DISTRIBUTION AND CLAY MINERALOGY OF ORGANIC-RICH MUD SEDIMENTS IN THE PAMLICO RIVER ESTUARY, NORTH CAROLINA

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ABSTRACT

The Pamlico River estuary is a funnel-shaped, oligohaline water body extending from the mouth of the Tar River southeastward where it empties into Pamlico Sound. This 50 km-long estuary formed from inundation of the easternmost Tar River drainage system by the rising of sea level during the Holocene transgression. The estuary floor is rather flat, and is composed of brown to black silty organic-rich mud. Sediment thickness data indicate that this mud is an infilling of the drowned stream valleys within the estuary. The distribution and thickness of the mud are primarily controlled by the geomorphical configuration of the infilled stream valleys. Greatest accumulations of the mud occur in the lowermost reaches of the estuary where it is probably more than 20 m thick. The mud is thickest in local areas overlying the deeper portions of the underlying sub-mud topography. The drowning and mud infilling of the eastern Tar-Pamlico drainage system has apparently migrated upstream through time in response to the rising of sea level.

Clay mineralogical studies of the organic-rich mud indicate that the westernmost part of the estuary is characterized by a mixed kaolinite and dioctohedral vermiculite assemblege which decreases in abundance downstream. Illite and smectite occur in minor concentrations in the upper

estuary, but increase in abundance downstream. Clay mineral assembleges of the mud in the lateral estuaries along the Pamlico are identical with those found in mud sediments of adjacent open-water areas, suggesting a similar sediment source for both the trunk and lateral estuaries. The relative abundance of clay mineral species does not significantly change with depth in the mud.

The concentration of organic matter in the mud is quite variable. Concentrations in the upper estuary and lateral estuaries are greatest, usually exceeding 15% by weight. Subsurface mud samples generally contain more organic matter than overlying surface sediments.

The source of organic-rich mud is primarily fluvial in the upper estuary, but the lower estuary probably receives the greatest sediment input from erosion of local shoreline sediments and salt marsh peats. Transportation of muddy sediments from Pamlico Sound by wind-induced currents may also be an important source for the organic-rich mud.

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CONTENTS

TABLES

FIGURES

INTRODUCTION

During the Pleistocene epoch, eastern North Carolina was repeatedly subjected to inundation by glacially-induced sea level fluctuations. Retreat of the sea during the Wisconsin glaciation resulted in stream dissection of marine sediments that were deposited on the Coastal Plain during previous interglacial stages. Subsequent melting of glacial ice, some 15,000-18,000 years ago triggered a worldwide eustatic sea level rise, and drowning of Coastal Plain river systems resulted in the formation of the Roanoke-Albemarle, Tar-Pamlico, and Neuse river-estuary complexes along the northeast North Carolina coast (Fig. 1). The present rate of sea level rise for eastern North Carolina has been estimated to be 0.1 m/century (Riggs and O'Connor, 1974). Recent leveling data (Hicks, 1972) indicate that northeastern North Carolina may be experiencing vertical tectonic subsidence at a rate of 5 cm/century. Such subsidence would increase the relative rate of inundation of eastern drainage systems. As the drainage systems drown, the large estuaries serve as settling basins for incoming sediments. The sediment infilling of the drowned river channels has resulted in flat, featureless estuary bottoms that are composed primarily of silts and clays. However, the sedimentological processes involved in the infilling of the estuaries have not been thoroughly investigated. A reconnaissance survey

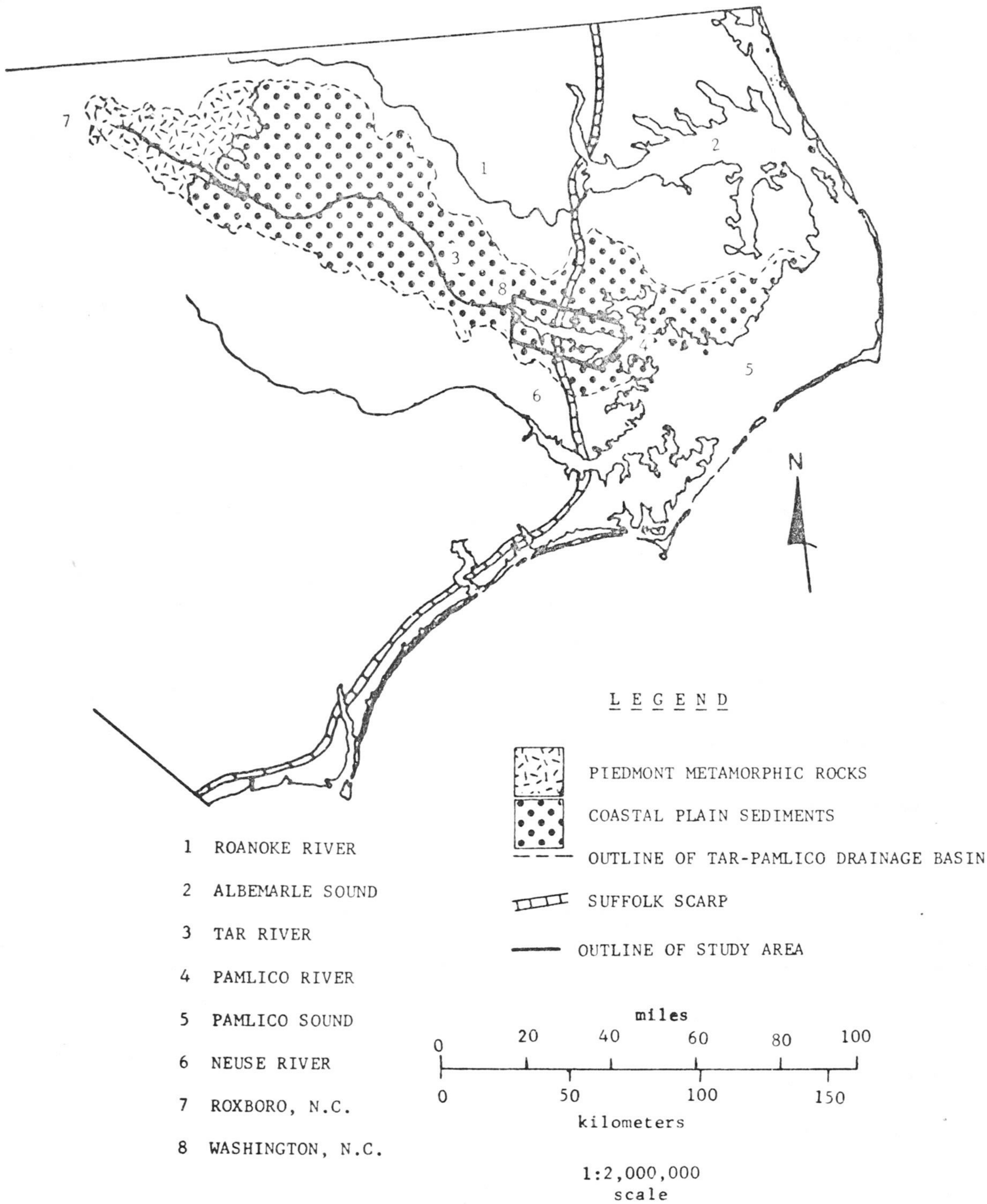


Figure 1. Geologic map of the Tar-Pamlico drainage basin.

made of the Pamlico River bottom sediments during the summer of 1975 by the author revealed that the primary sediment filling the estuary was a brown to black, diatom and arenaceous foram-bearing, silty to sandy organic-rich mud. The objectives of this study were to map the geometry of the mud-filled channels, to characterize this sediment type, and to determine the possible sources of the muddy sediments. The study area includes the Pamlico River and its major lateral estuaries from Washington, North Carolina to the mouth of the Pungo River (Fig. 1).

