

Particulate carbohydrates in the Arabian Sea

Particulate carbohydrates
Organic matter
Chlorophyll *a*
Arabian Sea
Glucides particulaires
Matière organique
Chlorophylle *a*
Mer d'Oman

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ABSTRACT

Particulate carbohydrate (PCHO) was measured for 183 samples collected from 8 depths at 23 stations. The (PCHO) concentrations varied from 22 to 125 $\mu\text{g}\cdot\text{l}^{-1}$ ($\bar{x} = 52.42 \pm 19.56 \mu\text{g}\cdot\text{l}^{-1}$) at the surface and decreased from 4.6 to 47.5 $\mu\text{g}\cdot\text{l}^{-1}$ ($\bar{x} = 19.46 \pm 12.21 \mu\text{g}\cdot\text{l}^{-1}$) at 300 m. Below 300 m, especially at 600 to 1000 m, PCHO concentrations increased and were similar to those observed at the surface or were 2 to 4 times higher at 1000 m. Spatial and temporal variations observed for PCHO seem to parallel the distribution of chlorophyll *a*. The deep water PCHO maximum was found embedded within the dissolved oxygen minimum layer. The observed pattern of PCHO distribution is discussed with respect to some biological and physico-chemical factors.

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RÉSUMÉ

Les glucides particulaires en mer d'Oman

Les glucides particulaires (PCHO) ont été dosés sur 183 échantillons d'eau prélevés à huit profondeurs en 23 stations de la mer d'Oman. En surface, les teneurs varient de 22 à 125 $\mu\text{g}\cdot\text{l}^{-1}$ ($\bar{x} = 52,44 \pm 19,56 \mu\text{g}\cdot\text{l}^{-1}$), puis elles diminuent jusque vers 300 m de profondeur où elles varient de 4,6 à 47,5 $\mu\text{g}\cdot\text{l}^{-1}$ ($\bar{x} = 19,16 \pm 12,21 \mu\text{g}\cdot\text{l}^{-1}$). Au-dessous de 300 m, en particulier entre 600 et 1000 m, les teneurs en glucides augmentent pour atteindre, à 1000 m, des valeurs comparables ou supérieures d'un facteur 2 à 4 à celles qui sont observées en surface. Les variations spatiales et temporelles des glucides semblent suivre la répartition de la chlorophylle *a*. Le maximum des glucides particulaires dans les eaux profondes a été observé dans la couche de concentration minimale en oxygène dissous. Le schéma de répartition des glucides particulaires est discuté en fonction de quelques paramètres biologiques et physico-chimiques.

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INTRODUCTION

The Arabian Sea is a semi-enclosed sea, bordered on the northern, eastern and western sides by the land masses of Asia and Africa. The total area of the Arabian Sea between latitudes 0 and 25°N and longitudes 50 and 80° E is about $6.255 \times 10^6 \text{ km}^2$. This is an area of negative water balance where evaporation exceed precipitation and runoff, the high rate of evaporation result in the formation of high-salinity water masses. Surface circulation in the Arabian Sea undergoes bi-annual reversal associated with the southwest (SW) and northeast (NE) monsoons. The NE is weak in the region but SW is very intense. Strong winds blowing along the Somali and Arabian coasts to the left cause intense upwelling off these coasts during the SW monsoon period. Moderate upwelling also occurs off the

southwest coast of India (Sastry, D'Souza, 1972). Although the Arabian Sea receives considerable runoff from Indian rivers such as the Narmada and the Tapti, the major source of terrestrial inputs ($2500 \times 10^6 \text{ t}$) is the river Indus in Pakistan (Ittekkot, Arain, 1986).

Numerous oceanographic cruises were undertaken during the John Murray expedition, the International Indian Ocean Expedition (IIOE), and more recently by India utilizing the vessels-I.N.S. Darshak, R. V. Gaveshani and O. R. V. Sagar Kanya. During these cruises most of the attention was focused on studies related to biological production measurements and the investigation of nutrient distribution in the region. Recently, excellent reviews on the biological production (Qasim, 1977; 1982) and chemical oceanography of the northern Indian Ocean (Sengupta, Naqvi, 1984) have been published.

