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Clay Minerals of the Sarada-Varaha Estuary, East Coast of India

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ABSTRACT

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Seasonal variability of clay mineral suites has been investigated in the Sarada-Varaha estuary, east coast of India. Montmorillonite, illite, and kaolinite occur in significant amounts. Chloride which is present in the adjacent continental shelf sediments is conspicuous by its absence in the estuarine sediments. Montmorillonite shows a general downstream decrease in December when the estuary is in a partially mixed state and an upstream decrease in April associated with a negative state estuary. Illite and kaolinite, in general, register inverse trends correspondingly. The temporal and spatial trends of clay minerals are related to the estuarine and tidal circulation, which form the dominant sediment distribution processes in December and April, respectively.

ADDITIONAL INDEX WORDS: *Estuarine circulation, sediments, seasonal variability.*

INTRODUCTION

Lateral distributions of clay minerals of the bottom sediments in estuaries have been attributed to various processes: diagenesis (POWERS, 1954; GRIFFIN and INGRAM, 1955; NELSON, 1960); differential settling and flocculation (WHITEHOUSE *et al.*, 1960; SCHIOZOWA, 1970; EDZWALD and O'MELIA, 1975); physical size segregation (GIBBS, 1977); and, estuarine circulation dynamics (FEUILLET and FLEISCHER, 1980). The few studies of the clay minerals of bed and suspended load of the Indian estuaries have only emphasized the relationship of estuarine clay mineral suites to their continental sources (GOLDBERG and GRIFFIN, 1970; SUBRAMANIAN, 1980; SERALATHAN and SWAMY, 1982; NAIDU *et al.*, 1985; SATYAKUMAR and SUBBA RAO, 1987). No seasonal studies of Indian estuaries for clay minerals are known. This paper reports on temporal and spatial trends of clay mineral suites in the Sarada-Varaha estuary, east coast of India in relation to the estuarine circulation systems. The results reported here should be of broad interest since clay mineral distributions in tropical estuarines are poorly known.

PHYSICAL SETTING

The Sarada and Varaha rivers originate in the Eastern Ghats, 100 km inland from the coast, and discharge into a small tidal bay on the east coast of India (at 17°25′N, 82°52′E), 50 km southwest of Visakhapatnam (Figure 1). The tidal bay is connected to the Bay of Bengal by a tidal inlet channel located between two hills. Sand characterizes the tidal inlet sediments while the intertidal banks of the inlet are rocky and devoid of a sediment cover. A small coastal plain stream (referred to as the central stream) also enters the tidal bay. The drainage area is classified as semiarid (SUBRAHMANYAM *et al.*, 1965).

Precipitation is intermittent and occurs through the southwest monsoon activity during June–September and due to cyclonic activity in the Bay of Bengal during October–November. The rivers and central stream are ephemeral and swell when considerable precipitation occurs in their catchment areas. They are dry from January to June, except for their seaward stretches which are influenced by the tidal regime. Flood tide and salt incursion reach 2 km inland in the Varaha, 8 km in the Sarada and 2 km in the central stream from the tidal inlet during the summer drought. Water depths range from 1–6 m, 1–3 m and 0.5–1 m in the Sarada, Varaha and Central streams, respectively. Tidal range is 0.5–2 m at the mouth. No data on sediment and water discharge from these rivers are available. The bay and the lower river segments affected by tidal regime together are referred to as the Sarada-Varaha estuary.

Khondalites (quartz-garnet-sillimanite gneisses and schists) form the hill ranges in the drainage basin. Leptynites (garnetiferous granulites), char-

