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Sediments of the James River Estuary, Virginia

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ABSTRACT

The James River estuary of the Chesapeake Bay region follows the course of a former river valley drowned within the last 9,000 years by the most recent rise of sea level. The floor is shaped into a central channel bordered by submerged shoals. Observations show suspended sediment is transported mainly by alternating tidal currents and secondarily by the net nontidal estuarine circulation. Transport results in a sequence of grain size distributions reflecting the mixing of two textural end members, clay and sand.

Silty clay is deposited in the river and upper estuary, whereas sand occurs near the mouth. Transitional types, clayey sand and sand-silt-clay, predominate in the middle estuary. Additionally, biogenic materials, oyster shells and fecal pellets, and small amounts of residual components eroded from older deposits are mixed into the sediments by currents, waves, and organisms. Bottom sediment types vary widely according to local relief, to varying intensity of environmental processes, and to changing rates of supply from different sources.

Deposition is greatest in the middle estuary where salinity ranges from 5 to 14 parts per thousand. An elongate zone of relatively high deposition in the lower estuary corresponds to the intersection of the level of no-net-motion with the bottom. Despite substantial infilling, it is believed the estuary is maintained by the continued rise of sea level and by currents that flush part of the river-borne load through the estuary.

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INTRODUCTION

The James River estuary is flooded by a variety of sediments deposited at different rates through a range of water depth and seaward changing conditions. On the bottom, sediments form one interface of the estuary, and in suspension, they constitute a vital ingredient of the estuarine water-biota-sediment milieu. Therefore, the essential character of sediments must be understood in order to understand the estuarine environment and to discover the fate of river-borne sediments in a critical part of the sedimentary cycle—the transition between fresh and salt water. The purpose of this paper is to describe the distribution of sediments and to relate the distributions to potential sources and to estuarine processes.

Few studies have been made of the bottom sediments. Campbell (1927) reported the tidal meanders, and Marshall (1954) described physiography of the oyster bars. Haven and Morales-Alamo (1968) determined the transport and composition of suspended fecal pellets. Geology of bordering land areas is given by Coch (1965, 1968) and Bick and Coch (1969). Studies of bottom sediments in nearby estuaries include Ryan (1953) in Chesapeake Bay, Harrison and others (1964), and Biggs (1967) in mid-Chesapeake Bay, Burnett (1966) in the Piankatank River estuary, and Kofoed and Gorsline (1966) in the Choptank River, Maryland. Procedural details and methods used in this study are presented in Moncure and Nichols (1968).

Recent History

Like other coastal plain estuaries leading into the Chesapeake Bay, the James follows the submerged course of a former river valley drowned during a recent rise of sea level. The chronology of sea level rise is traced by radiocarbon dated peat deposited mainly at the base of marshes near Brandon Point in the river (Fig. 1). These data indicate that the estuary floor was flooded between 9,000 and 6,500 years ago; drowning proceeded at approximately 0.16 meter per century up to the present time. Thus, the estuary is a relatively young feature.

The rise of sea level created the estuary and gave it a distinctive character. It flooded the axial river channel, which today defines the deeper parts of the estuary, to depths of 8 to 29 meters. Between the channel and the shoreline, flooding of river terraces produced submerged shoals. Some shoals are topped by oyster bars which probably grew upward as sea level rose. Others are mantled by modern deposits that form banks of mud or sand. Flooding of tributary streams produced creeks which indent the shoreline between bluffs of Miocene and Pleistocene sediments.

Figure 1. Postglacial rise of sea level in the James River estuary region, based on radiocarbon dating of basal peat deposits. Analyses by Geochron Laboratories, Cambridge, Mass.

Bathymetry of the Estuary

The estuary is narrowly funnel-shaped and relatively shallow, averaging 3.7 meters in depth at mean low water. With an average width of 6 kilometers, the width-to-depth ratio is 1,620 to 1; thus, the estuary is essentially a shallow pan, and the bottom is sensitive to stirring by wind waves as well as modification by fauna—both of which have shaped the minor relief of the floor. Bathymetry of the estuary, charted by the U. S. Coast and Geodetic Survey, 1943-1948, is shown in Figure 2.

From Brandon Point (BP, Fig. 2) to Wreck Shoal (WR, Fig. 2), a distance of 52 kilometers, the upper estuary consists of broad shallow bays interconnected by narrow deep channels. The channels are more or less V-shaped in cross profile (profiles 7, 8, 10, and 11, Figs. 3 and 4), whereas bay floors are broken by oyster reefs and dissected by small tidal channels. The reach east of Hog Point has a northeast ebb channel (e, Fig. 2) and a southwest flood channel (f, Fig. 2). Similarly, Burwell Bay (BB, Fig. 2) is an ebb channel, whereas Rocklanding Shoal channel (RL, Fig. 2) is mainly a flood channel. Circulation patterns observed in a hydraulic model of the estuary (Nichols, this volume) substantiate this interpretation of channel morphology. The greatest depth in the estuary, 29 meters, is situated just northwest of Mulberry Point (MP, Fig. 2) near the downstream juncture of the ebb-flood channels.

Between Wreck Shoal (WR, Fig. 2) and Newport News, a distance of 30 kilometers, the estuary consists mainly of a single irregularly U-shaped channel bordered by submerged shoals (profiles 3 and 4, Figs. 3 and 4). Farther seaward, the channel widens and deepens to about 18 meters forming a harbor, Hampton Roads. The harbor floor is dissected by man-made channels as well as by natural channels; locally, oyster reefs, tidal bars, and sand waves contribute to the bottom relief (Fig. 5). At the mouth the estuarine harbor is narrowed on the north and south by wave-built spits. Constriction of tidal flow through the entrance by channelward extension of the spits has scoured parts of the entrance floor and produced a prominent trough.

Figure 2. Bathymetric chart of the James River estuary, based on U. S. Coast and Geodetic Survey charts 400 and 529. BP is Brandon Point; RL, Rocklanding Shoal Channel; WR, Wreck Shoal; BB, Burwell Bay; MP, Mulberry Point; OPC, Old Point Comfort; RAP, Rappahannock River; e, ebb channel; f, flood channel.

