

Productivity variations, oxygen minimum zone and their impact on organic enrichment in the sediments

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Introduction

Organic carbon is a very important component in marine sediments. It is derived either from land as organic detritus or is derived from oceanic surface productivity. The concentration of organic matter in the sediments depends on the quantity of supply of organic matter and environment of deposition. An array of biological, physical and chemical factors such as primary productivity of overlying waters, dissolved oxygen in bottom waters, texture of sediments and rate of sedimentation are responsible for the preservation of organic matter in marine sediments (Trask, 1939; Bordovskiy, 1965; Muller and Suess, 1979; Demaison and Moore, 1980; Paropkari et al., 1987; Pedersen and Calvert, 1990; Stein, 1990). However, in any given situation the importance of one factor over the other is debatable since varied and complex environments are often encountered in the oceanic realm. One of the existing notions is that the black shales are formed under conditions of water column anoxia (Demaison and Moore, 1980) and the same is applicable to the modern sedimentary carbon enrichment. In contrast, Calvert (1987), Pedersen and Calvert (1990) and Calvert et al. (1991) suggested that high primary production and not the water column anoxia provides a first-order control on accumulation of organic-rich facies in Cretaceous, Quaternary and modern oceans. From the foregoing inferences, it is evident that a key problem in studies of modern and ancient organic carbon-rich sediments is whether the enrichment of organic carbon is caused by increased preservation of organic matter under oxygen-deficient deep-water conditions, or by an increased production of organic matter in surface waters, or by both. The Arabian Sea is characterized by high productivity and also has delicately poised mid-depth intense oxygen minima and is most suitable to address the above debate. Besides, the 'rate of sedimentation' is also advocated to be an important parameter determining organic concentrations in oxic deep-water sediments during geological past and present (cf. Stein, 1990). In this regard, Bay of Bengal provides an opportunity to assess the role of 'sedimentation rates' in determining organic carbon contents in the sediments being the world's highest depocentre of terrigenous materials supplied by several large rivers such as Godavari, Krishna, Cauvery, Mahanadi, Irrawaddy and most importantly by world's largest river system Ganges-Brahmaputra. Thus, by taking the advantage of natural settings of the Arabian Sea and the Bay of Bengal, here the distribution and concentration of organic matter with

reference to depositional and environmental parameters is reviewed.

Distribution of Organic Carbon

The northern Indian Ocean consists of two major water bodies i.e. the 'Arabian Sea' in the west and the 'Bay of Bengal' in the east. The distribution of organic carbon in the surficial sediments of these areas (Northern Indian Ocean) is shown in Fig. 1. This figure shows that:

In the Arabian Sea

1. Overall, the organic carbon content is higher in peripheral portions and exhibits a decreasing trend towards the center of the basin. Within this distribution pattern, significant differences are also noticed.
2. High organic enrichments (>4%) are observed only along the mid-slope of the Arabian Peninsula and western India.
3. The sediments of the deeper Arabian Sea are poor in organic carbon (< 1 %).

In the Bay of Bengal

4. The organic enrichment occurs on the mid-slope and deeper slope along the eastern margin of India and in the western Andaman Sea.
5. The sediments of the deeper Bay of Bengal are poor in organic carbon (< 1 %).
6. No significant organic enrichments similar to the Arabian Sea are seen.

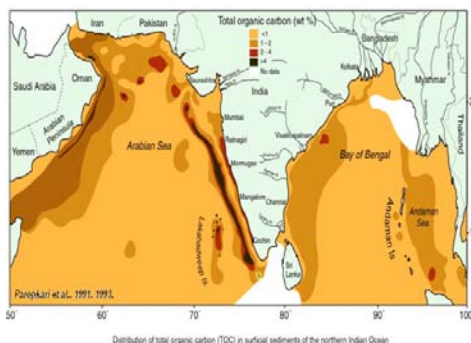


Fig. 1. Distribution of organic carbon in surficial sediments of the northern Indian Ocean (after Paropkari et al., 1991, 1993).

This distribution pattern is reviewed with reference to various depositional and environmental parameters in the following paragraphs.