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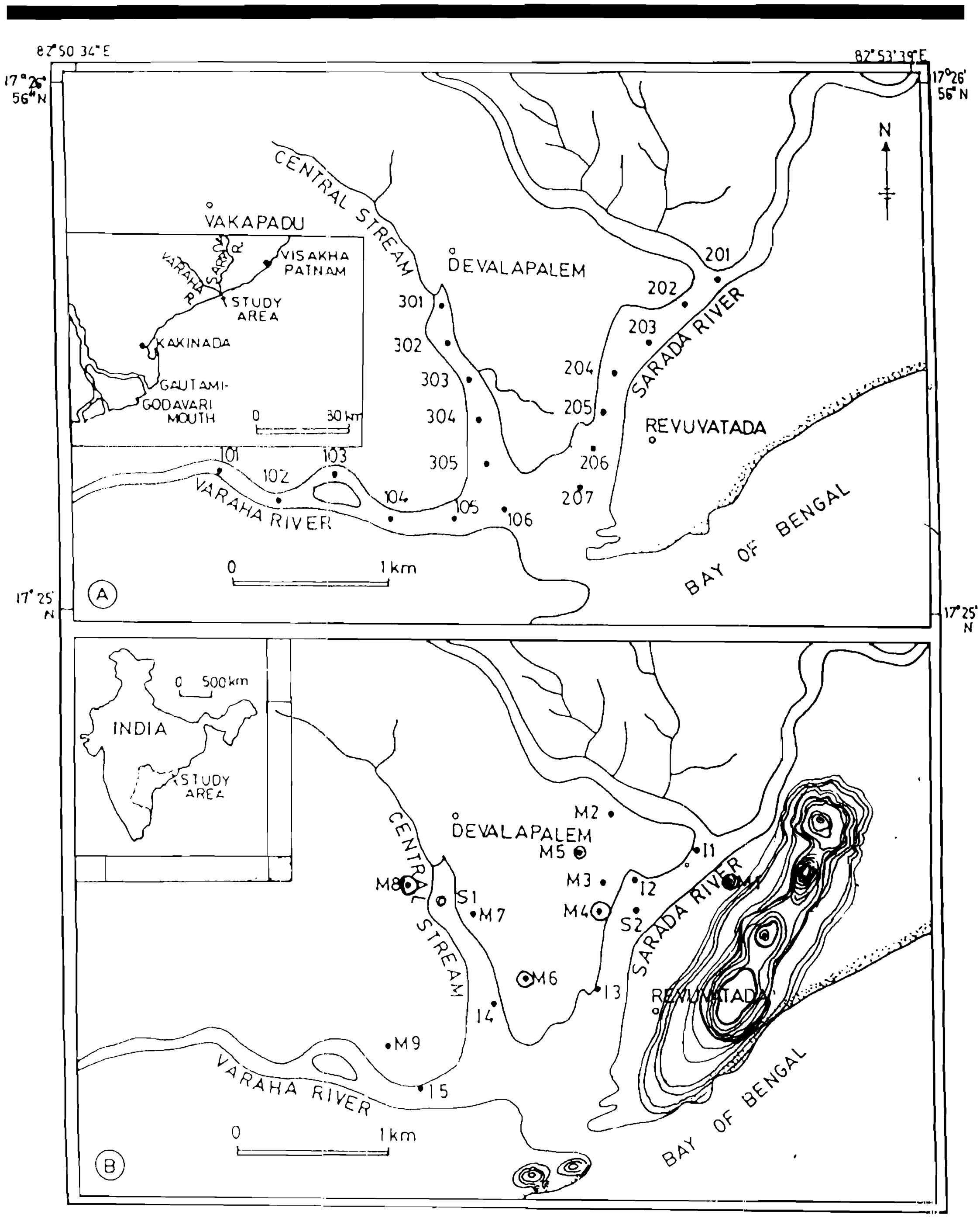

Figure 1. Sarada-Varaha estuary. (A) Showing midchannel sampling stations; (B) Showing sampling stations in the marsh areas (M) and the intertidal zone (I). Suspended sediment was collected at S1 and S2 locations. Sediment cores were also obtained in the marsh at stations marked ⊙.

nockites, calc-granulites, sapphirine granulites, and quartz and pegmatite reefs and veins also occur but are of limited areal extent. Laterite soils are extensive both on hills and in valleys (NARAYANA SWAMY, 1975; KAMINENI and RAO, 1988).

The interpretation of the water circulation dynamics in the Sarada-Varaha estuary is based on the limited salinity measurements made simultaneously with sediment sample collection in September, December, and April, 1984–1985, and comparisons with the reported salinity-structure patterns in the Visakhapatnam Harbour Channel (RAMARAJU *et al.*, 1987) and the Gautami-Godavari River (RAMASARMA and GANAPATI, 1972) (Figure 1). Precipitation in the catchment areas of the rivers is sporadic during June–November and flood stages in the rivers last for only short periods. During these periods, the nontidal water movements, generated by river discharge, define an estuarine circulation cell that maintains a turbidity maximum. The estuary returns to a partially mixed state soon after each spate as was the case in September, 1984. In this state, the lower salt water flow is dominant. As fluvial inputs totally cease, the estuary changes from a partially mixed state to a vertically mixed state and finally assumes a negative stage in the summer months of April–June. The negative state is characterised by a salinity increase upstream from the tidal inlet. The limited salinity data suggest that, in general, tidal circulation is the dominant process of sediment distribution during January–June and estuarine circulation during July–December.