BOTTOM PROFILES

VIEW UPSTREAM
LEFT, SW $\longleftrightarrow$ RIGHT, NE

VERTICAL
EXAGGERATION 143 X

FILL
SCOUR

Figure 3. Transverse bottom profiles based on U. S. Coast and Geodetic Survey charts of various dates and the Corps of Engineers, Norfolk District, profiles for 1964 showing cut and fill relations. For location of transects see Figure 4.

Figure 4. Index map to bottom profiles.

The longitudinal profile of the estuary floor displays marked irregularities (Fig. 6C). Near the head it is interrupted by deep holes with depths of 20 to 29 meters where the river narrows and meanders, whereas intervening segments have been smoothed and lowered by dredging to the 8.1-meter (25-foot) depth. With distance seaward, deepening of the main channel is reflected by a corresponding increase of cross-sectional area (Fig. 6B). At the mouth the channel serves as the main avenue of flooding and exchange between the estuary and lower Chesapeake Bay.

Water Characteristics and Circulation

The wide range of hydrographic conditions is dominated by tidal currents which vary from nearly 0 at slack water to a maximum of 80 centimeters per second 3 hours later. Tidal characteristics are such that maximum current velocities at mean range of the tide vary within narrow limits throughout the estuary length (Fig. 6A). Small changes of velocity of about 0.2 meter per second relate to slight changes in cross-sectional areas as the estuary passes from narrow to broad reaches. Superimposed on the alternating tidal flow over many cycles is a two-way density circulation in which water flows seaward near the

Figure 5. Sand waves with an amplitude of 1.3 m at a water depth of 20 m displayed on fathogram of the entrance reach near Old Point Comfort (OPC), 1966. Maximum tidal velocities, longitudinal distribution of cross-sectional areas, and longitudinal profile of James River estuary, Virginia.

Figure 6. A. Maximum flood and ebb current velocities near the bottom at selected stations along the estuary length. Velocities from hydraulic model tests number 2 and 5; $89 \text{ m}^3/\text{sec}$ inflow at Richmond and mean range of tide. B. Longitudinal distribution of cross-sectional areas. C. Longitudinal profile along the shipping channel and location of oyster production reach.

surface and landward near the bottom. This landward counterflow is potentially important in transporting sediment up the estuary, as demonstrated by Meade (1969).

Salinity increases with distance downstream from nearly 0 parts per thousand at the head to an average of 24 parts per thousand at the mouth. Stratification is greatest in the upper estuary during high river inflow; for example, salinity often varies 8 parts per thousand from the surface to the 8-meter depth. In spring, high river inflow limits salty water of 0.5 parts per thousand salinity to Hog Point, 38 kilometers above the mouth. With gradual recession of inflow during summer and fall, salty water reaches 87 kilometers upstream, more than twice the distance in spring. Distributions of salinity for contrasting seasons are documented in Figure 7.

With the seasonal change in river inflow, the distribution of salinity and dynamic structure of estuarine water changes from moderately stratified to well mixed, for example, from type B to type C of Pritchard (1955). This change is recorded both in the mean vertical distribution of salinity over eight to twelve tidal cycles and in the distribution of net nontidal flow through several cross sections. Changes in the level of no-net-motion, that is, the boundary between upper and lower layers of water, are illustrated schematically in Figure 8. In type B the level of no-net-motion is nearly horizontal except for a slight inclination upward toward the right, a trend due to the effects of the earth's rotation (Pritchard, 1955). Net upstream flow occurs in the channel, whereas downstream flow occurs mainly over the shoals and there is a net vertical motion from the lower layer to the surface layer. At low river inflow, tidal mixing reduces stratification, producing a vertically homogeneous estuary. In type C the level of no-net-motion is nearly vertical; net flow is landward on the right and seaward on the left; mixing takes place between the counterflows from the right to the left side. It remains to be found out how this mechanism of flow, which was initially proved in the James by Pritchard (1954), affects transport and deposition.

SUSPENDED SEDIMENTS AND SEDIMENT TRANSPORT

The amount of suspended sediment was determined from water samples obtained simultaneously with current measurements at four anchor stations along the estuary channel (stations 7, 10, 19, and 128, Fig. 16). Samples were pumped from four depth intervals, every hour for one to two tidal cycles, between March 11 and March 20, 1965, a time of average river inflow. The fraction coarser than 62 microns was separated by screening a known volume of water. Concentrations of both coarse fraction and total suspended sediment were determined gravimetrically after filtration with a 0.45-micron Millipore filter.

The total amount of suspended sediment increases from an average of about 30 milligrams per liter in the river above Jamestown (Fig. 9) to more than 100 milligrams per liter at the inner limit of salty water (Deep Water Shoal). Farther seaward concentrations fall to 12 milligrams per liter at the mouth. From slack to maximum current (Fig. 10 A and B), the gradient changes in intensity along the estuary length, but the over-all distribution pattern persists. Less material is carried in suspension through seaward reaches than landward reaches even though tidal velocities show no over-all decrease of competence with distance downstream (Fig. 6A). Instead, the seaward decrease can be accounted for by downstream dilution of the river-borne suspended load through mixing with salty water of relatively low concentration. The magnitude of mixing derived from salt exchange is such that volume discharge at the mouth exceeds the river inflow twenty times (Pritchard, 1954). Therefore, the intensity of the longitudinal gradient of suspended material changes with a seaward change in mixing; a small part of the material settles out in the lower estuary.

Maximum concentrations at the inner limit of salty water (Fig. 9) mark a so-called turbidity maximum. Longitudinal distributions defined monthly at slack water by Brehmer and Haltiwanger (1966) indicate the maximum persists most of the year, being most pronounced in spring when river inflow is high and weak

Figure 7. Salinity distribution along the estuary length for contrasting seasons, winter and spring. A is 21-year average, March 1 through May 15; B is 21-year average, November 1 through February 28, for years 1944 through 1965.

in fall when inflow is low. Located close to or slightly upstream of the 0.5 part per thousand isohaline, the maximum shifts upstream with landward penetration of salty water from spring to fall. This trend indicates that the position and intensity of the maximum may be partly controlled by the inner limit of salty water and in turn by the magnitude of river inflow.

