

Environmental controls on the distribution of organic matter in recent sediments of the Western Continental Margin of India

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ABSTRACT: A large number of surficial sediment samples from the western continental shelf and slope regions were analysed for the organic carbon and total nitrogen content. The organic carbon and nitrogen contents of these sediments exhibit marked regional trends along and across the shelf region. The C/N ratios suggest that the inner shelf sediments consist of an admixture of organic matter derived from detrital and marine sources. It is also indicated that the influence of the detrital organic matter decreases away from the coast, and is found to be negligible in the slope region. (The primary productivity values encountered in the shelf and slope regions are highly variable, further, there is no direct relationship between the productivity in the overlying waters and organic carbon content of the underlying sediments.) The differences in the organic carbon content observed between the inner shelf and the outer shelf sediments could be attributed to the differences in the grain size of sediments, rates of sedimentation, activity of benthic population and to the role of oxygenated water present in the shelf environment. As against this picture in the shelf region the markedly high organic carbon content associated with fine grained sediments of slope region could be ascribed to the impingement of oxygen minimum layer on the sea floor which prevents the destruction of organic matter through oxidation. The presence of thick sediments in the slope region, the high organic matter of planktonic origin and the reducing conditions; constitute a favourable environment for these sediments to act as source beds for petroleum.

INTRODUCTION

Understanding the source and depositional environment of organic matter in recent marine sediments has direct bearing on the process of formation of ancient petroleum source beds and also in search for new oil fields. Formation of sediments in the marine environment which contains substantial amounts of organic matter consists of varied and complex processes involving multiple source parameters from terrestrial and marine ecosystems. The organic matter present in the water column, both particulate and dissolved, initially consists of all the major naturally occurring organic constituents of living organisms such as sugars, polysaccharides, amino acids, lipids, etc. During the sedimentation process, only a small portion of the initial organic matter reaches the bottom (Bordovskiy, 1965; Tissot and Welte, 1978). Within the sediments this organic matter is further subjected to various

chemical reactions and biological attack and finally only the stable form is represented in the sediments. Study of organic matter also reveals the process of sedimentogenesis and diagenesis of marine sediments. Also, organic matter plays a significant role in geochemical cycles of major and trace elements that accumulate in sediments.

Evaluation of organic richness, which is a gross qualitative index of oil generative potential, is carried out by measuring the amount of organic carbon present in sediments (Demaison and Moore, 1980). The documented oil source beds and oil shales around the world, fall in the range of organic carbon content between slightly less than 1% to over 20% by weight.

Since the publication of the classic review paper by Trask (1939) on the distribution of organic matter in recent sediments, greater attention was paid to the study of organic matter in relation to genesis of petroleum and importance of

environment on its distribution in the continental margins and deep seas. A systematic study of distribution of organic matter in the sediments of western continental margin of India began during the International Indian Ocean Expedition (1962-65). During this period, Indian Naval Ship INS Kistna and German research vessel Meteor, cruised over the western continental margin of India and collected sea floor sediment samples along a few traverses spaced at very large intervals. Based on these collections, a broad picture of the distribution of organic carbon in the sediments of the continental margin was reported by Murty et al., (1969) and Marchig (1972). During the same period, American research vessels Oceanographer and Requisite, collected a few samples from the northern part of the continental margin and the organic carbon content in these collections were reported by Stewart et al. (1965) and Setty and Rao (1972). Subsequently, during the period November 1973 and May 1974, Indian Naval Ship Darshak, carried out a number of cruises in the northern half of the western continental margin of India and several sediment samples were collected along closely spaced traverses down to the south upto Dabhol. Based on these collections and a few collections made earlier aboard the same ship, a brief account of the organic carbon content in these sediments was reported by Kidwai and Nair (1972) and Paropkari (1979). After the acquisition of the first Indian oceanographic research vessel, R.V. Gaveshani, by National Institute of Oceanography in the year 1976, a systematic study of the continental margin was taken up and detailed sampling of the margin between Port Dabhol and Cape Comorin in the south, was carried out during several cruises, and a few hundred samples collected along traverses spaced around 20 km apart.

In the present paper, the authors endeavour to synthesise the limited published data and the large amount of unpublished data available with the authors (Paropkari, 1983 and Rao, 1983) to present a composite map of the organic carbon distribution, in detail, along the western continental margin of India and to discuss the same in relation to the various environmental parameters that control the distribution of organic carbon in the sediments. Further, an attempt is made to indicate the differences in the organic matter contained in the near shore sediments and the slope

sediments. Probable areas where the sediments could act as potential source beds for petroleum genesis are also indicated.

METHOD

For the purpose of compilation of the organic carbon distribution map, data from 578 stations covering the entire continental margin were utilised. Most of the data were obtained from the publications of the authors themselves, while data for 40 stations (along five different sections) reported by Marchig (1972) were also incorporated. A review of the concerned literature indicates that three different methods were employed for the analysis of organic carbon in these sediments. In the first case, Marchig (1972) has employed the method of Harre (1958) for the estimation of organic carbon. In the second case, the method of ElWakeel and Riley (1957), was used for the estimation of organic carbon in the sediment samples from different stations: 33 stations (Murty et al., 1969); 3 stations (Setty and Rao, 1972); 22 stations (Paropkari et al., 1978); 78 stations (Paropkari, 1979); 234 stations (Rao, 1983) and 32 stations (Paropkari et al., under preparation). In the third case, organic carbon in 26 samples between shelf off Vengurla-Mangalore and 136 sediment samples between shelf off Mangalore-Cochin (Paropkari, 1983) were analysed using Perkin-Elmer Elemental Analyser (CHN Analyser) Model 240 B, after treating the samples with dilute HCl for removal of carbonate carbon.

