carbon (POC) ratio (%) of the sedimented material at 22, 42 and 62 m during September 1985 to March 1986

The POC/PON (atomic) ratio of the sedimented material showed modest variations with season (Fig. 4B) and depth (Fig. 6C, D), suggesting changes in the composition of the organic matter and/or resuspension of bottom sediments.

The POC/Chl *a* equiv. (wt/wt) ratio was high during November and December and somewhat lower in September and October (Fig. 4C). The ratio was lowest in January-February and increased again in March (Fig. 4C). The organic matter deposited during the peak sedimentation in February was rich in plant pigments and had lowest POC/Chl *a* equiv. ratios (65 to 143) (Fig. 4C). The mean POC/Chl *a* equiv. ratio for the stratified period decreased from 22 to 42 m and increased again at 62 m (Fig. 6C). The mean ratio showed the reverse trend for the nonstratified period (Fig. 6D).

The POC/PSi (atomic) ratio was high during the stratified period and low during the nonstratified

period (Fig. 4D). The mean ratio showed no marked trend with depth for the stratified period, whereas it increased with depth for the nonstratified period (Fig. 6C, D). There was a good correlation between sedimentation rates of PSi and POC throughout the water column for the entire sampling period (Fig. 7). This relationship was highly significant ($p < 0.001$) for the nonstratified period.

The TCHO-C/TPM and AC-CHO/TCHO ratios decreased with depth (Table 2). The TCHO-C/POC ratio was higher at 62 than at 22 m throughout the period of investigation (Table 2). On the other hand, TCHO-C/POC ratio decreased between 22 and 42 m, especially during the stratification period (Table 2). A decrease in AL-CHO/TCHO and an increase in RS-CHO/TCHO ratios at 62 m was observed (Table 2). There were positive and highly significant correlations ($p < 0.001$, $n = 21$) between the fluxes of TCHO and TPM ($r = 0.88$), POC ($r = 0.78$), Chl *a* equiv. ($r = 0.78$) and PSi ($r = 0.81$).

DISCUSSION

Sedimentation rates measured with traps represent gross sedimentation rates. These rates include both net or primary sedimentation (particles falling for the first time) and secondary sedimentation (resuspended matter, turbulent upward transport and active transport by animals).

The reliability of data obtained with sediment traps depends on several factors including trap design, hydrodynamic conditions and properties of sedimenting particles (Smetacek et al. 1978, Gardner 1980a, b, Davies & Payne 1984, Skjoldal & Wassmann 1986). We employed cylindrical traps with height to diameter ratio of 3:1. This aspect ratio has been considered sufficient for minimizing resuspension of trapped particles by water turbulence entering the traps (Blöesch & Burns 1980, Gardner 1980b). Other studies, however, have shown that the above aspect ratio is in the lower range of ratios which give reliable results (Hargrave & Burns 1979, Blomqvist & Kofoed 1981). Furthermore, the traps, suspended at 22, 42 and 62 m, might have been influenced by variable hydrodynamic conditions. The few current measurements carried out in the study area (Anthony pers. comm.) suggest that the 22 m traps were perhaps subjected to greater water exchange between the traps and their surroundings than the 42 and 62 m traps and thus might have underestimated sedimentation rates. On the other hand, sedimentation traps at 62 m might have overestimated the particle flux due to resuspension of bottom sediments.

It is rather difficult to assess the actual influence of hydrodynamic conditions on the trapping efficiency of