Turbidity maxima have been observed in the fresh-salt transition of many estuaries. The phenomenon, termed a *bouchon vaseux* or mud plug (Glangeaud, 1938) has been found in estuaries of different size, shape, and dynamic character, both stratified and well mixed. Because the suspended concentrations are higher than in source river and sea water, much speculation has centered on how the maximum is formed. Some workers (Lüneburg, 1939; Ippen, 1966) attribute the maximum to flocculation at the fresh-salt boundary. Nelson (1959) suggested that deflocculation is the cause, because dispersed sediments at low salt concentrations have low settling rates. The Demerara Coastal Investigation (1962) found a maximum in reaches of maximum current velocity. Glangeaud (1938) and Meade (1968) believe suspended sediment is more or less trapped in a convergence where upstream flowing estuary water meets downstream flowing river water at the inner limit of salty water. Schubel (1968) showed that the maximum in upper Chesapeake Bay is produced by tidal resuspension of bottom sediments and is maintained by the net estuarine circulation, which effectively traps suspended sediment. Though estuarine circulation seems capable of maintaining the maximum and regulating its intensity, supporting data are few; most data are limited to longitudinal distributions of suspended sediment or to short-term serial observations of current and suspended sediment concentrations over one or two tidal cycles. It remains to be found out if net flow acting over many tidal cycles actually leads to an accumulation of suspended sediment in the convergence of river and estuarine water.

With the seaward change of total suspended material there is a change in other water properties. As shown by Figure 11, suspended organic material (as determined by weight lost on ignition; Brehmer and Haltiwanger, 1966) rises slightly in the same reach where total suspended material is high. Total phosphate, as well as dissolved phosphate, rise at the same place, a trend ascribed to trapping of particulate material and decomposition of organic material (above 80 kilometers, phosphate is supplied by river-borne pollutants). Despite the high nutrients, phytoplankton production (as indicated by chlorophyll "a" concentrations) is reduced. Evidently river-borne plankton are partly eliminated in salty water, and high turbidity in the reach limits production.

Vertical distributions of total suspended material over one to two tidal cycles (Fig. 12a-d, A and B) vary with current speed, being most pronounced near the bottom. At station 7, (Fig. 12d, A and B) concentrations near the bottom range 255 milligrams per liter from slack to maximum flood within 3½ hours. It is evident that about 20 percent of the suspended load remains in suspension at slack water, whereas the greater part is alternately suspended and settled out. These changes are not symmetrical about slack water or maximum current. Concentrations near the surface are slightly higher at the end of ebb than at the end of flood, a trend ascribed to shifting of the longitudinal concentration gradient. For example, at station 7 (Fig. 12d, B) ebb flow supplies water of high concentration from the upper estuary which predominates at slack before flood, a time of minimum salinity, whereas flood flow supplies water of relatively low concentration which predominates at slack before ebb. On the other hand,

TYPE B - HORIZONTAL BOUNDARY

TYPE C - VERTICAL BOUNDARY

Figure 8. Schematic diagrams of type B and type C estuarine circulation patterns. View landward. Upstream flow of relatively salty water represented by dark arrow; downstream flow of freshened water, light arrow; and mean direction of mixing, curled arrows.

Figure 9. Distribution of total suspended sediment concentrations and surface salinity along the estuary channel, based on average values over 1 to 2 tidal cycles between 50 km and the mouth, and on slack water concentrations between 50 and 80 km above mouth, March 11-20, 1965.

concentrations near the bottom are greater during flood, especially near maximum current, than during ebb, because flood currents attain greater speeds than ebb currents.

Vertical variations of the suspended sand fraction concentrations ($> 62\mu$; Fig. 12, a-d, A and C) go up and down with current velocity in much the same way as total concentrations. Because the sand content is so small, less than 4 percent of the total by weight, differences along the vertical and with time are proportionally smaller than for total suspended material. Microscopic analyses show that the main components are diatoms, plant debris, and fecal pellets. Additionally, small proportions of all these components are found in the bottom sediments. No floccules are observed, though aggregates of clay, silt, and organic debris are present. Throughout a tidal cycle high percentages of diatoms and plant debris are abundant near slack current, whereas fecal pellets are relatively abundant near maximum current (Fig. 13). Therefore, the number of different components varies with time according to the current speed, their composition, and their hydrodynamic character. Over many tidal cycles these local time variations should lead to selective transport in which relatively light components, which predominate in near-surface water, are moved downstream, and heavy components, which predominate near the bottom, are moved upstream. But the distribution of these components in the bottom sediments does not indicate fractionation, except for fecal pellets which are abundant in the channel of the upper estuary (stations 61, 64, and 66, Fig. 24). An account of fecal pellet transport is given by Haven and Morales-Alamo (1968). Other constituents are mainly an admixture resulting from wave and tidal action.

Rates of sediment transport over relatively short periods of one to two tidal cycles, derived from the product of the velocity and corresponding suspended concentrations, are greatest just above the estuary floor and least near the surface. Net transport is upstream near the bottom in the channel and downstream over the shoals, especially on the south side. Even though net flow is very small and inadequate to suspend sediment, it is believed to assume importance

Figure 10. Distribution of total suspended concentrations, at slack current (A) and at maximum current (B) along the estuary channel, March 11-20, 1965.

when sediment is once suspended and maintained in suspension over many tidal cycles.

