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## Distribution of Sediment Parameters and Depositional Environment of Mudflats of Mandovi Estuary, Goa, India

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### ABSTRACT



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Tidal flats are being used to understand sea level changes, pollution history, and depositional environment. From the part of the long-term study, distribution of sediment components, organic carbon, total phosphorus, and selected elements (Fe, Mn, and Cr) are used in this paper to understand diagenetic processes and hydrodynamic processes involved during the deposition of sediment. The present study revealed that the sediment components, organic carbon, and phosphorus play an important role in controlling the distribution and concentration of elements. Importance of the oxic-anoxic layer in the distribution and concentration of metals are discussed. Hydrodynamic conditions of the sediments deposited are delineated using triangular diagram.

**ADDITIONAL INDEX WORDS:** *Sediment components, diagenetic processes, depositional environment, Mandovi estuary*

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### INTRODUCTION

Tidal flats are often defined as low relief environments where sediments accumulate (KLEIN, 1985) or where vertical and lateral accretion occur (REINECK, 1978) and best developed in settings of low wave energy (McCANN, 1980). Tidal flats have been used to understand palaeoenvironment and palaeoclimate (HARDIE, 1977), pollution history (SILVER, 1993), and rate of sedimentation (ZWOLSMAN, BERGER, and VAN ECK, 1993). Postdepositional migration of elements during diagenesis has been discussed by COLLEY *et al.* (1984); SPENCER, CUNDY, and CROUDACE (2003); and ZWOLSMAN, BERGER, and VAN ECK (1993).

In this paper an attempt is made to understand the distribution of sediment components, organic carbon, and selected elements (Fe, Mn, and Cr) with time within the tidal flats. Effort has also been made to understand the processes involved in the distribution of sediment components and selected elements and further to understand the hydrodynamic condition of the sediments deposited in the mudflat.

### STUDY AREA

River Mandovi is confined between latitude 15°09' and 15°33'N and longitude 73°45' and 74°14'E. Mandovi is one of the most important rivers of the state of Goa and is the largest among all the rivers. It is about 70 km in length and with an average depth of around 3.5 km. It covers a basin area of

about 1530 km<sup>2</sup> and it runs amidst a typical tropical setting along the midwest coast of India. Mandovi is remarkably influenced by monsoon maritime climate with its three distinct seasons, namely premonsoon (February–May), monsoon (June–September), and postmonsoon (October–January).

The annual freshwater runoff of the Mandovi River is approximated to be 16 km<sup>3</sup>, with a small summer runoff of ~0.06 km<sup>3</sup>. The river carries drainage from 435 km<sup>2</sup> of forestland. The state of Goa is known for iron ore mining. About two-thirds of the total mining activities in Goa are located within the Mandovi basin. There are about 27 large mines in the basin area of Mandovi that generate 1500–6000 tons of rejects per day per mine, a substantial portion of which is expected to ultimately end up in the river. The river flows through these mining areas and is heavily used to transport iron and manganese ores to the Marmugao harbor from the hinterlands.

### MATERIALS AND METHODS

The sediment cores were collected from tidal mudflats of Mandovi Estuary from three different locations (Figure 1), namely Nerul (core B), Charao (core C), and Santa Cruz (core D). Among these three cores, two (B and D) were collected from lower estuarine regions and core C was collected from middle estuarine regions. Within the lower estuarine region, core B was collected from middle portion and core D from landward end of the mudflat. The cores were collected using an acrylic tube, about 50 cm long, with a diameter of 5.5 cm. The cores were subsampled at the spot of collection with 2-cm intervals.

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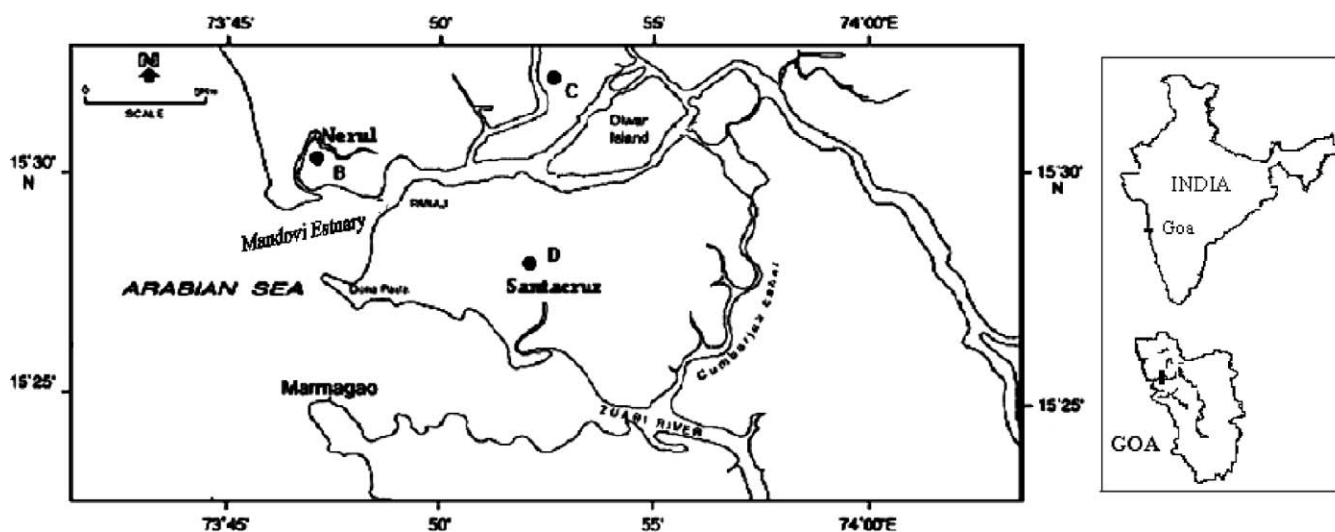


Figure 1. Location of sample collection.

In the laboratory, the sediment samples were dried in the oven at 60°C to remove associated water. Part of the dried sediment samples were finely ground and used for sediment digestion, which was carried out by total decomposition of the sediment (LORING and RANTALA, 1992) using HF and aquaragia in a sealed Teflon decomposition vessel (Teflon bomb). Organic carbon was determined using Walkley and Black method and phosphorus was determined by the procedure given by MURPHY and RILEY (1962). The second part of the sediment was used for carrying out pipette analysis to determine sand : silt : clay ratio. The clay fraction was digested using the same procedure followed for the whole sediment sample. The samples were then aspirated into an atomic absorption spectrophotometer for determination of concentration of trace metals.

## RESULTS

The abundance and distribution of various parameters are described in the three cores separately below.