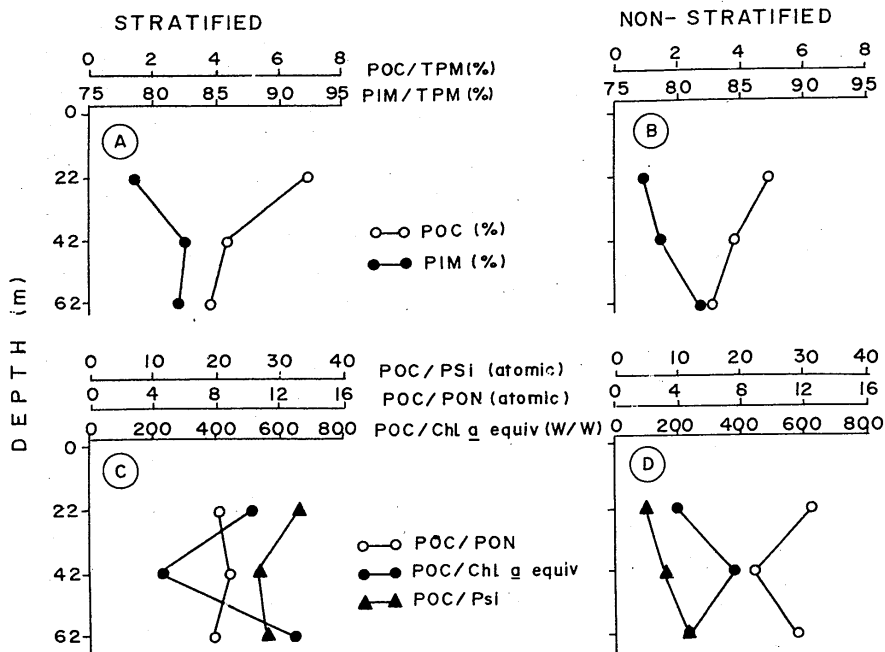


Fig. 6. Vertical profiles of mean ratios characterizing sedimented material for the stratified (A, C) and non-stratified (B, D) periods. A, B: particulate inorganic material (PIM, ●) and particulate organic carbon (POC, ○) as percentages of total particulate material (TPM); C, D: POC/Chl a equiv. (●), POC/PON (atomic) (○) and POC/PSi (atomic) (▲) ratios based on contents of particulate organic carbon (POC), particulate organic nitrogen (PON), particulate biogenic silica (PSi) and chlorophyll a equivalents (Chl a equiv.)

the sedimentation vessels (Bloesch & Burns 1980, Gardner 1980a, b, Butman 1986). Deployment of replicate traps at the same depth may, however, provide useful information on the accuracy of the data obtained. Data on TPM collected using duplicate or triplicate traps indicated that the coefficient of variation was generally less than 15% and rarely exceeded 21% (Table 1). The average coefficient of variation was about 14.34% ($n = 18$). This is slightly higher than the lower limit of 10% but well within the higher limit of 20% to 25% obtained with sediment traps of different

designs (Pennington 1974, Hargrave et al. 1976, Kimmel et al. 1977, Prouse & Hargrave 1977, Davies & Payne 1984, Bodungen et al. 1986, Nelson et al. 1987).

It could be argued that the seasonality observed in sedimentation rates resulted from contamination originating from the oil production platform and fouling on the inside walls of the sediment traps. Presumably, this has not to a great extent influenced the sedimentation rates. If this was the case, then we would have expected a less consistent set of data with depth and season than was actually found.

During both the periods the mean mass flux of TPM and PIM generally tended to be highest at 62 m (Fig. 3A, B). Increasing mass flux with depth seems to be a regular feature in many coastal, shelf and slope environments (Hargrave & Taguchi 1978, Smetacek 1980, Gulliksen 1982, Davies & Payne 1984, Ducklow et al. 1985, Hargrave & Phillips 1986, Harding et al. 1987, Liebezeit & Bodungen 1987, Nelson et al. 1987). The greater quantity of material collected in the bottom traps 16 m above the sea floor suggest increased resuspension due to increasing turbulent flow near the bottom which would lead to increased particle concentrations near the bottom and subsequently higher rates of trapping.

Decreasing concentration of POC and TCHO-C (as % of TPM) with increasing depth observed during both the periods (Fig. 6A, B; Table 2) could be due to loss of carbon by remineralization, ingestion and assimilation of carbon by midwater organisms or through dilution by input of resuspended particles that are lower in organic content.

Sedimentation rates of TPM and POC in different

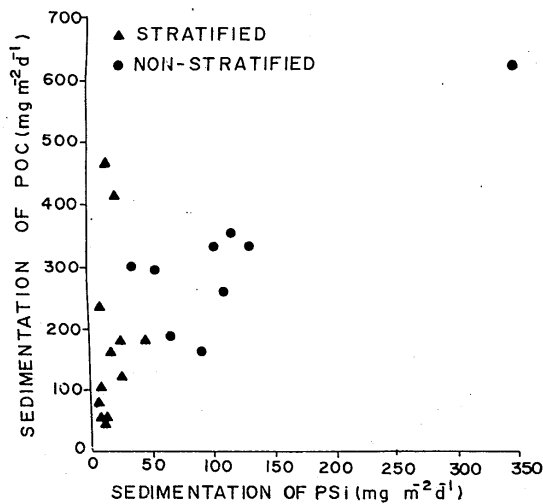


Fig. 7. Relation between sedimentation rates of particulate organic carbon (POC) and particulate biogenic silica (PSi) for the stratified and nonstratified periods. Correlation coefficients (r) were 0.21, 0.90 and 0.75 for the stratified ($n = 12$), nonstratified ($n = 9$) and total period ($n = 21$), respectively