DESCRIPTION OF THE TAR-PAMLICO DRAINAGE SYSTEM

The combined Tar-Pamlico drainage basin covers more than 8000 km^2 of the Piedmont and Coastal Plain of North Carolina. Headwaters for the Tar River lie near the town of Roxboro, North Carolina, and the mouth of the river is located 200 km to the southeast at Washington, North Carolina. The river widens at Washington to become the Pamlico River estuary. The Tar River drainage basin comprises approximately three-fourths of the total drainage system. The Pamlico River extends 61 km to the southeast where it empties into Pamlico Sound (Fig. 1).

Rock types exposed in the drainage basin include highly weathered crystalline rocks (saprolites) in the Piedmont, with Cretaceous and Tertiary sediments comprising the Coastal

Plain (Fig. 1). Studies by Rich and Cook (1963), Leith and Craig (1965), and Leo and others (1977) indicate that residual weathering of the Piedmont crystalline rocks results in soil formation that is rich in kaolinite and dioctohedral vermiculite, with lesser concentrations of illite. Coastal Plain formations usually contain high concentrations of smectite with lesser illite, although a few kaolinite-rich formations do exist (Reves, 1956; Heron and others, 1965). Pevear (1968) has suggested that suspended loads of major drainage systems are primarily derived from the Piedmont, the relief of which is greater than that of the Coastal Plain. Streams that originate within the Coastal Plain contain little or no suspended load (Heron and others, 1964) except during periods of extremely high discharge (Riggs, 1974).

Discharge for the Tar River averages over 200 m^3/second, with greatest flow during the winter months (Benton, S. B., pers. comm., 1977). Although rainfall in eastern North Carolina is greater during summer months, runoff is reduced, presumeably due to evapotranspiration. Suspended sediment data measured at Tarboro, North Carolina averages 220 metric tons/day (Allen, 1964), and at Greenville averages 56.4 mg/l (Benton, pers. comm., 1977).

The Pamlico River estuary is a funnel-shaped, oligohaline water body extending from the mouth of the Tar River southeastward to the Pamlico Sound. Water depths vary, averaging 3 m for the uppermost reaches of the estuary and over 4 m east of Blount's Bay. Numerous lateral creeks (and their embayed estuaries) empty into the Pamlico River, but due to the low relief and small size of the creek drainage basins, freshwater discharge in these creeks is minor.

Lunar tides within the estuary are quite small (<0.2 m) due to the damping effect of the Outer Banks inlet system. Wind tides are predominant, occasionally reaching 1.5 m. Seasonal storms, such as northwest storms during the winter and spring and hurricanes create extremely high wind tides, causing extensive shoreline erosion and local flooding. The effective fetch increases downstream, exceeding 50 km along the lower reaches of the estuary. Major wind circulation patterns are from the northeast during the fall and winter, but shift to the southwest during the spring and summer.

Water temperatures are quite uniform throughout the estuary and closely parallel the average air temperature. Seasonal variations range from a low of 1.9°C during the winter to a summertime high of 34.0°C (Hobbie, 1970).

The average pH value for the estuary varies between 6 and 8. Changes in pH result from: acidic fresh water fluvial discharge during periods of high precipitation; alkaline salt water encroachment from Pamlico Sound during dry seasons of the year; and from biologic activities, primarily algal photosynthesis. During periods of high algal productivity, CO_2 is removed from the system, making the water basic (Hobbie and others, 1972).

Salinity data demonstrates a general increase downstream averaging 1-2°/oo in the upper estuary and 15-18°/oo in the lower reaches of the estuary (Fig. 2). Salinities are generally (10-15°/oo) lower during the spring and summer and slightly higher during the fall and winter. Salinities as high as 10-15°/oo occasionally extend as far up the river as Washington during periods of low precipitation and runoff (Hobbie and others,1972). During calm weather periods, or when great amounts of fresh water enter the estuary, vertical salinity stratification may result. During these

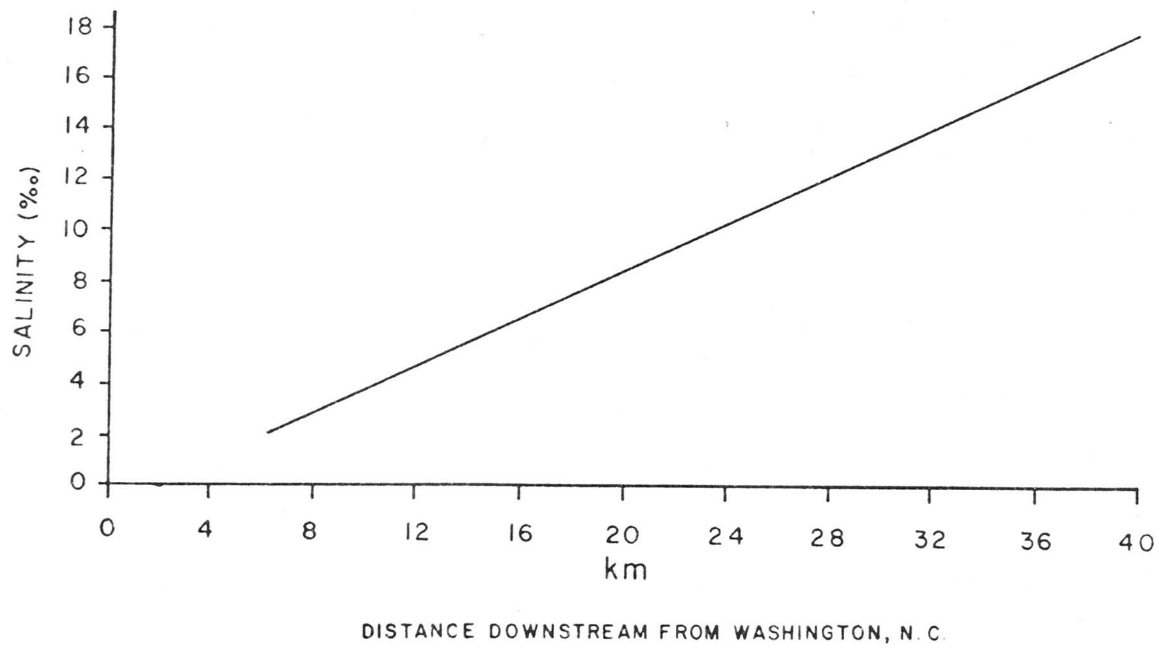


Figure 2. Average salinity as a function of distance in the Pamlico River estuary (Hobbie, 1970).

periods the bottom waters often become anaerobic due to increased biologic activities, resulting in extensive kills of benthic organisms (Tenore, 1967). However, this stratification is usually short-lived due to the strong mixing effect caused by wind action. Vertical salinity stratification occurs mostly in the late summer, whereas lateral salinity zonation is common all year. Water on the northern side of the estuary is generally 2-3^{o}/oo more saline than that on the southern side. This lateral distribution has been attributed to the Coriolis Effect (Hobbie, 1970).