### Core B

The percentage of sand varies from 2.50% to 14.90%. The values decrease from bottom to top with the highest value seen at the bottom 24 cm (Figure 2a). The percentage of silt shows a trend of alternating increase and decrease from bottom to top. The variation of clay percentage is opposite to that of silt. More pronounced variations are seen from 10 cm to 22 cm. From the bottom 24 cm to the top, the values of organic carbon decrease except two higher values recorded at 8 cm and 4 cm. Organic carbon shows good association with sand from a depth of 2 cm to 12 cm, silt from 16 cm to 24 cm, and with clay from 2 cm to 4 cm, 14 cm to 16 cm, and 22 cm to 24 cm (Figure 2a). Phosphorus values decrease continuously from the bottom 24 cm to the top until a depth of 8 cm and then there is a large increase in the values except at

the surface. Phosphorus shows association with sand from depths of 2 cm to 6 cm and from 20 cm to 24 cm, with silt from 6 cm to 12 cm, with clay from 16 cm to 20 cm, and with organic carbon from 2 cm to 6 cm and from 10 cm to 16 cm.

Iron in sediment shows association with sand in the upper portion from a depth of 2 cm to 10 cm, silt in the lower portion from 16 cm to 24 cm, and clay from 2 cm to 4 cm, 10 cm to 16 cm, and 22 cm to 24 cm (Figure 2b). The lowest value of Fe recorded at 14 cm coincides with a low value of clay at that depth. Iron also shows good association with organic carbon all along the depth from 2 cm to 24 cm and phosphorus from 2 cm to 6 cm, 14 cm to 16 cm, and 20 cm to 22 cm. Manganese in sediment shows all along the entire depth alternating increasing and decreasing trend. It also shows good association with sand in the upper portion from 2 cm to 12 cm and 16 cm to 22 cm, with silt in the lower portion from 10 cm to 14 cm and 16 cm to 24 cm, with clay from depths of 2 cm to 4 cm and 22 cm to 24 cm depth, with organic carbon almost along the depth from 2 cm to 14 cm and 16 cm to 24 cm, and with phosphorus from of 2 cm to 6 cm, 10 cm to 14 cm, and 20 cm to 22 cm. Chromium in sediment shows association with sand and organic carbon from depth of 6 cm to 10 cm and 16 cm to 20 cm, with silt in the upper portion from depth of 2 cm to 6 cm and in the middle portion from 14 cm to 20 cm, and with clay from depth of 4 cm to 6 cm, 10 cm to 14 cm, and 20 cm to 24 cm.

Iron in the clay component shows good association with organic carbon all along the depth from 2 cm to 24 cm and with phosphorus from 2 cm to 6 cm, 10 cm to 16 cm, and 20 cm to 22 cm (Figure 2c). Manganese in the clay component shows association with clay from depths of 2 cm to 4 cm and 22 cm to 24 cm, with organic carbon all along the depth from 2 cm to 14 cm and 16 cm to 24 cm, and with phosphorus from 2 cm to 6 cm, 10 cm to 14 cm, and 20 cm to 22 cm. Chromium in the clay component shows association with clay from depths of 2 cm to 4 cm, 10 cm to 14 cm, and 22 cm to 24 cm;

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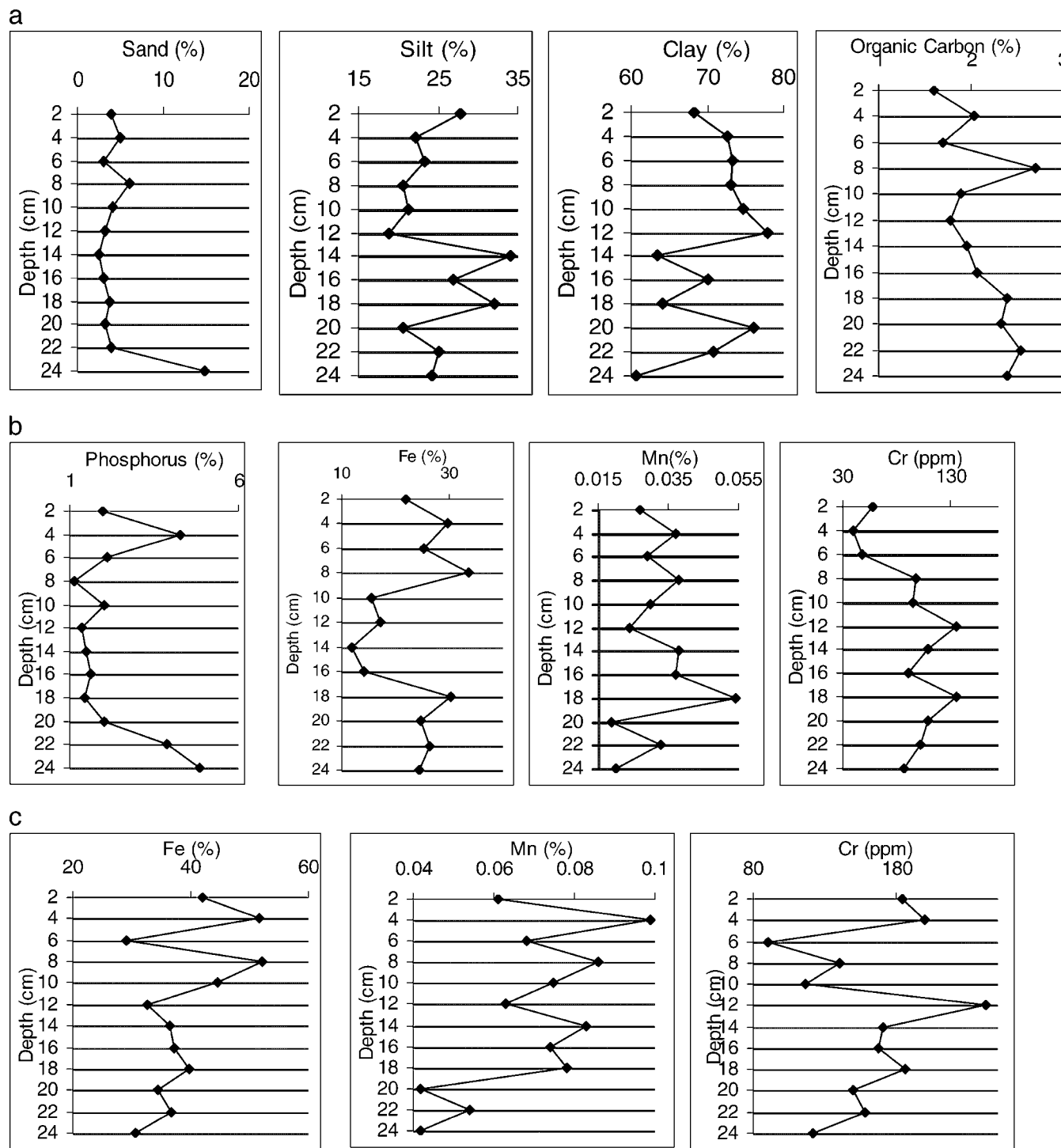


Figure 2. Vertical profiles of (a) sediment components and organic carbon with depth in core B (location: Candolim and Nerul); (b) phosphorus, Fe, Mn, and Cr in sediments with depth in core B (location: Candolim and Nerul); and (c) Fe, Mn, and Cr in the clay component with depth in core B (location: Candolim and Nerul).

with organic carbon depth of 2 cm to 10 cm and 16 cm to 24 cm; and with phosphorus from depths of 2 cm to 6 cm and 20 cm to 22 cm.