Upwelling and Primary Productivity

Arabian Sea is characterized by seasonally reversing monsoon-driven surface circulation caused by typical wind patterns during SW monsoon and NE monsoon (Fig. 2). This results in variable upwelling, variable productivity and resulting variable export flux of organic matter to the seafloor (Nair et al., 1989; Haake & Ittekkot, 1990; Haake et al., 1993; Rixen et al., 1996; Haake et al., 1996; Lee et al., 1998; Honjo et al., 1999).

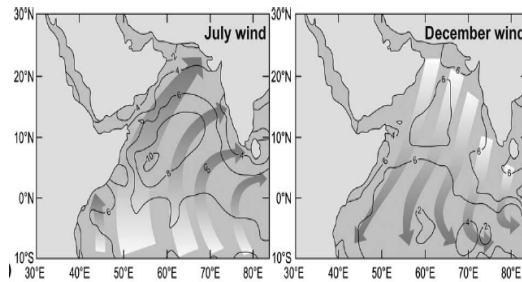


Fig 2. The seasonally reversing wind patterns of the Arabian Sea. (from Honjo, 1997).

The Arabian Sea covers about 1% of the world's ocean surface but, due to intense upwelling caused by the SW Monsoon and reversed circulation and mixed-layer deepening created by the NE Monsoon (Fig. 2), it accounts for some 5% of global marine primary production (e.g., Qasim, 1977, 1982). Primary productivity is highly variable, both seasonally and spatially, with periods of low productivity between monsoons and a general gradient from more eutrophic waters in the northern and western regions to more oligotrophic waters to the eastern and southeastern regions. As a result, the productivity is highly variable in space and time resulting in variable export flux with northwestern Arabian Sea recording highest export flux in world oceans (Fig. 3).

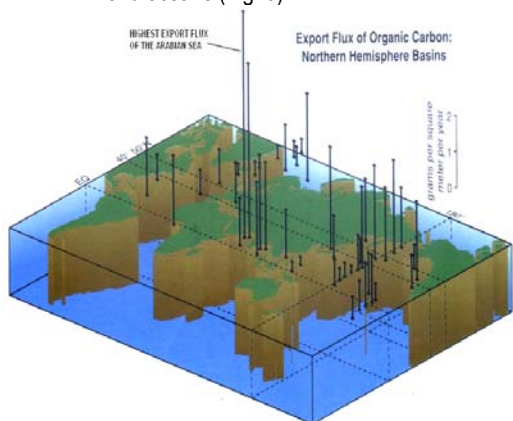


Fig. 3. The export flux of organic carbon in the Northern Hemisphere. (modified after Honjo, 1997).

In general, the distribution of organic carbon (Fig. 1) mirrors the surface productivity in the Arabian Sea

(Fig. 4), both being high in the peripheral portions compared to the central part suggesting that the surface productivity is the main source of organic matter in the sediments of the Arabian Sea. Further, various studies, such as C/N ratios (Paropkari et al., 1987), $\delta^{13}\text{C}$ values (Fontugne and Duplessy, 1986) and organic geochemical investigations (Caratini et al., 1981) confirmed that organic matter in the Arabian Sea is primarily marine. Nevertheless, an in-depth comparison reveals that the regions of high biogenic productivity ($> 0.75 \text{ g C/m}^2/\text{day}$) such as those off the Arabian Peninsula, Iran and Pakistan are underlain by sediments having variable organic carbon contents from very low to high concentrations ($< 1-7.54\%$). Comparatively, the productivity along most of the western Indian margin is almost threefold lower and yet the overall organic carbon contents are higher by a factor three to five. These observations show that the organic carbon distribution does not strictly reflect the surface productivity pattern.

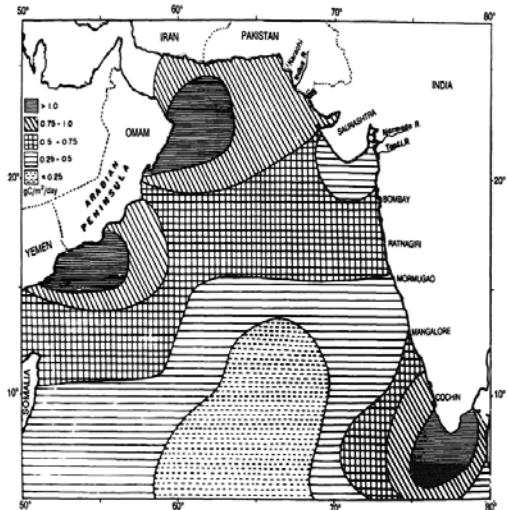


Fig. 4. Average annual column productivity of the euphotic zone in the Arabian Sea.