Suspended load in the estuary averages 20.7 mg/l, with lowest concentrations during the summer and fall (Benton, pers. comm., 1977). Intense wave activity during storms alters this pattern by suspending mud sediments from the river bottom, and by the influx of sediments from shoreline erosion.

REVIEW OF PREVIOUS CLAY MINERALOGIC STUDIES

The clay mineralogy of the Pamlico River estuary has been studied by Allen (1964), Pevear (1968, 1972), Park (1971), Dobbins and others (1970), Hathaway (1972), and Edzwald (1972). In each of these investigations, kaolinite was found to be the dominant clay in the upper estuary, decreasing in abundance downstream. Dioctohedral vermiculite (sometimes termed "intergrade chlorite") exhibits a trend similar to kaolinite, with greatest concentrations in the sediments of the upper estuary. Illite increases in abundance in the lower estuary and into Pamlico Sound. Montmorillonite occurs in minor amounts throughout the estuary and shows a general increase in concentration in the lower estuary and Pamlico Sound. Edzwald (1972) and Dobbins and others (1970) do not report trends for dioctohedral vermiculite and smectite. This may be due to their sample preparation techniques or interpretive differences with other workers.

The distribution of the clay minerals in the Pamlico River bottom sediments has classically been attributed directly to source areas. Allen (1964) and Edzwald (1972) attribute the distribution of clay minerals to differential coagulation and flocculation of clays derived from the Tar River in response to the salinity gradient in the Pamlico River. However, since kaolinite is more stable than montmorillonite in saline solutions (Edzwald, 1972), montmorillonite should be concentrated in the upper estuary where it would first encounter the brackish water environment. According to previously mentioned studies, montmorillonite abundance increases downstream, indicating that some other source for montmorillonite exists.

Allen (1964) and Park (1971) suggest that illite may be forming diagenetically by the collapse and uptake of potassium ions in more saline waters by montmorillonite. This seems unlikely because: 1) montmorillonite increases in abundance relative to the potassium ion availability in the Pamlico River (Dobbins and others, 1970); and 2) studies by Keller (1970) indicate that montmorillonite is stable in saline solutions.

Pevear (1968, 1972) has studied the distribution of clay minerals of nearshore marine and river sediments along the east coast of the United States. He found that the suspended sediments of coastal rivers with headwaters in the Piedmont are dominantly kaolinite and dioctohedral vermiculite, with lesser amounts of illite, chlorite, and montmorillonite. Allen (1964) established the dominance of kaolinite and dioctohedral vermiculite in the suspended sediments of the Tar River. Pevear (1968, 1972), Park (1971) and Hathaway (1972) suggest that the suspended sediments from the Tar River are deposited primarily in the upper estuary, while the lower estuary derives its illite-montmorillonite assemblege from either 1) landward transport of illitic marine sediments by current activity and/or 2) erosion of local shoreline strata containing these minerals.

DISTRIBUTION OF ORGANIC-RICH MUD

The sampling regime and procedures utilized for mapping the distribution and thickness of organic-rich mud in the study area are outlined in Appendix A. The sheer number of the smaller lateral creeks necessitated excluding them from the study. Although the methods employed for mapping the mud are somewhat primitive, the method is rapid and the results obtained are valid for use in construction of the mud distribution and paleogeographic maps. Due to logistics problems encountered in certain areas of deep water and/or especially thick accumulation of mud, the total mud thickness could not always be measured. In these areas, the actual thickness is recorded as "greater than" the measured thickness.

Examination of Figures 3 and 4 indicates that the distribution of the organic-rich mud is directly related to the topographical configuration of the surface underlying the mud. It is obvious that the continued drowning of the relict eastern Tar River basin has resulted in the accumulation of organic-rich mud sediments. Increasing thickness of the mud downstream reflects the easterly slope of the buried stream valleys. Assuming that the gradient of the sub-mud surface approximates the gradient of the lower Tar River valley (0.4 m/km), then the mud thickness increases eastward and in the easternmost reaches of the estuary may exceed 20 m! The western reaches of the estuary exhibit the least mud accumulation, inferring that sediment infilling has been operating for a shorter duration in the west than the east. Such a trend would be expected since rising sea level would first drown the easternmost areas of the drainage basin. The cross-sections in Figure 5 illustrate the nature of the relationship between mud and the sub-mud topography.

X-RAY DIFFRACTION IDENTIFICATION OF CLAY MINERALS

Clay minerals are hydrous layer-lattice silicates, except for palygorskite and sepiolite which are considered pseudo-layer silicates, with individual particle sizes less than 2 µm. The most common procedure for clay mineral identification is through the use of X-ray diffraction techniques. The identification of clay minerals is based on the basal (001) reflections of oriented mounts (see Appendix B for techniques). Since some clay minerals have overlapping basal reflections, special treatments must be utilized for distinguishing their identities in a mixture. Heat treatments of oriented clay mounts may cause structural contraction or collapse along the c-axis. Absorption of organic molecules (glycerine) causes structural expansion of smectite group minerals and a certain variety of chlorite. The combined uses of heat treatment and glyceration of clay minerals allows for simplified identification of clay minerals in the mixtures.

Kaolinite, dioctohedral vermiculite, illite, and smectite are the major clay minerals present in the organic-rich mud of the Pamlico River estuary.

Kaolinite--The chemical composition of kaolinite is $2Al_2Si_2O_5(OH)_4$ (Carrol, 1974). Each unit cell is composed of one tetrahedral layer and one octohedral layer (Fig. 6). Strong basal reflections at 7.2A (angstrom) and 3.58A are diagnostic for kaolinite. Kaolinite is typically a very pure alumino-silicate with no isomorphous substitutions within the octohedral layer. Prolonged exposure to temperatures above 450°C results in the collapse of the unit cell structure, and is marked by disappearance of the basal reflections from X-ray diffractograms. Kaolinite is unaffected by treatment with glycerine.