#### Core D

Sand increases and silt decreases from top to bottom except between 6 cm and 8 cm. Clay shows good association with silt from depths of 2 cm to 4 cm and 10 cm to 16 cm and largely opposite to sand (Figure 3a). Organic carbon shows good association with sand from 6 cm to 10 cm, with silt in the upper portion from depths of 2 cm to 8 cm and in the lower portion from 10 cm to 16 cm and with clay from 2 cm to 4 cm and 8 cm to 16 cm. Phosphorus shows good association with silt and organic carbon in the upper position from 2 cm to 6 cm, with clay from 2 cm to 4 cm and 10 cm to 14 cm, and organic carbon from 2 cm to 6 cm.

Iron in the sediment component shows good association with silt from depths of 2 cm to 6 cm and 10 cm to 14 cm, with clay from 6 cm to 14 cm, with organic carbon from 2 cm to 6 cm and 8 cm to 14 cm, and with phosphorus in the upper portion from 2 cm to 8 cm and lower portion from 12 cm to 16 cm (Figure 3b). Manganese in the sediment component shows association with sand from depths of 8 cm to 14 cm, with silt from 2 cm to 8 cm, with organic carbon from 2 cm to 10 cm, and with phosphorus from 2 cm to 6 cm. Chromium in the sediment component shows association with sand from depths of 8 cm to 16 cm, with silt, organic carbon, and phosphorus from 2 cm to 6 cm, and with clay from 6 cm to 10 cm.

Iron in the clay component shows good association with clay from 2 cm to 4 cm and 8 cm to 12 cm, with organic carbon all along the depth from 2 cm to 16 cm except between 12 cm and 14 cm, and with phosphorus from 2 cm to 6 cm (Figure 3c). Manganese in the clay component shows good association with clay from 8 cm to 16 cm, with organic carbon all along from 2 cm to 16 cm, and with phosphorus and Fe in sediment from 2 cm to 6 cm. Chromium in the clay component shows association with clay from depths of 8 cm to 16 cm, with organic carbon all along the depth from 2 cm to 16 cm, and with phosphorus from 2 cm to 6 cm.

#### Core C

From depths of 2 cm to 28 cm, the trend of variation of sand is almost opposite to silt, *i.e.*, as sand decreases, silt increases. Clay shows good association with sand from 2 cm to 6 cm, 10 cm to 14 cm, and from 24 cm to 26 cm and is almost opposite to silt with depths from 2 cm to 16 cm and also 18 cm to 20 cm, 24 cm to 26 cm, and 28 cm to 30 cm, *i.e.*, as silt increases, clay decreases (Figure 4a). Organic carbon shows association with sand from 10 cm to 14 cm and from 16 cm to 26 cm, with silt from 26 cm to 30 cm, and with clay from 6 cm to 16 cm and from 24 cm to 28 cm. Phosphorus shows good association with sand from 2 cm to 4 cm, 10 cm to 14 cm, and 20 cm to 22 cm; with clay from 2 cm to 4 cm, 6 cm to 16 cm, 18 cm to 20 cm, and 24 cm to 30 cm; and with organic carbon in the upper portion from 4 cm to 18 cm and lower portion from 24 cm to 28 cm.

Iron in the sediment component shows good association with sand from a depth of 10 cm to 26 cm, with clay from 6

cm to 14 cm and 26 cm to 30 cm, with organic carbon all along the depth 4 cm to 28 cm, and with phosphorus from 2 cm to 18 cm and 24 cm to 30 cm (Figure 4b). Manganese in the sediment component shows association with sand from depths of 10 cm to 14 cm and 24 cm to 30 cm, with silt from 2 cm to 6 cm and 20 cm to 24 cm, with clay from 6 cm to 14 cm and 18 cm to 26 cm, with organic carbon from 4 cm to 12 cm and 28 cm to 30 cm, and with phosphorus from 4 cm to 14 cm, 16 cm to 20 cm, and 22 cm to 26 cm. Chromium in sediment component shows association with sand from depths of 10 cm to 14 cm and 24 cm to 30 cm, with silt from 20 cm to 26 cm and 28 cm to 30 cm, with clay from 6 cm to 26 cm, and with organic carbon and phosphorus from a depth of 2 cm to 16 cm.

Iron in the clay component shows good association with clay from a depth of 6 cm to 16 cm, with organic carbon all along the depth from 2 cm to 30 cm, and with phosphorus in the upper portion from 2 cm to 18 cm (Figure 4c). Manganese in the clay component shows good correlation with clay from depths of 6 cm to 14 cm and 18 cm to 28 cm, with organic carbon from 2 cm to 14 cm and 24 cm to 30 cm, and with phosphorus from 4 cm to 14 cm, 16 cm to 20 cm, and 22 cm to 28 cm. Chromium in the clay component shows good correlation with clay from 6 cm to 26 cm, with organic carbon in the upper portion from 2 cm to 16 cm, and with phosphorus from 4 cm to 16 cm, 18 cm to 20 cm, and 22 cm to 26 cm.

## DISCUSSION

The data analyzed for various subsamples of core B reveal differences in the set of association of elements with that of sediment components, organic carbon, and total phosphorus. On the basis of these associations, the core can be divided into five parts, namely 0 cm to 6 cm, 6 cm to 10 cm, 10 cm to 14 cm, 14 cm to 20 cm, and 20 cm to 24 cm. When the elemental distribution and association within the bulk sediment and clay fractions are viewed together, a systematic alternating layer basically due to the association of total phosphorus is seen. For example, layers from 0 cm to 6 cm, 10 cm to 14 cm, and 20 cm to 24 cm consist of total phosphorus along with organic carbon and elements, whereas in the other two layers, namely 6 cm to 10 cm and 14 cm to 20 cm, the total phosphorus is not associated with the elements Fe, Mn, and Cr.

JACOB and QASIM (1974) have reported close association of phosphorus and organic carbon with finer sediments. Association of Fe and Mn with organic matter in the upper oxidized layer of the sediments has been reported by SELVARAJ *et al.* (2003). WIESE, BUBB, and LESTER (1995) reported that the distribution and concentration of Fe, Cr, and Ni in the mudflats are entirely dependent on sediment particle size. In core B, it is observed that in the clay fraction the elemental distribution is mainly controlled by the presence of organic carbon and total phosphorus. However, in the sediment, along with organic carbon and total phosphorus, components such as sand, silt, and clay also play an important role in the distribution of elements. Specific association of Cr with silt and clay; total phosphorus with Fe and Mn; and organic carbon with Fe, Mn, and Cr reveals the role of organic carbon,

