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Organic Carbon in Sediments of the Southwestern Margin of India: Influence of Productivity and Monsoon Variability During the Late Quaternary

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Abstract: The texture, organic carbon (OC), $CaC0_3$ and Rock-Eval parameters of the sediments from two gravity cores collected at depths below the oxygen minimum zone (OMZ) of the southwestern margin of India are presented and compared the results with those within the OMZ. *Clayey* silt/ silty clays are the characteristic sediments. The OC in the core top sediments between Cape Comorin and Mangalore is higher below the OMZ than those from the OMZ. However, it is higher within the OMZ than those below the OMZ in the sediments between Mangalore and Goa. The down-core variations of OC are identical in these cores. In both the cores, relatively high OC content and low sedimentation rates correspond to the intervals of late Holocene and Last Glacial Maximum (LGM) and, low OC and high sedimentation rates to the early Holocene sediments. The $CaC0_3$ follows sand content in a core off Cape Comorin, with low values at the core top, increase marginally in the early Holocene and LGM and then decrease in the late Pleistocene sediments. The $CaC0_3$ values in a core off Mangalore are higher in the intervals of the late Holocene and early deglaciation than m early Holocene and LGM intervals. Rock-Eval parameters distinguish the sources of organic matter only at high OC concentrations.

The high OC during the LGM may be related to the productivity, associated with convective mixing occurring during the NE monsoon. The low $OC/CaC0_3$and high clay content during the early Holocene may be the consequences of the intensified SW monsoon that results in stronger near-surface stratification leading to low productivity High OC and low $CaC0_3$ during the late Holocene suggest increased productivity and early diagenesis in the near surface sediments. We suggest that the variations in productivity and downslope transport of sediment controlled the OC enrichment.

Keywords: Organic carbon, Sediment cores, Productivity, Late Quaternary, SW margin of India.

INTRODUCTION

The OC content in recent marine sediments is usually high (>0.5%) on the continental margins (continental shelf and slope) and marginal basins and low (0.25%) in the adjacent deep sea (Romankevich, 1984). The distribution of terrestrial organic matter in the oceans largely depends on river source and its proportions decrease steadily offshore (Emerson and Hedges, 1988). The enrichment of marine organic matter depends on the primary productivity, which is high in areas of coastal upwelling. High primary productivity not only.leads to high organic matter burial in the sediments but also promotes intense oxygen minimum conditions at mid-water depths leading to denitrification in some areas.

There are two schools of thought on OC enrichment in the sediments of the continental slope. Some workers consider that high primary productivity in the photic zone leads to a high burial rate of OC (Pedersen et al. 1992; Calvert et al. 1995; von Rad et al. 1999). Others stress the presence of oxygen-depleted waters at intermediate depths, which slows down the decomposition of organic matter and enhance preservation (Demaison and Moore, 1980). Investigations, however, have also shown that the mid-depth OC maxima on several continental margins either extend over a larger depth range than the regional oxygen minima or completely decoupled (Sarnthein et al. 1982; Pedersen et al. 1992).

Here, two sediment cores collected below the OMZ depths of the southwestern margin of India were investigated for the OC distribution and compared the results with that of a core within the OMZ (Fig. 1).: The purpose of the paper is to understand the controls and influence of late Quaternary monsoon variability on OC distribution.

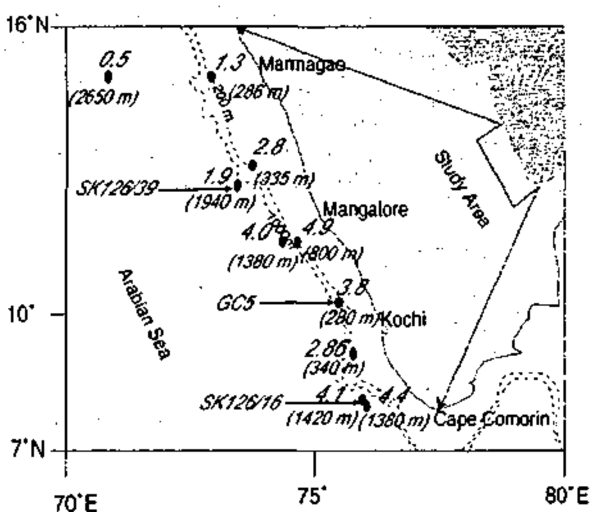

Fig.1. Map showing the location of the sediment cores. Cores SK126/16 and SKI26/39 arc investigated for this paper. Core GC5 is also referred in the text. Each location has two values. The number in brackets represents depth at which the cores were collected. The number in italics represents the OC content (%) in surface (core top) sediments of each core. (OC data: this paper, Thamban et al. 1997 and unpublished data with the authors)

PREVIOUS STUDIES

Paropkari et al. (1987,1993) reported high OC (generally 1-12 wt%, and up to 16 wt%) in the sediments of the continental slope and low OC (l-4wt%) on the shelf off western India. They have also reported the sediments with high OC and high hydrogen index (HI) within and below the OMZ and explained that the OC enrichment is due to its preservation in OMZ and extension of OMZ to deeper depths. Calvert et al. (1995) found not much difference in HI values among the contemporary sediments accumulated above, within and below the OMZ. Several workers reported distribution of OC in the surficial sediments and sediment cores collected along the western margin of India and related OC variations in glacial and interglacial times to changes in water masses, productivity and intensity of monsoons both at regional and global scales (Sarkar et al., 1990; Babu et al., 1999; Naidu and Shankar, 1999; Thamban et al., 2001; Agnihotri et al., 2003; Pattan et al., 2003). Luckge et al. (2002) reported high OC, TN and HI in sediment cores collected within and below the OMZ of the Pakistan margin and related low HI values to poor preservation.