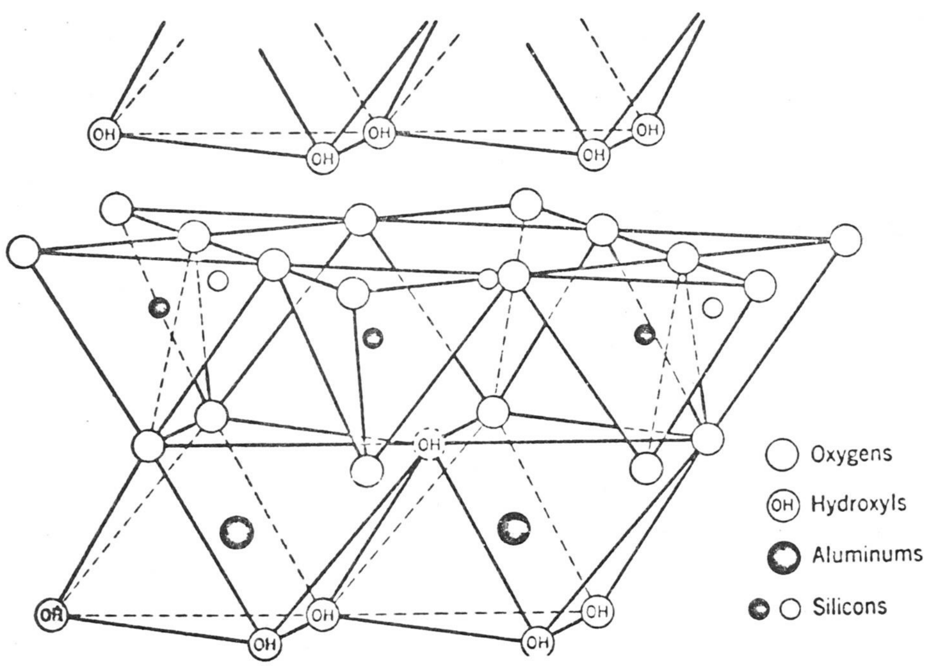


Figure 6. Diagrammatic sketch of the kaolinite structure (after Grim, 1968).

Dioctohedral Vermiculite--No single specific composition for all dioctohedral vermiculite is possible due to isomorphous substitution in both the tetrahedral and octohedral sheets. Carrol (1974) gives the general composition of vermiculite to be $Mg_3Si_4O_{10}(OH)_2$ x H_2O. The basal reflection of vermiculite is 14A which will collapse to 10A after heat treatment above 500°C. Dioctohedral vermiculite is unaffected by treatment with glycerine.

Illite--The structural formula of illite is similar to that of muscovite ($(OH)_4K_2(Si_6 \cdot Al_2)Al_4O_{20}$), but contains less potassium and more silicon and water. Illite is composed of two tetrahedral and one octohedral layers per unit cell (Fig. 7). Basal reflections occur at 10, 5, 3.3A and are unaffected by heat or glycerine treatment.

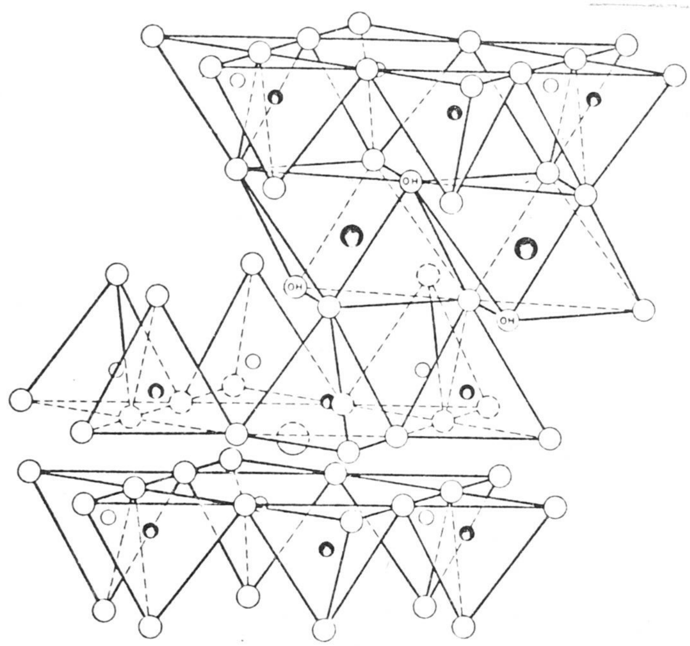


Figure 7. Diagrammatic sketch of the illite structure (after Grim, 1968).

Smectites--Smectites are a group of minerals in which the component layers are bonded by water molecules, termed interlayer water (Fig. 8). Variability of isomorphous substitution within the tetrahedral and octohedral layers make species identification difficult, if not impossible, in modern sediments. Minerals within the smectite group are characterized by a strong basal (001) reflection at 13A or 15A that expands to 17A upon treatment with glycerine. Heat treatment above 300°C results in expulsion of interlayer molecules and collapse of the structure to 9A-10A. The term "montmorillonite group" has been replaced by "smectite" in recent literature. Montmorillonite is actually just one of many minerals in the smectite group.

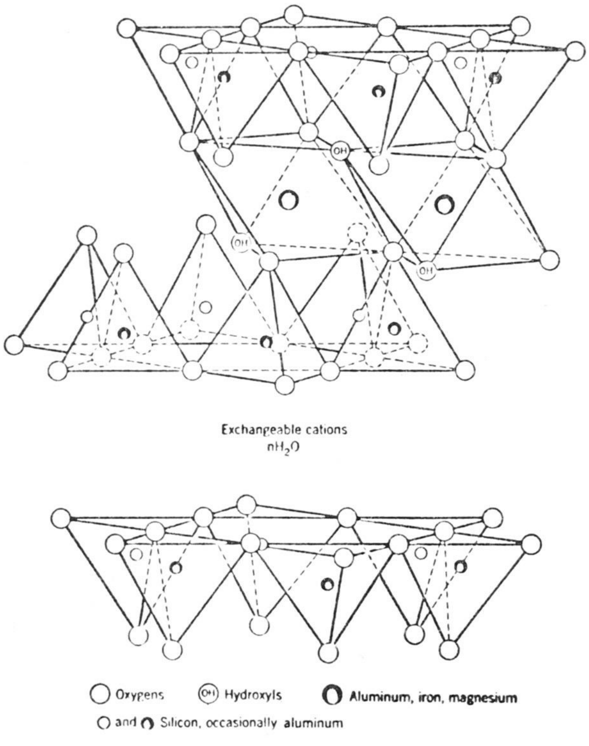


Figure 8. Diagrammatic sketch of the smectite structure (after Grim, 1968).

CLAY MINERALOGY OF THE PAMLICO RIVER SEDIMENTS

The location of twenty-five cores of organic-rich mud taken in the Pamlico River estuary is shown in Figure 9. Samples from the uppermost and lowermost 0.3 m of each core were analyzed for organic content and clay mineral composition.

The problems encountered in quantification of clay minerals have been reviewed by Gibbs (1965) and Pierce and Siegel (1969). Factors that influence results obtained from X-ray diffractograms are 1) chemical and structural variations between mineral groups and within the same mineral types, 2) sample preparation techniques, 3) sample treatment, 4) equipment conditions, and 5) the methods employed to calculate the relative abundance of each mineral within the sample. Attempts to quantitatively determine the percentage of a particular clay mineral are difficult and unrealistic. However, if sampling and laboratory procedures are consistent, the relative abundance of a mineral in the sample can be delineated by the relative intensity of the (001) reflection in oriented mounts. Comparison of the change in relative intensity of the basal reflections yields the relative change in abundance of the mineral among samples.