In the Bay of Bengal, the oxic outer shelf sediments are characterized by very low contents of organic carbon ($< 1.0\%$), except for few localized patches of intermediate concentrations (1-2%) (Fig. 1). Almost half the length of the shelves is characterized by poor productivity in overlying waters (Fig. 5). However, moderate to high and very high productivities covering large areal extent (more than half) of shelf occurs off major river mouths i.e. Godavari, Ganges-Brahmaputra and off Irrawaddy. The organic contents are uniformly high in outershell/upperslope regions even in the zones of poor productivity. This mismatch between productivity of overlying waters and organic content in sediments indicating that the primary productivity has no bearing on the organic content of bottom sediments. This is also supported by various investigations on the type of organic matter which have revealed that the organic

matter in the Bay of Bengal is mainly derived from the land.

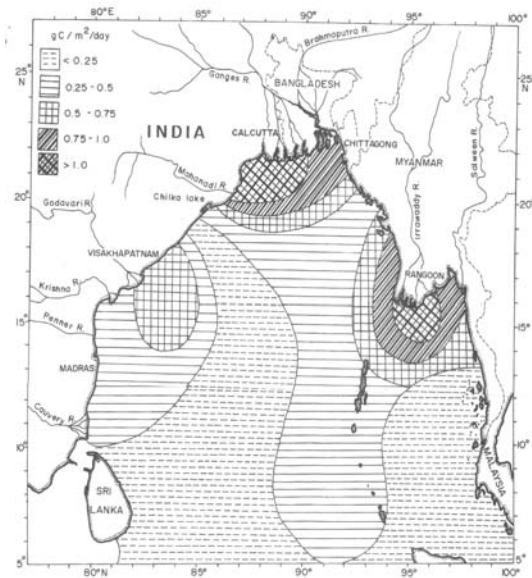


Fig. 5. Average annual column productivity of the euphotic zone in the Bay of Bengal.

The above observations clearly suggest that the surface productivity cannot be taken as a first-order control on organic enrichment in the bottom sediments.

Dissolved oxygen in bottom waters

The molecular oxygen reacts with the organic matter, causes its decomposition and destruction, and ultimately reduces its concentration. On the contrary, absence of molecular oxygen in the water column results in preservation of organic matter. Hence, the dissolved oxygen in the water column is an important parameter that can influence the organic matter in marine sediments. In relation to the preservation of organic matter, the *Oxygen Minimum Zone* (OMZ) is the layer of the 'anoxic' waters containing dissolved oxygen < 0.5 ml/l. This definition is based on the almost disappearance of sedimentary benthic organisms in response to the dissolved oxygen in bottom waters.

The distribution of dissolved oxygen in the northern Indian Ocean has been investigated thoroughly (Fig. 6). This shows that the water at shallower zones (up to 120 m) and at greater depths (below 1200 m) in the Arabian Sea are oxic (dissolved $O_2 = > 0.5$ to 5 ml/l) whereas anoxic waters prevail in mid-depths of 120 – 1200 m (Fig. 4; Wyrski, 1971; Von Stackelberg, 1972) and this zone is known as OMZ. In the Bay of Bengal severe oxygen depletion (dissolved $O_2 < 0.2$ ml/l) is found between about 100-600 m in the northwestern bay. (Wyrski, 1971; Naqvi et al., 1979). Presence of mid-

depth intense Oxygen Minimum Zone (OMZ) in the Andaman Sea is also reported (Rodolfo, 1969).

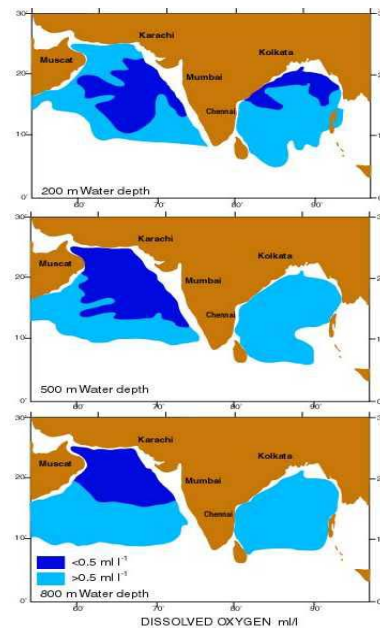


Fig. 6. Distribution of dissolved oxygen in the Northern Indian Ocean ('Oxygen minimum zone' defined as $O_2 = < 0.5$ ml/l shown in deep colour).