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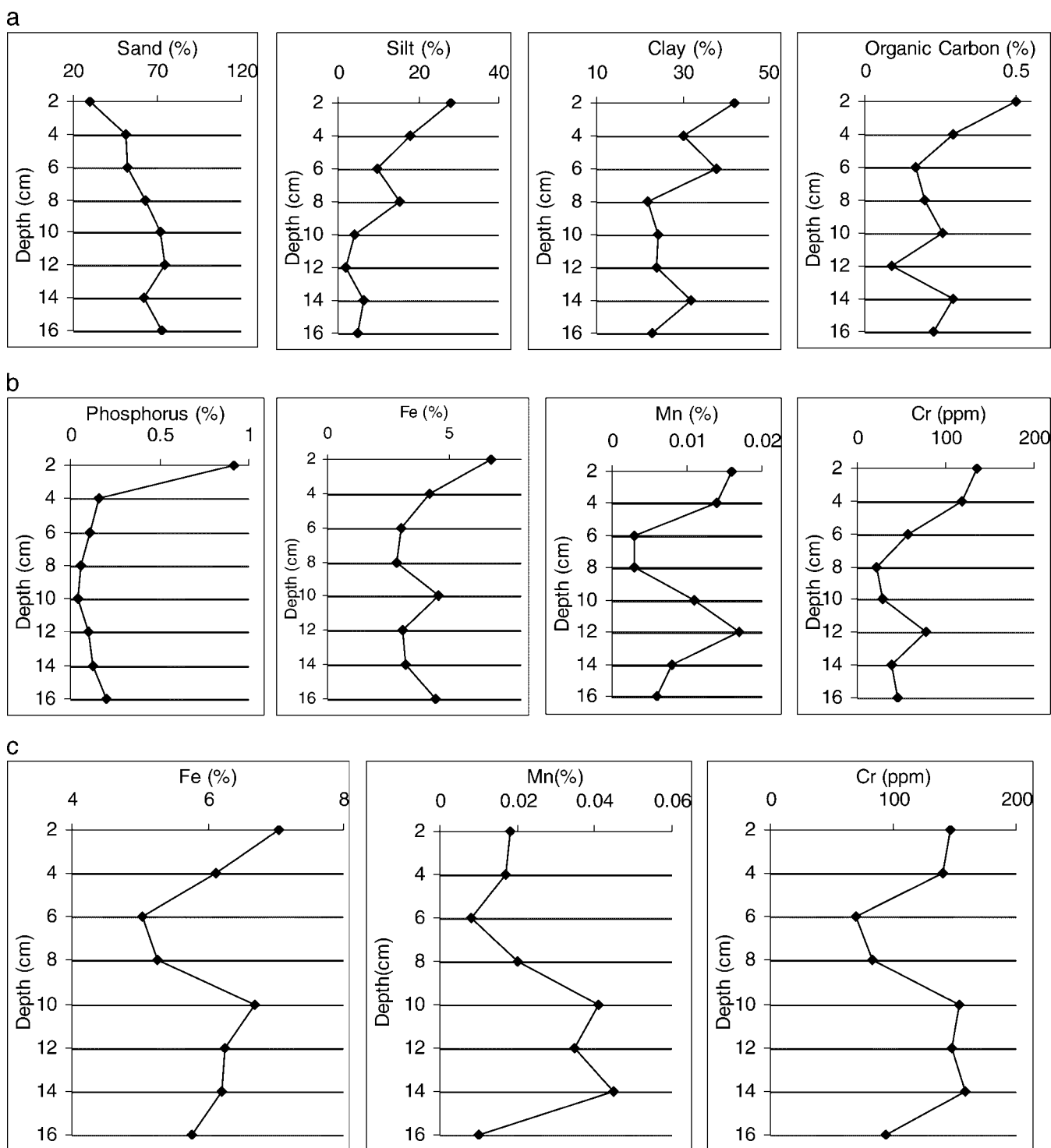


Figure 3. Vertical profiles of (a) sediment components and organic carbon with depth in core D (location: Santa Cruz); (b) phosphorus, Fe, Mn, and Cr in sediment with depth in core D (location: Santa Cruz); and (c) Fe, Mn, and Cr in the clay component with depth in core D (location: Santa Cruz).



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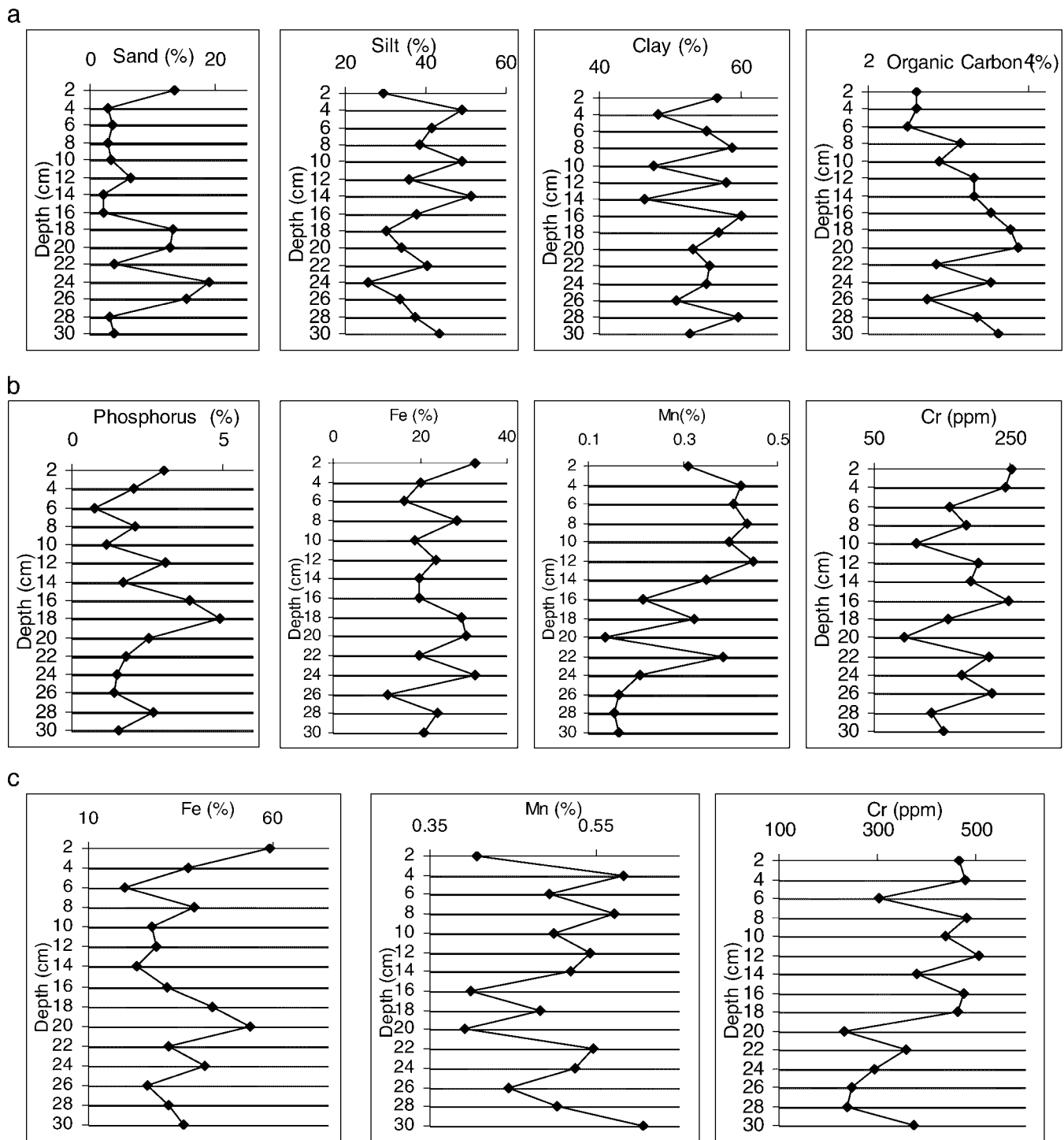