SAMPLE COLLECTION

Bottom sediment samples were collected in September, December, and April, 1984–1985 at 18 fixed midchannel stations, using a Van Veen grab sampler. The top 1 cm sediment layer, which is believed to represent recent deposition, was extracted from each sample and preserved in polythene sachets. The samples of September represent the inter-flood condition, those of December the post-flood condition and those of April the summer drought condition of sedimentation in the estuary. Samples representative of full flood condition are lacking. In addition, nine surficial sediment samples from the dry marsh areas marginal to the river channels, and five from the wet intertidal areas along the river channels were collected in April, 1985. Four sediment cores, each 50 cm long, were also obtained from the dry marsh areas and the top and bottom 1 cm layer was separated from each core and preserved. Two water samples were collected shortly after the ebb-tide low in April, 1985—one from the Sarada and the other from the central stream. Suspended sediment from these water samples was extracted later in the laboratory. The location of sample stations is shown in Figure 1.

LABORATORY PROCEDURES

Sand, silt, and clay ratios were determined by sieving and settling following the techniques of CARVER (1971). Sediment-texture nomenclature is from FOLK (1974). For X-ray analysis, the <2 μm fractions were separated, following CARVER (1971). Oriented slides were prepared of all the samples by the pipette-on-glass slide technique (STOFFERS and MULLER, 1972; STANLEY and LIYANAGE, 1986). The slides were run on Philips XRD system PW1730/PW1390 untreated and glycolated from 3° to 30° at 1° 2θ min^{-1} using Ni-filtered CuK_α radiation. One-third of the samples were heated to 550 °C for one hour and run again. A few representative samples were slow scanned from 23° to 26° at 0.25° 2θ min^{-1}. Techniques of clay mineral identification were from CARROLL (1970) and BRINDLEY and BROWN (1980) and quantification from BISCAYE (1965). The clay mineral data were subjected to a discriminant analysis using a computer programme to discover differences between the different estuaries and between seasons (KNEBEL *et al.*, 1968, 1977; KARLIN, 1980; JOHNSON and KELLEY, 1984). For comparing the groups, Snedecor's F statistic was computed from Mahalanobis D^2 (a measure of the separation of two groups). When compared with critical values, the F statistic indicates significant differences between groups*.

RESULTS

Sediment Texture

Both temporal and spatial variability of sand, silt and clay relative abundances are high in the different segments of the Sarada-Varaha estuary (Figure 2). In September, clay is high (avg. 33%) and sand low (avg. 42%) in the Varaha relative to the other two segments; in December, clay is

* As three variables are being simultaneously considered in this problem, multivariate statistical analysis is appropriate. Mahalanobis D^2 test statistic is used to test whether observed differences in two sets of variate values are significantly different. A constant multiple of D^2 test statistic is F with the appropriate degree of freedom depending on the sample sizes and number of variates considered simultaneously.