OCEANOGRAPHIC CONDITIONS IN THE STUDY AREA

Surface circulation in the Arabian Sea is controlled by seasonal variations in winds. The winds blow from the SW direction (SW monsoon) during the summer (June-August) leading to precipitation over the Indian Peninsula. These winds reverse their direction (NE monsoon) during the winter (December to February). Based on changes in monsoon winds, surface currents also change their direction along the SW continental margin of India. The surface current, the West Indian Coastal Current (WICC), moves towards the equator during the SW monsoon. During the same period, an undercurrent carrying nutrient-poor waters of the southern origin flows northward with its core at about 150 m (Shetye et al., 1990). However, this feature is absent during the NE monsoon (Naqvi et al., 1990) when the surface current (WICC) moves northwards (Shetye et al., 1990). During the SW monsoon, biological productivity in the Arabian Sea lies around the centres of seasonal upwelling, off Arabia, Somalia and southwest India (Qasim, 1977). During this time the upwelled waters on the southwestern margin of India are capped by thin (5-10 m) lens of low-salinity water, which originates in part from the local precipitation and in part from runoff from the narrow coastal plain that receives heavy rainfall (Stramma, 1996).

The surface productivity along the southwestern margin of India during the SW monsoon is ~ 232 mg $Cm^{-3}day^{-1}$ (Krey and Babenerd, 1976). Upwelling was also observed along this coast sometimes in February, well before the onset of the SW monsoon, which can be explained in terms of coastal Kelvin and Rossby waves (Shankar and Shetye, 1997). A pronounced OMZ with dissolved O_2<0.5 ml l^{-1} (~22 µM) exists perennially in the Arabian Sea at intermediate water depths and impinges the continental slope between 150mand 1200m(Wyrtki, 1971; von Stackelberg, 1972). The thickness and intensity of the OMZ vary from north to south (Sen Gupta and Naqvi, 1984).

MATERIALS AND METHODS

Two sediment gravity cores, SK126/16 (referred to here as core 16) off Cape Comorin (8.03° N; 76.05° E) at 1420 m depth and SK126/39 (core 39) off Mangalore (12.63° N; 73.33° E) at 1940 m depth were recovered during the 126th cruise of *ORV Sagar Kanya* at depths below the lower boundary of the OMZ from the southwestern margin of India (Fig. 1). Colour of the sediment was noted onboard immediately after the recovery of cores. Sub-sampling of the cores was done onboard at 2 cm intervals for the top 20 cm and 5 cm intervals for the rest of the core.

The textural analysis of the sediments was carried out on representative samples, following Folk (1968). The >63 µm fraction was studied under binocular microscope for the constituents. The $CaCO_3$ content of the bulk sediments was determined by rapid gasometric technique, following Hulsemann (1966). Reproducibility of the measurements, as checked by running replicates of samples, was found to be better than ±5%. The OC and total nitrogen (TN) were determined on a CNS elemental analyser (NCS 2500) and OC/TN was calculated. The accuracy of the analyses was found to be better than 0.2% for OC and 0.3% for TN using BBOT (2,5-Bis(5tert-butyl-benzoxazol-2-yl)thiophene) standard. The parameters of Rock-Eval Pyrolysis (HI, T_{max}, and S_2) were also determined on bulk samples. The reproducibility of these measurements is ± 8% for HI and S_2 and ±1% for T_{max} values. Sediment accumulation rates were calculated based on non-linear regression equation developed by Clemens et al. (1987), using variations in $CaCO_3$ content.

Chronostratigraphy is based on ^{14}C ages (Table 1). For each core the species *Globigerinoides ruber was* separated from >63µm fraction of three selected samples and measured their age by the accelerated mass spectrometry (AMS) method at the Leibniz-Labor of University of Kiel, Germany. Two bulk (mixed carbonate plus organic carbon) sediment dates for each core were also obtained by the conventional radiocarbon method at the Birbal Sahni Institute of Paleobotany, Lucknow, India (Table 1). The measured ages were corrected for local ΔR correction (100 years) and calibrated using the CALEB 4.3 program of Stuiver et al. (1998). The term 'late Pleistocene' is used in this paper for the sediments below LGM (> 22 ka BP).

RESULTS

Colour, Texture and Grain Size

Core 16 shows predominantly grey olive silty clay/clayey silt sediments, with a zone of green black clayey silts at 200-230 cm interval (~32 ^{14}C ka) (Fig. 2). In core 39, silty clays are dominant through out the core. The sediments are moderate brown in colour between the core top and 30 cm (7 ka BP), light olive grey between 30 cm and 150 cm (7 ka - 21 ka BP) and then olive grey up to end of the core (Fig.3).

The sand content in core 16 ranges from 4% to 41%, with high values in the late Holocene sediments (until 7 ka BP). A dome-shaped distribution of sand, with higher proportions of sand around LGM and gradually decreasing proportions in the early Holocene and late Pleistocene sediments can be seen in Fig. 2. Clay content is higher in the early Holocene (11 ka BP - -7 ka BP) than in the late Holocene (up to 7 ka BP) and LGM (22 to 18 ka BP) sediments (Fig. 2). In core 39 the sand content is extremely low (l%-6%). The clay content is higher during the early Holocene than in late Holocene and LGM sediments (Fig. 3).

