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Onshore Transport of Shelf Sediments into the Netravati-Gurpur Estuary, West Coast of India: Geochemical Evidence and Implications

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ABSTRACT

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Surface accumulation of a long band of frothy material is frequently noticed in the Netravati-Gurpur and other estuaries along the central west coast of India. This is prominently seen in the flood phase of the tidal cycle, during summer. In order to understand its source and the process of formation, water samples along with frothy material were collected from the Netravati-Gurpur estuarine front during the summer of 1987. Also collected were riverine and estuarine-coastal suspended particulates and surficial sediments from the adjoining inner shelf. Salinity of water samples was measured and the remaining samples were subjected to bulk and partition geochemical analyses. Suspended particulate matter (SPM) concentrations in the estuarine front in the flood tide during summer (February–May) is anomalously higher (4,310 mg/l) than in riverine (51 mg/l) and estuarine-coastal (11 mg/l) waters during monsoon (June–September) and post-monsoon (October–January) seasons, respectively. The frothy material is composed chiefly of fine particles ($<$ 63 microns) with a minor proportion of shells (foraminifers, ostracods and gastropods) and plant debris in the coarse fraction. Geochemically, the frothy material is similar to the Netravati-Gurpur SPM, but has low Al (13.87%), high organic matter (22.62%) and an order of magnitude higher Ca content (2.91%). All these lines of evidence suggest that the frothy material is detrital and that it is derived from the marine environment by resuspension and landward transport of bottom sediments during the flood phase of the tidal cycle. This inference is in agreement with similar reports from many parts of the west coast of India. Implications of this process are discussed in terms of siltation in the navigational channel of the Old Mangalore Port, estuarine morphology and disposal of effluents from the existing and proposed industries along the west coast of India.

ADDITIONAL INDEX WORDS: *Estuarine front, onshore transport, siltation, geochemistry.*

INTRODUCTION

Rivers transport about 35 × 10^3 km^3 of fresh water (MILLIMAN, 1991) and 16 × 10^9 tons of sediment (suspended particles + bedload including sediments from flood events (HE SONGLIN, 1987) annually to the world oceans. However, only about 8% of the terrigenous sediment reaches the deep-ocean floor (HE SONGLIN, 1987). Most of the fluvial sediment is trapped in estuaries and continental shelves (GIBBS, 1981; SCHUBEL and KENNEDY, 1984; HE SONGLIN, 1987). Removal of suspended sediments in these regions takes place by aggregation processes (flocculation, agglutination and fecal pelletization) because of rapid change of physico-chemical conditions, higher concentration of suspended matter and biological activity (HE SONGLIN, 1987). The aggregated particles have high settling velocities (50–200 m/day) and hence are rapidly deposited in shallow water regimes (WELLS and SHANKS, 1987). However, suspended sediments in estuarine and nearshore areas undergo repeated cycles of erosion, transportation and deposition by ebb and flood tidal currents prior to accumulation (NICHOLS, 1986).

Estuaries are ephemeral features that are constantly modified with respect to tidal, diurnal, seasonal or glacial-interglacial cycles (GORSLINE, 1967; KEMPE, 1988). Anthropogenic activities are an important factor in changing the composition of dissolved and suspended inputs to estuaries (KEMPE, 1988).

The physical mixing of fresh river water with saline sea water in the estuary depends on fresh water influx, the depth and width of an estuary, tides, wind and coastal current patterns, etc. Estuarine mixing may produce fronts and plumes (KEMPE, 1988; BOWMAN, 1988; VAN LEUSSEN and DRONKERS, 1988). All these physical processes play an important role in the sedimentation of fine particles in shallow waters. Therefore, the study of cohesive sediment transport processes has attracted considerable attention as a result of increased urbanization near estuaries, diversion of river water for urban and agricultural use, the need for maintaining navigational channels with deeper drafts, and also because of the high adsorptive capacity of fine sediments for the removal of dissolved chemicals and pollutants (MEHTA, 1986 and references therein).

The Netravati-Gurpur Estuary and other estuaries along the central west coast of India (Figure 1) are characterized by frequent occurrence of a narrow, long band of brown,

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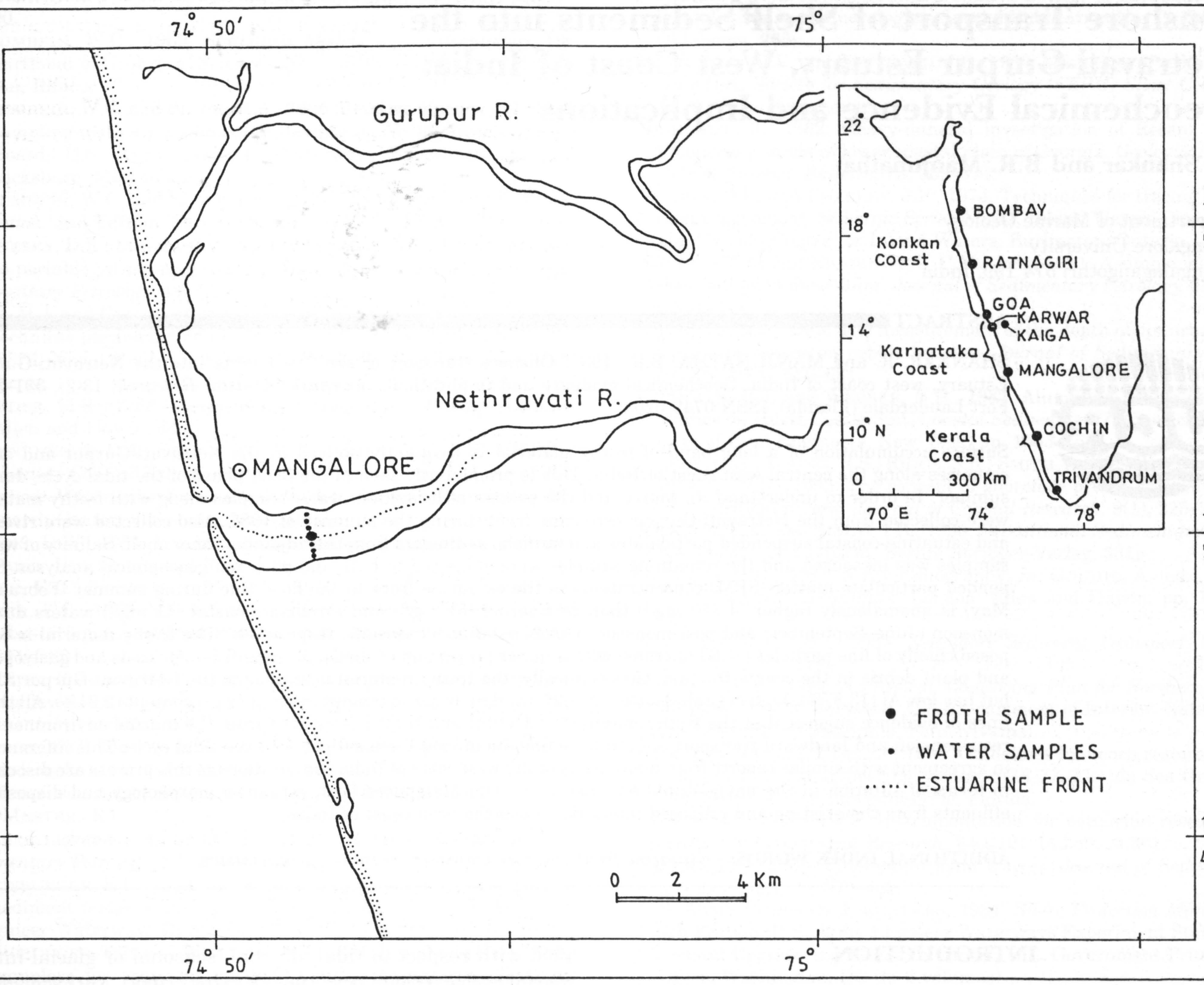