The total nitrogen content of sediments between Ratnagiri and Mangalore (26 stations) and between Mangalore and Cochin (136 samples) (Paropkari, 1983) was estimated using Perkin-Elmer Elemental Analyser (CHN Analyser) Model 240 B along with organic carbon. This data and the nitrogen data from Marchig (1972) for 40 stations, analysed by the gas volumetric method of Pregi and Roth (1958) were utilised for compiling the C/N ratio distribution map.

Though different methods were employed in the above mentioned literature, our experience shows that in spite of the differences with methods adopted, the ranges of values obtained for the different sediment facies remained more or less same within the limits of the experimental error.

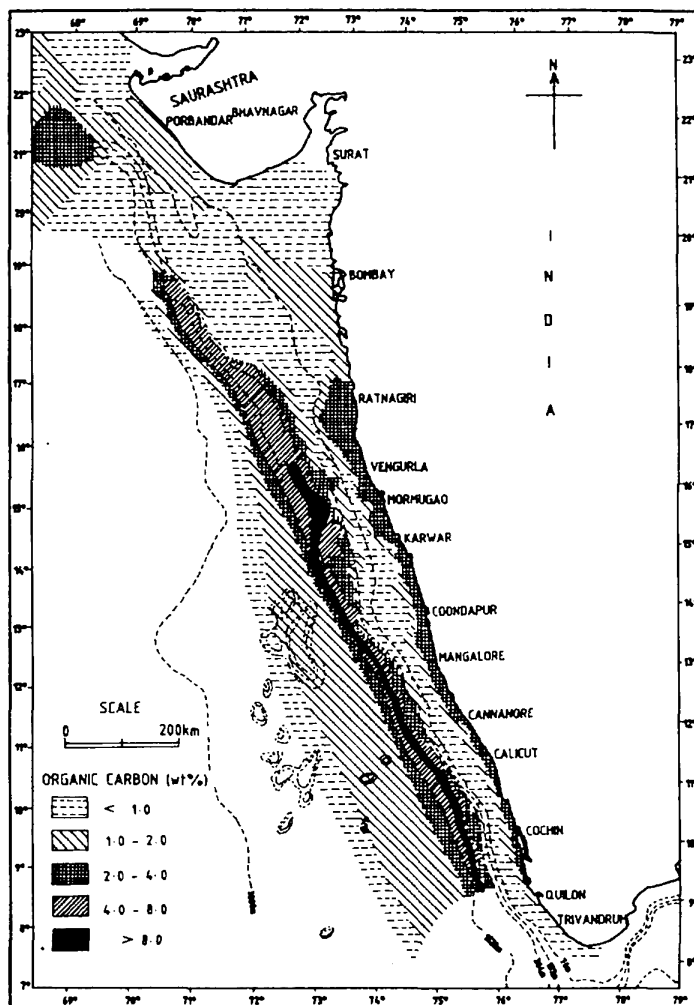


Figure 1. Distribution of organic carbon.

RESULTS AND DISCUSSION

From the values obtained for organic carbon and the total nitrogen content, areal distribution maps are prepared showing the distribution of organic carbon in the sediments and the distribution of C/N ratios in figures 1 and 3, respectively. An examination of these figures permits the following observations to be made.

Organic carbon

The organic carbon content of these sediments exhibits marked regional trends along and across the shelf region.

Along the shelf (from north to south) sediments of the region north of Ratnagiri have their organic carbon content in range <1.0-2.0%; sediments from the region between Ratnagiri and Quilon 1.0-4.0%; and the sediments in the southern region <1.0%.

Table 1. Ranges of the organic carbon content and their averages in the different regions of study area.

Area	Region	Range (wt%)	Average
North of Ratnagiri	Inner shelf	0.24 - 3.10	1.35
	Outer shelf	0.20 - 1.83	1.01
	Slope	0.62 - 6.40	3.10
Between Ratnagiri and Quilon	Inner shelf	0.35 - 3.53	2.03
	Outer shelf	0.04 - 3.99	2.90
	Slope	0.58 - 12.00	3.43
South of Quilon	Inner shelf	0.10 - 0.60	0.22

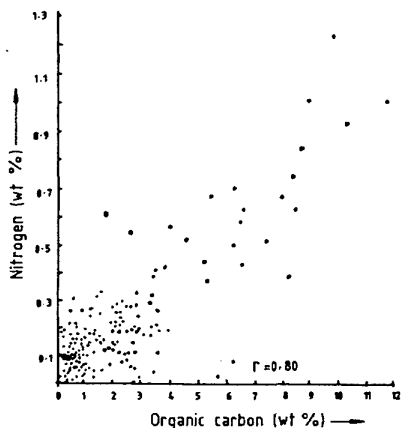


Figure 2. Relation between organic carbon and total nitrogen

Across the shelf, organic carbon content exhibits a clear cut zonation, in that, the sediments of the inner shelf region (< 50 m depth) have relatively high organic carbon content compared to that associated with the sediments of the outer shelf region (50-120 m depth). This is particularly true for the region between Ratnagiri and Quilon, while in the region north of Ratnagiri, major portion of the shelf region is characterized by very low (< 1.0%) organic carbon content with only few localised patches having organic carbon content between 1.0-2.0% occurring off Bombay and off Saurashtra coasts.