SEDIMENTATION

Unlike many estuaries, the main site of deposition is not at the inner limit of salty water but in the middle part of the estuary where salinity ranges from 5 to 14 parts per thousand. Rates of sedimentation and erosion were determined by measuring depth changes on U.S. Coast and Geodetic Survey boat sheets between 1873 to 1874 and 1943 to 1948. As shown in Figure 14, sedimentation rates locally are greater than 2 meters per 70 years in Burwell Bay (b, Fig. 14), an area where tidal currents are weak. Interestingly, a zone of relatively high deposition extends seaward along the south channel shoulder (a, Fig. 14) at depths of $3\frac{1}{2}$ to 5 meters; this zone extends farther seaward in the deeper water of Hampton Roads at depths of 5 to 7 meters; thus, the lower estuary appears to be filling laterally or channelward. Much attention has centered on how sediment accumulates in this elongate zone inasmuch as it is one of positive

relief, intermediate salinity, and a relatively straight reach exposed to the alternating sweep of tidal currents.

One plausible explanation is that sediment accumulates along the intersection of the level of no-net-motion and the bottom, as illustrated in Figure 15. Sediment accumulates at the boundary between upstream and downstream density currents, where the net velocity is zero. Elsewhere, sediment is carried landward up the channel and seaward down the south (left) shoals. This relation is supported by the fact that the level of no-net-motion coincides with the zone of sedimentation for 21 kilometers along the estuary length. Both the zone and the intersection of level on the bottom lie at progressively greater depths with distance seaward.

BOTTOM SEDIMENT CHARACTERISTICS

Texture

Most of the bottom sediment consists of three textural types: (1) silty clay, (2) sand, and (3) an admixture of sand-silt-clay or clayey sand. The distribution of bottom sediment types was compiled from several sources of information. The 156 samples collected throughout the estuary (Fig. 16) were analyzed by sieving and pipette (Moncre and Nichols, 1968). Resulting particle size data were used to classify the sediments according to a scheme proposed by Shepard (1954).

Figure 11. Distribution of total suspended concentrations, salinity, suspended organic matter, total phosphate, and chlorophyll "a." Data based on near-surface slack water samples by Brehmer and Haltiwanger (1966), May 9-11, 1966.

12a

STATION 128, ESTUARY MOUTH

Figure 12a through 12d. Vertical distributions of total suspended material, suspended coarse fraction, and current speed over 1 to 2 tidal cycles, March 11-20, 1965. a. Station 128 near the estuary mouth. b. Station 19 in the lower estuary. c. Station 10 in the upper estuary. d. Station 7 at the head of the estuary.

b**STATION 19, MID-ESTUARY**

Figure 12 (continued)

12c

STATION 10, ESTUARY HEAD

Figure 12 (continued)

d

STATION 7, ESTUARY HEAD

Figure 12 (continued)

Figure 13. Tidal cycle variations of sand fraction components at 4.5-m depth in Rocklanding Shoal channel, station 10, March 16-17, 1965. "Light" minerals represent mainly quartz and feldspar.

The sand-silt-clay terminology was altered by adding a prefix shelly or gravelly where the sediment contains more than 5 percent shell or gravel coarser than 2 millimeters in size. Distribution of dense oyster shells, representing the natural oyster reefs, is based on charts of Moore (1910). Bottom notations by the U.S. Coast and Geodetic Survey, 1945-1952, provided supplementary information on bottom types.

Silty clay is the most predominant sediment type throughout the estuary (Fig. 17). It covers a wide area about the estuary head near the Chickahominy River mouth and is present around the meander bend at Hog Point. Farther downstream, silty clay covers the shallow channel floor of Burwell Bay and extends seaward into the lower estuary south of the main channel. It is the predominant type about the mouth of the Nansemond and Elizabeth Rivers.

Sand is abundant on inner shoals bordering the estuary shore. In the upper estuary the sand zone is narrow, less than 500 meters in width, whereas in the middle and lower estuary it extends more than 900 meters in width. High percentages of sand are also present on the estuary floor about the mouth (Figs. 17, 18). Sand predominates on the north side of the estuary near Newport News and extends in diminishing percentages farther headward along the north side of the main channel. Sand occurs locally on the channel floor in narrow reaches of the upper estuary, off Mulberry Point and Jamestown.

Clayey sand and sand-silt-clay are present between areas of sand and silty clay as well as on oyster grounds and in narrow reaches of the upper estuary. In the lower estuary off Newport News, sand grades into sandy clay, and upstream on the north side of the channel, clayey sand passes into sand-silt-clay—a trend that parallels the upstream decrease in sand percentages. A similar association is encountered where predominately finer sediments border marginal sands in a

Figure 14. Patterns of deposition and erosion in James River estuary determined from depth changes over a 70-year period. Prominent zone of deposition (a) in the lower estuary; Burwell Bay (b), the main site of deposition. Dotted line is 4-m depth contour. Arrows represent direction of net flow along bottom.

Figure 15. Schematic cross section of the level of no-net-motion in relation to a prominent zone of sedimentation. Arrows represent direction of net nontidal flow.

narrow zone around the estuary shore. In these areas sand on the shoals grades outward into sandy clay or sand-silt-clay and subsequently into silty clay in deeper water. Often the change in sediment type takes place on a gentle slope near the shoulder of the shoals at about the 2-meter depth. Because of the relatively wide sampling interval used in this study, these transitions are probably more extensive than shown on the lithologic chart of Figure 17. As a consequence, patterns of silty clay often adjoin clayey sand, whereas transitional sediment actually may be present in a narrow zone.

The sandy clay and sand-silt-clay are probably a product of redistribution and mixing by estuarine processes. In narrow reaches, as off Mulberry Point and Jamestown, sand is derived from the channel floor by tidal scour and subsequently mixes upstream and downstream into finer sediments. Along margins of shoals, sand is intermittently moved into deeper water during storms and deposited with silty clay. Mixing by physical processes is probably augmented by burrowing action of organisms and by man in his efforts to maintain oyster grounds.

Areas charted as dense oyster shells occupy shoals of the middle estuary that are mainly sites of natural oyster reefs more than 3 meters thick. Shells are scattered about the natural reefs; in some areas they are concentrated in beds 10 to 30 centimeters thick. The seaward extent of living oysters is believed to be controlled partly by intensive harvesting and in part by oyster predators that live in saline water greater than 10 parts per thousand salinity. Their upstream limit is controlled by spring flooding and freshets.