In this study, the first order basal reflection (001) of each clay mineral was compared to the 4.26A reflection of a quartz standard analyzed prior to each sample run.

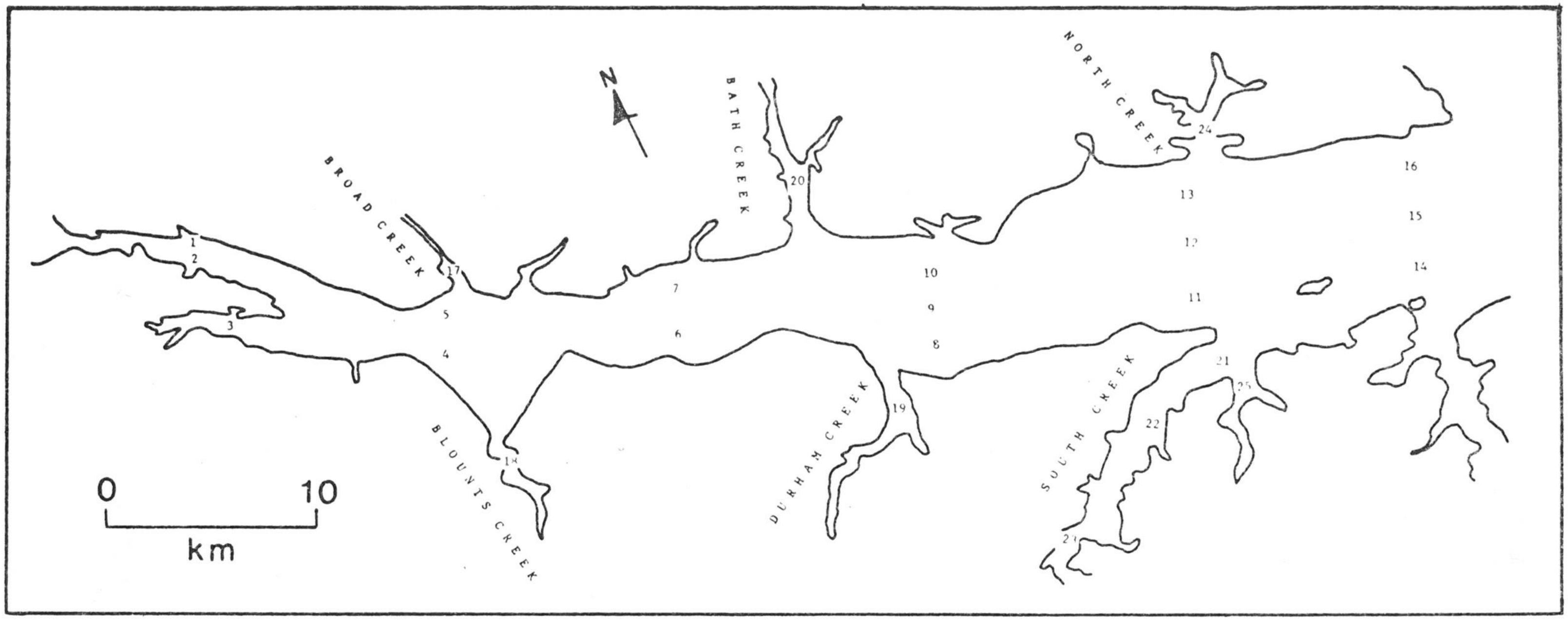


Figure 9. Core localities in the Pamlico River estuary.

The intensity of the predetermined basal reflection was compared to the standard and formulated as the following ratio: I_{clay} / $I_{standard}$. The relative intensity of the standard remains constant even though equipment settings are altered. Thus, changes in the ratio between samples would indicate relative changes in mineral abundance.

For the purpose of graphical representation, the values obtained for each mineral along a traverse were averaged and plotted versus distance downstream (Fig. 10). Kaolinite and dioctohedral vermiculite are the dominant surface clays within the western reaches of the estuary, but decrease in an easterly direction. An increase in the relative concentration of kaolinite and vermiculite is evident in the vicinity

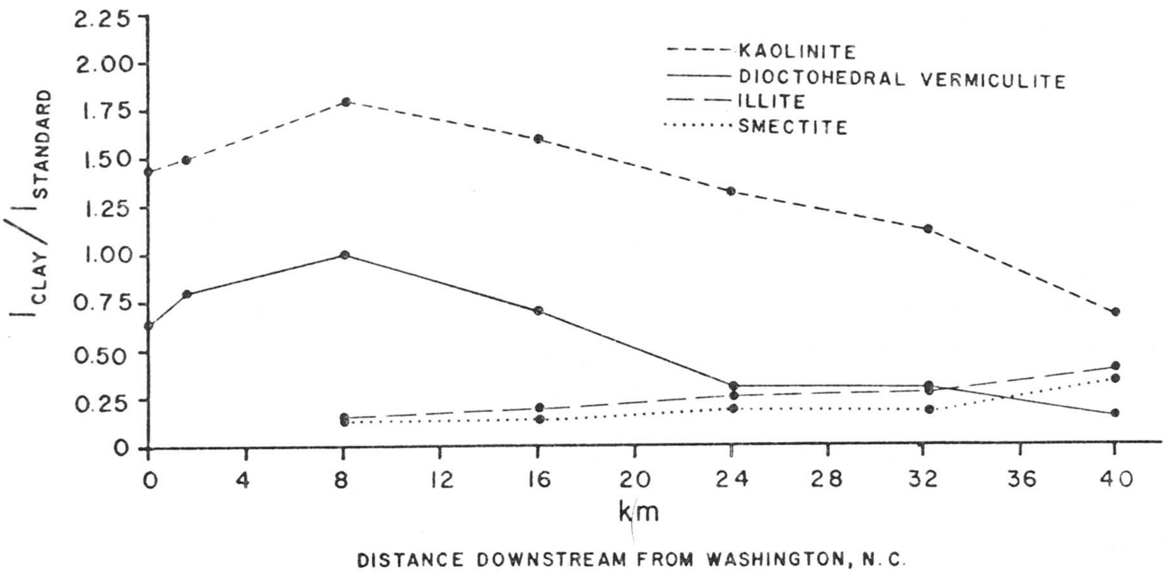


Figure 10. Relative intensity distribution of clay minerals in Pamlico River surficial samples.

of Blount's Bay and has been previously reported by Allen (1964). Illite and smectites are present in minor amounts in the upper estuary, and increase in relative abundance downstream. No significant lateral variation in clay mineral abundance among samples taken along the same traverse was observed.

The distribution of clay minerals in the subsurface samples closely parallels that of the surficial samples (Fig. 11). However, compaction of the mud during sampling (see Appendix D) may cause trend analysis of the subsurface samples to be subject to error.