Figure 1. Map showing the locations of sampling stations across the Netravati estuarine front. Inset map shows the locations of places that are discussed in the text.

frothy material along the axis of the estuarine channel. This is the estuarine front which is recognized by surface accumulation of foam and buoyant material and its alignment parallel to the estuarine channel (NUNES and SIMPSON, 1985; SIMPSON and TURREL, 1986; HUZZEY and BRUBAKER, 1988). Fronts form in stratified estuaries also, when stratification is broken down by intense tidal stirring and a density structure analogous to the shallow sea front is produced (BOWMAN and IVERSON, 1977). Many workers have attempted to understand estuarine frontogenesis which seems to be related to the interaction of tidal flow with fresh water buoyancy input producing axial convergence (NUNES and SIMPSON, 1985; SIMPSON and TURREL, 1986). HUZZEY and BRUBAKER (1988) have shown that differential advection between the channel and shoal regions, when acting upon a constant longitudinal density gradient, is of sufficient magnitude to generate strong lateral gradients and thus the fronts. Fronts play an important role in intra-tidal dynamics.

In order to understand what the frothy material of the Netravati-Gurpur Estuary is and what processes are responsible for its formation, base metal geochemistry (bulk and partition) of the frothy material was studied and salinity determined for surface water samples collected across the estuarine front. Suspended particulate matter (SPM) from riverine and estuarine-coastal environments and surficial sediments from the shelf were also investigated. The results are discussed in terms of base metal adsorption-desorption phenomena and association of base metals with different phases of sediment in the estuarine environment. In this study, the emphasis is more on deciphering the source of frothy material through geochemical comparisons of the Netravati-Gurpur riverine, estuarine and coastal SPM, and the adjoining inner shelf bottom sediments, than on physical parameters/dynamics of front formation. The implications of this study in terms of (a) changes in estuarine morphology, (b) siltation in the Netravati-Gurpur river-estuary and its effect on navigation and water-bearing capacity of the river channel, and (c) effluent disposal, are discussed.

Physiographic Setting of Estuaries Along the West Coast of India

The west coast of India has coastal features that are a result of long-term changes in sea-level and climate, besides other factors like lithology, structure and local tectonic movements (WAGLE, 1987). In contrast to deltas along the east coast of India, the west coast is marked by Ria-type estuaries, estuarine marshes, lagoons, tidal swamps and mud-flat deposits, spits and sand bars, tombolos, etc., indicating the influence of marine deposition (AHMED, 1972; BRUCKNER, 1989). Ria-type estuaries are common along the Konkan Coast (19° 30′ N–16° N), where sea water encroaches up to 30–45 km inland and the river mouths are widened to form broad creeks (BRUCKNER, 1989). Estuaries of the Karnataka Coast (15° 30′ N–12° 45′ N) are shallow, characterized by relatively narrow river mouths and the tidal influence is barely seen beyond 15–20 km.

The Netravati-Gurpur Estuary

The Netravati-Gurpur Estuary is characterized by a mixed type of semidiurnal tides (REDDY *et al.*, 1979). The Netravati and Gurpur Rivers deliver $12{,}015 \times 10^6$ m^3 and $2{,}822 \times 10^6$ m^3 of fresh water and 14×10^5 and 1×10^5 tons of sediment annually to the Arabian Sea through this estuary (SUBRAMANIAN *et al.*, 1987; KARNATAKA IRRIGATION DEPARTMENT, 1986). The mean annual rainfall in the drainage area is 3,954 mm; of which, nearly 87% is received during the southwest monsoon (MURTHY *et al.*, 1988). Therefore, currents in the river mouth are controlled by fresh water discharge during the southwest monsoon and by tides during the rest of the year (REDDY *et al.*, 1979). For this reason, ebb flow is dominant during the southwest monsoon and flood flow during winter and summer. Marshes and brackish water ponds connected to the estuarine drainage are subjected to frequent inundation due to tidal activity. A 200 m long sand bar is present near the Netravati-Gurpur river mouth at a depth of 2–3 m (REDDY *et al.*, 1979).

MATERIALS AND METHODS

Buoyant material along with turbid water from the estuarine front was collected in an acid-cleaned, 25-litre polypropylene can on March 3, 1987 (Figure 1). After keeping the can undisturbed for about a day, three sub-samples were separated by centrifugation: material that floated (F-flo), settled (F-set) and still suspended (F-susp). A month after this sampling, six surface water samples were collected across the front to evaluate the salinity (WALLACE and PHLEGER, 1979) distribution. The subsamples of frothy material were oven-dried at 110 °C. The dry weight of particulates and the volume of water collected were used to calculate the suspended particulate matter (SPM) concentrations.

Large volume (ca. 35–70 litre) samples of water were collected in acid-cleaned polypropylene cans from riverine and estuarine-coastal regions in the study area during monsoon and post-monsoon seasons respectively (Figure 2). Suspended particles were separated as mentioned earlier. Surficial sediments were collected from the inner shelf off Mangalore by the Geological Survey of India in 1986, using a Van-veen grab sampler.