Gravelly sediment is limited to the channel floor off Newport News, shoals of Burwell Bay, and the floor of Rocklanding Shoal where dredging may have cut into older deposits. Gravel is reported at greater depths in deposits around Hog Point, Jamestown, and off the mouth of the Chickahominy River. Near Newport News, the gravels are unique inasmuch as they are composed of assorted chert, quartz, and volcanic rock cobbles. These are accumulations of former ship ballast dumped on the channel floor.

In a few localities the natural distribution of surface sediment is altered by excavation of the channel floor and subsequent disposal of spoil. As an emergency measure during and shortly after World War II, spoil was dumped in the entrance channel. Consisting largely of silty clay, it is a marked contrast to the natural sandy sediment of the channel floor. When redistributed by tidal

Figure 16. Locations of sediment sampling stations and major zones of the James River estuary.

Figure 17. Areal distribution of bottom sediment types in the James River estuary, Virginia. For sediment nomenclature see triangular diagram, Figure 19.

Figure 18. Distribution of sand in bottom sediments of James River estuary, Virginia.

currents and mixed with the sand, it produces a transitional sediment type. In the reach between Jamestown and Fort Eustis, sandy spoil is banked along the channel shoulder and locally is redistributed over nearby shoals.

Sand-Silt-Clay Ratios. The bottom sediment samples fall into a relatively narrow zone on a sand-silt-clay triangular diagram (Fig. 19). Most samples vary in sand content from 0 to 100 percent, while the silt-clay ratio varies within narrow limits, about one part silt and two parts clay. None of the samples fall into groups associated with distinctive features, such as depth zones, shoals and channels, fill and scour, upper and lower estuary (Fig. 19B). Instead, the distribution suggests a mixture of two elemental types, or end members—sand and silty clay. Sand generally increases whereas clay decreases toward the mouth (Fig. 20B). Locally sand is contributed by erosion of shores and marginal shoals. Oyster reefs supply shell detritus of sand size adding to the variations. Elsewhere textural changes are affected by the variable relief of the estuary floor as well as different rates of sedimentation. Silt reaches a maximum in tidal reaches of the river 100 kilometers above the mouth; farther downstream its abundance generally parallels clay content. Sand-mud ratios (Fig. 20A) range widely along the estuary, but corresponding silt-clay ratios vary within narrow limits. The highest ratios occur in the river and at the mouth. When channel samples are examined alone, the longitudinal trends of average sand, silt, and clay percentages are less variable (Fig. 20D). Though sand percentages are locally high on the channel floor in narrow reaches, for example, 35 to 40 kilometers above the mouth near Mulberry Point, they generally increase seaward. On the other hand, clay generally decreases seaward except in the river. These trends differ from those in the Rappahannock (Nelson, 1961) but are similar to those in the Piankatank (Burnett, 1966).

Grain Size Distribution. Size-frequency distributions were made on selected samples from different reaches of the estuary; the curves fall into an envelope bounded by an upper sandy sediment curve (106, Fig. 21) and a lower clayey curve (J21, Fig. 21). Many of the curves parallel each other, indicating that they have about the same degree of sorting irrespective of their coarseness. Sorting varies from poorly sorted in fine sediment to better sorted in coarse sediments. Curve 106 is a normal frequency distribution that is both symmetrical and unimodal. A non-normal distribution may result from mixing of different log-normal, end member, sand and clay populations. For example, curve J12 (Fig. 21) representing a sample from the lower estuary, may be dissected following Spencer (1963) into two populations: (1) 25 percent sand, with a median diameter of 3.6ϕ and (2) 75 percent clay with a median diameter of about 9ϕ . Thus, the curve is essentially a product of two log-normal populations. Such a mixture is part of a broad spectrum ranging between sandy sediment (for example, curve 106 from the estuary mouth or curve 136 from the shoals) and clayey sediment (for example, curve J21 from Burwell Bay). Sediments from different parts of the estuary are related to one another inasmuch as they have the same fundamental end members and are simply mixed in different proportions. Mixing processes affecting grain size act throughout the estuary with variable intensity to produce the spectrum of curves in Figure 21. Within the spectrum coarseness generally decreases from upper left to lower right across the diagram, corresponding to increasing distance from the mouth. The diminished contribution of sand is partly determined by upstream transport away from the

source of supply near the mouth, whereas increasing contributions of clay reflect nearness to a river source.

The cumulative curves were classified into groups (*for example*, Doeglas, 1946; van Andel and Postma, 1954), in which the coarsest sediment, type A (Fig. 21), is moderately well sorted. Type A curves are slightly asymmetrical and frequently have a sharply defined maximum size and a marked lower limit with very small percentages of clay. These sediments are found either on the channel floor near the entrance, where tidal currents reach 0.4 meter per second, or close to the shoreline, where wave action winnows the bottom. These processes suspend clay, whereas grains coarser than about 4ϕ settle out.

Type B curves (Fig. 21) are very poorly sorted and lack well-defined upper and lower limits. Curves of this type are strongly positively skewed with an excess of fine sediment in the tail. They bend broadly at about 3 to 5ϕ , the minimum size of the coarse material supplied. A few curves of this type exhibit S-shaped bends in the coarse tail owing to contributions of sand size shell particles. Type B sediments are found in the lower estuary, both on the shoals and on the channel floor, where alternating tidal currents reach 0.3 meter per second. Sediment is probably supplied to the lower estuary from two sources: (1) sand transported upstream from seaward areas; and (2) clay settled out of suspended river-borne load.

Type B curves grade into type C curves as the sediment becomes finer toward Burwell Bay. Type C size distributions have a well-defined upper size limit at

Figure 19. Percentage of sand, silt, and clay in bottom sediments plotted in a triangular diagram. A. Samples for entire estuary. B. Samples from upper and lower reaches of the estuary.