In the slope region a wide variation is observed in the organic carbon content of the sediments. Even within this wide variation, a clear cut zonation is discernible between Bombay and Quilon. Lowest values of organic carbon (< 1.0%) are

encountered at the foot of the slope (depth > 2,000 m). The values of organic carbon content show a progressive increase eastwards upto the shelf edge (zones of 1.0-2.0%, 2.0-4.0% and 4.0-8.0%). However, a sedimentary zone having its organic carbon content > 8.0% occurs in the mid slope region sandwiched between the zone of 4.0-8.0% in the upper slope and in the lower slope. This high organic carbon content zone is restricted to the region between Vengurla and Quilon. As against the higher values registered in the continental slope region between Bombay and Quilon, comparatively low values of organic carbon content are observed in the northern part of the slope region (1.0-4.0%).

The zone of higher organic carbon content in the region between Ratnagiri and Karwar is much wider than in the other parts of the slope.

The ranges of organic carbon content of the sediments and their averages are presented in table 1.

Nitrogen

The total nitrogen content in the sediments varies from 0.1-1.25% and its distribution is broadly similar to that of organic carbon. The scatter plot (Fig. 2) shows that there is a strong positive correlation between organic carbon and total nitrogen content. The C/N ratios computed for the sediments vary from 0.5-57. The C/N ratios show a distinct pattern of distribution (Fig. 3) which is described below:

In the region north of Vengurla, the ratios are in general less than 10.

In the region between Vengurla and Cochin, the C/N ratios show a clear cut zonation along and across the shelf and slope. Higher ratios (10-15 and > 15) are invariably associated with the sediments of the inner shelf region (< 50 m), however, small patches having a ratio of < 10 occurring here and there. In the outer shelf region (50-120 m)

the majority of values are < 10 and higher values (10-15 and > 15) occur in small pockets all along the length (north to south) of outer shelf. Further, sea ward in the upper slope region, the sediments are characterised by higher C/N ratios (10-15 and > 15). This higher zone, extends all along from Vengurla to Cochin with occasional patches of values < 10 occurring here and there. Thus the distribution of C/N ratios closely follows the organic carbon content of sediments.

The sediments of lower slope (> 1,500 m depth) and further deeper portion of the western continental margin have C/N ratios less than 10.

It is a well established fact that distribution of organic matter is governed by a set of hydrographical, as well as, sedimentological parameters. Sverdrup et al. (1942) pointed out that abundant supply of organic matter in the overlying water column, rapid rate of accumulation of fine grained inorganic matter and low oxygen content of water immediately above the bottom sediments favours preservation of organic matter in marine sediments. Recently, Demaison and Moore (1980) reviewed the distribution of organic carbon in the world oceans in relation with various biological and physical parameters especially in relation with anoxic environments and oil source bed genesis. Therefore, an attempt is made here to discuss the distribution of organic carbon in relation with various parameters such as upwelling and primary productivity, dissolved oxygen in bottom waters, texture of sediments, rate of sedimentation and benthic fauna.

Upwelling and primary productivity

The presence of strong seasonal upwelling along the western continental shelf of India is well documented (Jayaraman and Gogate, 1957; Banse, 1959, 1967; Carruthers et al., 1959; Ramamirtham and Jayaraman, 1960; Varadachari and Sharma, 1964; Reddy and Shankaranarayanan, 1966; Sharma, 1968). These studies have revealed that there is a time lag in the occurrence of this phenomenon from south to north followed by a decrease in its intensity also from south to north.

Upwelling of water along west coast, fertilise surface layers of sea which readily support phytoplankton production. Primary productivity along western continental margin of India was studied at several stations during different seasons

and an average annual picture of the column productivity of waters of the region is given by Qasim (1977). The column productivity of waters varies from 0.25 - 1.0 gC/m²/day (Fig. 4). The area under study can be divided into three regions- high, medium and low- based upon the productivity values.

1. The area off Gulf of Kutch and the region off southwest coast of India from Calicut to southern tip of India as a region of high productivity (0.75-1.0 gC/m²/day).
2. The areas off Saurashtra coast and the region between Bombay and Ratnagiri and between Mangalore and Calicut as regions of medium productivity (0.50-0.75 gC/m²/day).
3. Regions between Gulf of Kutch and Bombay and between Ratnagiri and Mangalore as regions of low productivity (0.25-0.50 gC/m²/day).

Dissolved oxygen in bottom waters

Considerable amount of data is available on the dissolved oxygen content of the bottom waters along the western continental margin of India (Reddy and Shankaranarayanan, 1968; Sharma, 1968; Stackelberg, 1972; Rao et al., 1978; Sen Gupta et al., 1980). The dissolved oxygen content in the waters of the continental shelf of Quilon, Cochin, Calicut and Mangalore is given in figure 5. (Sharma, 1968). The distribution pattern of dissolved oxygen content in the slope waters is given in figure 6 (Stackelberg, 1972). These figures clearly indicate that the shelf waters are well oxygenated upto a depth of about 150m, while the waters in the slope region are depleted in their dissolved oxygen content. These low oxygenated waters (less than 0.5 ml/l) extend from a depth of 150-1,500m.