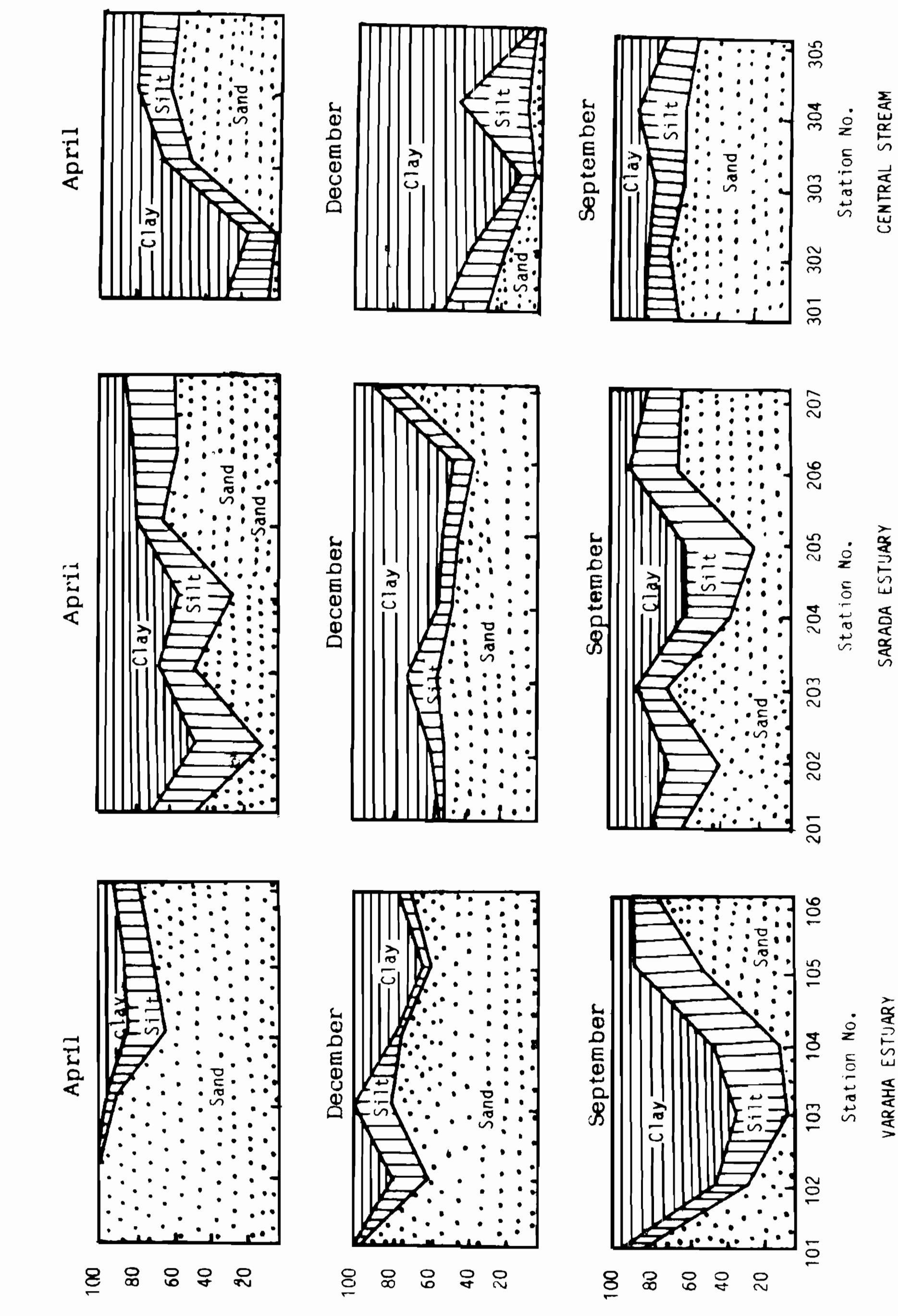

Figure 2. Relative abundance of sand, silt and clay in Sarada-Varaha estuary.

Table 1. *Average textural composition of sediments in the estuarine system.*

Area	Month	% Sand	% Silt	% Clay	Average Silt/Clay Ratio
Sarada-Varaha estuary	September	53	23	26	1.0
	December	51	11	38	0.3
	April	58	19	23	0.8
Inter-tidal margins	April	33	56	11	5.7
Marsh (surface)	—	37	53	10	6.0
Marsh (subsurface at 50 cm depth)	—	30	55	15	3.8

very high (avg. 65%) and sand very low (avg. 17%) in the central stream compared with the other segments; in April, the Varaha records 83% sand, 10% silt and 7% clay compared with the Central stream with 41% sand, 20% silt and 39% clay and the Sarada with 49% sand, 25% silt and 26% clay, on average. Average textural composition of the Sarada-Varaha estuary shows that sediments are enriched in clay in December relative to September and April (Table 1). Silt/clay ratios indicate that silt and clay components occur in equal/nearly equal proportions in September and April, whereas clay is very abundant in the mud fraction in December. Sand content is nearly constant (51–58%) in the estuarine system (Table 1). Depletion of clay between December–April indicates increased turbulence during the period. Apparently, clay is resuspended and transported in suspension into the open sea during December–April.

In contrast, inter-tidal, and surface and subsurface marsh sediments are generally uniform in texture. They consist of sandy silts. They are enriched in silt (>50%) and impoverished in clay (<20%) and sand (<40%) relative to the adjacent estuarine sediments (Table 1). However, subsurface marsh sediments contain 15% clay and 30% sand compared to 10% clay and 37% sand in the surface sediments on average.