Figure 4. Vertical profiles of (a) sediment components and organic carbon with depth in core C (location: Charao); (b) phosphorus, Fe, Mn, and Cr in sediment with depth in core C (location: Charao); and (c) Fe, Mn, and Cr in the clay component with depth in core C (location: Charao).

total phosphorus, and finer sediments in remobilization of the elements within the sediment.

The data presented for core D also reveal difference in the set of association of elements with that of sediment compo-

nents, organic carbon, and total phosphorus. As in core B, in core D also systematic layering exists basically due to the association of phosphorus. For example, in 0-cm to 6-cm and partly in 10-cm to 16-cm layers phosphorus is associated with

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Fe, Mn, Cr, organic carbon, and sediment components. However, the layer from 6 cm to 10 cm is without the association of phosphorous. Fe, Mn, and Cr in sediments are associated with silt along with organic carbon and total phosphorus in the uppermost layer, *i.e.*, 0 cm to 6 cm. In the clay fraction the distribution of all three elements, Fe, Mn, and Cr, seemed to be controlled by the presence of organic carbon and total phosphorus. Between 6 cm and 10 cm, Fe and Cr in sediment are associated with clay. However, Mn shows closer association with organic carbon. In the clay fraction between 6 cm and 10 cm, Fe, Mn, and Cr are associated with organic carbon. Further down in the bottommost set, between 10 cm and 16 cm, Mn and Cr are associated with sand, whereas Fe shows association with silt, clay, and organic carbon in the sediment component. Phosphorus association is restricted to the 12-cm to 16-cm depth. In the case of clay fractions, Mn and Cr seem to be associated with clay and organic carbon whereas Fe shows association only with organic carbon.

From the distribution and association of elements it is clear that there is a large similarity between core B and core D. Core B has been divided into five layers and core D into three layers. The uppermost three layers of core B can individually be related to layers of core D with reference to the distribution of elements and sediment components. For example, in the first layer, *i.e.*, 0 cm to 6 cm, within the sediments, Fe and Mn are associated with organic carbon and phosphorus. Special association of Cr with silt has been observed in both cores. The only difference noted is association of Fe and Mn with sand in the case of core B, which is not clear in core D. The clay fraction in the same layers in both cores shows association of Fe, Mn, and Cr with organic carbon and phosphorus. In the second layer between 6 cm to 10 cm, especially in the clay fraction, association is the same in both cores, *i.e.*, Fe, Mn, and Cr are associated with organic carbon. In the same layer within the sediment, Mn association with organic carbon has been noted in both cores. However, Fe and Cr are associated with clay in core D and with sand in core B. In addition, very close association of silt with phosphorus has been observed in the case of core B. In the third layer, within the sediment, Fe is associated with clay in both cores. However, Mn is associated with silt in core B and sand in core D. Cr shows association with sand in core D and clay in core B. In core D, Fe is also associated with silt and organic carbon and in core B; organic carbon shows good association with phosphorus. Within the same layer in the clay fraction, Fe is associated with organic carbon, and phosphorus and Cr association with clay have been observed in both cores. The difference is, in core B; Mn is associated with organic carbon and phosphorus, whereas in core D, Mn is associated with clay and organic carbon. In core D, Cr is also associated with organic carbon and clay.

Except for few differences, largely three layers of different cores, namely core D and core B, show similar associations, strongly supporting similar environment of sediment deposition. The differences, like the presence of sand in the bottom layer of core D and clay in core B, are possibly due to core location from the main channel.

Core C is divided into six parts on the basis of the association, namely 0 cm to 6 cm, 6 cm to 10 cm, 10 cm to 16 cm,

16 cm to 20 cm, 20 cm to 26 cm, and 26 cm to 30 cm. The layering and the association in core C are found to be different from that of core B and core D. Within the sediments from top to bottom of core C, organic carbon and phosphorus are associated except for phosphorus in the layer 20 cm to 26 cm. Similarly, from 10 cm to 30 cm, *i.e.*, in the lower four layers, sand or clay are associated with organic carbon. In the top two layers they are replaced by silt in the 0-cm to 6-cm layer and clay in the 6-cm to 10-cm layer. The elemental association seems to be very selective with sediment components organic carbon and phosphorus, and they vary from one layer to the other. Fe and phosphorus are significant in the top three layers as well as in the bottom-most layers. In the clay fraction, organic carbon and phosphorus seem to control the distribution of elements in the top four layers, and organic carbon alone in the bottom two layers. It is also important to mention that the clay component is associated with organic carbon or phosphorus along with trace elements except for the bottommost and topmost layers.

From the above associations it can be revealed that within the sediment, in addition to organic carbon and phosphorus, various components of sediment control the distribution of elements. However, within the clay fraction, organic carbon, phosphorus, and clay component control the distribution of elements.

Diagenetic cycles of Fe and Mn (SANTSCHI *et al.*, 1990) and the role of organic matter in retaining the metals in sediments (MARCOVECCHIO and FERRER, 2005) are well known. In the present study, especially in core B and core D, association of Fe, Mn, and phosphorus along with organic carbon are well recorded. In the oxic surface layer of core B, the distribution of phosphorus is related to that of Fe. Fe cycling seems to control the distribution of phosphorous in the oxic layer of core B, possibly due to the process of early diagenesis (BACHE, 1963). GOLTERMAN (1988) stated that iron hydroxides are the main carriers for phosphorus in the aquatic environment. The manganese enrichment seen in the younger sediments may be partly reprecipitated in the form of insoluble oxyhydroxides. In the oxic sediment layer, trace metals are mobilized and partially reabsorbed onto Fe and Mn oxyhydroxides. Therefore distribution of trace metals in the sediments is modified to a great extent by diagenetic processes.

The distribution pattern obtained for three cores *viz.* core B, core D, and core C (Figures 5–7) between organic carbon *vs.* metals and metal *vs.* metal showed very good correlation in most of the combinations for core D, good correlation in a few combinations in the case of core B, and none of the combinations showed good correlation in the case of core C. This indicates that mobilization of elements during early diagenesis is high if the percentage of coarser material (sand) present is high as can be seen from core D and to some extent in core B. In the case of core C finer sediments (clay and silt) dominated, which possibly restricts the mobilization of elements within the deposited sediments.