Table 5. Daily sedimentation rates of total particulate material (TPM) and particulate organic carbon (POC) and the POC/TPM ratio (%) in different environments

Location	Depth of trap (m)	Sedimentation ($\text{g m}^{-2} \text{d}^{-1}$)		POC/TPM (%)	Source
		TPM	POC		
Daparture Bay, B.C., Canada	30	8.22	0.55	6.7	Stephens et al. (1967)
Loch Ewe, Scotland	30	—	0.16	—	Steel & Baird (1972)
St. Margaret's Bay, N.S., Canada	60	4.11	0.33	7.9	Webster et al. (1975)
Bedford Basin, N.S., Canada	20	2.16	0.16	7.3	Hargrave et al. (1976)
	30	2.69	0.19	7.2	
	40	2.94	0.21	7.2	
	50	2.79	0.20	7.4	
	60	3.71	0.25	6.8	
Northeast Pacific	50	—	0.43	—	Knauer et al. (1979)
Western Kiel Bight, FRG	15	1.76–4.60	0.10–0.22	4.6–5.9	Smetacek (1980)
	18	1.67–4.96	0.10–0.28	4.8–6.1	
Fanka Bay, Japan	40	0.56–31.40	—	—	Tsunogai et al. (1980)
Dabob Bay, WA, USA	50	—	0.19	—	Lorenzen et al. (1981)
Kanehohe Bay, Hawaii	15	5.45	0.45	8.3	Taguchi (1982)
Lindåspollene (fjord), Norway	10	1.16	0.14	12.5	Wassmann (1983)
	20	1.47	0.30	20.5	
	40	0.61	0.08	12.9	
	70	0.42	0.07	16.7	
	85	0.40	0.06	15.6	
Mid Atlantic Bight	34	—	0.34	—	Falkowski et al. (1983)
Nordåsvannet (fjord), Norway	20	1.63	0.23	14.1	Wassmann (1985)
	40	1.34	0.22	16.6	
	45	1.17	0.17	14.5	
	50	1.10	0.17	15.4	
	65	1.06	0.16	15.1	
Mid Atlantic Bight	10	2.5–12.6	0.31–0.73	5.8–18.0	Ducklow et al. (1985)
	82	0.10	0.008	8.0	
	88	0.10	0.007	7.0	
St. Georges Bay, N.S., Canada	7	2.74	0.15	5.6	Harding et al. (1987)
	14	1.51	0.27	18.4	
	21	6.44	0.23	3.6	
	28	7.12	0.26	3.7	
Santa Monica San Pedro Basin, CA, USA	100	0.24	0.03	14.4	Nelson et al. (1987)
Northwest Pacific	25	—	0.17	—	Sasaki et al. (1988)
Arabian Sea Shelf	22	1.00–12.20	0.06–0.62	2.0–10.1	Present study
	42	2.06–7.88	0.06–0.35	1.3–7.7	
	62	3.98–10.83	0.05–0.46	1.1–8.6	

marine environments have been compiled and presented in Table 5. From this it is evident that our sedimentation data are comparable to those obtained in previous studies.

There is an apparent relationship between hydrography and phytoplankton development. Due to infrequent sampling we might have missed small-scale variations in the diatom numbers. Nevertheless, a general pattern of the development of diatoms is evident from the data (Fig. 2D). The period September to October, with low winds (Anthony pers. comm.) and

relatively high temperature, is not conducive to vertical mixing (Fig. 2). The algal concentrations should decline to low levels (Radhakrishna et al. 1978, Banse 1984, 1986) as corroborated by the data on Chl *a*, diatom numbers (Fig. 2D) and sedimentation rates (Fig. 4). The subsequent period of November was characterized by low subsurface temperature, poorly oxygenated and nutrient rich water (Venugopalan 1988) below a shallow mixed layer (Fig. 2). The high levels of nutrients in close proximity to the surface layer set the stage for high algal concentrations. With the development of

cold and dry northeast winds in December, the barrier of thermal stratification is removed thereby bringing nutrients into the surface layer (Ryther et al. 1966, Banse 1984, 1986, Venugopalan 1988). These changes were accompanied by an increase in the diatom numbers from December onwards with a maximum in February (Fig. 2D). In February, very high sedimentation of particulate material, relatively rich in plant pigments and biogenic silica (Fig. 4C, D), was observed. This indicates cessation of algal growth. Studies from other localities (Smetacek 1980, Peinert et al. 1982) have shown that sedimentation of phytoplankton cells does not take place to a larger extent as long as healthy populations are growing. The increase in cell sinking rate that accompanies the cessation of algal growth (Smetacek 1984), however, results in mass sedimentation of cells when grazing is low. In our investigation it is likely that nutrient depletion caused the sudden termination of diatom growth. Of the various nutrients, phosphates and silicates are unlikely to be limiting nutrients in these waters as their concentrations did not change significantly during the course of the study (Venugopalan 1988). In contrast to this, surface nitrate concentration was seldom high in these waters (ca 0.52 to 1.4 $\mu\text{g-at. l}^{-1}$), and showed a minimum level (ca 0.2 $\mu\text{g-at. l}^{-1}$) in February that may have been associated with the termination of diatom growth. Furthermore, zooplankton biomass, especially copepods, was also relatively low during this period (Bhat 1988). These factors could account for the high sedimentation rates of particulate material observed in February (Figs. 3 and 4).