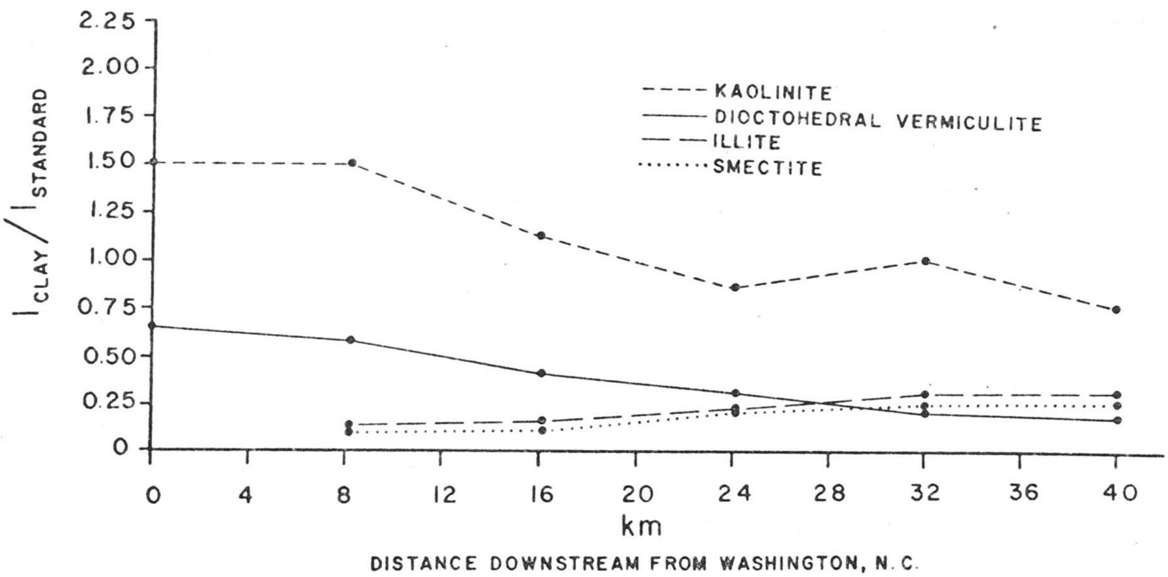


Figure 11. Relative intensity distribution of clay minerals in Pamlico River subsurface samples.

The relative abundance of the constituent clay minerals in lateral estuaries closely resembles that of adjacent sediments in the Pamlico River (Fig. 12). This suggests that the lateral estuaries probably serve as settling sites for suspended sediments derived from the main river.

ORGANIC CONTENT OF PAMLICO RIVER MUD

Organic matter in unpolluted estuaries is primarily composed of vegetal material, although a small quantity is contributed to the system by fauna. Vegetal detritus may be either autochthonous, derived from vegetation from within the estuarine waters, or allochthonous, transported into the estuary from another system. Darnell (1967) gives the following possible sources of organic detritus in estuaries:

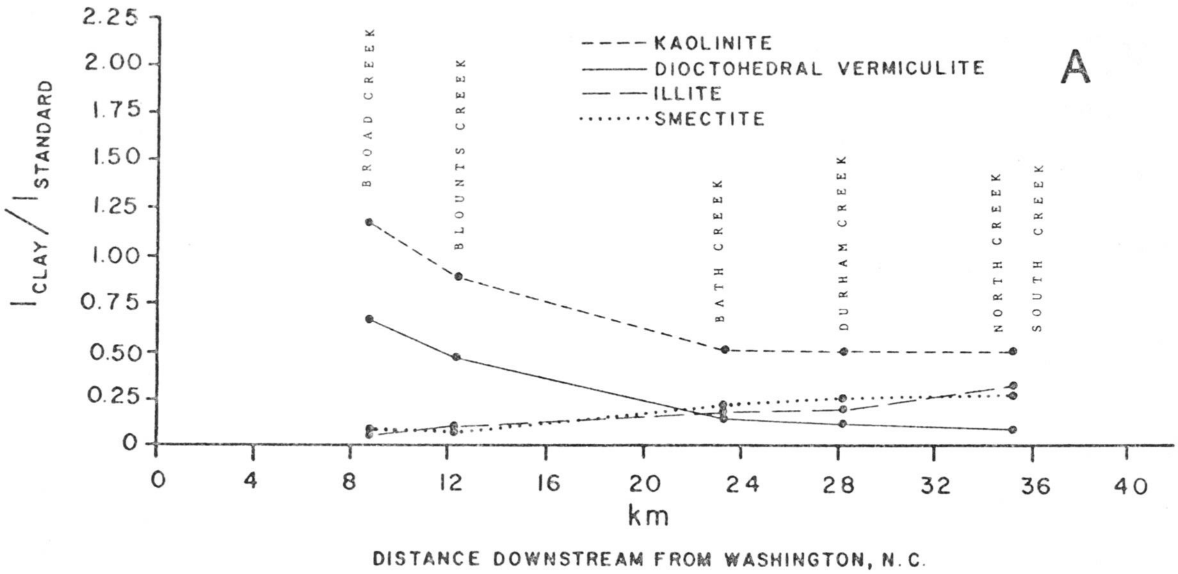
Autochthonous sources

1. Phytoplankton
2. Submerged vegetation
3. Diatoms and algae
4. Periphyton

Allochthonous sources

1. Marsh vegetation
2. Swamp vegetation
3. River-borne phytoplankton and organic debris (including pollutants)
4. Shore materials washed into the estuary during periods of high water
5. Windblown material (leaves and pollen)
6. Phytoplankton and other sources within the adjacent marine environment

All of these appear to be potential sources of organic detritus within the Pamlico River system.



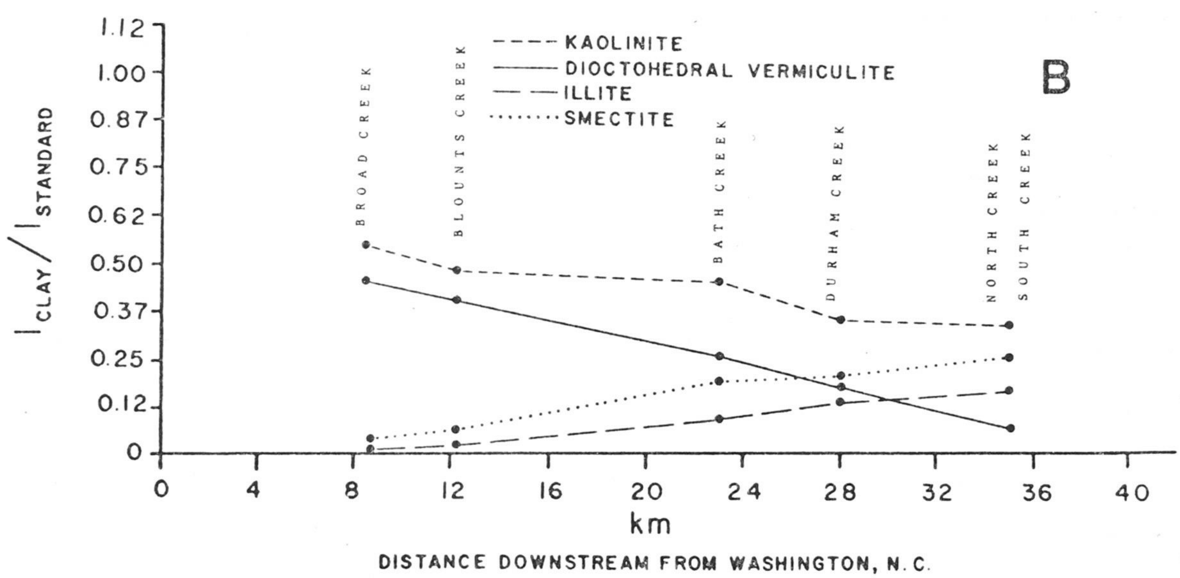


Figure 12. Relative intensity distribution of clay minerals in lateral estuary surficial (A) and subsurface (B) samples.