Various factors control the distribution of elements within the sediments. Bioturbation is one such factor. Bioturbation has been shown to have a greater effect on solute transport than on solids (BERG *et al.*, 2001). Further, bioturbation can affect generally up to 3 cm and rarely up to 5 cm from the

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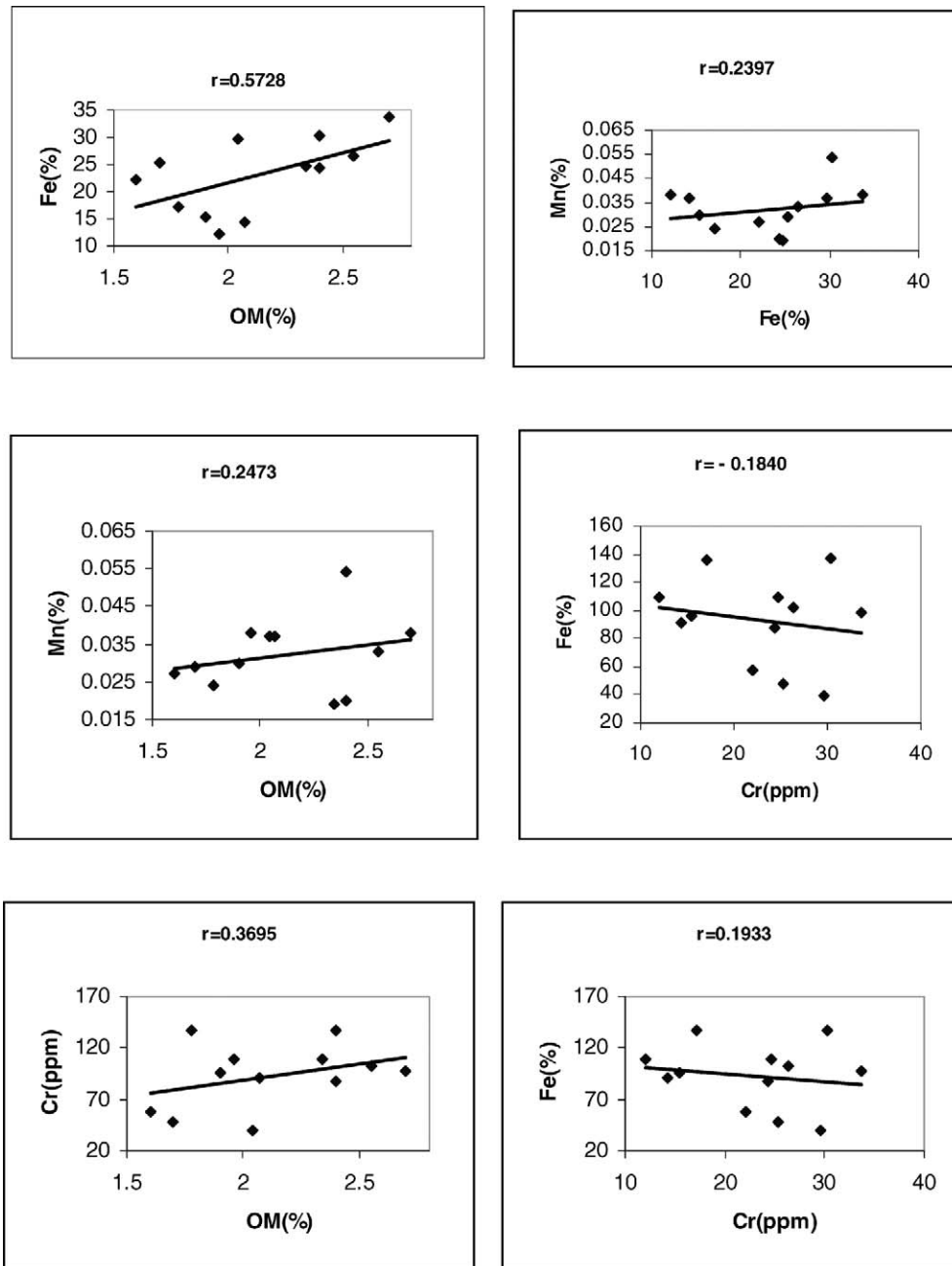


Figure 5. Distribution pattern and correlation—OM vs. metals and metal vs. metal of core B.

sediment surface (BRADSHAW, KUMBLAD, and FAGRELL, 2006). In the presently studied cores, upon collection, field observations were recorded on physical characteristics. From these observations, it is found that the features supporting activity of bioturbation were absent or negligible.

The sediments show a vertical redox zonation with an oxic upper layer where organic carbon is oxidized, overlying a reduced layer where generally sulfides are precipitated (ZWOLSMAN, BERGER, and VAN ECK, 1993). Diagenetic reactions are important near the sediment–water interface, re-

sponding to redox changes and affecting metal concentrations in vertical sediment profiles (SANTSCHI *et al.*, 1990). Dissolution of Fe and Mn hydroxides in partly reduced sediment layer is responsible for reprecipitation of Fe and Mn near the oxic–suboxic interface (ZWOLSMAN, BERGER, and VAN ECK, 1993).

Concentration of Fe, Mn, and Cr decreases dramatically below the oxic–suboxic interface, which is around 18 cm depth in core B. The depth profiles of core C and core D also show a similar pattern. However, the oxic–anoxic boundary