Clay Minerals

The clay mineral relative abundances are shown in Tables 2 and 3. Montmorillonite, illite and kaolinite occur in significant amounts in all the estuaries. Chlorite is not detected at any season. The broad clay mineral trends in Tables 2 and 3 are:

(1) Between September and December, the differences in clay mineral composition are only marginal between the three estuaries. In contrast, between December and April, montmorillonite decreases while illite and kaolinite increase; and in April, the Central stream is abnormally impoverished in montmorillonite and moderately to significantly enriched in illite and kaolinite relative to the Sarada and Varaha estuaries.

(2) The statistical evaluation of the clay mineral variability by Mahalanobis D^2 statistic (Snedecor's F statistic) (Figure 3) shows that (a) in the Varaha estuary seasonal differences in clay mineralogy are not significant; (b) in the Sarada estuary differences are significant between April and December and between April and September at the 5% and 10% levels, respectively; practically no difference is revealed between September and December; and (c) in the Central estuary there is a highly significant difference between April and December (at 1% level) and a significant difference at the 5% level between April and September; there is practically no difference between September and December.

When the pooled data of the three estuaries are considered by taking averages of the corresponding mineral concentrations, it is found that the observed differences are highly significant both between April and September and between April and December. In contrast, neither in any individual estuary nor in the total estuary system are the clay mineral differences significant between September and December.

(3) The prominent lateral trend consists of the montmorillonite increasing in September and April and decreasing in December downstream. Inverse trends to this are registered by illite and kaolinite correspondingly.

(4) The Sarada records both seasonal and lateral trends while the central stream only seasonal trends. No trends are evident in the Varaha.

(5) In April, high montmorillonite content

Table 2. *Clay minerals in <2 μ fractions expressed as peak area percentages.*

Sample No.	September 1984			December 1984			April 1985		
	M	I	K	M	I	K	M	I	K
Varaha									
101	42	31	27		No clay			No clay	
102	42	34	24	43	28	29		No clay	
103	42	35	23	38	33	29		No clay	
104	51	30	19	36	37	27	36	38	26
105	36	36	28	41	31	28	33	35	32
106	41	35	24	43	36	21	45	28	27
Av.	42	34	24	40	33	27	38	34	28
S.D.	4.4	2.2	2.9	2.8	3.2	3.0	5.1	4.2	2.6
Sarada									
201	36	34	30	51	27	22	34	40	26
202	41	31	28	53	27	20	29	37	34
203	50	30	20	39	38	23	32	37	31
204	41	29	30	51	21	28	29	38	33
205	34	37	29	42	34	24	43	33	24
206	49	28	23	42	33	25	42	33	25
207	59	24	17	41	31	28	42	30	28
Av.	44	30	25	46	30	24	36	35	29
S.D.	8.2	3.9	4.9	5.4	5.2	2.8	5.9	3.2	3.7
Central Stream									
301	52	30	18	40	35	25	17	47	36
303	40	35	25	36	40	24	18	41	41
305	55	29	16	37	40	23	23	40	37
Av.	49	31	20	38	38	24	19	43	38
S.D.	6.5	2.6	3.9	1.7	2.4	0.8	2.6	3.1	2.3
Combined Estuary System									
Av.	45	31	24	42	33	25	32	27	31
Suspended Sediment									
S-1 (Central Stream)							53	21	26
S-2 (Sarada)							50	26	24

M = montmorillonite, I = illite, K = kaolinite, S.D. = standard deviation

(>50%) characterizes the suspended sediments compared with its low incidence in the bottom sediments (17–23% in the central stream and 29–42% in the Sarada).

(6) Marsh and intertidal sediments are similar in their clay mineral composition. Illite is dominant (41–42%), followed by montmorillonite (29–32%) and kaolinite (27–29%). These sediments are slightly enriched in illite relative to the subaqueous sediments in the estuary channels.

(7) The subsurface marsh sediments at 50 cm depth are enriched in montmorillonite relative to the surface ones.

(8) Inter-sample consistency in clay mineral composition in the two marsh settings, as shown by the low standard deviation values (Table 3), validates the clay mineral trends as reported above.