The low organic content (< 1 and 1-2%; Fig. 1) of sediments on the oxic shelves and upper slopes of Somalia, the Arabian Peninsula, Iran, Pakistan and Eastern and Western shelves of India (except a part of inner shelf), irrespective of primary productivity variation (Fig. 3), is mainly ascribed to decomposition of organic matter in contact with oxygenated bottom waters. Similarly, presence of oxic waters in the deeper slope and abyssal plains cause destruction of organic carbon which results in its lower concentration (Fig. 1). The relationship of dissolved oxygen with the bottom sediments in the Arabian Sea is depicted in Fig. 7.

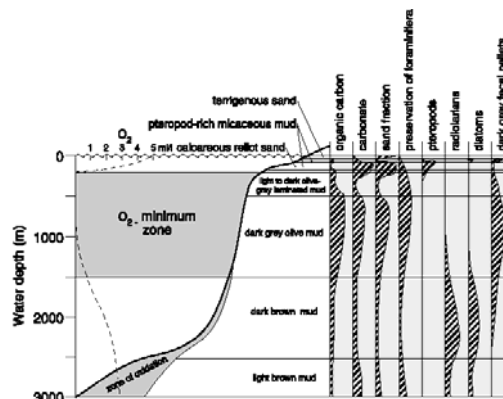


Fig. 7. Schematic diagram depicting the relationship between the dissolved bottom waters with the seafloor sediments (after Von Stackelberg, 1972)

In the western Arabian Sea, the surface productivity is very high which also influences the sedimentation of this region as revealed by the high content of biogenic components (Sirocko and Samrathin, 1989). Perhaps the influx of organic matter on the bottom exceeds the rate of its destruction by oxidizing bottom waters resulting in moderate (1-4%) organic enrichment. The zone of these moderate concentrations on the lower slope occurs as a wide band even in the deep sea adjoining the coast. This extensive coverage of high organic carbon is mainly attributed to the extension of high productivity zone ($>0.75 \text{ gC/m}^2/\text{day}$) far offshore.

In the central open Arabian Sea, low organic carbon content ($< 1\%$) can be ascribed to various depositional parameters such as the decrease in productivity away from peripheral land masses and scavenging and decomposition of organic fallout during its transit through a high water column reduces the marine biogenic supply to bottom sediments. Aeolian marine sediments provide the major part of sediments in the central Arabian Sea (Sirocko and Lange, 1991) and induce dilution of organic carbon. The poor supply of organic matter from the Indus (Ittekkot and Arain, 1986) may be one of the causes for the low organic content on the deeper Indus cone.

High organic enrichment (>4 up to 7.54%) is observed as bands along the mid-slope coinciding with the oxygen minima off Oman, along the Arabian Peninsula slope. Similarly, high organic contents are found as a wide and long band along the western Indian slope. The organic matter present on the anoxic slope is primarily of marine origin (Fontugne and Duplessy, 1986; Paropkari et al., 1987) derived from the productivity of overlying waters. It must be noticed that the high organic carbon band continues to be present on the slope despite variations in the productivity from low to moderate (Fig. 4). Moreover, the overall productivity is almost three fold lower along western slope of India than that of other coasts of the Arabian Sea. Nevertheless, moderate to very high concentrations of organic carbon (Fig. 1) are invariably associated with the entire slope sediments, forming a long and wide band in contact with oxygen minima from Saurashtra to the southern tip of India. It may be noted that the highest organic carbon values occur between Ratnagiri and Mangalore, precisely where the productivity is very low ($0.25\text{-}0.50 \text{ gC/m}^2/\text{day}$; Fig. 4). This mismatch of productivity and organic enrichment is a classic example that clearly demonstrates that the productivity of surface waters, although an important contributor of organic matter, does not necessarily cause the organic enrichment of underlying sediments.