Calcium Carbonate Content and Coarse Fraction

The $CaCO_3$ content is relatively higher in core 16 (16% - 57%) than in core 39 (16% - 30%). In core 16 the variations in $CaCO_3$ follow sand content *(see* Fig. 2). The $CaCO_3$ content is low (37%) at the core top, increases marginally in the early Holocene and LGM sediments and then decreases in the late Pleistocene sediments. In core 39 the $CaCO_3$ values are higher for the intervals of late Holocene and early deglaciation and, lower for the early Holocene and LGM sediment (Fig.3). The $CaCO_3$ content does not vary much in the late Pleistocene sediments.

Biogenic components are predominant in the 125-250 µm fraction of the sediment. In core 16, the benthic foraminifers are low (1-18%) compared to the planktic

Table 1. Details of the samples analysed for ^{14}C ages in core 16 and 39

Sr. No	Cruise/ Core No.	Sediment interval in the core	Lab code	Measured Age (years)	Calibrated age (ka BP)
1	SK126/16$	20-25 cm	KIA14563	6875 ± 40	7.29
2	SK126/16$	45-50 *cm*	KIA14564	10090 ±55	10.73
3	SK126/16$	75-80 cm	KIA14565	16000 ± 80	18.40
4	SK126/16#	95-l00cm	B5-1583	20630 ± 220	23.71
5	SK126/16#	190-200 cm	B5-1581	32470 ± 580	—
6	SK126/39$	25-30 cm	KIA 15267	6720 ±30	7.15
7	SK126/39$	55-60 cm	KIA 14567	9275 ± 45	9.74
8	SK126/39$	120-130 cm	KIA 14568	15120 ±70	17.39
9	SK126/39#	150-160 cm	B5-1573	18790 ± 680	21.61
10	SK126/39#	230-240 cm	B5-1570	22230 ±360	—

$ - AMS ages measured on *G. ruber* at Leibniz Labour fur Altersbestimmung und Isotopenforschung, Christian-Alberchts-Universitat, Kiel, Germany.

- Bulk sediment ages measured by conventional radiocarbon method at BSIP, Lucknow

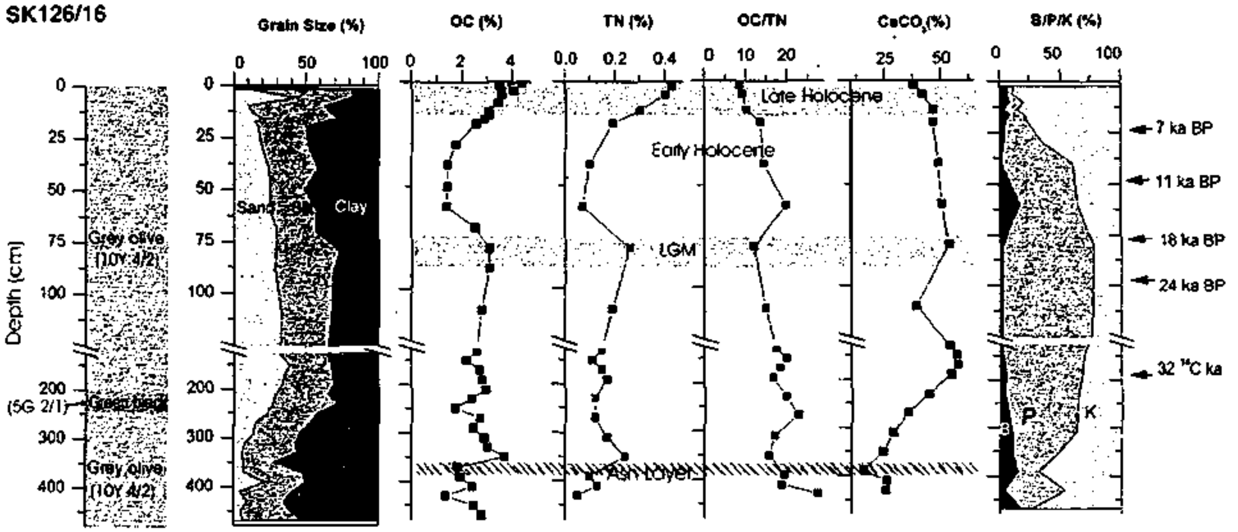

Fig.2. Down-core variations of the colour, grain size, organic carbon (OC), total nitrogen (TN), OC/TN ratio, $CaCO_3$ content, benthic (B), planktic (P) foraminifers and keels (K) in sediment core SK126/16.

foraminifers (4-74%) and keels (rims of foraminifers remaining after dissolution; 24-90%) (Fig. 2). The planktic foraminifers dominate during the LGM and early deglacial sediments and, decrease gradually with a corresponding increase in keels from early Holocene to present. The late Pleistocene sediments exhibit down-core decrease in planktic foraminifers and increase in keels (Fig.2). Ash layer was observed at 360-370 cm and was also documented by several others (see Pattan et al. 2003). Pyritized grains are present throughout the core. In core 39 the benthic foraminifers are low (5% - 57%) compared to that of the planktic foraminifers (5% - 75%) and keels (9% - 90%). The abundance of planktic foraminifers is found to be low during the late Holocene and LGM, and high during the early Holocene. Post-glacial sediments exhibit dominance of planktic foraminifers (Fig.3). The LGM sediments of both the cores showed the presence of *Globorotalia truncatulinoides.*