Despite these oceanographic studies, very little information on the distribution of organic matter and its constituent fractions including carbohydrates, proteins and lipids is available from the Indian Ocean in general and the Arabian Sea in particular. Menzel (1964) determined the contents of dissolved and particulate organic carbon in samples collected from surface to 3200 m depth in the Arabian Sea. Recently, we reported on the distribution of particulate organic carbon (Bhosle *et al.*, 1988 a), dissolved carbohydrate (Dhople, Bhosle, 1987) and dissolved and particulate lipids (Bhosle *et al.*, 1983; Nandakumar *et al.*, 1987) in the Arabian Sea. Carbohydrates are among the most important constituents of and produced by phytoplankton during the process of photosynthesis (Handa, 1967; Hecky *et al.*, 1973; Tanoue, Handa, 1987). They also form a part of dissolved and particulate matter (Romankevich, 1984; Thurman, 1985). Studies on the distribution of particulate carbohydrates (PCHO) of suspended particles (Handa, 1967; Handa, Yanagi, 1969; Handa *et al.*, 1972; Hitchcock, 1977; Ittekkot *et al.*, 1982; Liebezeit, 1984; Tanoue, Handa, 1987) collected by conventional sampling bottles and sedimenting particles intercepted by sediment traps (Ittekkot *et al.*, 1984 a; b; Liebezeit, 1987; Tanoue, Handa, 1987) suggest that the content of these compounds change as the particles sink to greater depth. The decrease in carbohydrate content of suspended and sedimenting particles is probably caused by respiration of water-extractable reserved carbohydrate by diatoms sinking below the euphotic zone and/or heterotrophic uptake (Handa, 1967; Handa, Tominaga, 1969; Tanoue, Handa, 1987).

In this paper, we report on the distribution of PCHO in the Arabian Sea. The general picture emerging from the data is discussed with respect to biological and physico-chemical parameters.

MATERIAL AND METHODS

Seawater samples (183) were collected from surface (~1 m) to 1000 m depths using 5- or 10-litre PVC Niskin bottles during the 13th cruise of O. R. V. Sagar

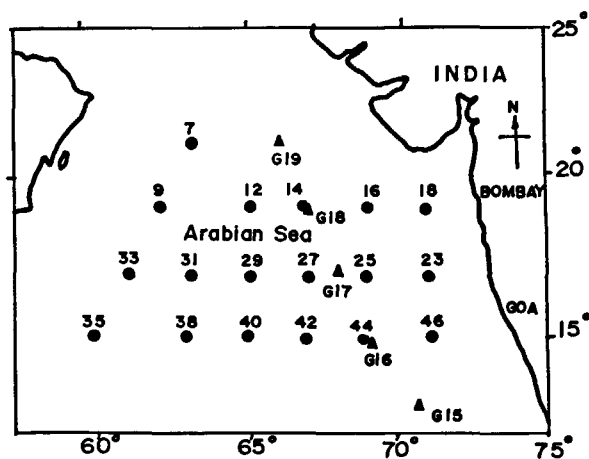


Figure 1 Location of the stations sampled in the Arabian Sea during the 13th cruise of O. R. V. Sagar Kanya (●) and the 160th cruise of R. V. Gaveshani (▲).

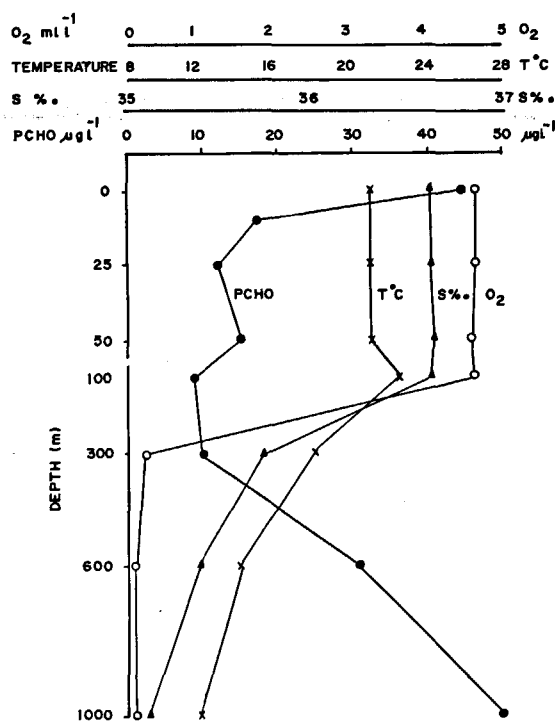


Figure 2 Vertical profiles of salinity, temperature, dissolved oxygen and particulate carbohydrate (PCHO) at station 7.