Samples were powdered, digested with $HF\text{-}HNO_3\text{-}HClO_4$ and analysed for Cu, Pb, Zn, Ni, Co, Mn, Fe and Al by AAS (model Varian AA-30). Calcium was determined by EDTA titrimetry (VOGEL, 1978) and loss-on-ignition (LOI) by measuring the weight loss after heating the samples at 450 °C for four hours in a muffle furnace. Initially, all three subsamples were leached with acetic acid (CHESTER and HUGHES, 1967), hydroxylamine hydrochloride (CHAO, 1972) and hot 50% HCl (CRONAN and GARRETT, 1973) to determine the partition of base metals in carbonates and loosely sorbed ions, easily reducible and resistant phases of frothy material. As the frothy material is rich in organic matter, an additional step of leaching with hydrogen peroxide (GUPTA and CHEN, 1975) was included in the sequential extraction scheme to determine the proportion of base metals associated with the organic phase of the frothy material. Elemental concentrations in the leachates were determined by AAS. Procedural blanks, duplicate samples and USGS standards (SGR-1, MAG-1 and SCo-1) were processed in a similar way to check the analytical errors which are <3% for Cu, Pb, Mn and Fe, 3–9% for Al and Co, and 9–13% for Ni and Zn.

RESULTS AND DISCUSSION

The front is seen only during the flood phase as in the Conway Estuary, U.K. (NUNES and SIMPSON, 1985). It stretches continuously for 5–6 km, and front formation is more frequent in summer (February–May). In other seasons, it is not prominently seen. Sometimes the Netravati Estuary exhibits multiple convergence lines that are related to the complex morphology of the estuary (NUNES and SIMPSON, 1985). Front formation in the Netravati-Gurpur Estuary appears to be similar to that in the Conway Estuary (NUNES and SIMPSON, 1985). In this estuary also, the front forms during the flood phase and disappears during the ebb phase of the tidal cycle when estuarine waters are vertically homogenous (NUNES and SIMPSON, 1985).

Physico-chemical Investigations

The SPM concentration in the estuarine front water (4,310 mg/l) was anomalously high in contrast to that in the Netravati and Gurpur R. (53.85 and 52.28 mg/l) and in the estuarine-coastal environments (11.06 mg/l). It should be noted that SPM concentration in the front is high even when the river discharge is insignificant in summer. Salinity at the sampling station was 24.64‰. Particle size analysis was carried out only on subsample F-set by wet sieving. It is chiefly composed of silt and clay (< 63 μm). However, shells (foraminifers, ostracods and gastropods) and plant debris occur in the >63 μm fraction. Salinity of surface water samples varied from 24.64 to 36.16‰. NUNES and SIMPSON (1985) have

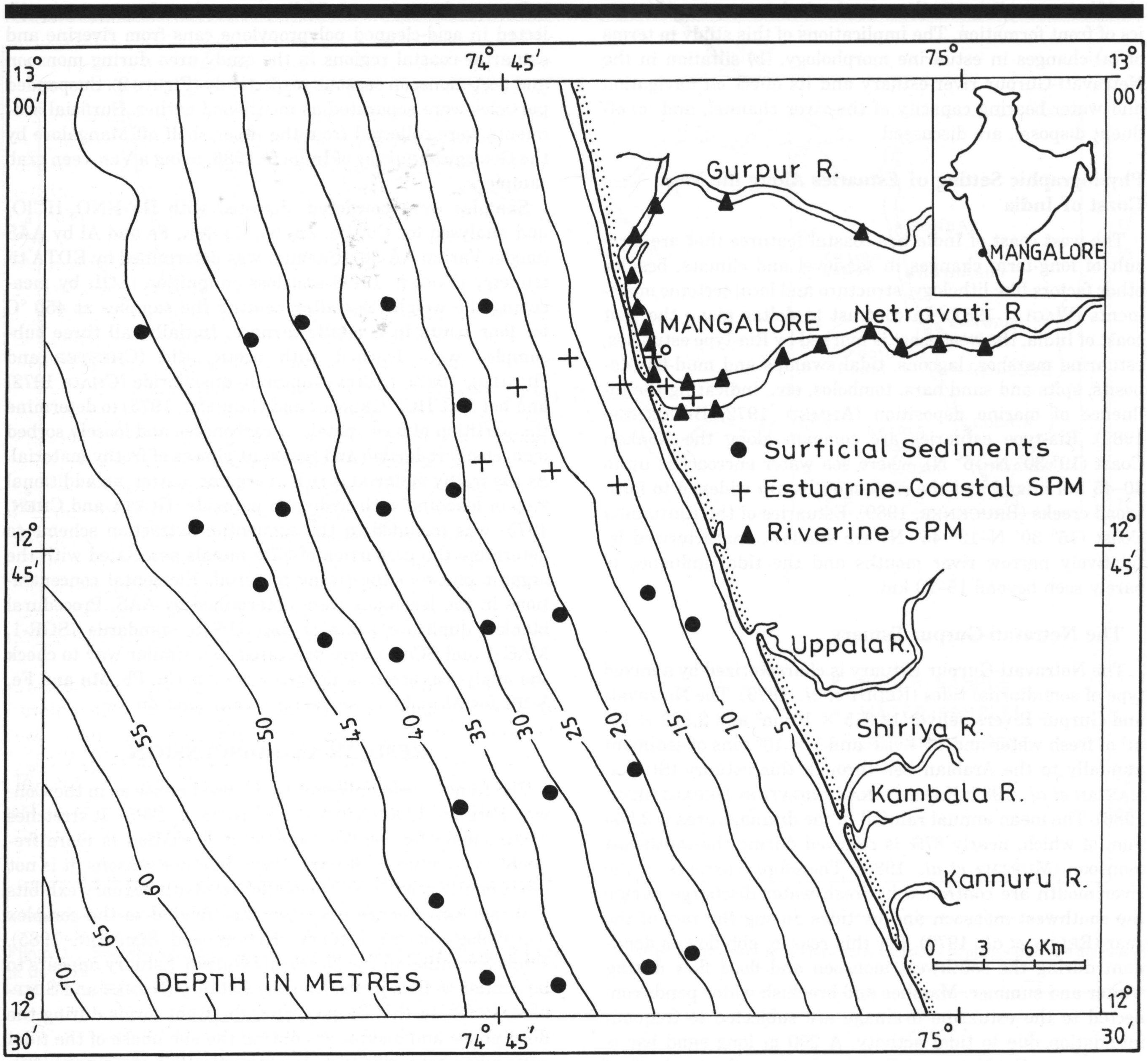

Figure 2. Map showing sample locations in the riverine, estuarine-coastal and shelf environments off Mangalore.

shown that salinity is consistently higher at the channel centre compared to that on either side. However, data for a similar set of samples collected later showed that there is no variation in salinity across the front (33 ± 0.7‰).