The concentration of organic matter varies inversely with the grain size of the sediments (Folger, 1972). Clay generally contains more organic matter than sands or gravels. Thus, it would be anticipated that the Pamlico River estuarine sediments would be organic-rich since most of the sediments within the estuary are silt and clay sizes and, numerous sources for organic detritus are available.

The prevelence of organic detritus in estuaries has been discussed by Darnell (1967). He emphasizes that organic detritus represents an important part of the estuarine ecosystem. Organic materials may be: 1) a major storage of organic matter which is produced at one time and later released; 2) transported away from the point of production; 3) a buffer that supplies nutrients at times of low primary production.

The weight percent of organic detritus in the samples was obtained through low-temperature oxygen-plasma techniques (see Appendix B). The analytical results are shown in figure 13. Interpretation of variances in the data is difficult since the quantity of organic detritus in each sample reflects complex biologic and hydrologic relationships. However, several trends are apparent: 1) organic content increases away from nearshore areas; 2) subsurface samples generally contain more organic material than surface samples; and 3) organic concentration is higher in lateral estuaries than in the adjacent Pamlico River.

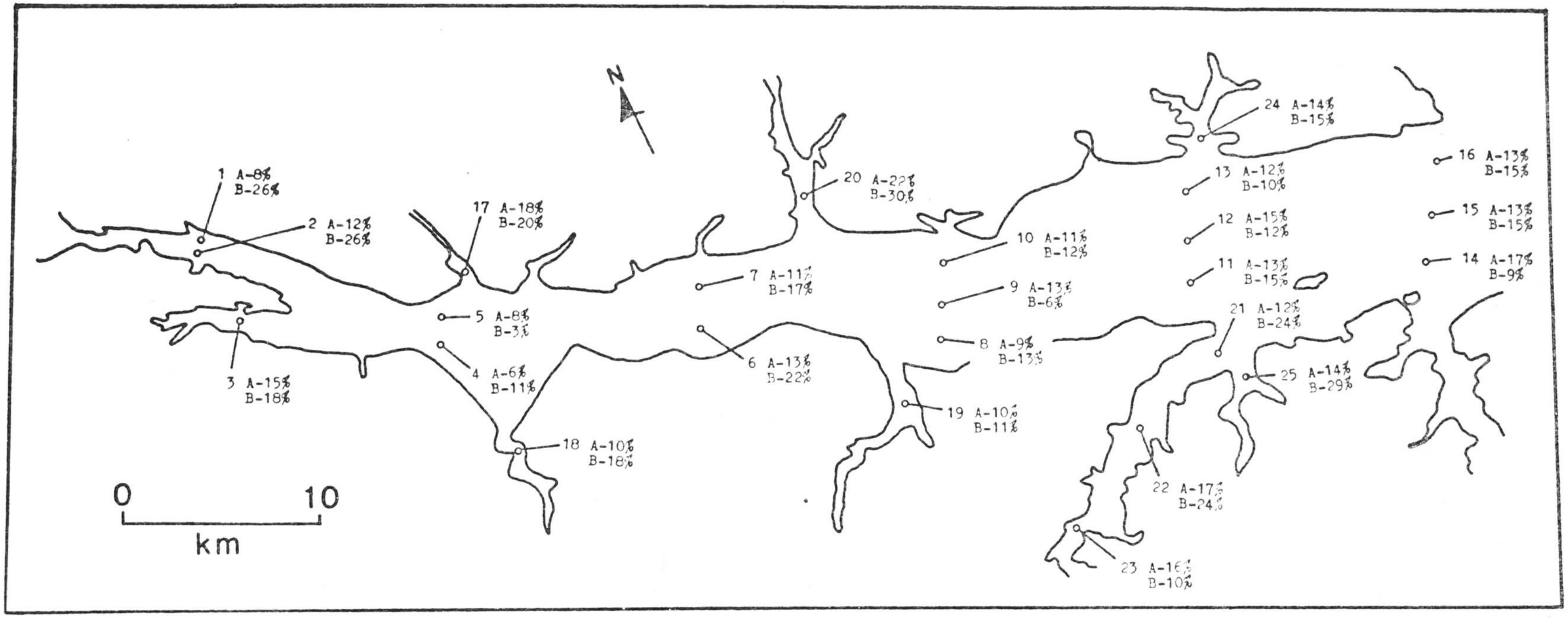


Figure 13. Weight percent organic matter in the uppermost (A) and lowermost (B) sections of each core.

The organic content of the Pamlico River sediments is considerable higher than that in Pamlico Sound. Sediments in the Pamlico Sound rarely contain organic detritus exceeding 4%, although concentrations as high as 8% have been reported (Pickett, 1965). The sound is dominated primarily by sandy sediments, with intense wave action that tends to limit the concentration of organic materials.

Studies by Whitehouse and others (1960) demonstrate that organic compounds influence the settling rates of various clay minerals. Carbohydrates were found to increase the settling rate of montmorillonite, and proteins decreased the settling rates of montmorillonite and kaolinite. The influence of organic compounds upon settling rates in the sedimentological regime of the Pamlico River estuary is not known, but would seemingly influence the system to some extent.

DISCUSSION

Numerous investigations have dealt with the sediment infilling of estuaries (Meade, 1969; Pevear, 1968; Potsma, 1967; Rusnak, 1967). Primary source areas for these sediments include: 1) sediments derived from inflowing rivers and creeks; 2) landward transport of bottom sediments by tidal action; 3) and influx of eroded estuarine shoreline strata. Since lunar tidal action within the Pamlico River is minimal, any upstream transport of bottom sediments is probably the result of wind tides.

The Pamlico River is the estuarine counterpart of the Tar River; thus the estuary is greatly affected by the flow regime of the river. Numerous creeks empty into the estuary, but their input is probably insignificant due to the small size of their drainage basins. The suspended load of the Tar River is composed of silt, clay, and organic detritus. Allen (1964) found that the clay mineralogy of these fresh-water suspended sediments reflects the mineralogy of the soils within the drainage basin. Kaolinite and dioctohedral vermiculite are most abundant, and minor amounts of illite and smectite are present. Upon reaching the estuary, these clays coagulate and flocculate to the estuary floor. As previously stated, the rate of coagulation and flocculation is primarily a function of the relative stabilities of clay minerals in saline solutions.