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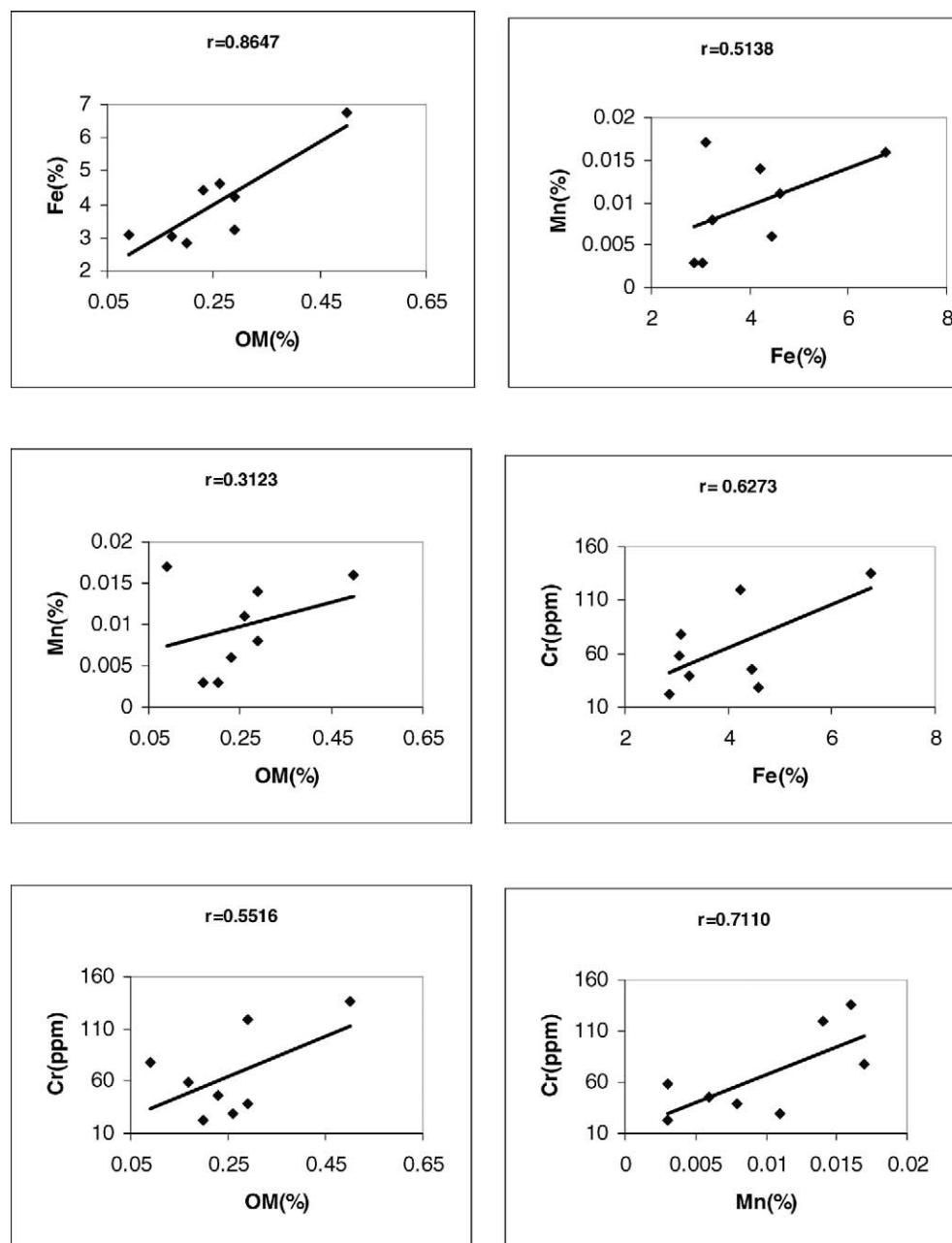


Figure 6. Distribution pattern and correlation—OM vs. metals and metal vs. metal of core D.

varies from one core to the other. For example, for core D it is at 12 cm and for core C it is at 22 cm. Fluctuation of the redox boundary in the salt marshes was related to frequent flooding by VRANKEN, OENEMA, and MULDER (1990). Possibly, at the oxic-anoxic boundary, phosphorous controls remobilization of Fe in the cores studied. Generally, at greater depth, trace metals are coprecipitated with (iron) sulfides. Enhanced Fe values in the lower part in cores D and C are again controlled by the presence of phosphorous and not by formation of iron sulfide in reducing conditions as explained

earlier by GAILLARD, PAUWELLS, and MICHARD (1989) in the study area. Increase in Mn and Fe at depths is related to trapping of these elements by authigenic carbonate formation (CUNDY and CROUDACE, 1995).

When layers of core C are compared with those of core B and core D, large variations in association are noted, though mainly the organic carbon and phosphorus are controlling the distribution of elements in all the cores. The associations are well defined in core B and core D compared to core C. Higher concentrations of organic carbon and phosphorus recorded in

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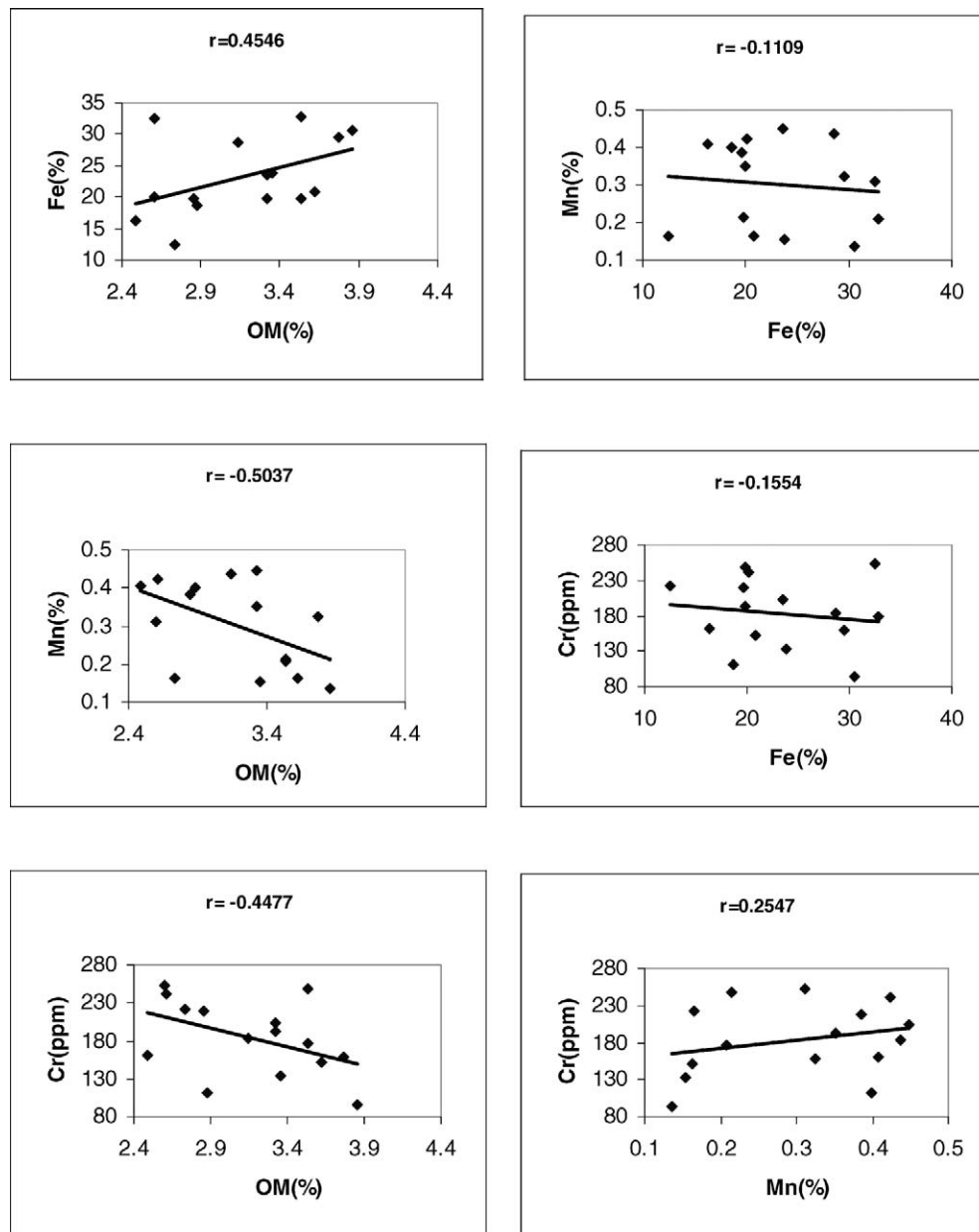


Figure 7. Distribution pattern and correlation—OM vs. metals and metal vs. metal of core C.

core C compared to core B and core D must be due to larger sinks of these components. It is reported by COELHO *et al.* (2004) that the inner area of the estuary represents the largest sink for phosphorus, which decreases seaward.