SEAWARD CHANGE IN TEXTURE

Figure 20. Variation in sediment texture along the James River estuary, Virginia. A. Average seaward change in silt-clay ratio and sand-mud ratio, including samples from both shoals and channel. B. Average seaward change in percent sand, silt, and clay, including samples from both shoals and channel. C. Average seaward change in silt-clay ratio and sand-mud ratio, including samples from the channel only, greater than 6 m depth. D. Average seaward change in percent sand, silt, and clay, including samples from the channel only, greater than 6 m depth.

Figure 21. Cumulative grain size distribution curves in ϕ units for samples from different stations (numbers). For explanation of groups A, B, and C see text.

about 5 ϕ with a bend at 6 ϕ . The sediments are a mixture in which clay predominates over sand. They are caused by somewhat less rigorous currents than those controlling type B sediments. With increasing fineness, type C distributions lose their positive skewness and become nearly straight, chiefly clay. This type is a product of almost complete settling out in relatively quiet water (for example, Burwell Bay) where currents are less than 0.2 meter per second.

Color

Although the color of bottom sediments varies widely, nearly all sediments fall within the range of three colors designated by the ISCC-NBS system (Kelly and Judd, 1955): (1) olive gray including shades of 5 Y 3/1 and 5 Y 4/1; (2) olive brown including 2.5, 7.5 YR 3/2, 7.5 YR 4/4, 10 YR 4/2, 10 YR 3/2, 10 YR 4/4; and (3) grayish olive and olive including 5 Y 4/2, 5 Y 3/2, 5 Y 2/1, and 5 Y 4/4. The distribution of color (Fig. 22) shows that olive and overtones of grayish olive predominate in the lower and middle estuary, whereas olive brown is common to the upper estuary, particularly around Hog Point and near the mouth of tributaries. Olive gray is present locally in the middle and lower estuary; patches of grayish olive are found in the upper estuary.

Figure 22. Distribution of surface sediment color in James River estuary, Virginia, based on the ISCC-NBS color system.

Differences in color are due to the following constituents: clay minerals, which make up the bulk of the fine-grained sediment, are often olive colored; organic constituents such as fecal pellets and diatoms, may also contribute. Iron oxide, which occurs as a coating on sand grains, yields yellowish brown colors; reduced ferrous-rich compounds yield gray-colored sediments. Land-derived ferric iron mixed with olive-colored constituents may be responsible for the olive brown color in sediments of the upper estuary.

Oxidation Layer

A conspicuous feature of the bottom sediments is a near-surface oxidation layer ranging from less than 1 millimeter to more than 40 millimeters thick. The distribution of the oxidation layer thickness (Fig. 23) shows that the lower estuary has a relatively thin layer, less than 5 millimeters thick, whereas the upper estuary has a variable thickness from 1 to more than 40 millimeters. Sediments with thick oxidation layers are olive brown colored, whereas sediments with thin oxidation layers are grayish olive or olive. Below the oxidation layer is a black layer, 5 to 20 centimeters thick and farther down a gray zone which predominates in most of the deposits. Cores from the upper estuary often display alternating bands of brown, black, and gray colors. An account of such depth transformations, which are common to recent sediments in many nearshore environments, is given by Biggs (1967) and Van Straaten (1954).

COMPOSITION AND MINERALOGY

Sand Fraction

The sand fraction changes from station to station but generally increases with distance seaward (Figs. 24, 25). Frequency counts of various coarse fraction

components were made under a binocular microscope. Major constituents include light minerals, fecal pellets, plant debris, and aggregates of silt and clay. Minor constituents include dark-colored minerals (mainly heavy minerals), mica, glauconite, and pyrite; shell fragments and ostracode valves; tests of Foraminifera and Thecamoebina; and particles of coal, fly ash and cinder, as well as black-coated wood debris.

Light-colored minerals, mainly quartz and feldspar, make up the bulk of the sand fraction. Light mineral percentages from both shoal and channel stations increase irregularly with distance downstream from about 20 percent near the river to 95 percent near the mouth. They reach a local peak percentage in narrow reaches of the upper estuary channel near Jamestown (station 40) and Mulberry Point (station 72, 79).

Fecal pellets are generally abundant in the upper estuary, particularly between Jamestown and Mulberry Point, and diminish in abundance both upstream and downstream. Produced by benthic mollusks like oysters and *Rangia*, they are susceptible to transport by tidal currents (Haven and Morales-Alamo, 1968) and may accumulate near the inner limit of salty water or where tidal velocity is reduced locally. Aggregates include an undifferentiated group of silty and clayey masses; many have a reddish orange iron cement, but others are green and contain fragments of plant debris. Aggregates make up 20 percent of the coarse fraction near the river, but throughout the estuary they are less than 5 percent. Plant debris, including leaves, wood, marsh-produced fibers, and detritus, is abundant (up to 36 percent) near the river entrance. Plant debris decreases gradually downstream; therefore it probably has a source in the river and bordering marshes.

Figure 23. Distribution of thickness of oxidation layer in James River estuary, Virginia.

SEAWARD CHANGE IN SAND COMPOSITION

Figure 24. Variations in percent sand composition of minor components (upper) and major components (upper middle) along the estuary channel. Stars represent trace amounts of glauconite.

Mica is the most conspicuous and widespread minor component. It is most abundant near the river, where it reaches 10 percent, and generally decreases with distance seaward. Small variable percentages of shell fragments, diatoms, fly ash, cinder, and coal are present, and traces of glauconite occur in most samples.

Clay Fraction

The clay mineralogy reported by Moncure and Nichols (1968) is superseded by new analyses of the same samples (Table 1). The presence of kaolinite was determined by the shape and position of the 25.0° peak. If the greater portion of the peak lay above 25.0° , the M chlorite was assumed to be predominant, whereas if the greater portion lay below 25.0° , kaolinite was assumed. Montmorillonite peaks at 6.3° and 17.8° shifted to 5.1° after glycolation. Illite peaks at 8.8° and 26.6° were not affected by glycolation. Relative proportions of different clay minerals were estimated by determining the peak-area percentage.