During the upwelling period, the low oxygenated waters reach the subsurface and sometimes surface layers near the coast. Reports of heavy mortality of bottom animals during certain seasons (Carruthers et al., 1959; Seshappa, 1953) and consequent anoxic conditions are perhaps a transient or passing feature and not long enough to maintain low redox potentials, and hence reducing conditions. Another factor that maintains oxidation conditions in the shelf waters is the considerable mixing that takes place in them.

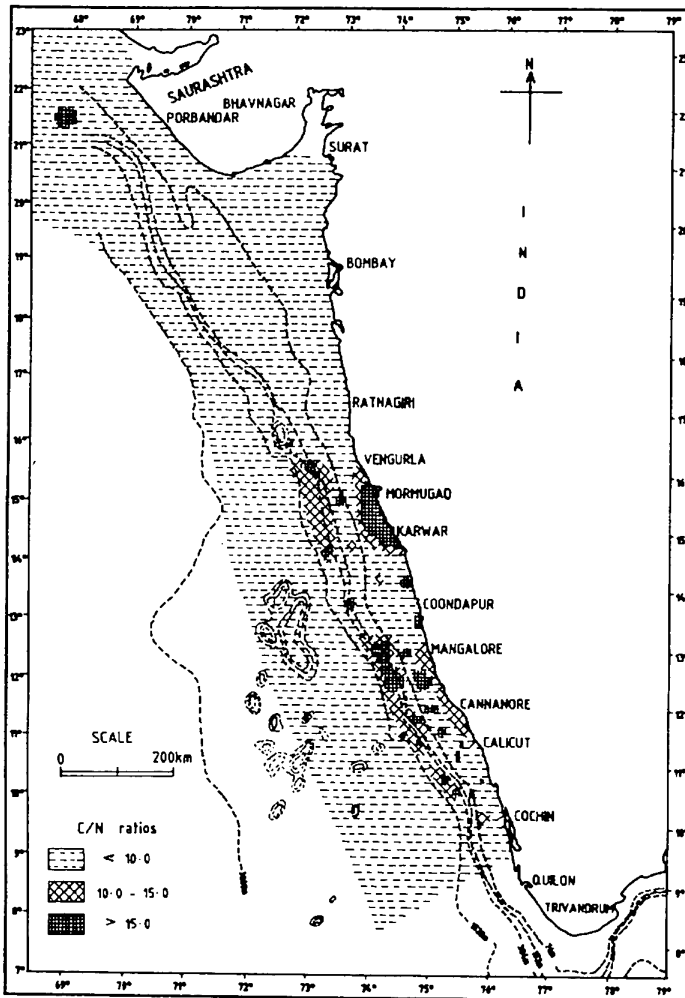


Figure 3. Distribution of C/N ratios

Texture of sediments

Sediment distribution map prepared for the western continental margin of India is presented in figure 7. From this map it could be seen that texturally the sediments could be classified into clays, silty clays, clayey silts, silt, silty sand, clayey sand, sandy clay, sand-silt-clay and sand. As regards their distribution, the fine grained sediments (clays, silty clays, clayey silts) are confined

to the inner shelf region (less than 50m depth) upto Quilon, south of which is covered by terrigenous sands. These are followed sea wards by sands, silty sands and clayey sands in the outer shelf region (50-120m depth). While this is the distribution of sediments in the region between Gulf of Kutch and Cape Comorin, the entire shelf region north of Gulf of Kutch is completely covered by fine grained sediments. In the continental slope region, fine grained sedi-

ments are again encountered as in the inner shelf region.

Chemically, the inner shelf sediments are characterised by very low calcium carbonate content. The coarser sediments in the outer shelf region are associated with high calcium carbonate content mostly contributed by skeletal and non-skeletal components. This distribution pattern is found to be characteristic of the region between Gulf of Kutch and Mangalore. In the southern region, though sands occur in the outer shelf region as in the north, they differ chemically from the sands in the north, in that, they are mostly quartz sands. In the slope region, the calcium carbonate content of the sediments is relatively low compared to the carbonate content of the sediments in the outer shelf region, in the region between Gulf of Kutch and Mangalore, while in the southern region the reverse is the case. However, it should be mentioned here, that the high calcium carbonate content recorded in the slope region in the southern half (south of Mangalore) is not a continuous feature but occurs in patches (Paropkari, 1983).

This western continental shelf of India was subjected to Holocene transgression and the sediments of the outer shelf region are classified as relict in nature (Stackelberg, 1972; Nair and Hashimi, 1980).

Rates of sedimentation

The presence of terrigenous silts and clays in the inner shelf region and the coarse grained carbonate sands in the outer shelf region clearly indicate that the inner shelf region is characterised by a rapid rate of sedimentation than the outer shelf region. A few quantitative estimates made in the inner shelf region have indicated that the maximum rate of sedimentation is of the order of 1.5-1.9 cm/1000 years (Stackelberg, 1972; ZoBell, 1973; Borole et al., 1982). It may be mentioned here that the values reported by Borole et al. are from off the river mouths (Narmada and Tapi) and perhaps they cannot be taken as general rates of sedimentation for the entire west coast. It is quite likely that where major rivers are not present, which is the general case along the west coast, the rates are expected to be much lower and, further, the differences in the rates from region to region cannot be precluded.