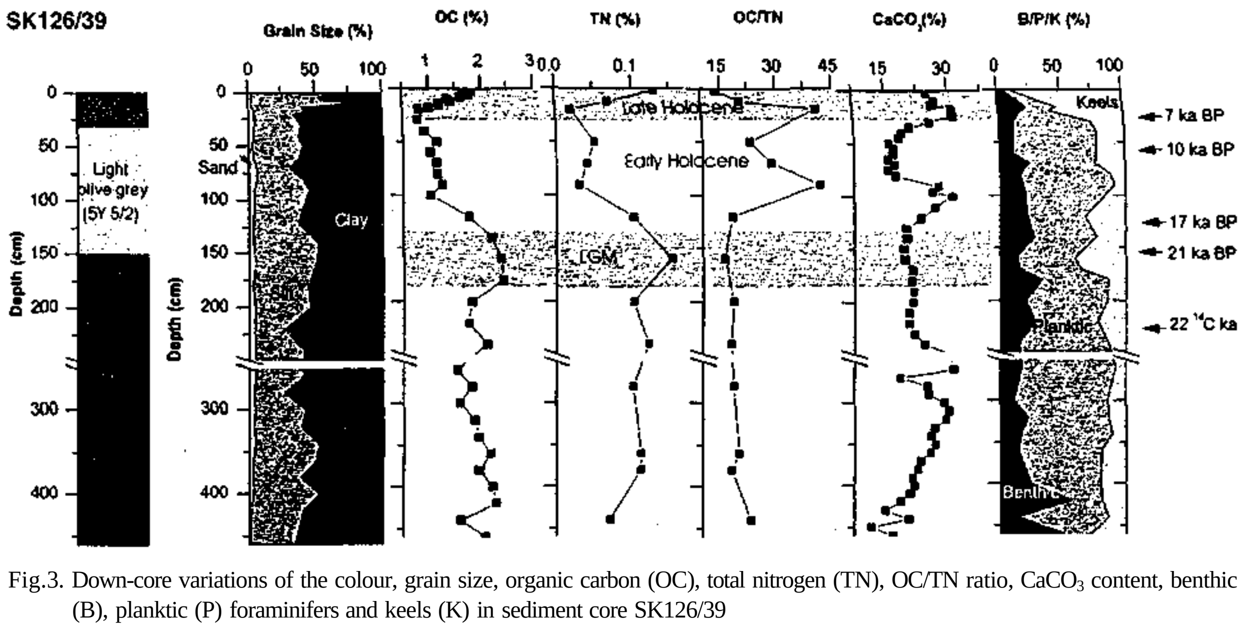

Fig.3. Down-core variations of the colour, grain size, organic carbon (OC), total nitrogen (TN), OC/TN ratio, $CaCO_3$ content, benthic (B), planktic (P) foraminifers and keels (K) in sediment core SK126/39

Organic Carbon (OC), Total Nitrogen (TN) and OC/TN Ratio

The OC content is higher in core 16(1.4% - 4.4%) than in core 39 (0.8%-2.4%). In core 16, the OC in the late Holocene (2.5% - 4.4%) and LGM intervals (3.1%) are higher than in early Holocene (1.7%-2.5%) intervals (Fig. 2). It varies from 1.4% to 3% in the late Pleistocene sediments (Fig. 2). In core 39 the down-core variations of OC in the post-glacial sediments mimic those in core 16. The OC content in LGM sediments is higher (2.2%-2.4%) than in early Holocene (0.8%-1.2%) sediments (Fig.3). It increases progressively in the late Holocene sediments, with 0.5% at 7 ka BP to 1.8% at the core top. The late Pleistocene sediments contain ~1.5% - 2% OC.

The total nitrogen (TN) content is higher in core 16 (0.05% to 0.43%) than in core 39 (0.02% to 0.15%). The down-core distribution of TN follows the trend of OC (Figs. 2 and 3). The OC/TN ratios are lower in core 16 (8.5-27.2) than in core 39 (14.1-40.5) (Figs. 2 and 3). In core 16 OC/TN ratio is low during the late Holocene and LGM and high during the early Holocene. The OC/TN ratios reach up to 40.5 in the post-glacial sediments of core 39. The OC/TN ratios in the late Pleistocene sediments of both the cores remain above 15 and do not show significant variations.

Rock-Eval Pyrorysis

The cores exhibit significant variations in the parameters of Rock-Eval Pyrolysis (HI, T_{max} and S_2- Figs. 4 and 5). In core 16, HI, T_{max} and S_2 are higher and their values range from 81 to 456 mg HC/g OC, 421°C to 432°C and 1.3 to 11.4 mg HC/g rock, respectively. The HI, T_{max} and S_2 values for core 39 are lower with values of 14 to 46 mg HC/g OC, 377°C to 412°C and 0.05 to 0.37 mg HC/g rock, respectively. In core I6, S_2 and HI follow the trend of OC. However, in core 39 HI increases with decreasing OC.

The HI, S_2 and T_{max} values in core 16 (81 to 456 mg HC/g OC, 1.3 to 11.4 mg HC/g rock, 421 °C to 432°C) are found to be much higher than that of core GC5 (24 to 198 mg HC/g OC, 0.35 to 7.56 mg HC/g rock, 390° to 421°C - Thamban et al. 1997), which was collected at 280 m within the OMZ waters from the same region (*see* Fig. 1 for location).