The main clay minerals in the estuary are illite and chlorite. Illite alone is the most abundant constituent of fresh reaches of the river, while chlorite is generally more abundant at the mouth. This suggests a seaward source for chlorite. By contrast, montmorillonite, though scarce, generally decreases with distance downstream and this suggests a landward source. Kaolinite, though variable, is generally more abundant in the upper estuary than elsewhere. These distributions reflect the mixing of both upstream and downstream source materials.

Heavy Minerals

Although heavy minerals make up generally less than 3 percent of the sand fraction by weight, they are distinctive. Goodwin (1967) showed that kyanite and sillimanite are relatively abundant in the river and diminish downstream through the estuary. They probably are supplied from Piedmont metamorphic and igneous rocks. By contrast, staurolite is relatively scarce in the river but

TABLE 1. RELATIVE CLAY MINERAL ABUNDANCE EXPRESSED AS PROBABLE PEAK-AREA PERCENTAGE

Station	Distance upstream km	Montmorillonite	Illite	Kaolinite	Chlorite
5-1	-1.0	6	47	9	37
114	5.8	10	38	17	34
159	12.9	6	34	30	30
97	20.1	24	34	21	21
7-1	21.5	24	34	21	21
156	22.4	12	26	31	31
91	32.2	8	37	28	28
85	33.6	14	32	18	37
79	37.8	8	20	36	36
18	43.9	14	25	30	30
59	47.5	8	25	45	23
31	75.6	12	32	28	28
160*	123.0	18	44	15	23
162†	152.3	19	45	18	18
161††	161.0	13	44	22	21

* At Hopewell in the James River.

† At Drewry's Bluff in the river.

†† At Richmond in the river.

SEAWARD CHANGE IN SAND COMPOSITION

Figure 25. Variations in percent sand composition of minor components (upper) and major components (upper middle) along the estuary shoals. Stars represent trace amounts of glauconite.

increases seaward toward the mouth which suggests a source in Chesapeake Bay. Other heavy minerals examined by Goodwin exhibit a great deal of variation both along and across the estuary.

SEDIMENT CHEMISTRY

Hydrogen Ion Concentration (pH)

The pH of surface sediments varies from an average of 6.6 near the head to about 7.1 near the mouth (Fig. 26C). The pH of most surface sediments is close to that recorded in overlying water, probably because tidal currents alternately suspend them and because they retain large amounts of water. High values (pH = 7.5) in the middle estuary reflect the influence of calcium carbonate in oyster shell which acts as a buffer reserve. Distinctly acid conditions in the upper estuary are most likely due to oxidation of organic matter which is more abundant in this area. Evidently the normal buffering capacity of overlying water is overcome in surface sediments by production of carbonic acid.

Oxidation-Reduction Potential (Eh)

Oxidation-reduction potentials in surface sediments are positive. Values range from +40 millivolts to +431 millivolts (Fig. 26B) and average +220 millivolts. The values fall within a range of Eh values for fresh and marine waters given by Baas Becking and others (1960). Predominantly positive values are expectable inasmuch as overlying water is well oxygenated most of the time. Below the sediment surface, however, Eh is often negative, and this condition is probably associated with bacterial decay of organic matter and depletion of oxygen.

Calcium Carbonate

The carbonate content varies greatly, from 2.4 percent near the head to a maximum of 40.8 percent in the middle estuary (Fig. 26D). Most of the calcium carbonate occurs as skeletal carbonate, mainly oyster shell fragments in the estuary proper and shell fragments of the clam *Rangia* in the river. Finely divided carbonate supplied from limestone deposits or river bank erosion in the upper drainage basin is present in minor amounts. Acid pH in the sediments favors solution of carbonate so that there is little chance for its survival except as massive oyster reefs.

Total Carbon

The total carbon, determined by combustion of untreated sediment in a Leco furnace, ranged from 0.3 to 5.9 percent. The measurements include (1) organic fragments of plants, or residues of animals and microorganisms in various stages of decomposition; (2) elemental organic carbon, chiefly coal and fly ash; and (3) carbonate carbon in minerals such as calcite and aragonite. Therefore, the values represent a composite of all organic forms and give the maximum carbon in the sediments. Peak concentrations in the middle estuary correspond with peak values of carbonate (Fig. 26D) and parallel the downstream trend of organic matter determined by oxidation.

Organic Matter

Organic matter determined by hydrogen peroxide digestion averages 2.2 percent (1.2 percent organic carbon) and generally decreases with distance

SEAWARD CHANGE IN SEDIMENT PROPERTIES

Figure 26. Variations along the length of the estuary in A, water content in percent; B, oxidation-reduction potential (Eh) in mv; C, hydrogen-ion potential (pH); D, calcium carbonate content in percent; E, total carbon and organic material in percent.

toward the mouth (Fig. 26E). In the estuary, organic matter is derived from different sources and varies widely in composition and in size. Plant debris is abundant in coarse fractions near the head. Another part consists of phytoplankton, mainly blue-green algae, and fecal pellets. Haven and Morales-Alamo (1966) have shown that sediments enriched with fecal pellets have a higher organic carbon content than average bottom sediments. The seaward decrease parallels the seaward increase in clay and distance away from organic sources.

Water Content

Near-surface sediments are typically so soft and "soupy" that the top few millimeters may be lost during sampling. Expressed as percent wet weight, water content generally decreases with distance downstream; values average 65 percent at the head and 40 percent at the mouth (Fig. 26A). Water content closely parallels clay percentages along the estuary. For example, a local peak of 72 percent water content at 33 kilometers upstream corresponds to a peak in percentage clay. Departures in the clay-water content relation may result from organic materials, such as diatoms and fecal pellets, which when mixed with clayey sediment contribute to an excess water content. By contrast, older sediments exposed at the surface by scour after compaction by prior burial have relatively low water content.

MINOR STRUCTURES

Most estuary sediments are indistinctly mottled by variations of color and grain size that result mainly from burrowing activity of organisms. Regular horizontal layering, the basic structure of water-laid sediment swept by tidal currents, occurs only in the upper estuary around meander bends and off the Chickahominy River entrance (Fig. 27). Locally, sediments are irregularly layered or homogenous (Fig. 27), according to the classification of Shepard and Moore (1955).