The upper continental slope is also

characterised by high rates of sedimentation though not as high in the coastal areas. The estimated rate of sedimentation in this zone is around 40 cm/1000 years (ZoBell, 1973). Further in the deeper regions, the rates of sedimentation steeply decrease to values as low as 1.0 cm/1000 years (Stackelberg, 1972; ZoBell, 1973). In the outer shelf region recent sedimentation can be said to be practically nil considering the absence of fine size material and the presence of many relicts of planktonic organisms and exposure of relict sands rich in oolites which were formed in very shallow stirred waters during the time of lower strands of sea level.

A comparative study of the distribution pattern of organic carbon with the environmental parameters described above have brought out the following salient features:

1. The organic carbon content of the sediments follows closely the texture of the sediments. This explains partly the higher organic carbon content associated with the inner shelf and continental slope regions and the lower organic carbon content with the outer shelf region.
2. Within this broad pattern of distribution, considerable variations are noticed in the organic carbon content even in the sediments of the same textural characteristics.
3. In the inner shelf region, although fine grained sediments are encountered all along the shelf except south of Quilon, the organic carbon content shows considerable variations - sediments of the region north of Ratnagiri have lower values of organic carbon content (less than 1% and 1-2%), sediments of the region between Ratnagiri and Quilon have higher ranges of organic carbon content (less than 1% to 4%) while the sediments south of Quilon are very poor in their organic carbon content (less than 1%).
4. While the low organic carbon content associated with the coarser sediments of the outer shelf do not show any appreciable difference except in the northern most part of the area, off Saurashtra coast, the sediments of the continental slope are characterised by high organic carbon content, sometimes two or three times more than the inner shelf fine grained sediments.
5. A consideration of the environmental parameters indicate that this shelf is subjected to seasonal upwelling with differing intensities and time lag from

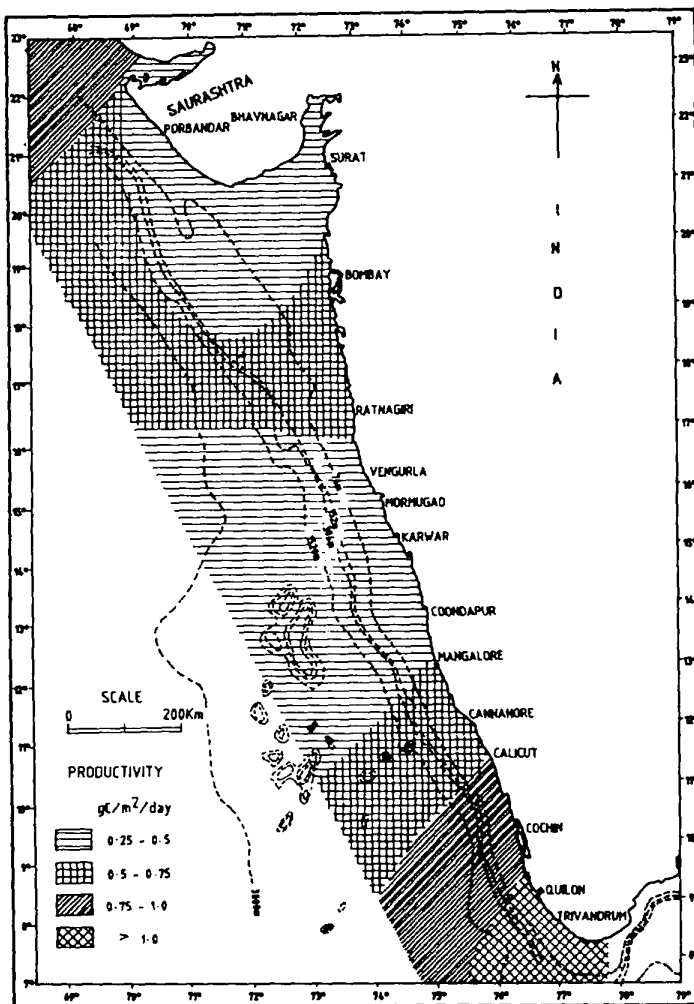


Figure 4. Column productivity of overlying waters (Quasim, 1977)

south to north, high biological productivity and well oxygenated waters except in the depth region between 150 and 1,500m water depth, where anoxic conditions prevail. Since the influence of upwelling and the ranges of dissolved oxygen content in the bottom waters are found to be more or less similar all over the shelf region, the other factors, namely biological productivity, texture of sediments, rates of sedimentation and perhaps activity of benthic fauna, seem to play an

important role in bringing out the differences in the distribution pattern of organic carbon observed in the shelf region. The same is discussed zone wise.