Geochemical Investigations

Bulk Geochemistry

Table 1 lists the elemental composition, organic matter as loss-on-ignition (LOI), metal/Al ratios and the coefficients of variation for the three sub-samples of frothy material, Netravati-Gurpur R. SPM, estuarine-coastal SPM and surficial sediments from the adjoining inner shelf. Since the coefficient of variation for the three sub-samples is negligible (0–4.6%) except for Ca (20.6%), only the average composition of frothy material is discussed.

Compared to the Netravati-Gurpur riverine SPM, frothy material has similar base metal concentrations and metal/Al ratios (except Mn and Mn/Al ratio), but an order of magnitude higher Ca content. Aluminum content is low, whereas LOI is high probably because of higher biological productivity in estuarine and coastal waters during summer (Sampathkumar, 1984; Patil, 1987). All these parameters (except Ca) show that the frothy material is detrital in

Table 1. Elemental concentrations, LOI and metal/Al ratios for frothy material from the Netravati estuarine front, Netravati-Gurpur riverine and estuarine-coastal SPM and inner shelf sediments off Mangalore.

Sample Description	SPM (mg/l)	Cu	Pb	Zn	Ni	Co	Mn	Fe	Al	Ca	LOI	Cu/Al	Pb/Al	Zn/Al	Ni/Al	Co/Al	Mn/Al	Fe/Al
		(ppm)						(%)				$(\times 10^{-3})$						
F-flo	430	64	45	66.5	170	50	1,027	6.80	14.08	2.48	23.26	0.45	0.32	0.47	1.20	0.36	7.29	0.48
F-set	3,530	64	45	66.5	170	50	1,058	6.70	13.50	3.76	22.20	0.47	0.33	0.50	1.26	0.37	7.84	0.50
F-susp	350	63	45	66.5	170	50	978	6.75	14.08	2.50	22.40	0.48	0.32	0.47	1.21	0.36	7.01	0.48
Mean froth	4,310 (total)	63.60	45	66.5	170	50	1,021	6.75	13.89	2.91	22.62	0.46	0.32	0.48	1.22	0.36	7.35	0.49
Coefficient of variation	—	0.3	0.0	0.0	0.0	0.0	3.2	0.60	1.96	20.6	1.50	2.60	1.40	2.90	2.10	1.29	4.60	1.90
Mean net.[a] Gurpur R. SPM	53.07	72	49	90	173	61	706	6.50	17.09	0.26	14.55	0.42	0.29	0.53	1.01	0.36	4.13	0.38
Mean est.[a] coastal SPM	11.06	96	112	247	157	41	574	6.21	13.97	1.93	20.00	0.71	0.84	1.86	1.12	0.29	4.05	0.45
Mean surficial[a] sediment off Mangalore	—	32	25	44	88	25	301	4.80	7.90	6.44	11.10	0.41	0.32	0.56	1.11	0.32	3.81	0.61

[a] Manjunatha (1990)

nature. However, it is not delivered by rivers because riverine SPM has an order of magnitude lower Ca content, and sediment discharge is negligible during summer when the sampling was done. On the contrary, it appears to have been derived from the nearshore environment, where bottom sediments are resuspended and flushed into the estuary, as shown by the following lines of evidence: Netravati-Gurpur R. SPM, estuarine-coastal SPM, frothy material and surficial sediments off Mangalore show a systematic trend of increasing Ca from 0.26 through 1.93 and 2.91 to 6.44% respectively. Riverine SPM has very low Ca content because this element is derived only from chemical weathering processes. Calcium increases in estuarine-coastal SPM and surficial sediments off Mangalore because of productivity in surface waters and the seaward decrease in the terrigenous component. From this pattern of Ca distribution, it is inferred that the material was derived from the nearshore region. Hence, Ca content can be used to differentiate between riverine and coastal sediments in this tropical regime. This readily determinable parameter (Ca content) can be used as a natural tracer, in addition to chemical, mineralogical and isotopic composition, to determine mixing ratios in estuarine sediments (Salomons and Mook, 1987). The utility of Ca content in making such a distinction gains importance in the light of the remarks made by Postma (1988) that relatively little attention is devoted to geologically related subjects like riverine vs. marine origin of sediments.

Metal/Al ratios (except Mn/Al) in frothy material are similar to those of surficial sediments off Mangalore. Therefore, varying metal concentrations in these two materials merely reflect their different clay contents. This is shown by the contrasting Al contents of 7.9 and 13.89%. In fact, this parameter also systematically varies from 7.9 through 13.89 and 13.97 to 17.09% in surficial sediments off Mangalore, frothy material, estuarine-coastal SPM and Netravati-Gurpur R. SPM, respectively. About 79% of the total Mn is present in the acetic acid-soluble fraction (Table 2). Furthermore, the 3.5-fold higher Mn content and the two-fold higher Mn/Al ratio in the frothy material may be due to re-adsorption of Mn onto the surface of clay minerals that are brought from the high salinity nearshore environment and introduced into the low salinity estuarine environment. The process of Mn re-adsorption is opposite to what takes place when riverine SPM encounters waters of high salinity, *i.e.*, desorption (Manjunatha, 1990). Release of trace metals, particularly Mn, from reducing sediments and their subsequent adsorption and precipitation in the oxygenated coastal and estuarine waters with particulate matter has been reported by many workers (Bewers and Yeats, 1978, 1979; Sundby *et al.*, 1981; Trefry *et al.*, 1984; Brugmann, 1988; Van Der Sloot *et al.*, 1988). Manganese-rich particles are carried either to the open ocean (Yeats *et al.*, 1979; Sundby *et al.*, 1981) or transported landward (Sundby *et al.*, 1981) as in the area of study, depending on the direction of bottom currents. A progressive landward increase of dissolved and particulate Mn in bottom waters has been observed in the St. Lawrence estuary (Sundby *et al.*, 1981). These authors have deciphered erosion of the sea-bed and subsequent transportation of Mn-rich particles by the activity

Table 2. *Geochemical partition data[a] for subsamples of frothy material from the Netravati Estuarine front.*

Sample Numbers	Copper				Lead				Zinc			
	1	2	3	4	1	2	3	4	1	2	3	4
F-Flo	7.81	—	87.50	4.69	—	22.22	44.44	33.33	13.53	1.50	73.68	11.28
F-set	6.25	—	87.50	6.25	—	22.22	44.44	33.33	12.03	3.01	75.19	9.77
F-susp	7.94	—	77.78	14.29	—	22.22	44.44	33.33	12.03	7.52	67.67	12.78

[a]1. HOAc (carbonate phase); 2. $NH_2OH \cdot HCl$ (easily reducible phase); 3. Hot 50% HCl (resistant/detrital phase); 4. $HF\text{-}HNO_3\text{-}HClO_4$ (acid insolubles/highly resistant phase)

of landward-flowing bottom currents. This mechanism has been termed as 'broom effect'.