DISCUSSION

Nature of Organic Carbon in Core 16

High OC and TN occur throughout the core (Fig. 2). As the core is located within the upwelling-related high productivity (>1 gC/m^2/day - Qasim, 1977) region and on the lower continental slope one would expect abundant marine OC. The OC/TN ratio is 5 to 8 for fresh algae and,

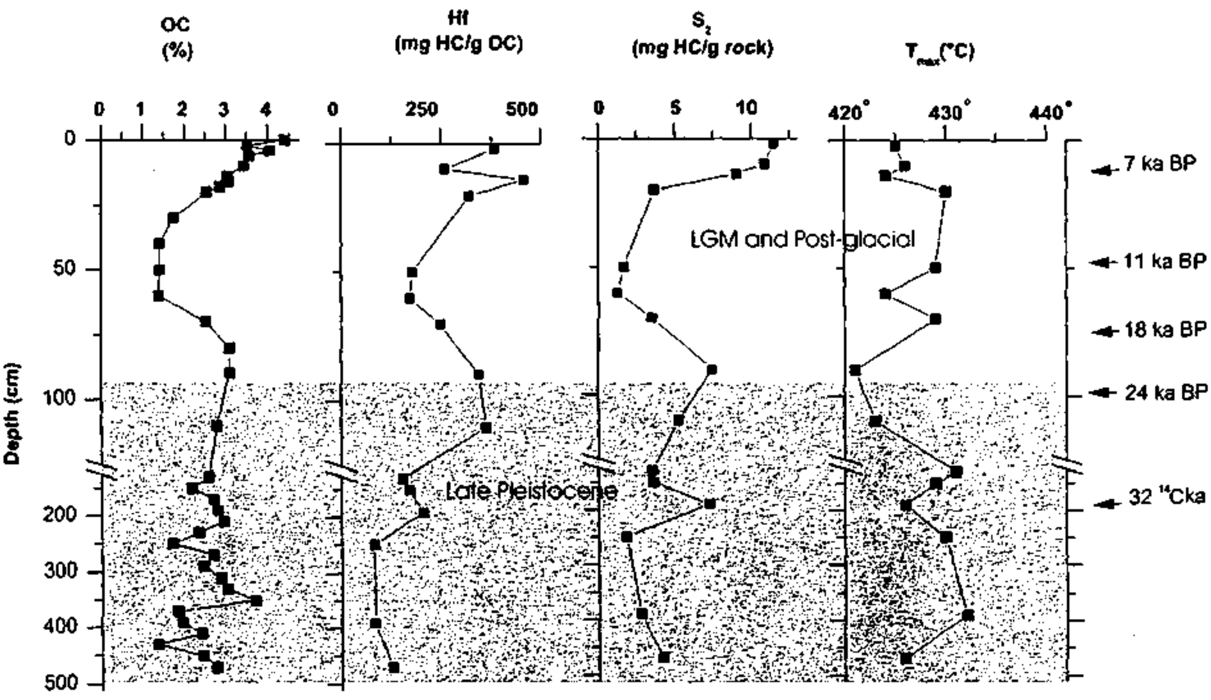

Fig.4. Down-core variations of the Rock-Eval parameters (organic carbon - OC, S_2 hydrogen index (HI) and T_{max}) in sediment core SK126/16.

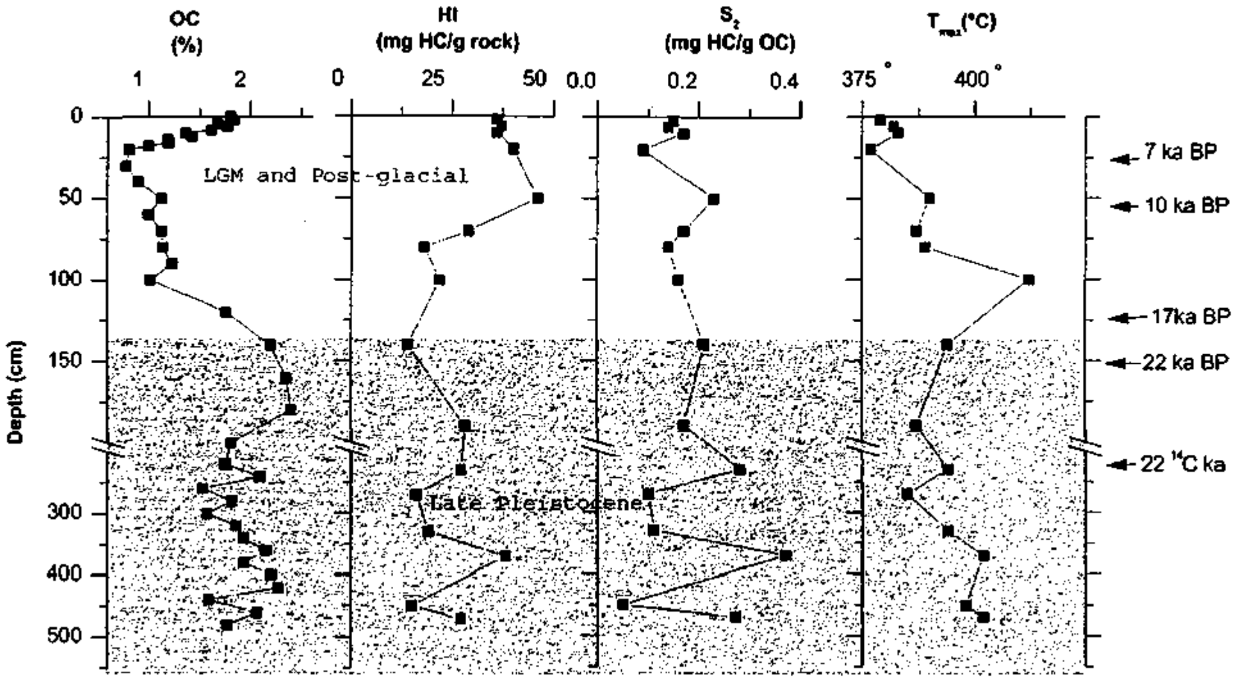

Fig.5. Down-core variations of the Rock-Eval parameters (organic carbon - OC. S_2 hydrogen index (HI) and T_{Max}) in sediment core SK126/39.