Inner shelf region

In the inner shelf region, the regions of high biological productivity are encountered off north of Gulf of Kutch and the region off southwest coast of

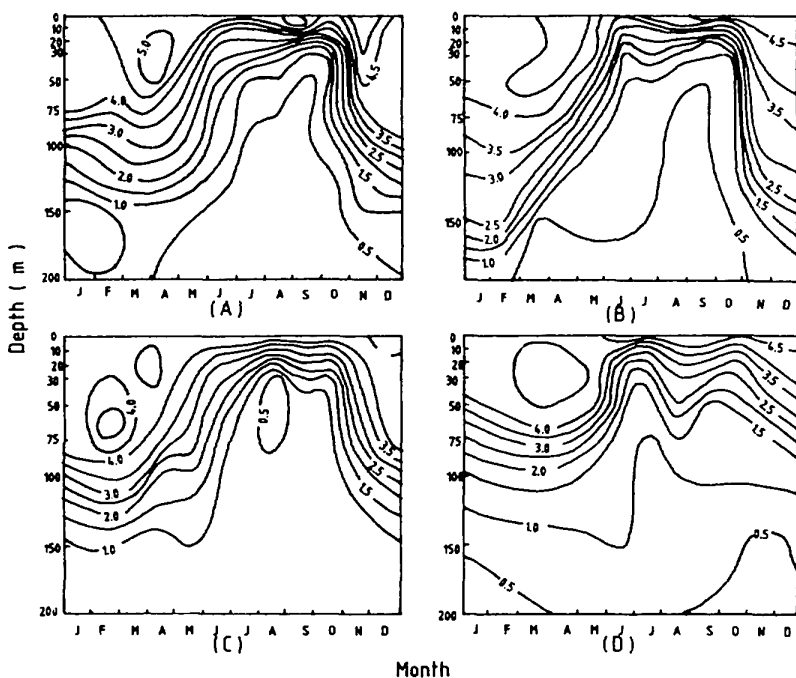


Figure 5. Vertical time section of dissolved oxygen content of the shelf waters off (A) Mangalore, (B) Calicut, (C) Cochin, and (D) Quilon (Sharma, 1968)

India from Calicut to southern tip of India; medium biological productivity off the areas of Saurashtra coast, the region between Bombay and Ratnagiri and between Mangalore and Calicut; low biological productivity between Gulf and Kutch and Bombay and between Ratnagiri and Mangalore. While the biological productivity is a consequence of the seasonal upwelling, the organic carbon content of the underlying sediments does not seem to bear a direct correlation with the productivity observed in the overlying waters. The lowest values of organic carbon content (less than 1%) encountered in the region north of Gulf of Kutch and off Gulf of Cambay, appear to be more due to the high rates of sedimentation in these areas and the consequent dilution of organic carbon by fine grained inorganic material. But at the same time, the organic carbon content in the range of 1-2% contained in the bottom deposits off the the Saurashtra coast appear to be due to slightly higher values of primary productivity, reported from this region, presence of

a thin veneer of fine grained sediments on the sea floor as evidenced from the echograms (Nair et al., 1982) which indicates low rates of sedimentation and consequently lesser amounts of dilution of organic carbon. The low organic carbon content registered off Bombay-Ratnagiri area (1-2%) could be due to low rates of sedimentation as compared to Gulf of Cambay and partly due to oxidation of organic carbon by the oxygenated bottom waters. Another factor which may be contributing to the low organic carbon content of these deposits is the rich benthic fauna that characterise this area (Harkantra et al., 1980).

In the region between Ratnagiri and Quilon, the high organic carbon content encountered in the inner shelf sediments is due to the presence of fine grained sediments with probably sedimentation rates not high enough to dilute the organic carbon content too much and also due to the greater intensity of upwelling. While this is broadly so, within this region, the higher organic carbon content noticed in the inner shelf

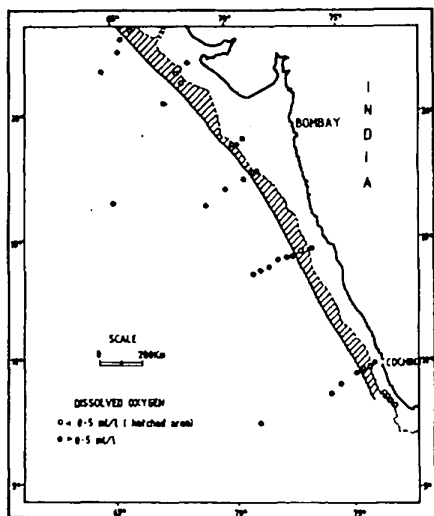


Figure 6. Dissolved oxygen in the bottom waters (Stackelberg, 1972)

sediments between Ratnagiri and Mangalore in spite of low biological productivity in the overlying waters, seem to be the result of (1) additional supply of organic material from the land through rivers directly to the nearshore region in the absence of any coastal lagoons, and (2) the presence of very little benthic population in the bottom deposits. In the region between Mangalore and Quilon, though the biological productivity is high as compared to Ratnagiri-Mangalore region, the organic carbon content of the underlying sediments is similar to the region between Ratnagiri and Mangalore. This can be ascribed to moderate rates of sedimentation, high percentage of benthic population that inhabits this region and trapping of most of the land derived organic material in the coastal lagoons present along the coast upto Quilon.

In spite of the very high biological productivity in the overlying waters, the lowest values of organic carbon present in the sediments south of Quilon is due to the presence of coarse sediments high dissolved oxygen content of the bottom waters and lack of fine grained inorganic material to provide any protection to the organic carbon content against oxidation.