Partition Geochemistry

The partition of base metals in various sedimentary phases of frothy material and the mean surficial sediments from the inner shelf off Mangalore is given in Tables 2 and 3 and diagrammatically shown in Figure 3a and b. The data are used to elucidate geochemical changes that the sediment undergoes from the reducing, inner shelf to the more oxidizing estuarine environment. As mentioned earlier, 79% of the total Mn is present as adsorbed species (Step I). The proportions of other metals associated with the acetic acid-soluble fraction are similar in frothy material and surficial sediments (Table 3). As the frothy material occurs in the oxidizing estuarine environment, it has relatively higher proportions (6.6 to 22.2%) of metals in the easily reducible phase compared to the reducing surficial sediments off Mangalore (0.4 to 8.8%). Easily reducible phases include MnO_2 that formed when diagenetically remobilized Mn was oxidized and precipitated; MnO_2 has scavenged dissolved trace metals.

Although frothy material has a higher content of organic matter, the proportions of Cu, Pb, Zn, Ni and Mn associated with the organic matter are lower (0 to 27.8%) than in surficial sediments (1.5 to 39%). The higher proportion of metals in the hydrogen peroxide leach of surficial sediments could be due to their association with sulphide minerals, such as authigenic pyrite, besides organic matter (MANJUNATHA, 1990).

Iron is present principally in the hot, 50% HCl-soluble phase, whereas other metals are present both in this and the acid insoluble/most resistant phase. The higher proportions of metals (Cu, Zn, Ni, Co and Mn) in the hot, 50% HCl leach of frothy material as opposed to surficial sediments off Mangalore (Table 3), suggest that only fine particles (< 63 μm) are resuspended and transported into the estuary. It is known that hot, 50% HCl attacks the clay structure (CRONAN and GARRETT, 1973).

Landward Transport of Sediments

Suspended particulate concentration in the water sample collected from the front is anomalously high (F-flo + F-set + F-susp = 430 ± 3,530 + 350 = 4,310 mg/l). Such a high SPM concentration in landward-flowing water may often imply erosion of the sea-bed (MEADE, 1969). From this and the geochemical data presented above, it appears that nearshore sediments are resuspended and transported landward into the Netravati-Gurpur Estuary and the adjacent marshy area. This process is common to many estuaries (NUNES and SIMPSON, 1985; SIMPSON and TURREL, 1986; HUZZEY and BRUBAKER, 1988). HUZZEY and BRUBAKER (1988) have also emphasized that horizontal pressure gradients that produce the surface convergence zone act over a distance much greater than the width of the estuary during flood tide. It appears that front formation (invariably during flood phase) in the Netravati-Gurpur Estuary is also due to similar processes. The surface accumulation of frothy material in the estuarine front could be due to aggregation of silt and clay-sized particles during the resuspension and landward transport of coastal sediments. The aggregation of fine sediment, particularly at lower salinities (0–10‰) is common in many estuaries (GIBBS *et al.*, 1989; LI *et al.*, 1993). In addition, coastal upwelling could also bring 'dense flocs' to the water surface which will be transported landward or seaward, depending upon estuarine circulation patterns (LI *et al.*, 1993). In this area of study, coastal upwelling (up to 50 m water depth) is prevalent during summer (RAMANA *et al.*, 1988), which may be one of the processes leading to aggregation of fine-grained sediments. However, no such detailed studies involving measurements of salinity and current velocity and direction were carried out for the Netravati Estuary to understand frontogenesis. Asymmetry in tidal currents is an important factor

Table 3. *Geochemical partition data (average)[a] for frothy material along with surficial sediments off Mangalore.*

Sample Description	Copper					Lead					Zinc				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Froth	7.86	14.15	24.84	52.67	0.47	—	22.20	27.78	16.67	33.33	4.88	14.63	21.95	31.71	26.83
[b]	8.17	1.14	38.06	18.69	33.92	10.05	8.78	39.10	27.21	14.85	4.71	1.66	31.32	28.28	34.04

[a]I. HOAc (carbonate phase); II. $NH_2OH \cdot HCl$ (easily reducible phase); III. Hot 50% HCl (resistant/detrital phase); IV. $H_2O_2\text{-}NH_4OAc$ (organic fraction including sulphides); V. $HF\text{-}HNO_3\text{-}HClO_4$ (acid insolubles/highly resistant phase).

[b]Mean surficial sediments from the shelf off Mangalore (MANJUNATHA, 1990)

Table 2. *Extended.*

Nickel				Cobalt				Manganese				Iron			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
5.88	5.88	58.82	29.41	—	20	60	20	87.63	2.92	6.82	2.63	3.99	—	91.18	4.85
5.88	—	70.59	23.53	—	20	60	20	80.81	—	14.56	4.63	4.07	—	95.52	0.45
5.88	—	58.82	35.29	—	20	40	40	67.93	0.31	16.47	15.29	3.67	—	87.41	8.89

controlling the residual transport of suspended matter (GORSLINE, 1967). Because of the negligible sediment load of the Netravati-Gurpur R., this estuary is still unfilled, and coastal sediments are being brought into the estuary, resulting in siltation and formation of a 200 m long bar. Filling up of the estuary is also aided by flocculation of suspended sediments.

MEADE (1969) has reported landward transport of bottom sediments in estuaries along the east coast of the U.S. based on variations of physico-chemical parameters at fixed sampling stations over a tidal cycle. MEADE (1982) has estimated that 95% of riverine suspended matter is trapped in the estuaries and coastal marshy lands along the Atlantic coastal plain of the United States. OFFICER *et al.* (1984) have demonstrated that the Chesapeake Bay not only traps all the river transported sediment, but also imports sediment from the ocean. Thus, some estuaries are filled up with sediment from rivers at the landward end and from the continental shelf at the seaward end (MILLIMAN, 1991). LI *et al.* (1993) have inferred rapid siltation in the Jiaogiang Estuary, East China Sea, during dry weather conditions, *i.e.*, summer. The processes responsible for siltation are: 1) upwelling which brings 'dense flocs' towards the surface, 2) tidal pumping (with stronger peak flood than ebb tidal currents) that generates a turbidity maximum zone, and 3) rapid flocculation of suspended sediments at low salinities of 5–10‰ (LI *et al.*, 1993).