DISCUSSION

In December, the Sarada-Varaha estuary is in a partially mixed state due to diminished fluvial water inputs into the estuary, as inferred in a previous section.

As is the case in partially mixed estuaries, a turbidity maximum or high suspensate concentration is formed at the head of the salt water intrusion for two reasons: (1) The landward bottom flow is sufficiently strong to move suspended sediment up the estuary to the head of salt intrusion. This sediment may be fluvial material that has settled from the upper into the lower layer, but it may also be of marine origin, depending on the concentration of suspended matter in the river or in the sea (Postma, 1980); (2) The upper surface of salt intrusion (surface of no net motion) intersects the estuary bottom at a point known as the 'intersection point'. Fluvial fresh water meets salt water first at the intersection point. Suspended clay particles in the fresh water often flocculate to form a high suspensate concentration around the intersection point (POSTMA, 1967). The region of high suspensate concentration can then migrate considerable distance over a tidal cycle (FEUILLET and FLEISCHER, 1980). Illite, kaolinite and montmorillonite apparently flocculate simultaneously in the area of turbidity maximum, although experimental evidence of WHITEHOUSE *et al.* (1960) shows that illite and kaolinite flocculate first, followed by montmorillonite. However, other studies indicate that differential flocculation is not likely in natural environments (MANHEIM and HATHAWAY, 1972; GIBBS, 1977).

That the clay content is much higher in December than in September in the Sarada and Central stream (Figure 2) suggests that clay material, essentially of fluvial derivation, has accumulated as a result of flocculation. A clay mineral suite consisting of 49% montmorillonite, 28% illite and 23% kaolinite characterizes the sediment at the upstream end of the Sarada. This suite possibly is representative of the freshwater sediment of the river. On the other hand, in the lower section, the clay mineral floccules during their relatively long residence time in the lower saline water layer may break up and reform depending on turbulence and other factors (POSTMA, 1967). Possibly illite and kaolinite settle differentially while lighter montmorillonite particles diffuse upward. This is evidenced by the lower section sediment which is enriched in illite and kaolinite relative to the upper section. Thus, the water circulation dynamics in a partially mixed estuary produces clay mineral trends characterized by a downstream montmorillonite decrease corresponding to an upstream illite-kaolinite decrease. These trends are prominent in the Sarada, only suggested by the data in the Central stream, and not evident in the Varaha.

In April, the estuary is characterised by negative estuarine circulation in which net movement of bottom water is seaward and that of surface water is landward. The driving force is excess evaporation causing high salinities—and corresponding high densities of water—in the upper section. In such a situation, silt (and clay) will be exported by the bottom water (POSTMA, 1980). Sediment texture (Figure 2) indicates that clay is lost from the lower sections while added to the upper sections. It is likely that a part of the bottom sediment eroded from the lower sections is transported upstream in suspension by flood currents. The suspended sediment in overlying waters contains more than 50% montmorillonite (Table 2) while the underlying sediment is characterised by much less montmorillonite and more illite than the suspended sediment or the sediment deposited in December. Obviously, illite and kaolinite are differentially deposited in the upper sections. The differential settling is enhanced because the denser salt water in the upper section retards settling of finer montmorillonite particles. Increased silt content between December and April (Figure 2) provides supportive evidence of this view. The upstream increasing illite-kaolinite trend corresponding to the inverse montmorillonite trend is conspicuous in the Sarada segment while not evident in the Varaha. Although no lateral clay mineral trends are produced in the Cen-

Table 3. *Clay minerals in <2 μ fractions of marsh and intertidal sediments in April 1985.*

Sample No.	Peak Area Percentage Of: Montmorillonite	Illite	Kaolinite
Marsh area—surface sediments			
M-1T	32	38	30
M-2	39	37	24
M-3	36	39	25
M-4T	29	40	31
M-5T	24	46	30
M-6	37	41	22
M-7	33	41	26
M-8T	34	40	26
M-9	27	42	31
Av.	32	41	27
S.D.	4.6	2.5	3.2
Marsh area—subsurface sediments at 50 cm depth			
M-1B	42	35	23
M-4B	36	43	21
M-5B	30	40	30
M-8B	45	32	23
Av.	38	38	24
S.D.	5.8	4.2	3.4
Intertidal area sediments			
I-1	28	44	28
I-2	34	41	25
I-3	27	40	33
I-4	24	47	29
I-5	31	39	30
Av.	29	42	29
S.D.	3.4	2.9	2.6