Organic matter deposited during the nonstratified period had low POC/Chl *a* equiv. and POC/PSi ratios (Figs. 4C, D and 6C, D). These ratios are not very different from those obtained for phytoplankton (Parsons et al. 1961, Antia et al. 1963, Welschmeyer & Lorenzen 1984, Brzezinski 1985). This suggests that fairly fresh organic matter derived from phytoplankton settled during this period. However, this organic matter had a relatively high C/N (atomic) ratio, implying that it was poor in nitrogen (Fig. 6D). Low POC/Chl *a* equiv. and POC/PSi ratios were also recorded at 42 m during the stratified period particularly in September and October (Fig. 4C, D). A 2- to 4-fold increase in the concentration of chlorophyll *a* as compared with surface layer was observed below 25 m during this period (Venugopalan 1988). Export from a subsurface chlorophyll *a* maximum was perhaps responsible for the relatively low POC/Chl *a* equiv. and POC/PSi ratios of trap samples during the period of water column stratification. Recently, the importance of the subsurface chlorophyll maximum layer as a source of sedimentation to greater depth has been reported (Skjoldal & Wassmann 1986).

The poorly oxygenated stratified water observed in November was associated with high sedimentation rates of TPM, POC and TCHO (Figs. 2, 4 and 5). Moreover, the organic matter deposited during this period had high POC/TPM, POC/Chl *a* equiv. and POC/PSi ratios (Fig. 4), suggesting sedimentation of resuspended highly degraded organic matter.

The marked decrease with depth in the sedimentation rates of chlorophyll *a* equiv. and PSi during the nonstratified period (Fig. 3E, F) suggests remineralization or dissolution either in the water column or the traps. In many other sedimentation studies, the decrease in sedimentation of these components has been attributed to mineralization or dissolution (Wassmann 1983, 1985, Skjoldal & Wassmann 1986).

In general, the AC-CHO/TCHO ratio as well as the fluxes of AC-CHO showed a decrease with depth (Fig. 5; Table 2). The observed decrease implies that these compounds were utilized by heterotrophic organisms. The preferential consumption of AC-CHO polysaccharides by heterotrophic organisms has been reported (Handa & Tominaga 1969, Handa & Yanagi 1969, Hitchcock 1977, Ittekkot et al. 1982, 1984, Liebezeit 1987, Tanoue & Handa 1987). The decrease in AL-CHO/TCHO and an increase in RS-CHO/TCHO ratios at 62 m probably suggests the influence of resuspended sediments.

There were positive and highly significant ($p < 0.001$) correlations between the fluxes of TCHO and TPM, POC, Chl *a* equiv. and PSi, suggesting common origin of these compounds. The observed relationships between the fluxes of TCHO and Chl *a* equiv. and PSi also suggest that diatoms were the major source of TCHO.

It has been suggested that large particles such as faecal pellets, faecal matter and marine snow play an important role in rapid transport of material to the sea floor (Honjo 1982, Asper 1987). The vehicle for transport of organic material to deeper water here appears to be sinking diatom cells, whether or not associated with faecal pellets, as indicated by the highly significant correlation coefficient obtained between the fluxes of PSi and POC (Fig. 7). The relation between sedimentation of PSi and organic material was highly significant ($r = 0.90$; $p < 0.001$) during the nonstratified period, but was not significant for the stratified period ($r = 0.21$; $p > 0.1$). The low correlation observed for the stratified period is probably due to low numbers of diatoms and/or sedimentation of resuspended organic matter during this period.

Surface sediments at 78 m had organic carbon and TCHO percentages of dry weight of 0.72 % and 0.16 %, respectively (National Institute of Oceanography - ONGC report unpubl.). Under these circumstances, the substantial supply of biogenic organic matter

due to settling phytoplankton during February may have a stimulatory effect on the growth and reproduction of benthic organisms (Graf et al. 1982, 1983, Billett et al. 1983).

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