FORAMINIFERA

Foraminifera are the most conspicuous organic element in the components of the sand fraction. Because they live on the sediment surface and often form a shell or test of agglutinate sand or silt particles, they are intimately associated with sediments. Although Foraminifera make up less than 1 percent of the sand fraction, total populations vary in number from an estimated 369 specimens to more than 24,000 per 20 milliliter sample. A maximum of 101,400 specimens per sample occurred at one station near Rocklanding Shoal. Highest populations occur in the upper estuary where the tide and salinity range is greater than elsewhere. Living populations range from 10 to 2,166 specimens per 20 milliliter sample, and their abundance throughout the estuary generally parallels the abundance of total populations. An account of the species composition and their distribution in relation to ecological parameters is given by Nichols and Norton (1968).

DEPOSITIONAL FACIES

The different properties can be combined into units which characterize estuary sediments according to common origin, transportation history, and

Figure 27. Distribution of minor sedimentary structures in near-surface sediments classified according to Shepard and Moore (1955).

depositional environment. The term facies denotes the sedimentary record of an environment or group of interrelated environments. Although this summary is limited to spatial distributions of surface sediments, it should be valuable for predicting characteristics of ancient estuarine sediments. The bulk of the sediment is derived from preexisting rocks and transported to its site of deposition either from the river or the sea. It consists of clay and silt deposited from the suspended load, or sand derived from the bedload. Closely related but having a different history are residual sediments eroded from older sedimentary deposits, mainly Pleistocene or Miocene, on the channel floor or the shore bluffs. Redistributed by local waves and currents, this sediment is marked by iron-stained grains or fossiliferous sand rich in glauconite. A third kind of sediment is biogenic, chiefly oyster shell with minor amounts of arenaceous Foraminifera, diatoms, and fecal pellets, all of which are produced in the estuary. Sediments of the James form three facies: (1) marine, (2) fluvial-estuarine, and (3) estuarine. They grade into each other with indistinct boundaries (Fig. 28).

The marine facies occurs in relatively saline water (greater than 15 parts per thousand) near the estuary mouth and is characterized by sandy sediment rich in "light" minerals. There are minor amounts of mica, clay with high proportions of chlorite, shell fragments, and heavy minerals of which staurolite is characteristic. The calcareous Foraminifera, *Elphidium*, and scarcity of oyster shell distinguish this facies from the estuarine facies farther upstream.

The fluvial-estuarine facies in fresh-water tidal reaches of the river is characterized by clayey sediment with relatively high proportions of illite and montmorillonite. Organic material exceeds 2 percent on the average and is greater

than in other facies. The sediments are generally acid (pH 6.4 to 7.1) and oxidizing, and vary in structure from regular layers to mottled and homogenous. Among the coarse fraction components, plant debris, mica, and aggregates are greater than in the estuarine facies. *Thecamoebina*, a fresh-water protozoa, is the most distinctive microfauna; *Rangia*, a fresh-to-brackish-water clam, is the dominant invertebrate.

Sediment deposited in the estuarine facies, where salinity ranges from 0 to 15 parts per thousand, is a variable mixture of different textural and compositional types. It is partly clayey silt, sand-silt-clay, or clayey sand with poor sorting. Sediments typically are mottled and oxidized ($Eh \geq +100$ mv); oyster shell and arenaceous Foraminifera are distinctive. Rates of sedimentation are greater than elsewhere but vary widely according to the strength of tidal currents and the dynamic structure of estuarine circulation. Sediment of the estuarine facies is derived from both upstream and downstream sources, as well as from the estuary itself. Clay with high proportions of illite and minor amounts of montmorillonite, variable proportions of plant detritus and mica, and the heavy minerals kyanite and sillimanite suggest a river source. Quartz sand containing staurolite, calcareous Foraminifera, and the clay mineral chlorite indicate a seaward source. Added to these are residual sediments derived from local shore bluffs and the channel floor. Biogenic materials, mainly oyster shell, are produced in the estuary itself. Finally, a part of the sediment has been mixed by man in his effort to dredge channels, harvest oysters, and reclaim land.

PROBLEMS

This study defines several gaps in our knowledge of estuarine sedimentation that require further inquiry. Many of the problems are common to other

Figure 28. Distribution of depositional facies (marine, estuarine, and fluvial-estuarine) in relation to sediment origin and dispersal (inferred arrows).

estuaries. Knowledge of sediment transport could be advanced by learning how suspended sediment responds to different modes of flow. Although tidal and net nontidal currents have received most attention, secondary currents, wind drift, and eddy diffusion may produce a significant transport. When sediments are studied in relation to flow, it is logical to ask: With what mode of flow do they interact? What element(s) of flow maintain sediment in suspension? What features of flow determine the time-dependent statistical behavior of sediment, which is subject to transient states of settling, scour, and turbulent diffusion? Do variations in speed and duration of flood or ebb, repeated over many tidal cycles, lead to a net transport? Of the several modes of flow, net nontidal flow has received most attention. In practice, net flow is computed from a series of instantaneous tidal speed measurements and averaged for ebb and flood directions over many tidal cycles. Measurements over at least 8 tidal cycles are required in the Chesapeake region to average out effects of varied wind stress and other disturbances. When the vertical distribution of net flow is determined, an internal circulation can be delineated in which freshened water moves seaward near the surface and salty water moves landward near the bottom. It is remarkable how net flow up to .04 meter per second develops in relatively well-mixed water where salinity differs only 2 parts per thousand in a depth of 20 meters. This circulation is often treated as being in a steady state rather than in a variable state. Similarly, model studies are often run under sustained inflows, stable salinity, and mean tide, whereas most rivers discharge the bulk of their load during short periods of flooding when estuarine circulation is continuously changing. Therefore, attention needs to be focused on transport during transient inflows of high sediment discharge. In particular, the changes in transport history need to be traced from the beginning of freshening to maximum flood and to final intrusion of salt, all of which may either trap or flush sediment through estuaries into the sea.

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