20 or greater for vascular plants (Emerson and Hedges, 1988). The OC/TN ratio is high (up to 19.5) for LGM sediments and decreases to 8.5 towards the core top (see Fig. 2) indicating mixed terrigenous and marine OC at the LGM and becoming dominantly marine towards the late Holocene. High OC/TN ratios (~13-14) in some parts of coastal upwelling, however, have been related to reflect degree of degradation of marine organic material, but not to the differing percentages of admixed terrestrial and marine material (Tyson, 1995).

The OC vs. S_2 plot (Langford and Blanc-Valleron, 1990) shows that the top 20 cm sediments (7ka BP) of the core fall within the domain of Type II kerogen (Fig. 6A). The sediments between 20 and 250 cm fall on or close to the boundary of the Type II and Type III kerogen and the sediments below 250 cm fall within the domain of Type III kerogen (Figs. 6A and 6B). Type II kerogen signatures may be the result of reworked sediments transported from the OMZ. The HI values of post-glacial sediments range from 171 to 456 mg HC/g OC. Organic carbon may represent a lipid-rich kerogen, since its HI values are more than 150 mg HC/g OC. It is expected to contain high phytoclast material as its HI values are >300 mg HC/g OC (see Tyson, 1995). Further, the slope of the regression line (Fig.6A) lies between that of Type II and III boundaries, indicating the dominance of marine OC (see Langford and Blanc-Valleron, 1990). This is also supported by the increase in number of planktonic foraminifers. However, OC/TN ratios are high, except for the surface samples. Selective preservation of terrestrial organic matter also increases the OC/TN ratio (see Tyson, 1995). The high OC/TN ratios and clay content at 11 ka - 7 ka BP may suggest increased terrestrial input (Fig. 2). It thus appears that the OC at the core top is largely marine with increased terrigenous influence towards the early Holocene.

The late Pleistocene sediments fall on or close to the boundary of Type II and Type III kerogen (see Fig.6B). This indicates the increase in terrigenous or reworked organic matter with depth in the core. It is not possible to invoke abundant terrigenous organic matter supply during the lowered sea levels since the adjacent shelf is a carbonate bank (Wedge Bank) consisting of abundant coarse carbonate skeletals and low OC. Reworking of marine organic matter can also results in increased OC/TN values. The OC is therefore marine with some reworked OC derived from the upper slope.

Nature of Organic Carbon in Core 39

Relatively low OC (0.8% - 2.4%) and high OC/TN ratios (14.1 - 40.5) are characteristic of core 39. As the core lies below the denitrification zone (Naqvi, 1991), high OC/TN ratios can be attributed to the loss of TN. HI values are also

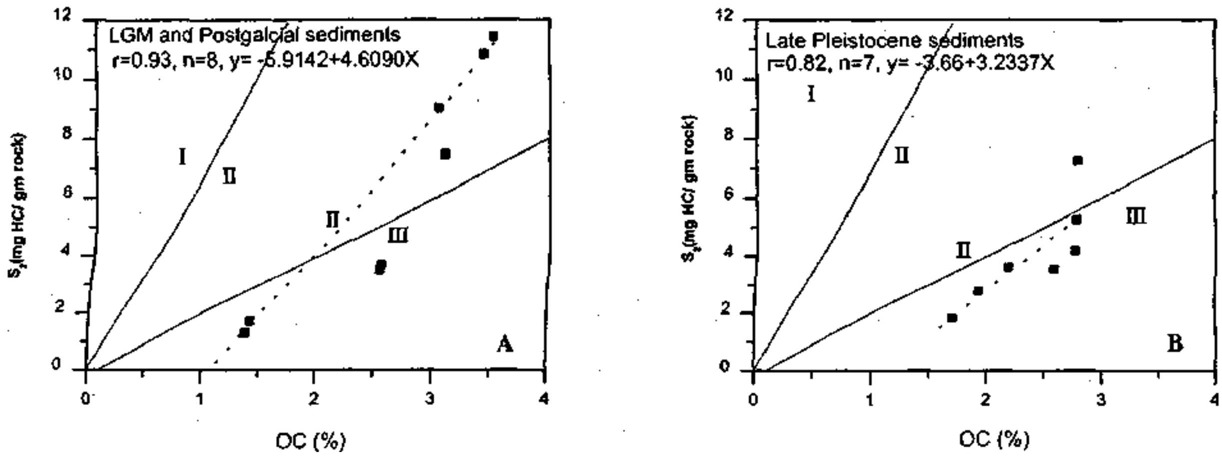

Fig.6. Relationship between OC and S_2 in LGM and post-glacial sediments (A), and late Pleistocene sediments (B) in core SK126/16. Solid lines are boundaries for Type I, II and III kerogens.

significantly low, indicating HI is affected by the amount of OC that is adsorbed onto or retained by the mineral fraction of the sediment during pyrolysis. The upcore increase of OC and planktic foraminifers, however, implies dominant marine OC in the sediments (Fig. 3). Moreover several workers reported the dominance of marine OC in this region, based on $d^{13}C$ values of OC (Naidu and Shankar, 1999; Thamban et al. 2001; Agnihotri et al., 2003). It is therefore likely that the OC is marine. Sediments exhibit Type III kerogen (Figs. 7 A and 7B) may be because of the degraded organic matter (that settled through OMZ), reworked organic matter transported from the upper slope and influence of denitrification on the organic matter. We therefore suggest that the Rock-Eval parameters may not be able to distinguish the type of OC at low OC concentrations.