Several studies carried out along the west coast of India also have indicated landward transport of sediments. MURTY *et al.* (1976) have suggested onshore transport of sediments based on a study of the Aguada Bar, located at the mouth of Mandovi River, Goa. The abundant occurrence of planktonic foraminifera in Cochin breakwaters has been interpreted by SEIBOLD (1972) as due to onshore transport of sediments. Similarly, the presence of grapestone (non-skeletal carbonate component in the >63 μm fraction of sediment) in nearshore regions off Ratnagiri is indicative of possible onshore transport of sediments on the western continental shelf (HASHIMI and NAIR, 1976). Radioactive effluents discharged from the Tarapur and Bombay nuclear power reactors into the Arabian Sea are concentrated in the coastal zone (KAMATH *et al.*, 1970; BHAT *et al.*, 1981). This also suggests landward circulation and transport of sediments.

Implications

Landward transport of sediments into the Netravati-Gurpur Estuary has been inferred from the geochemical data on frothy material (composed mainly of particles <63 μm) associated with the front. In addition, it is conjectured that coarser particles, like sand, are also probably transported as bedload. In this connection, it is interesting to note that siltation in the navigational channel of the Old Mangalore Port has been reported by REDDY *et al.* (1979). JAYAPPA and SUBRAHMANYA (1989) report a net gain of 74.2 m^3 of sand per linear metre of beach per year across the beaches of Netravati-Gurpur Estuary, in spite of erosion at some places. According to fishermen of Mangalore, siltation takes place not only in the bar of the Old Mangalore Port area but all along coastal Karnataka (quoted in VAZ, 1989). Visual observation over the last 13 years also suggests siltation in the estuary. As a result, the estuarine morphology has been changing. Progressively larger areas of estuarine bottom are being exposed at ebb tide. Vegetation that has started growing in such areas has further helped in trapping sediments which leads to stabilisation of tidal flats. Once fine sediments are deposited on the estuarine bottom, a higher energy than that at which they were deposited is needed to resuspend them. This is because of their cohesive property. In addition, algal growth on estuarine bottoms also helps to prevent resuspension of particles (GORSLINE, 1967). Siltation in the Old Mangalore Port, Netravati-Gurpur river mouth and the nearby bar has reduced the width and draught of the navigational channel resulting in navigational problems. More than 62 accidents have occurred involving various types of boats in the Port area since 1981, leading to the death of 12 fishermen and an estimated loss of more than 25 million INR (Indian rupees) to fishermen (VAZ, 1989). Because of the unfilled nature and tidal asymmetry of the Netravati-Gurpur Estuary,

Table 3. *Extended.*

Nickel					Cobalt					Manganese					Iron				
I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
5.56	6.56	15.67	38.89	33.33	—	20	20	34	26	78.94	11.07	—	2.64	7.34	3.85	—	—	91.56	4.59
2.93	0.74	19.03	29.56	47.73	8.12	2.45	7.32	20.34	61.80	31.31	0.37	14.97	24.48	28.28	4.57	1.09	1.53	77.78	15.03

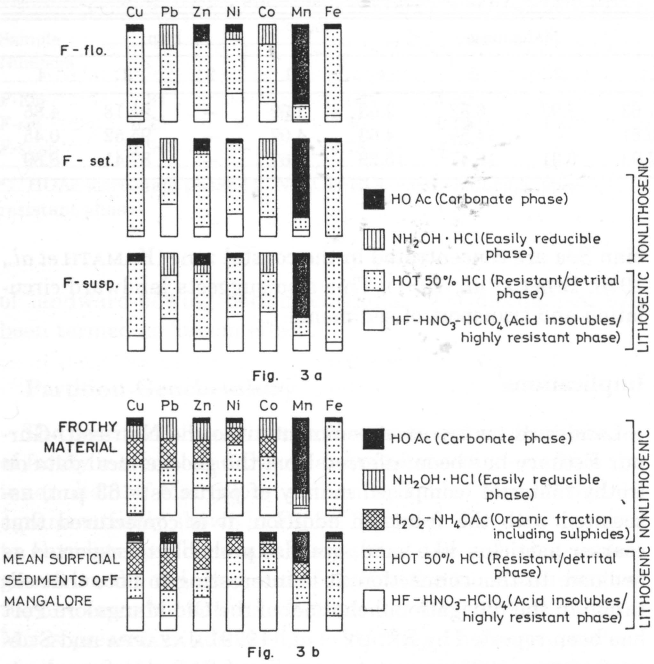

Figure 3. Partition of base metals in various sedimentary phases of frothy material from the Netravati estuarine front and (mean) surficial sediments off Mangalore.

nearshore sediments are being flushed into the estuary as shown above. Therefore, dredging of the Port and navigational channel cannot be a permanent solution to the problem of siltation. However, dredging can be done every year, immediately after the monsoon to reduce the effect of siltation and sediment bar formation (REDDY *et al.*, 1979). De-siltation can only offer temporary relief. Therefore, establishing a new port to the north of the existing Old Mangalore Port was a wise decision.

In the context of dredging in the Old Mangalore Port, it is pertinent here to quote the instance of the Savannah R. Estuary. After dredging was done in this estuary to allow the passage of large ships, salt water moved easily up the new channel and landward bottom flow was firmly established. The consequence of dredging was entrapment of river sediments in the estuary that otherwise would have reached the sea, plus movement of sediments from outside into the estuary (SIMMONS, 1965, quoted in MEADE, 1969).

Dredging of the Netravati R. Channel may achieve the intended objective only in the short run. Because of the reasons mentioned above, the river channel is likely to be filled up rapidly, and dredging may lead to several changes in the natural system. For instance, particles resuspended while dredging lose their cohesive strength, thereby increasing the suspended sediment concentrations by factors of 10–100 in the lower parts of the water column. Dredging operations cause not only resuspension of sediments, but also change the equilibrium between estuarine morphology and currents (NICHOLS, 1986).

Coastal oceans have been used as dumping grounds for effluents of different kinds. GOUVEIA and VARADACHARI (1979) have reported that tidal influence is negligible at 4 km distance off Mangalore, and the disposal of effluents may be desirable beyond such a point. The landward component of the circulation pattern in the Netravati-Gurpur Estuary should be taken into consideration for effluent disposal. This is also true for effluents from various industries located all along the west coast of India, including the Kaiga nuclear power plant and the Mangalore petroleum refinery that are developing. Although the severity of pollution along the west coast of India has not yet reached the magnitude that is found in industrialized countries, coastal areas in the vicinity of industrial sites and cities are beginning to show noticeable contamination (UNEP, 1982). Enrichment of various types of pollutants (heavy metals, radioactive pollutants as nuclear fission products, hydrocarbons, fecal coliforms, sulphates, sulphuric acid, etc.) is noticed around Bombay, Goa, Cochin and Trivandrum (UNEP, 1982). Studies should also be made to delineate the "line of no return" on the shelf beyond which no sediment returns to the coast or into the estuary (POSTMA, 1988).