Kanya in February/March 1985 and 160th cruise of R. V. Gaveshani in November/December 1985 in the Arabian Sea. Stations sampled during these cruises are shown in Fig. 1. Immediately after collection, triplicate aliquotes of 0.1 to 1.0 litre were filtered through precombusted (450°C, 3 h) 47 mm GF/C glass fibre filters for particulate carbohydrate (PCHO) analysis. The PCHO was analyzed as suggested by Hitchcock (1977) using the phenol-sulphuric acid method. Standard curves were prepared for each batch of new reagents with D-glucose as standard. Precombusted filters were analyzed with each batch of samples and were used as blanks. Mean standard deviations and coefficients of variation for triplicate analyses of PCHO varied from ±0.29 to 7.07 and 4.90 to 18.05%, respectively.

Temperature and salinity data were collected using the ME-Multisonde CTD profiling system installed on board the vessel. The accuracy of measurement was: temperature ±0.02°C and salinity ±0.01. Dissolved oxygen was determined by the Winkler method (Carpenter, 1965).

RESULTS AND DISCUSSION

Typical vertical distribution profiles of PCHO, dissolved oxygen, temperature and salinity for station 7 are shown in Figure 2. The detailed distribution of temperature, salinity, dissolved oxygen and nutrients in the study area has been reported earlier (Dhople, Bhosle, 1987; Boshle *et al.*, 1988 a). A mean value of 4.90 ml.l⁻¹ of dissolved oxygen was observed for the surface waters; this decreased with depth and a minimum 0.2 ml.l⁻¹ was observed at about 300 m. A thick oxygen minimum layer extending from about 300 to 1000 m was very conspicuous for all the stations (Bhosle *et al.*, 1988 a).

PCHO concentrations varied from 22 to $125 \mu\text{g.l}^{-1}$ ($\bar{x} = 52.42 \pm 19.56 \mu\text{g.l}^{-1}$) at the surface and decreased to 4.6 to $47.5 \mu\text{g.l}^{-1}$ ($\bar{x} = 19.46 \pm 12.21 \mu\text{g.l}^{-1}$) at 300 m (Fig. 3, Tab.). Below 300 m, especially at 600 to 1000 m, PCHO concentrations increased and were similar to those observed at the surface, becoming two to four times higher at 1000 m.

Based on the surface distribution of PCHO, stations were divided into three groups. Group A, consisting of stations 9, 14, 40 and G-17, showed very low values (22 to $30 \mu\text{g.l}^{-1}$). Intermediate concentrations (32 to $46 \mu\text{g.l}^{-1}$) were observed at group B comprising stations 12, 27, 29, 31, 33 and 35. On the other hand, very high values (> 50 to $125 \mu\text{g.l}^{-1}$) were recorded at group C with stations 16, 18, 23, 25, 38, 42, 44, 46, G-15, G-16, G-18 and G-19. This distribution pattern of PCHO seems to parallel the distribution of chlorophyll *a*. For example, chlorophyll *a* concentrations were very low (0.02 to $0.06 \mu\text{g.l}^{-1}$), intermediate (0.065 to $0.16 \mu\text{g.l}^{-1}$) and high (0.45 to $0.64 \mu\text{g.l}^{-1}$) at groups A, B and C, respectively (Plant, pers. comm.).

Surface concentrations of PCHO generally decreased in an offshore direction (Fig. 3). Stations near the coast showed higher production of phytoplankton biomass in comparison with offshore stations, thus showing the enrichment of PCHO at the former.