Controls on OC Distribution in Sediment Cores

The OC content in marine sediments is controlled by primary productivity, oxygen content of the water or sediments, sedimentation rate, particle surface area, water depth and terrestrial vs. marine organic matter supply. High OC is not always associated with intervals of high sedimentation rates. For example, the LGM sediments showed high OC, low sedimentation rates (3.8 cm/ka in core 16 and 7.1 cm/ka in core 39) and high OC accumulation rates (0.03 and 0.02 g C cm^{-2} ka^{-1} for cores 16 and 39, respectively). While in the early Holocene sediments, low OC is associated with relatively high sedimentation rates (~7.4 cm/ka for 11 -7 ka BP in core 16; 12 cm/ka for 10-7 ka BP in core 39) and low OC accumulation rates (0.02 and 0.01 g C cm^{-2} ka^{-1} for cores 16 and 39, respectively).

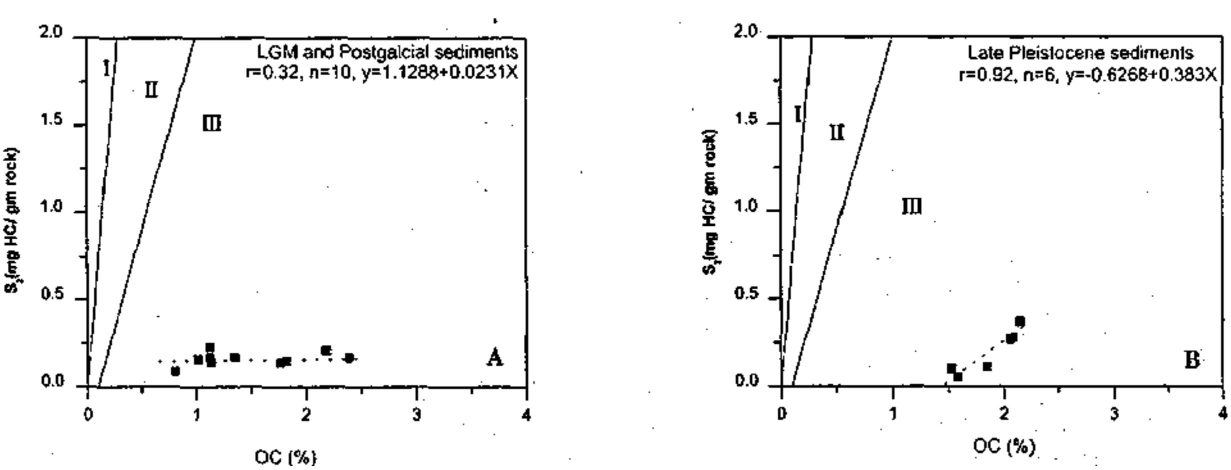

Fig.7. Relationship between OC and S_2 for LGM and post-glacial sediments (A), and late Pleistocene sediments (B) in core SK126/39. Solid lines are boundaries for Type 1, II and III kerogens.

Similarly, the late HoloCene sediments (since 7 ka BP) are characterised by high OC content, low sedimentation rates (3.4 and 4.2 cm/ka for cores 16 and 39, respectively) and low OC accumulation rates (0.02 and 0.004 g Ccm^{-2} ka^{-1} for cores 16 and 39, respectively). Therefore the sedimentation rate may not be the major controlling factor for OC enrichment.

The OC content (1.4% - 4.4%) in core 16, located below the OMZ, is higher than that of the core GC-5 (1.3% - 3.5% - Thamban et al., 1997), located within the OMZ. Therefore, preservation under oxygen-depleted waters may not explain the OC variations.

Demaison and Moore (1980) used HI as a preservation index and suggested that the sediments with high HI are deposited under oxygen-deficient bottom waters. HI values are relatively higher in core 16 (81-453 HC/g OC) located in well-oxygenated waters below the OMZ than in core GC5 (24-198 HC/g OC) located within OMZ. This implies that the preservation state of organic matter may not be completely related to the presence / absence of OMZ. The results are in agreement with those of Calvert et al. (1995), who reported high HI values at the lower margin of the OMZ and low HI in the oxygen-deficient zone. The results also suggest that the notion 'hydrogen-richness of the sediments preserved under anoxic / low-oxic conditions (Demaison, 1991)' may not work in all the areas. The influence of depth and particle surface area on OC content would remain nearly consistent, as both the cores were collected below the OMZ and the sediments are largely silty clay/clayey silts, Productivity and terrestrial/marine OC supply thus seem to be the major controls for OC variations.

PAST PRODUCTIVITY VARIATIONS IN CORES 16 AND 39

At about LGM and Late Pleistocene

The LGM sediments in both the cores are characterised by high OC and TN, and high planktic foraminiferal content in core 16 and high keels content in core 39 (Figs. 2 and 3). The high OC during the LGM is not unique to these cores, but reported by several others in the eastern Arabian Sea (~6% - Duplessy, 1982; Prell, 1984; 2-3% - Sarkar et al. 1990; 2.1% - Naidu and Shankar, 1999; 1.6% - Thamban et al. 2001). High productivity during the glacial stages in the southeast Arabian Sea was attributed to stronger NE monsoon that induced deepening of surface mixed layer and injection of nutrients to the euphotic zone (Rostek et al., 1993, 1997). The presence of *G. truncalulinoides*, an indicator of deep convective mixing (see Reichart et al., 1998), at LGM levels in both the cores suggests that our results corroborate earlier studies of Rostek et al. (1993, 1997) and Thamban et al. (2001).

The high $CaCO_3$ sand and planktic foraminiferal contents are centred at around 24 ka BP and 32 ^{14}C ka in core 16 (see Fig. 2). Here the maximum carbonate content is associated with low OC. This indicates that active redeposition of allochthonous material from the shelf during the lowered sea levels diluted the OC content. Processes such as turbid-layer transport or episodic gravitational redeposition have been described for the sediments of the Eastern Arabian Sea (von Stackelberg, 1972). The late Pleistocene sediments in core 39 are fine-grained with low sand and carbonate contents (Fig. 3). This implies that the fine-grained lithic material redeposited from the upper slope may have been the source of OC.