CONCLUSIONS

The surface accumulation of brown frothy material in the Netravati-Gurpur and other estuaries (like Kali, Sita and Swarna) along the central west coast of India indicates the landward transport of fine-grained nearshore sediments through estuarine front formation. It is conjectured that coarse particles are also transported landward as bedload. These two processes have led to siltation in the estuary, creating navigational problems. Front formation is prominently seen in the flood phase of the tidal cycle during summer. The frothy material consists mainly of silt-clay fraction, plus a minor quantity of shells (foraminifers, ostracods and gastropoda) and plant debris in the coarser fraction. Geochemical studies indicate that the nearshore sediments are flushed into the estuary during the flood phase of the tidal cycle. Compared to the Netravati-Gurpur riverine SPM, the frothy material has similar elemental concentrations and metal/Al ratios (except Mn and Mn/Al), but an order of magnitude high Ca, low Al and high organic matter, suggesting adsorption of Mn onto the particulate phase, and high biological productivity in the estuarine and coastal waters.

The geochemical data presented here for the onshore transport of nearshore sediments is in good agreement with several lines of evidence for the same process, manifesting at several places along the west coast of India. There is an urgent need to consider the landward component of circulation, while planning the disposal of effluents from various industries, both existing and proposed, along the west coast of India. It is also necessary to demarcate the "line of no return" of sediments (POSTMA, 1988) in the continental shelf in this regard.

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LITERATURE CITED

AHMED, E., 1972. *Coastal Geomorphology of India.* Bombay: Orient Longman, 222p.

BEWERS, J.M. and YEATS, P.A., 1978. Trace metals in the waters of a partially mixed estuary. *Estuarine, Coastal and Marine Science,* 7, 147–162.

BEWERS, J.M. and YEATS, P.A., 1979. The behaviour of trace metals in estuaries of the St. Lawrence Basin. *Naturaliste Canada,* 106, 149–161.

BHAT, I.S.; PATEL, B., and KAMATH, P.R., 1981. Cycling of radionuclides and impact of operational releases in the nearshore ecosystem off the west coast of India. *Proceedings of Symposium on Impact of Radionuclide Releases into the Marine Environment* (I.A.E.A., Vienna), 431–448.

BOWMAN, M.J., 1988. Estuarine fronts. *In:* KJERFVE, B. (ed.), *Hydrodynamics of Estuaries,* Vol. 1, Estuarine Physics. Boca Raton, Florida: CRC Press, pp. 85–132.

BOWMAN, 'M.J. and IVERSON, R.L., 1977. Estuarine plume and fronts. *In:* BOWMAN, M.J. and ESAIAS, W.E. (eds.), *Oceanic Fronts in Coastal Processes.* New Jersey: Springer-Verlag, 87–104.

BRUCKNER, H., 1989. Late Quaternary shorelines in India. *In:* SCOTT, D.B.; PIRAZZOLI, P.A., and HONING, C.A. (eds.), *Late Quaternary Correlation and Applications.* Maine: Kluwer, pp. 169–194.

BRUGMANN, L., 1988. Some peculiarities of the trace-metal distribution in Baltic waters and sediments. *Marine Chemistry,* 23, 425–440.

CHAO, T., 1972, Selective distribution of manganese oxides from soils and sediments with hydroxylamine hydrochloride. *Journal of Soil Science Society America,* 47, 225–232.

CHESTER, R. and HUGHES, M.J., 1967. A chemical technique for the separation of ferromanganese minerals, carbonate minerals and adsorbed trace elements from pelagic sediments. *Chemical Geology,* 2, 249–262.

CRONAN, D.S. and GARRETT, D.E., 1973. Distribution of elements in metalliferous Pacific sediments collected during the Deep-Sea Drilling Project. *Nature,* 242, 88–89.

GIBBS, R.J., 1981. Sites of river-derived sedimentation in the ocean. *Geology,* 9, 77–80.

GIBBS, R.J.; TSHUDY, D.M.; KONWAR, L., and MARTIN, J.-M., 1989. Coagulation and transport of sediments in the Gironde Estuary. *Sedimentology,* 36, 987–999.

GORSLINE, D.S., 1967. Contrasts in coastal bay sediments on the Gulf and Pacific coasts. *In:* LAUFF, G.H. (ed.), *Estuaries.* American Association for the Advancement of Science, 219–225.

GOUVEIA, A.D. and VARADACHARI, V.V.R., 1979. Coastal and nearshore circulation off Mangalore. *Mahasagar,* 12, 175–182.

GUPTA, S.K. and CHEN, K.Y., 1975. Partitioning of trace metals in selective chemical fractions of nearshore sediments. *Environment Technology Letters,* 10, 129–158.

HASHIMI, N.H. and NAIR, R.R., 1976. Carbonate components in the coarse fraction of western continental shelf of India (Northern part). *Indian Journal of Marine Sciences,* 5, 51–57.

HE SONGLIN, 1987. On the aggregation of suspended fine-grained matter and behaviour of trace metals in estuaries: A review. *In:* DEGENS, E.T.; KEMPE, S., and WEIBIN, G. (eds.), *Transport of Carbon and Minerals in Major World Rivers.* Geologisch Palaeontologisches Institut, University of Hamburg, SCOPE/UNEP Sonderbad 64, 195–206.

HUZZEY, L.M. and BRUBAKER, J.M., 1988. The formation of longitudinal fronts in a coastal plain estuary. *Journal of Geophysical Research,* 93, 1329–1334.

JAYAPPA, K.S. and SUBRAHMANYA, K.R., 1989. Beach morphological changes between Talapadi and Suratkal, Dakshina Kannada. *Geological Survey of India Special Publication* No. 24, 299–306.

KAMATH, P.R.; BHAT, I.S., and GANGULY, A.K., 1970. Environmental behaviour of discharged radioactive effluents at Tarapur Atomic Power Station. *Proceedings of International Symposium on Environmental Aspects of Nuclear Power Stations* (I.A.E.A., New York), pp. 475–493.

KARNATAKA IRRIGATION DEPARTMENT, 1986. *River Discharge Data.* No. 5, Gauging Sub-division, Shimoga, India. (Unpublished).

KEMPE, S., 1988. Estuaries—Their natural and anthropogenic changes. *In:* ROSSWAL, T.; WOODMANSEE, R.G., and RISSER, P.G. (eds.), *Scales and Global Change.* SCOPE, New York: Wiley, pp. 251–285.

LI, Y.; WOLANSKI, E., and XIE, Q., 1993. Coagulation and settling of suspended sediments in the Jiaogiang River Estuary, China. *Journal of Coastal Research,* 9, 390–402.