Distribution of dissolved oxygen in the waters of Bay of Bengal have revealed the presence of mid-depth intense 'oxygen minimum zone' (OMZ) between the

water depths of $\sim 100 - 500 \text{ m}$ (Wyrski, 1971). Subsequent studies in the western bay have indicated presence of pronounced oxygen minimum layer in the northwestern bay lying approximately between 100-800 m while two oxygen minima were observed in the southwestern bay at 100-250 m and 400-600 m (Naqvi et al., 1979). The OMZ is relatively very thin (only $\approx 400 \text{ m}$) and occupies an area circumventing the slope from almost from southern most part of east coast of India up to central Myanmar coast. At times, the OMZ is very intense occasionally causing near-anoxic conditions along eastern outerslope / upperslope of India (Naqvi et al., 1979). The sediments in contact in this OMZ are invariably have higher organic carbon concentrations ($>1\%$), particularly in a small patch off Vishakhapatnam. Presence of mid-depth intense OMZ in the Andaman Sea is also reported (Rodolfo, 1969; Sen Gupta et al., 1981) in the Andaman Sea between 150 - 800 m water depths. The sediments in contact with the OMZ exhibit higher organic carbon contents ($> 1\%$), particularly upperslope of eastern margin of India as well the along the western slope of Andaman Sea.

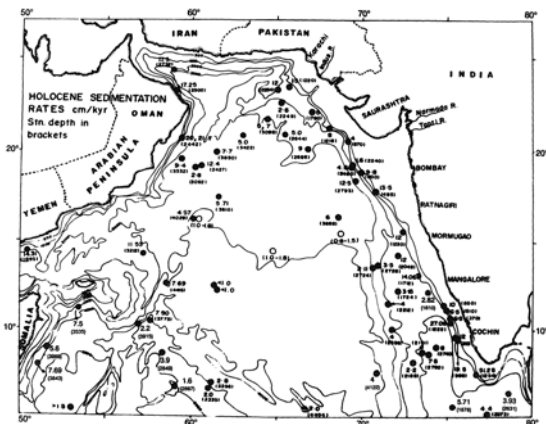


Fig. 8. The sedimentation rates in the Arabian Sea (compilation from various sources by Paropkari et al.,)

The sedimentation rates in the Arabian Sea are high in near-shore regions, especially in the eastern Arabian Sea (Fig. 8). The sediments of these near-shore regions are enriched in organic carbon contents. This high organic content is attributed to higher organic input, mainly of terrigenous nature as indicated by C/N ratios (10-30), protection of organic matter from oxidation by the fine nature of the sediments and higher rates of fine terrigenous deposition which lead to the preservation of organic carbon (Paropkari et al., 1987). The slopes are characterized by intermediate sedimentation rates which favor the preservation of organic matter by rapid burial. However, lowest sedimentation in deeper sea allows longer exposure of organic matter to the oxygen rich bottom waters and thereby causing their destruction. As a result, the sediments of this region are poor in their organic contents.

In the Bay of Bengal, the inner shelf areas off some of the river mouths are characterized by very high sedimentation rates (Fig. 5, Rodolfo, 1969; Sarin et al., 1979; Kuehl et al., 1989) which eventually result in low organic contents of shelves off these river mouths. The lower slopes (Fig. 5), are assumed to have moderate sedimentation rates ranging between 9 to 20 cm/kyr. In general, fine texture, abundance of smectite and moderate sedimentation rates result in enhanced organic carbon contents of these sediments. Higher sedimentation rates are common all along the deep bay bordering the continent (Fig. 5) indicating higher terrigenous input from coastal land mass as also evident from their low carbonate contents (Siddiquie, 1967; Kolla and Rao, 1990). However, the sedimentation rates are relatively much higher in the western bay than the central and the eastern bay (Fig. 5) suggesting higher terrigenous input in the former region particularly in the zone of organic-rich band. Thus, we believe that the organic-rich band owes its existence to higher sedimentation of terrigenous material largely comprising of smectite-rich mineral matter along with its detrital organic component. The sedimentation rates are invariably low in a large part of the eastern bay comprising upper and middle fan except in the vicinity of slope off Myanmar and in Nicobar Fan (east of Andaman islands) (Fig. 5). This results in low organic carbon contents of these regions. The organic carbon content of these sediments is low (<1%) which is attributed to dominance of organic-poor Ganges-Brahmaputra derived sediments and lower rates of sedimentation which permits effective destruction of organic matter. The increasing trend of calcium carbonate towards the central bay (Siddiquie, 1967; Kolla and Rao, 1990) as well as highly negligible sedimentation rates ranging between 0.2 to 0.7 cm / kyr in this region (Fig. 5; Udintsev, 1975; Sarin et al., 1979) indicates less terrigenous input from the surrounding land masses. This eventually leads to low input of detrital organic matter, a principal source of organic carbon in the sediments of the bay as revealed by afore mentioned studies. In the western Andaman Sea, the elevated concentrations of organic carbon are attributed to intermediate sedimentation rates along the foot of the western slope.