Surface values of PCHO observed here were similar to those recently reported for the Bay of Bengal (Bhosle *et al.*, 1988 *b*). However, these values were rather high as compared to those reported from other oceanic waters. For example, Hobson (1967) observed 15 to $30 \mu\text{g.l}^{-1}$ of PCHO in the open surface waters of the

Pacific off the Washington and Oregon coasts. Handa and Yanagi (1969) reported a range of 10 to $26 \mu\text{g.l}^{-1}$ PCHO carbon for surface waters of the Kuroshio current and slightly higher values of 12 to $39 \mu\text{g.l}^{-1}$ for the Oyashio area. Similarly, in Sagami Nada off Honsyu, Japan, PCHO of $48.28 \mu\text{g.l}^{-1}$ were observed at the surface which decreased to $11.64 \mu\text{g.l}^{-1}$ at 1000 m (Handa, 1970). In another observation made by Romankevich (1984) in the Pacific Ocean, PCHO concentrations of $19.50 \mu\text{g.l}^{-1}$ in 0 to 100 m and $4.4 \mu\text{g.l}^{-1}$ below 1000 m were recorded.

Average primary production of the Indian Ocean is about $228 \text{mgCm}^{-2} \cdot \text{d}^{-1}$ (Qasim, 1977; 1982). Qasim also compared the primary production of the Indian and the Pacific Oceans and observed that production is higher by about 75% in the former. This higher primary production was also evident in the particulate

Table

Vertical distribution of particulate carbohydrate at different stations in the Arabian Sea.

Depth (m)	Range	\bar{X}	SD	CV (%)	n
0	22.20 to 125	52.42	19.56	37.31	23
10	16.00 to 96	46.79	25.50	54.50	23
25	11.30 to 150	40.47	27.01	66.74	23
50	13.40 to 145	39.14	30.43	77.76	23
100	9.00 to 250	37.30	50.06	134.20	22
300	4.60 to 47.5	19.46	12.21	62.74	17
600	13.50 to 97.6	61.15	24.85	40.63	17
1000	24.00 to 110	71.70	23.23	32.40	22

SD=standard deviation; CV=coefficient of variation; n=number of samples.

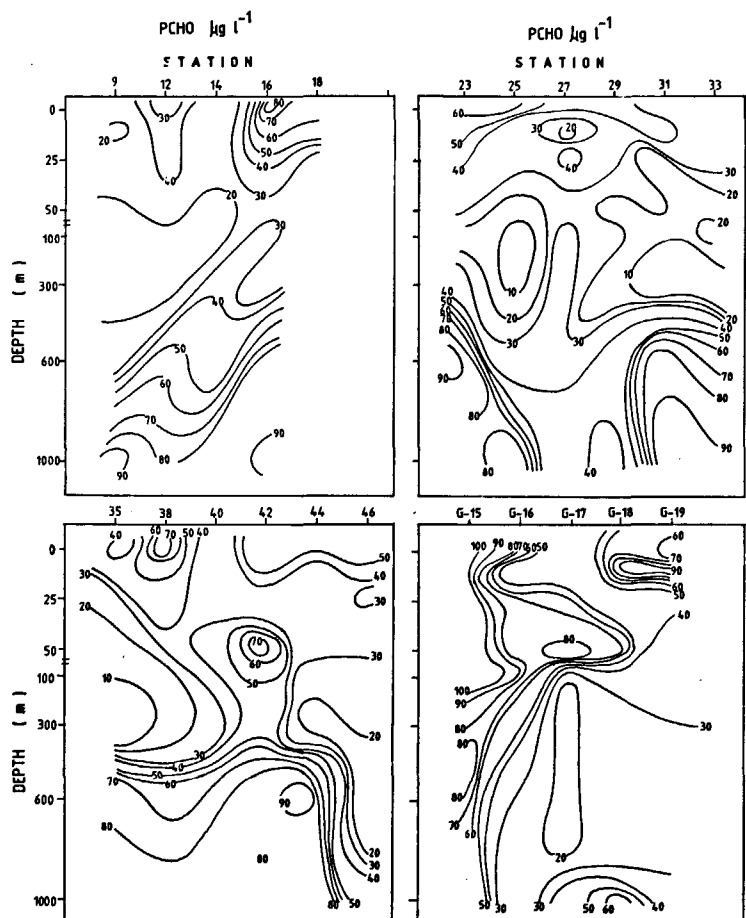


Figure 3
Distribution profile of PCHO in the Arabian Sea.

organic carbon (POC) distribution (Bhosle *et al.*, 1988a). POC concentrations in the surface water varied from 154 to 554 $\mu\text{g.C.l}^{-1}$ in the study area. These values are much higher than those reported from other oceanic waters (Copin-Montegut, Copin-Montegut, 1983; Romankevich, 1984; Gordon, Cranford, 1985). Thus, higher primary production and POC content were probably responsible for the higher content of PCHO in the region.