Outer shelf region

Irrespective of the differences in the biological productivity of the overlying waters, uniformly low values of organic carbon content are encountered all over the outer shelf region. This low organic carbon content is attributable to (1) the coarse grained nature of the sediments coupled with high carbonate content in the region upto Mangalore and further south of their high silica content, (2) the presence of oxygenated waters in the region from the surface to bottom which accelerate the decomposition of the organic material both in the water column, as well as, at the sediment-water interface and subsurface levels. Further, the low rates of sedimentation as evidenced from the absence of any significant amounts of fine grained inorganic material in the deposits and the scouring of the sea floor by strong currents contribute to the low organic carbon content recorded in these sediments.

Continental slope region

The continental slope region presents altogether different conditions from those in the inner and outer shelves. In the terminology of Schott (1968) and Stackelberg (1972), the continental slope region is carpeted by laminated mud, olive gray mud and dark brown mud. The distribution of the sediments in this region is to a considerable extent determined by the morphology of the sea bed. The material originating from the continent and/or the shelf is less transported by the action of the water than by the force of gravity.

The upper continental slope is characterised by the presence of fine material most of which has been whirled up in the zone of the relict sands of the outer shelf and deposited in this region. The rates of sedimentation also are considered to be qualitatively high. This zone is followed seawards by olive gray mud deposits and further down, dark brown mud. The first two deposits, namely the laminated mud and the olive gray mud, are overlain by oxygen minimum waters at the bottom (150-1,500 m). Above and beyond this oxygen minimum layer, somewhat higher dissolved oxygen waters are to be observed at the sea bottom (150-1,500 m). Bottom fauna and consequently bioturbation is totally absent in the first two sediment facies.

In the environmental conditions des-

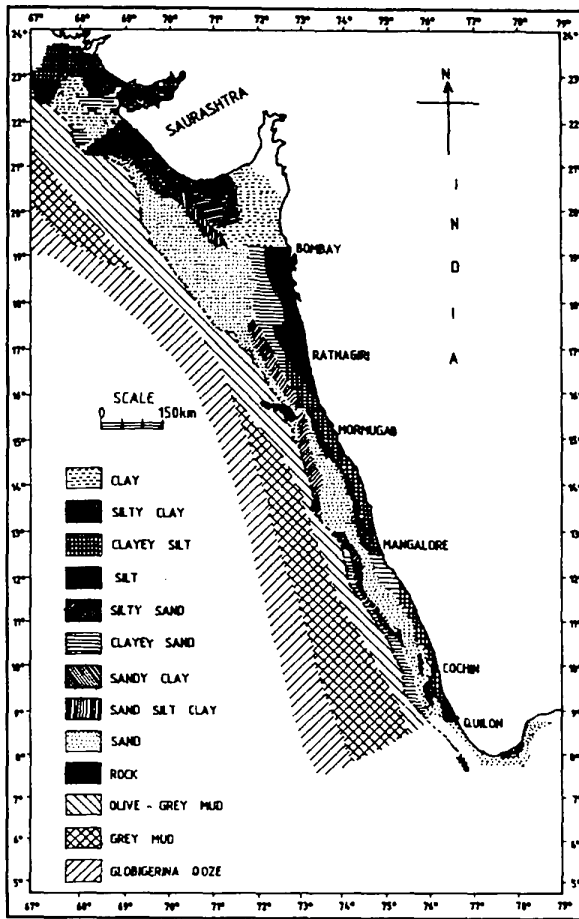


Figure 7. Sediment distribution map (after Nair and Hashimi, 1980; Hashimi, Kidwai and Nair, 1981; Stackelberg, 1972)

cribed above, the organic carbon content registered in these sediments is much higher compared to the inner shelf sediments, but at the same time, variations are found in different parts of the slope region. The generally high organic carbon content noticed in the slope region can be attributed to the low oxygen content of the waters (150-1,500 m water depth), the fine grained nature of the sediments and the total absence of benthic fauna presumably due to the reducing conditions in this region.

Even within the high ranges of organic carbon content noticed in this region,

wide variations are also noticed. In the northern part of the continental slope between Gulf of Kutch and Bombay, the sediments have a low organic carbon content (<2%) except for a patch off Saurashtra coast. This low organic carbon content can be due to the lower productivity of the overlying waters and the dilution by the inorganic material brought through heavy discharge by the Indus river. In the rest of the area, the organic carbon content is very high in spite of the difference observed in the productivity of the overlying waters. This could be due to (a) relatively

low rates of sedimentation as compared to the northern region, and (b) the settling velocities of planktonic foraminifera, and the clays present in the slope region being of the same order and preservation of the organic matter both in the water column, as well as, in the bottom, due to the low oxygenated waters. The highest organic carbon content (> 8%) observed in the mid slope region can be attributed to the same factors described above, but perhaps acting with greater intensity in this region.

The progressive decrease in the organic carbon content noticed from the foot of the continental slope region and beyond could be due to (a) the absence of oxygen minimum layer in this region, and (b) the presence of oxygenated waters even at the bottom as evidenced by the presence of dark brown muds.

Source of organic matter

The two main sources of organic matter in the marine environment are (1) terrestrial organic matter supplied through the land drainages, and (2) in-situ organic matter produced in the marine environment. The relative proportions of these two types depend upon dominance of the source from which it is derived. In order to differentiate the source for the organic matter in the marine environment, usually C/N ratios are taken as an index factor (> 10 for terrestrial organic matter and < 10 for marine organic matter). However, these ratios could be modified by the diagenetic alterations taking place in the milieu.