S.D. = standard deviation

VARAHA ESTUARY

	S (n = 5)	D (n = 6)
A n = 3	D^2 = 2.78 F = 2.17 df (2, 5)	D^2 = 0.61 F = 0.52 df (2, 6)
D	D^2 = 1.01 F = 1.23 df (2, 8)	

SARADA ESTUARY

	S (n = 6)	D (n = 6)
A n = 6	D^2 = 2.55 F = 3.45+ df (2, 9)	D^2 = 3.50 F = 4.73++ df (2, 9)
D	D^2 = 0.83 F = 1.14 df (2, 9)	

CENTRAL STREAM

	S (n = 3)	D (n = 3)
A n = 3	D^2 = 25.10 F = 14.12++ df (2, 3)	D^2 = 77.34 F = 43.50+++ df (2, 3)
D	D^2 = 5.92 F = 2.94 df (2, 3)	

ENTIRE ESTUARY

	S (n = 14)	D (n = 15)
A n =12	D^2 = 2.28 F = 7.07+++ df (2, 23)	D^2 = 2.33 F = 7.45+++ df (2, 24)
D	D^2 = 0.07 F = 0.24 df (2, 26)	

A = April
S = September
D = December

\+ Significant at the 0.1 level of significance
++ Significant at the 0.05 level of significance
+++ Significant at the 0.01 level of significance

Figure 3. Values of Mahalanobis D^2 and Snedecor's F computed from the discriminant analysis. F values with no designation are insignificant at the 0.1 level.

tral stream, montmorillonite is winnowed from the stream between December–April. The central stream and flanking shallow expanse, located close to the tidal inlet, is subjected to intense turbulence caused by tidal currents and local wind-generated waves. Bottom sediment is continuously reworked and montmorillonite (fine clay) is put in suspension and transported to the sea. The end result is that the central stream sediments are impoverished in montmorillonite under the effects of tidal circulation dynamics. It appears that the length of the estuary is a control on lateral clay mineral gradients: the longer the estuary channel and the longer the salt excursion landward, the more prominent the clay mineral gradients would be.

Silt-rich intertidal sediments and their illite-dominant clay mineral suites are best explained by the 'settling lag' and 'scour lag' effects of tidal circulation (Postma, 1967). At the turn of tide from flood to ebb, coarser illite and kaolinite particles settle more quickly than montmorillonite. Flood currents during the next high flood stage rework the previous deposit in the intertidal area and finer montmorillonite particles are resuspended and transported away during the following ebb cycle. However, a comparison of the data in Tables 2 and 3 reveals that only illite is enriched in the intertidal sediments. Kaolinite is neither enriched nor impoverished in the Sarada and Varaha but is impoverished significantly in the Central stream intertidal areas, relative to the adjacent channel sediments in the respective areas. This shows that kaolinite responds differently from illite to the 'settling lag' and 'scour lag' influences.

The process of building up the marsh include occasional inundations during storms, when the incoming tidal surge is heavily loaded with silt that is subsequently deposited in the marsh (POSTMA, 1980). Abundant silt in the surface and subsurface marsh sediments points to the possible build-up of the marsh by storm-induced tidal surges. High proportion of clay is the possible cause of montmorillonite enrichment in the subsurface sediments relative to the surface ones of the marsh. The clay-rich layers may be attributed to episodic deposition.

Chlorite is reported in the adjacent continental shelf sediments (POORNACHANDRA RAO *et al.*, 1988; RAO, 1991). Its conspicuous absence in the Sarada-Varaha estuary suggests that the shelf sediments derive their chlorite content from sources other than the Eastern Ghats rocks.

CONCLUSIONS

The Sarada-Varaha estuary passes from a salt wedge/partially mixed to vertically well mixed to negative state over an annual cycle. Clay mineral distribution trends, especially of montmorillonite and illite, appear to respond to changing water-circulation dynamics. In a partially mixed state, montmorillonite shows a seaward decreasing trend, flocculation being the major process in the upper section and differential settling in the lower section. In a negative estuary, the trend is reversed under the combined influence of tidal circulation and differential settling. Montmorillonite registers a sharp fall quantitatively in the upper section of the estuary relative to the partially mixed state. Illite is differentially concentrated in the intertidal sediments by the 'settling lag' and 'scour lag' effects of tidal circulation.

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