In order to assess seasonal variations in PCHO distribution two stations — 14 and 44 (Fig. 1) which were sampled in February/March 1985 during the 13th cruise of O. R. V. Sagar Kanya were resampled in November/December 1985 during the 160th cruise of R. V. Gaveshani (stations G-16, G-17). Surface concentrations were higher in November/December as compared with February/March 1985 (Fig. 4). At greater depth (~ 1000 m), on the other hand, the pattern was reversed. At this depth (~ 1000 m), PCHO values were higher in February/March as compared with November/December. This suggests seasonal variability of the organic matter and supports the contention that organic matter varied with time (Riley, 1970; Mel'nikov, Pavlov, 1978; Harrison *et al.*, 1987).

The spatial and temporal variability observed in PCHO distribution was also evident in POC distribution. POC varied spatially by a factor of about 5 and similar variability was also observed for PCHO. Such variation in the organic matter was probably to be expected in an area such as the Arabian Sea, where the surface productivity exhibits exceptionally high variability both in space and time and for example, vary by a factor of about 8 (Qasim, 1982).

PCHO carbon as a percentage of POC showed large variations (Fig. 5). Total carbohydrate content as a percentage of POC varied from 2.5 to 9.6 in the Bransfield Strait (Liebezeit, 1984) and from 3 to 15 in the North Sea (Ittekkot *et al.*, 1982). On the other hand, very high values, exceeding 30%, were reported for the Pacific Ocean (Handa, 1970; Handa *et al.*, 1972). The carbohydrate content of phytoplankton is influenced by the nutrient status of the community (Morris, 1981). Thus, nutrient deficient culture or natural phytoplankton populations will increase their carbohydrate and/or lipid content at the expense of protein (Liebezeit, 1984). During these cruises, nitrate was almost undetectable in the upper 20 m water column at most of the stations, or occasionally present at very low levels (0.3 to $1 \mu\text{g at l}^{-1}$) at a few stations. Thus, variability in PCHO content could be due to nutrient limitation. In addition to the latter, variation in phytoplankton species composition could also affect carbohydrate content. For example, Hecky *et al.* (1973) observed large variation in total cell wall carbohydrate for various fresh and brackish water diatom species. It is thus likely that PCHO varied because of the variation in the phytoplankton species and/or nutrient limitations.

PCHO decreased in the upper 300 m, suggesting that these compounds were utilized by *in situ* aquatic organisms. After this initial decrease, PCHO carbon as a percentage of POC increased at greater depths, especially between 300 to 1000 m. This suggests that

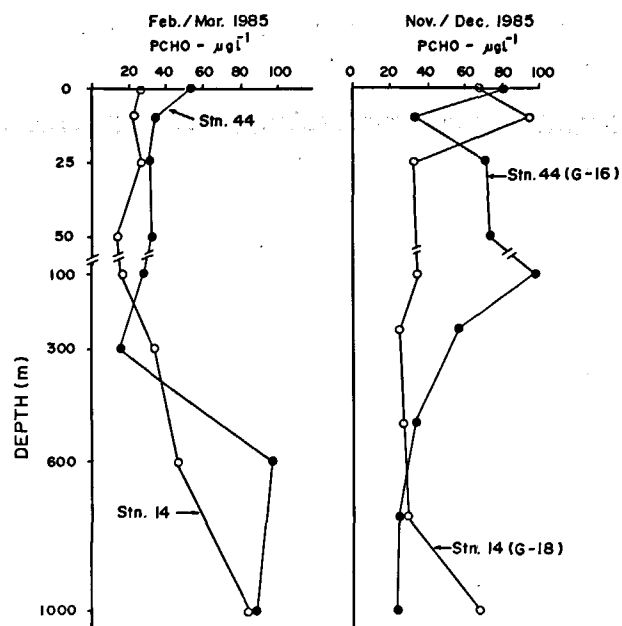


Figure 4
Seasonal variations in the distribution of PCHO in the Arabian Sea.

some of the carbohydrates are preferentially utilized, whereas others are resistant to biological degradation. It was observed that the PCHO consists of reserved and structural carbohydrates (Handa, Yanagi, 1969; Handa *et al.*, 1972; Hitchcock, 1977; Tanoue, Handa, 1987), the former being easily degradable while the latter are resistant to biological decay. Thus the low values of PCHO observed in the upper 300 m were probably caused by the preferential degradation of reserved PCHO. Subsequent accumulation, on the other hand, at greater depths (> 300 m) would be due to structural PCHO or additional inputs of organic matter. The former appears unlikely because in that case we could expect a uniform distribution or small decrease in PCHO content with depth. However, this is not the case. Alternatively, additional inputs seem to be a probable source of PCHO.