Figure 2 shows a strong positive correlation between organic carbon and total nitrogen present in these sediments, indicating that the total nitrogen present in the sediments is primarily derived from organic sources. However, the C/N ratios computed and depicted in figure 3 show a very wide variation in the area studied (from < 0.5 to 57). Apart from these variations, they also show certain regional patterns with a few deviations.

It is observed that most of the shelf, particularly northern half and deep sea regions (> 1,500 m depth) exhibit the C/N ratios of < 10 suggesting that the organic matter along the western continental margin is predominantly of marine origin. The association of higher C/N ratios with the sediments of shelf and slope regions could be explained in terms of source, sedimentation pattern and diagenetic alterations. For example, the higher C/N values in the near shore regions (> 10, sometimes even

exceeding the value of 30) indicate that the organic matter in these small areas to be mainly of terrigenous origin. The influx of the terrigenous organic matter having higher C/N ratios (> 10) is restricted to the near shore regions only as evidenced by the sedimentation patterns (Nair and Hashimi, 1980) as well as from the suspended load studies from the northern regions (Rao and Rajamanickam, 1978) which indicated rapid decrease of terrigenous material away from the coast. However, some of these higher ratios also could be due to leaching of sediment nitrogenous compounds of marine organic matter with the reworking and redistribution of surface sediments by benthic organisms (Kemp, 1971) which are present in abundance in these sediments. Higher ratios of C/N (10-15 and > 15) are also observed in patches or in small pockets in the outer shelf. The original C/N ratios of this organic matter could have been close to marine organic matter and present higher values could be due to processes involving the microbial and chemical decomposition and transformation of organic matter in which loss of nitrogen containing radicals takes place under oxidizing conditions. Very high ratios of C/N which even reach the value of 57 could be due to exposure of relict terrestrial organic matter not overlain by modern biogenic sediments (Walsh, 1980). In the slope region, the organic matter is undoubtedly of marine origin. However, the higher ratios of C/N obtained in this region (10-15, > 15) are due to subsequent modification involving the denitrification of organic matter under anaerobic conditions (Rittenberg et al., 1955). Recent sediment trap data elsewhere indicated that the higher C/N ratios are found with increasing depth in the open ocean (Honjo, 1980). Further in the deeper region, the sediments have low C/N ratios (< 10) suggesting that the organic matter in these sediments is predominantly of marine origin. However, these low ratios also could be due to the mineralization of organic matter under the extreme oxidation conditions or due to presence of relatively large amount of fixed ammonium associated with the clay fraction in these slowly accumulating sediments (Muller, 1977).

It could be concluded that the higher C/N ratios encountered in the inner shelf region could be due to the contribution of both terrestrial and marine organic matter to the near shore region (perhaps predominantly terrestrial), while the higher ratios encountered in the slope

region are attributable to the various diagenetic alterations taking place in these sediments under the anoxic conditions. From the fact that very little fine grained material reaches the slope region from the continent and/or shelf (Stackelberg, 1972) it is quite possible that most of the organic carbon present in these slope sediments is of marine origin. Under the anoxic conditions prevailing in this region there is every possibility for the retention of a higher percentage of hydrogen in the kerogen part of this organic matter unlike in the near shore region where hydrogen of the organic matter is more or less leached out before it is deposited in the near shore regions. This fundamental difference in the organic matter between that present in the near shore regions and slope region, the presence of the muds and the existence of ideal conditions for preservation in the slope region render these beds of slope region to effectively act as source beds for generation of petroleum. It may not be out of place to mention that the thickness of sediments in the slope region on an average is more than 1.0 - 1.5 km (Naini, 1980) and the process of upwelling along the western continental margin of India started as early as Early Eocene, unlike in the other parts of the world (Siddiquie et al., 1976) supports the above surmise.

CONCLUSIONS

No direct correlation between the primary biological productivity in the overlying waters and the organic carbon content of the underlying sediments is discernible under oxic conditions in the shelf region. In this region, factors other than primary productivity, such as, texture of the sediments, dissolved oxygen content in the bottom waters, benthic population and rates of sedimentation, control the distribution of organic carbon.

The organic carbon content of the sediments follows the texture of the sediments.

Bottom fauna, to a certain extent, seems to govern the differences found in the organic carbon content of the sediments of the similar texture in the different regions of the inner shelf region, both, under high and low biological productivity in the overlying waters.

Oxygen minimum layer impinging on the sediments in the slope region between 150 - 1,500 m depth appears to be the

major environmental factor controlling the preservation and enrichment of the organic carbon content in these deposits, in spite of differences in the rates of biological production and rates of sedimentation.

The differences in the organic matter content found in the inner shelf region and in the slope region in that the former consists of an admixture of terrestrial, as well as, marine organic matter, whereas, the latter is derived mainly from the marine source. The possibility for a higher content of hydrogen molecules being present in the kerogen of this region coupled with considerable thickness of sediments suggest that this region has all the potential required for the generation of hydrocarbons and needs very detailed investigations from the point of view of organic geochemistry.

At this point it may be mentioned that the zone of higher organic carbon content encountered in the wider part of the slope region between Ratnagiri and Karwar deserves greater attention. Sediments as thick as 4 km have been reported from this region (Naini, 1980).

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