MANJUNATHA, B.R., 1990. Geochemistry and magnetic susceptibility of riverine, estuarine and marine environments around Mangalore, west coast of India. Ph.D. Thesis, Mangalore University, 260p.

MEADE, R.H., 1969. Landward transport of bottom sediments in estuaries of the Atlantic coastal plain. *Journal of Sedimentary Petrology,* 39, 222–234.

MEADE, R.H., 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology,* 90, 235–252.

MEHTA, A.J., 1986. Introduction. *In:* MEHTA, A.J. (ed.), *Estuarine Cohesive Sediment Dynamics.* Lecture Notes on Coastal and Estuarine Studies. New York: Springer, pp. 1–4.

MILLIMAN, J.D., 1991. Flux and fate of fluvial sediment and water in coastal seas. *In:* MANTORA, R.F.C.; MARTIN, J.-M., and WOLLAST, R. (eds.), *Ocean Margin Processes in Global Change.* New York: Wiley, pp. 69–89.

MURTHY, T.R.S.; MADHYASTHA, M.N.; RAO, I.J., and CHANDRASEKHARAPPA, K.N., 1988. A study of physical determinants of natural environments and their impact on land use in Netravati and Gurpur river basins of Western Ghat region, Karnataka. *Department of Environment and Forest, Government of India, New Delhi, Project Report,* 60p.

MURTY, C.S.; DAS, P.K.; NAIR, R.R.; VEERAYYA, M., and VARADACHARI, V.V.R., 1976. Circulation and sedimentation processes in and around the Aguada Bar. *Indian Journal of Marine Sciences,* 5, 9–17.

NICHOLS, M.M., 1986. Effects of fine sediment resuspension in estuaries. *In:* MEHTA, A.J. (ed.), *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies.* New York: Springer, pp. 5–42.

NUNES, R.A. and SIMPSON, J.H., 1985. Axial convergence in a well-mixed estuary. *Estuarine, Coastal and Shelf Science,* 20, 637–649.

OFFICER, C.B.; LYNCH, D.R.; SETLOCK, G.H., and HELZ, G.R., 1984. Recent sedimentation rates in Chesapeake Bay. *In:* KENNEDY, V.S. (ed.), *The Estuary as a Filter.* Academic, pp. 131–157.

PATIL, S., 1987. Studies on the Distribution of Plankton in Relation to Hydrography of Netravati-Gurpur Estuary. Mangalore (D.K.). M.F.Sc. Thesis, College of Fisheries, Mangalore, 260p.

POSTMA, H., 1988. Physical processes in estuaries: Some evaluating remarks. *In:* DRONKERS, J. and VAN LEUSSEN, W. (eds.), *Physical Processes in Estuaries.* New York: Springer.

RAMANA, T.V.; NATHANIEL, D.E., and REDDY, M.P.M., 1988. Upwelling and sinking in the Arabian Sea off Someshwar–Manjeshwar Region. *In:* MOHAN JOSEPH, M. (ed.), *The First Indian Fisheries Forum Proceedings Asian Fisheries Society.* Indian Branch, Mangalore, pp. 333–338.

REDDY, M.P.M.; HARIHARAN, V., and KURIAN, N.P., 1979. Sediment movement and siltation in the navigational channel of Old Mangalore Port. *Proceedings of Indian Academy of Sciences,* 88 (Part II), 121–130.

SALOMONS, W. and MOOK, W.G., 1987. Natural tracers for sediment transport. *Continental Shelf Research,* 7, 1333–1343.

SAMPATHKUMAR, R., 1984. Studies on the Distribution of Plankton in Waters off Mangalore. M.F.Sc. Thesis, College of Fisheries, Mangalore, 231p.

SCHUBEL, J.R. and KENNEDY, V.S., 1984. The estuary as a filter: An introduction. *In:* KENNEDY, V.S. (ed.), *The Estuary as a Filter.* New York: Academic Press, pp. 1–11.

SEIBOLD, I., 1972. Preliminary report on the transport of foraminifera into Cochin backwaters. *Journal of Marine Biological Association of India,* 14, 452–455.

SIMPSON, J.H. and TURREL, W.R., 1986. Convergent fronts in the circulation of tidal estuaries. *In:* WOLF, D.A. (ed.), *Estuarine Variability.* San Diego: Academic, pp. 139–152.

SUBRAMANIAN, V.; BIKSHAM, G., and RAMESH, R., 1987. Environmental geology of peninsular river basins of India. *Journal of Geological Society of India,* 30, 393–401.

SUNDBY, B.; SILVERBERG, N., and CHESSELET, R., 1981. Pathways of manganese in an open estuarine system. *Geochimica et Cosmochimica Acta,* 45, 293–307.

TREFRY, J.H.; PRESLEY, B.J.; KEENEY-KENNICUTT, W.L., and TROCINE, R.P., 1984. Distribution and chemistry of manganese, iron, and suspended particulates in Orca Basin. *Geo-Marine Letters,* 4, 125–130.

UNEP, 1982. Pollution and the marine environment in Indian Ocean. *UNEP Regional Seas Reports and Studies* UNEP Report No. 13, 150p.

VAN DER SLOOT, H.A.; HOEDE, D.; HAMBURG, G.; DE LANGE, G.J.; MIDDLEBURG, J.J., and SOPHIAH, S., 1988. Suspended manganese-rich particles in Kau Bay, Halmera (eastern Indonesia). *Marine Geology,* 82, 251–259.

VAN LEUSSEN, W. and DRONKERS, J., 1988. Physical processes in estuaries: An introduction. *In:* DRONKERS, J. and VAN LEUSSEN, W. (eds.), *Physical Processes in Estuaries.* New York: Springer, pp. 1–18.

VAZ, G., 1989. Port dredging work to begin in October. *The Times of India,* 4, (17th September) p. 1 and p. 3.

VOGEL, A.I., 1978. *A Textbook of Quantitative Inorganic Analysis,* 4th Edition. New York: Longman, 925p.

WAGLE, B.G., 1987. Geomorphology and Evolution of the Coastal and Offshore Areas of Maharashtra and Goa, India. Ph.D. Dissertation, University of Bombay, 103p.

WALLACE, J.W. and PHLEGER, C.F., 1979. *Field Guide and Laboratory Manual for Oceanography: An Introduction.* Belmont, California: Wardsworth, 245p.

WELLS, J.T. and SHANKS, A.L., 1987. Observations and geologic significance of marine snow in shallow-water, partially enclosed marine embayment. *Journal of Geophysical Research,* 13, 185–189.

YEATS, P.A.; SUNDBY, B., and BEWERS, J.M., 1979. Manganese recycling in coastal waters. *Marine Chemistry,* 8, 43–55.