Vertical profiles of PCHO are similar to those recently reported for POC and dissolved carbohydrate (Dhople, Bhosle, 1987; Bhosle *et al.*, 1988a). However, this pattern of organic matter distribution differs greatly from those reported by Menzel (1974) and more recently by Gordon and Cranford (1985). In his review, Menzel (1974) opined that organic matter decreased very little and is homogeneous below a depth of about 300 m. Gordon and Cranford (1985), on the other hand, suggested that organic matter decreased with depth. The present result disproves both and implies that organic matter distribution in the Arabian Sea is more complicated than that reported from other regions.

Vertical profiles of all but one station suggest accumulation of PCHO at greater depths, especially below 300 m. This deep water PCHO maximum was embedded in the oxygen minimum layer. The deep water PCHO maximum exists probably because of increased supply or decreased loss. The exact factors controlling the distribution of PCHO at greater depths (> 300 m) are not known but the following factors may well have been involved.

It could be argued that the increased abundances of PCHO in the oxygen minimum zone simply result from advection of water masses containing variable organic matter. Two water masses Arabian Sea high salinity water in the upper 200 m and Persian Gulf water from 200 to about 1 000 m—could be indentified in the study area. Traces of Red Sea water could be noted below 700 m along 15°N. If these water masses were to influence the observed pattern of PCHO in deep waters (>300 m), then their maximum influence would be expected at western stations and should decrease in the southeasterly direction. However, increased abundances of PCHO in the oxygen minimum zone were recorded at all but one station. Therefore, it is unlikely that water masses were mainly responsible for controlling the PCHO distribution in deep waters.

Small, suspended particles (<50 m) are characterized for their very low sinking velocities, especially in the oxygen minimum zone. Furthermore, sinking rates of such particles are influenced by their density and the viscosity of the fluid medium. Changes in temperature and salinity were observed between 300 to 1 000 m (Dhople, Bhosle, 1987; Bhosle *et al.*, 1988 *a*). The σ_t values at these depths varied from 26.6 to 27.7. These changes in σ_t could have altered sinking speed of these small particles, resulting in the accumulation of organic matter in the oxygen minimum layer.

A third mechanism that could explain the observed pattern of PCHO distribution in deep water involves transport directly by sinking or entrainment in subsiding water. After this initial injection into deep water, PCHO could be transported laterally by advective pro-

cess. Garfield *et al.* (1979) proposed such a model to account for a secondary particulate protein maximum they observed in the upper 300 m water column. In our experimental area, we did not resolve any secondary PCHO maximum in the upper 300 m depth. It is thus unlikely that we sampled uncoupled patches of organic matter originating at the surface.

Migrating zooplankton (Harding *et al.*, 1987) have been implicated in the removal and transfer of organic matter from the water column by repackaging into fecal pellets which have high sinking rates. It is reported that zooplankton abundance is stronger in the top 200 m water column than at greater depths (Paulinose, Arvindakshan, 1977; Qasim, 1982). There was no significant difference in the zooplankton biomass between the hauls taken from 200 to 0 m and 900 to 0 m, implying that the organisms were largely confined to upper 200 m and tend to avoid the oxygen deficient layer below 300 m. Thus, it is likely that the deep water PCHO maximum observed below 300 m is due to a conspicuous lack of living zooplankton in the oxygen minimum zone.

Another possible source of deep water PCHO maximum could be river runoff. The Arabian Sea receives runoff from rivers—the Narmada and Tapti in India and the Indus in Pakistan. These rivers transport about $2,500 \times 10^6$ t of terrestrial sediment to the sea (Kolla *et al.*, 1981; Ittekkot, Arain, 1986). Furthermore, these rivers have depositional centers in well-developed deep sea fans extending several thousand kilometres offshore.