With reference to concentration and source of elements in the sediments, it is important to note here that the river Mandovi and its tributaries for most part of their lengths pass through regions of extensive mining activity of basically iron and manganese ore (NAYAK, 1998). There are 27 major mines within the Mandovi basin and the river provides cheap and effective means of transport of iron ore from the hinterlands to Marmugao harbour. The banks of its tributaries are

lined with mined material, loading platforms, beneficiation plants, ore stores, and massive dumps of rejects. It is reported (NAYAK, 1993) that the tributaries that pass through the mining zones and estuarine waters of Mandovi hold very high concentration of total suspended matter. BUKHARI (1994) has proved that the sediments in mid-reaches of the estuary and tributaries are affected by higher concentration of Fe, Mn, and Cr and are moderately to strongly polluted by these elements. Later NIGAM, NAYAK, and NAIK (2002) related decrease in foraminifera both in number and species to increase of suspended load due to mining within the Mandovi estuary.

According to CUNDY and CROUDACE (1995), the sediment

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record in a salt marsh contains valuable information on anthropogenic and natural inputs. The climate of the present study region is generally warm and humid and is largely controlled by the monsoon season, which is with average rainfall of 3000–3500 mm. Further, over 90% of the rainfall is received in 2 to 3 months during June through August every year. This largely supports removal of material from the hinterlands and supply to estuary and coastal regions. The source of elements within the cores is therefore largely from hinterland activities both natural and anthropogenic. However, it is difficult to make a quantitative estimate of the anthropogenic input of heavy metals. Mining activity in the catchment area of the Mandovi River being open cast type, it can only be stated that the large quantity must be from anthropogenic source.

Further, an attempt has been made in the present study to understand the hydrodynamics of the deposition of sediments within the mudflats.

It is a well-known fact that the grain size of the sediments not only reflects the size of the source material and transport mechanism but also depositional conditions including hydrodynamics involved. For example, sediments deposited within the estuarine channel are significantly different from those deposited within the tidal mudflats of estuaries.

A variety of ternary diagrams are in use today for classification of sediments and sedimentary rocks, distinguishing different depositional facies and for distinguishing hydrodynamic conditions of both recent and paleoenvironments. To mention a few known diagrams, there are those originally proposed by FOLK (1954, 1968); PEJRUP (1988); SHEPARD (1954); and TREFETHEN (1950). FLEMING (2000) has proposed a revision of textural classification of gravel-free muddy sediments on the basis of ternary diagrams. EVAN (1965) and YEO and RISK (1981) have used Shepard's diagram to classify sediments and to distinguish different sedimentary facies of estuarine environments. PEJRUP (1988), however, stated that Shepard's diagram is not well suited for separating different estuarine depositional facies. With the help of Pejrup approach, SHI (1992) could distinguish high mud zone and low mud zone formed by different hydrodynamic conditions within a microtidal estuary.

With this background, to understand the hydrodynamics of the deposition of the presently studied sediments within the mudflats, the triangular diagram proposed by PEJRUP (1988) has been used. The diagram based on sand, silt, and clay percentage of sediment is divided into four sections and each section is further divided into four classes. The triangle consists of 16 groups, each one of which is named by a letter indicating the type of sediment and a number indicating the hydrodynamic conditions during the deposition. For example, group DII represents sediments containing from 10% to 0% sand deposited under rather quiet hydrodynamic condition. PEJRUP (1988) has interpreted that section I indicates very calm hydrodynamic conditions rarely found in estuaries and sections II to IV indicate increasingly violent hydrodynamic conditions.

The various fractions of cores B, C, and D were plotted on the triangular diagram (Figure 8) proposed by PEJRUP (1988) separately. All the plots of the fraction of core B fall within

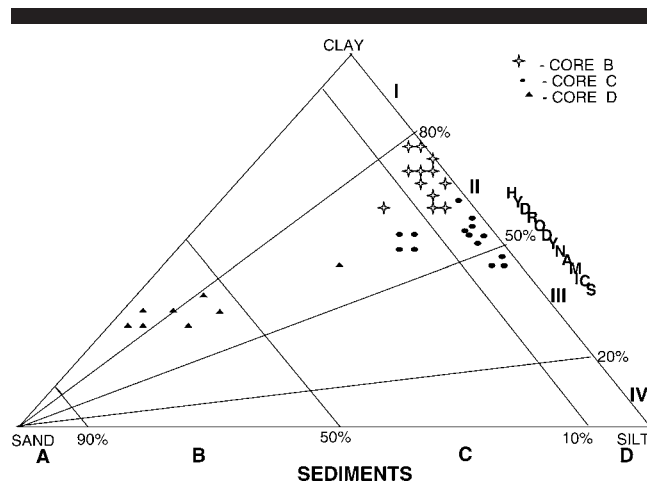


Figure 8. Triangular diagram for sand-silt-clay with various grades of hydrodynamic conditions (after Pejrup [1988]).

section II, core C falls within sections II and III, and core D falls within sections I and II. The plots reveal that core B collected from the lower estuarine portion falls within section II, indicating that the sediments here have deposited in less violent conditions. All the subsamples of core B fall within “D type” except one, indicating presence of poor sand and high concentration of silt and clay components. Core D, which was also collected from the lower estuarine portion, falls within sections I and II, indicating relatively quiet hydrodynamic conditions. It may be noted here that core B was collected from the middle portion of the mudflat and core D from the landward end of the mudflat. As per Pejrup, section I indicates very calm hydrodynamic conditions rarely found in estuaries, as mentioned earlier. Some subsamples of core D that fall within section I indicate very calm hydrodynamic conditions. Core D, being collected from the landward end of the mudflat, shows a mixture of estuarine and freshwater, which it receives from the lake nearby. All the subsamples of core D fall within “B type” except one, indicating the presence of sand-dominated sediment.

The various subsamples of core C plotted on the triangular diagram largely fall within section II, except three subsamples that fall within section III, indicating that core C also falls within less violent hydrodynamic conditions. Most of the subsamples of core C fall within D type except four, which fall within C type, indicating domination of silt and clay components.

## CONCLUSION

The present study revealed that the sediment components, organic carbon, and phosphorus play an important role in controlling the distribution and concentration of elements. The study is useful in understanding the remobilization of elements and early diagenetic processes operating and importance of the oxic-anoxic layer in the distribution and concentration of trace metals.

The hydrodynamic studies to understand the depositional environment have revealed that the sediments of core B rep-

representing the lower estuarine portion have deposited in less violent conditions. Core D, which was collected from the landward end of the mudflat, shows a mixture of estuarine and freshwater conditions. The sediments here have deposited under very calm hydrodynamic conditions. Core C, which was collected from the middle estuarine region, also shows that sediments here have deposited within less violent hydrodynamic conditions.

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