Fig. 9. Sedimentation rates in Bay of Bengal (compilation from various sources by Paropkari et al.,)

Texture

The textural characteristics considerably influence the organic content of the sediments of the Arabian Sea. On the shelves and upper slopes, predominantly coarse sediments (Stewart et al., 1965; Schott, 1968; Von Stackelberg, 1972; Nair, 1974; Udintsev, 1975; Paropkari, 1990; Hermelin and Shimmield, 1990; Shimmield et al., 1990) aid the effective destruction of organic matter by permitting easy diffusion of free oxygen and oxidizing salts in the sub-surface levels resulting in a lower organic carbon content. Further, the occurrence of residual/relict sands in these areas suggests deposition under high-energy environments whereby fresh organic matter is removed by the winnowing action of currents thus decreasing the organic content. This process is also aided by the narrow shelves, especially in the western Arabian Sea (almost absent at places along the Arabian Peninsula), which favors cross shelf transport thereby diverting the finer fraction towards the deeper sea.

In the Bay of Bengal and in the Andaman Sea the sediments are invariably fine-grained sediments derived from the major peninsular rivers systems of India as well as from Myanmar Rivers (Irrawaddy, Salween). These fine-grained sediments are responsible for the organic enrichments along the eastern slope of India and western Andaman Sea.

Clay minerals

The mineralogy of the clays also plays a significant role in the organic contents on the slopes of the Arabian Sea. The sediments on the continental slope along the Arabian Peninsula and that of Iran are depleted in their characteristic clay minerals and have abundant of carbonate minerals. These sediments are not favorable for accumulation of organic matter. The Indus derived illite- chlorite is abundant on the Pakistan slope and on the slope off Saurashtra (Guptha and Hashimi, 1985; Rao, 1991). These clay minerals also exhibit poor adsorption capacity for organic materials and hence are responsible for low organic content of this region. In comparison, river discharged smectite is a prominent clay mineral on most of the slope of western India (Paropkari, 1983; Rao et al., 1993) and in the western Bay of Bengal. This mineral has a relatively high reactive surface area and is thus capable of adsorbing more dissolved organic substances. This view is also supported by laboratory experiments of Hedges (1978). Therefore, smectite along the Indian margins may have aided preservation by adsorbing organics, which has also been noted by Kolla et al., (1981, ref). Thus presence of smectite clay mineral is responsible for the

higher organic carbon content. Further, the smectite on the Indian slope is the product of the tropical humid conditions, which prevail along the Indian coast, and do have some terrestrial organics bound to them. These organics, though insignificant, can also contribute to the total organic content of this slope region.

Conclusions

The above review clearly suggest that the preservation of organic carbon in the sediments of the Northern Indian Ocean is mainly controlled by the dissolved oxygen in bottom waters thereby resulting high organic enrichments in the areas in contact with the OMZ. The presence of slightly weaker OMZ and high

sedimentation rates perhaps result in slightly lower organic contents in the sediments of the Bay of Bengal. Nevertheless, higher organic contents even occurs on the deeper slopes of western Bay of Bengal which is attributed to intermediate sedimentation rates and the presence of smectite clays. Moreover, the sediments characterized by fine texture are enriched in organic contents than those with coarse texture in the entire northern Indian Ocean. Thus this study brings out the fact that although the dissolved oxygen is main reason for organic enrichments, other factors are also play crucial role in determining the organic contents of sediments.