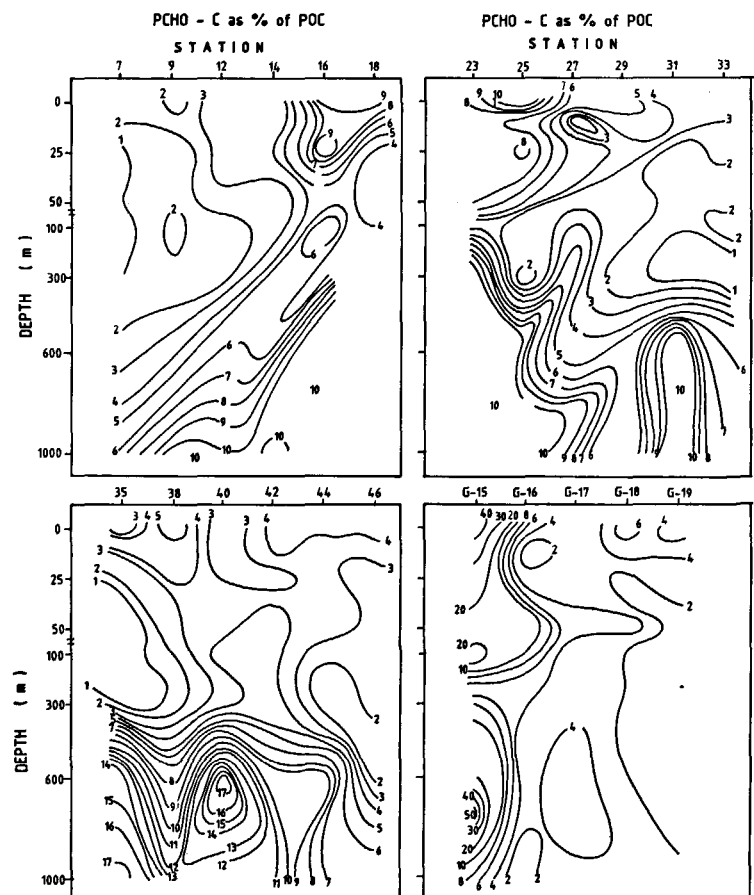


Figure 5
Distribution profile of PCHO-carbon as a percentage of particulate organic carbon (POC).

The secondary peak of PCHO at greater depths could also be due to chemolithotrophic microbial growth and carbon production yielding higher PCHO at these depths (Karl, Knauer, 1984). However, such a mechanism has been contested by others (Betzer *et al.*, 1984).

Whatever may be the mechanism of its formation, the PCHO maximum is perhaps to be associated with the development of the oxygen minimum, accompanied by a deep water nitrite maximum (Naqvi, 1988). During the 165th cruise of R. V. Gaveshani in February/March 1986 in the same area, limited samples of suspended matter were collected which were simultaneously analyzed for POC, PCHO and particulate protein (PP). All these parameters showed deep water accumulation in the oxygen minimum layer. The contribution of PP carbon to POC was much higher (~28%) than that of PCHO-carbon (~4.8%). This indicates the proteineous nature of the organic matter at these greater depths (*i. e.* 600 to 1 000 m). Such a high content of nitrogenous organic matter at these depths (> 300 m) was unusual. If the organic matter arriving at these greater depths was of surface origin, we would have expected very low protein and high PCHO in the suspended matter because the former compounds are preferentially utilized in comparison with the latter as the organic matter sinks to greater depth (Gordon, Cranford, 1985).

The increased abundance of organic matter in the mesopelagic zone, its proteineous nature and its associ-

ation with the oxygen minimum and nitrite maximum, perhaps indicate microbial activities at the depth of maximum. Intense microbial growth, diagenetic transformation and mineralization processes associated with small suspended particles have been reported to take place in the oxygen minimum zone (Wakeham, 1987; Cho, Azam, 1988; Karl *et al.*, 1988). Such microbial processes in the mesopelagic zone can give rise to large-scale production of fine (0.3 to 1.0 μm) non-sinking particles with high proteineous organic matter (Cho, Azam, 1988). Similar microbial processes could perhaps explain the increased concentrations of organic matter at the mesopelagic depths (600-1 000 m) in the oxygen minimum zone of the Arabian Sea. Such elevated levels of organic matter in the ocean's interior may have direct implications for the biogeochemical dynamics of the organic matter.

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