The Early Holocene

Reduced OC, TN and $CaCO_3$ values, increased clay content and relatively high sedimentation rates are characteristics of the early Holocene sediments (*see* Figs. 2 and 3). Low OC/TN points to low productivity. The occurrence of strong monsoonal event (11.5 - 6 ka BP - see Duplessy, 1982; van Campo, 1986; Sirocko et al., 1996; Thamban et al. 2001) was, however, reported during the early Holocene. Low productivity during times of intense monsoon is thus surprising. The following explains the discrepancy. During intense monsoon low saline cap (Stramma et al., 1996) and low saline nutrient-poor undercurrent (Naqvi et al. 1991) may have been well built. Low-saline surface waters (Rostek et al. 1993) and upwelling of low-saline waters (undercurrent) may have resulted in a stratified layer. Strong winds associated with the monsoon may not able to break the stratification and hence low productivity. Intensified monsoons were probably responsible for the increased clay content and sedimentation rates during this period.

The Late Holocene

The OC and TN increase towards the core top since 7 ka BP and are associated with the reduced sedimentation rates (Figs. 2 and 3). This increase probably reflects increased productivity in the overlying waters because of stronger monsoon-induced upwelling and preservation of OC in silty clay sediments. Several workers used $CaCO_3$/ sand content and abundance of *Globigerina bulloides* (upwelling indicator species) in the sediments as proxies for the productivity variations in the overlying waters (see Thamban et al., 2001 and references there in) and found co-varying patterns of these variables with OC. The increase in OC accompanied by decrease in $CaCO_3$ (Figs. 2 and 3) contradicts the above and needs explanation. Two possibilities may be considered, (a) The OMZ waters above core 16 are under saturated with respect to carbonate and would results in high corrosive effect on settling particles and dissolution of carbonate particles, especially pteropods. (b) During sediment diagenesis the $C0_2$ released due to the decomposition of OC deposited in oxygenated waters below the sediment-water interface can result in supralysoclinal $CaC0_3$ dissolution (Morse and Mackenzie, 1990). Covariance of the percentage of keels and OC (Figs. 2 and 3) supports this argument. Reichart et al. (1997) reported increased supralysoclinal dissolution of carbonate during the periods of high productivity on the Murray Ridge, northwestern Arabian Sea. We therefore suggest that these factors, operated simultaneously or independently at different times, are responsible for the overall decrease of carbonate/sand content of the sediments. The up-core decrease in clay percentage and low sedimentation rates may be due to the stabilisation of glacio-eustatic sea level at about 6,000 yrs BR This results in deposition of large sediment supply close to the coast and low supply at the continental slope.

Variations in OC on the Southwestern Margin of India

Fig. 1 shows the OC content in the surface (core top) sediments of 10 gravity cores collected between Cape Comorin and Marmagao. Except the core at 800 m, the OC content decreases from south to north in all other cores occurring either at shallow (286 m - 340 m) or deep depths (1380 m-2650 m) or, located within or below the OMZ. The decrease in OC may be due to the decrease in upwelling-induced productivity from south to north (Qasim, 1977; Shetye et al., 1990) under the influence of Rossby and coastal Kelvin waves (Shankar and Shetye, 1997). Significant lateral variations are, however, found between Marmagao-Mangalore and Mangalore-Cape Comorin. Between Marmagao and Mangalore the OC content in sediments below the OMZ is lower than those within the OMZ (see Fig. 1). It therefore appears that more OC is preserved in the OMZ sediments. However, Calvert et al. (1995) observed that the OC decreases westward away from the site of upwelling. The deeper water cores off Marmagao (2650 m) and North of Mangalore (1940 m) are indeed away from the coast (see Fig. 1) and decreased upwelling may have resulted in reduced organic carbon. The actual role of OMZ in these cores is yet to be ascertained. Between Mangalore and Cape Comorin the OC content in sediments below the OMZ (4.0%-4.4%) and at the lower boundary of the OMZ (see the core at 800 m depth with 4.9% OC) is higher than those within the OMZ (2.86% - 3.8% - see Fig. 1). The continental slope is also much steeper in this region (Rao and Wagle, 1997). The high OC values below the OMZ may thus related to increased productivity and down slope transport of OC. Off Mangalore the lowest dissolved oxygen content (DOC ~10 µM) in the water column corresponds to 150 m - 600 m, but the highest OC (4.9%) occurs at 800 m. This may also account the influence of productivity and down slope transport of OC, rather than oxygen minimum. Therefore the variations in OC content mimic the regional variations in the intensity of upwelling-related productivity and to some extent down slope transport of OC on the continental slope.

CONCLUSIONS

a) The OC in the sediment cores investigated here is dominantly marine origin.
b) Rock-Eval parameters distinguish the sources of organic matter only at high OC concentrations.
c) The spatial distribution of OC is related to the fluctuations in regional climate, its influence on sea surface hydrography and productivity.
d) The down-core distribution of OC in the sediments within and below OMZ is related to the productivity variations and down slope transport of OC.
e) High OC in the LGM sediments supports deep convective mixing on the southwestern margin of India. The low OC / $CaC0_3$ and high clay content during the early Holocene are consequences of the intensified SW monsoon, which resulted in a stronger near-surface stratification leading to low productivity. High OC and low carbonate content in the late Holocene sediments again suggest the influence of productivity and early diagenesis in near surface sediments.

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