The importance of biological activities in the removal and deposition of suspended sediments has not been evaluated. Haven and Morales-Alamo (1966, 1972) have determined that detritus and filter-feeders ingest particles as small as one micrometer, and excrete fecal pellets that range up to 3 mm in length. The fecal pellets will either be resuspended or incorporated into the bottom sediment. These organisms serve as converters of small suspended material to large, more compact fecal detritus.

The relative abundance of each clay mineral should vary downstream in an idealized estuary with regular downstream flow and increasing salinity. Using the stability values of Edzwald (1972) and Whitehouse (1960) the idealized downstream gradation of mineral types away from the source should be smectite-kaolinite-vermiculite-illite. This study demonstrates the dominance of kaolinite and dioctohedral vermiculite in the westernmost reaches of the Pamlico River estuary, and that they decrease downstream. The concentration of smectite, however, increases downstream, indicating that the idealized situation does not exist within the estuary. It appears that clay sediments within the upper reaches of the estuary are dominantly influenced by river-derived detritus, and that this influence decreases downstream. Since illite and smectite are only minor constituents of the suspended sediments of the Tar River, it is questionable that the apparent downstream abundance of illite and smectite is attributable to a fluvial source. Whitehouse and others (1960) have suggested that the types of clay minerals in sediments may have direct source significance. Since the illite-smectite assemblege in the lower Pamlico River estuary apparently has not been derived from freshwater sources, then alternate source areas must be considered.

Meade (1969) and Pevear (1968) have suggested that the illite-smectite assemblege in the Pamlico Sound and lower Pamlico River was derived from either landward transport of the clays from the open ocean by current activity, or by erosion and deposition of estuarine shoreline strata. Lunar tidal action in North Carolina's estuaries is quite small, thus it seems unlikely that bottom transport of clays by lunar tides could be of major importance. The major limiting factor to landward sediment transport is the barrier island inlet system. Since the water movement from the estuaries and open ocean is restricted by tidal inlets, the tidally influenced estuarine water circulation patterns are greatly dependent on the number and size of inlets along the barrier island chain. Estuarine lunar tidal fluctuation decreases with distance from an inlet, thus the effectiveness of bottom transport through the inlets would also decrease with distance. It has been shown by O'Connor and others (1972) that inlets were more numerous in past times than at present. Perhaps a large number of inlets may have once existed for sufficient tidal transport of illite and smectite into the estuaries. Tidal surges associated with seasonal storms may cause the influx of illitic marine clays into the estuaries through the inlets. This is rather conjectural and remains to be proven.

A likely source for the illite and smectite of the lower Pamlico River and Pamlico Sound would be from erosion of estuarine shoreline strata containing these minerals. An estuarine shoreline inventory by the United States Department of Agriculture Soil Conservation Service (1975) indicates that most of the shorelines along the Pamlico River and Pamlico Sound are rapidly eroding. Erosion rates for the Pamlico River average 0.5 m/year, contributing an estimated 550 tons of sediment per day. Shorelines along the upper estuary are not eroding as rapidly as those along the easternmost reaches of the estuary. This is primarily related to the larger fetch of the lower estuary.

The nature and extent of estuarine shoreline erosion in North Carolina has been studied by Bellis and others (1975). Results indicate that erosion within the estuary is a function of fetch and orientation of the shoreline, bank composition and height, and vegetation. The susceptibility of various shoreline types to erosion is shown in Table 1.

Table 1. Susceptibility of various shoreline types in the Albemarle-Pamlico region to erosion (from Bellis and others, 1975)

SHORELINE TYPE	EROSION RATE (ft/yr) (protected)	(exposed)
I. Sand and Clay Banks		
A. Low bank	1	3-8*
B. High bank	1	2-5*
C. Bluff	½	1-2
II. Swamp Forest	(negligible)	(negligible)
III. Grass Marsh	2	6-20

*Cropland generally more susceptible to erosion than forested land

It is particularly important to note that low bank and marsh grass shorelines are the most susceptable to erosion. Most of the estuarine shorelines east of the Suffolk Scarp fall into these categories. The volume of sediment produced by erosion of the low bank and marsh grass shorelines of the lower estuary must certainly have a substantial effect on the sedimentation in the lower estuary. Further research as to the distribution of clay mineral types exposed along the eroding shoreline is needed in order to qualify this relationship.

Comparisons of United States Coast and Geodetic Survey bathymmetric "smooth sheets" dated 1870, with recent nautical charts were made to determine measureable sediment infilling. No appreciable change in the bathymmetry was noted. However, there are a number of variables that may make such map comparisons vulnerable to error: 1) navigational and water depth measurement techniques have vastly improved since the first maps were compiled, and perhaps the earlier maps were not accurate; 2) sea level rise may affect the effects of sediment accumulation; 3) man-induced effects on the system may have altered the sedimentological regime. It is significant, nevertheless, that the bottom configuration and bathymmetry appear to have remained essentially unchanged for the past century. This indicates that either the infilling of the estuary is extremely slow or non-existant, or compaction of the clay and organic detritus results in undetectable accumulation of sediment for a 100-year period.

SUMMARY AND CONCLUSIONS

1) The occurrence of organic-rich mud is primarily restricted to the relict channels and valleys of the drowned Tar River drainage system. Mud thicknesses average around 3 m for the westernmost reaches of the estuary, and are estimated to exceed 20 m in thickness in the easternmost reaches of the estuary.

2) Organic-rich mud in the upper estuary is dominantly composed of kaolinite and dioctohedral vermiculite. These clays are primarily derived from coagulation and flocculation of suspended sediment influx of the Tar River. Illite and smectite increase in abundance downstream and are probably derived from erosion of estuarine shoreline strata and/or from influx of clays from Pamlico Sound.

3) The organic content of the estuarine mud averages 15% by weight. Mud sediments in the lateral estuaries contain slightly higher concentrations of organic matter than adjacent Pamlico River sediments.

4) The continual drowning and infilling of the Tar-Pamlico drainage system will presumeably continue to migrate up the drainage system as long as sea level is rising.

SUGGESTIONS FOR FURTHER RESEARCH

A number of suggestions for further research have resulted from this investigation:

1) Carbon-14 dating of the organic detritus in the mud both laterally and vertically would yield sedimentation rates for the estuary.

2) Analysis of the composition and movement of the suspended sediments within the estuary coupled with weather and water circulation data would aid in evaluating the sedimentological regime of the estuarine system.

3) Clay mineralogy studies of the strata exposed along the estuarine shoreline and of the soils within the drainage basin are necessary for evaluating the influence of these sediments on the mineralogy of the mud.

4) Analysis of the vegetal matter within the mud would indicate the sources for the high organic content of the bottom sediments.

5) The role of biodeposition and its effects on sedimentation needs extensive research.

6) Detailed mapping of the surface beneath the mud may aid in interpretation of the geomorphic controls that influence the depositional process.

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APPENDICES

APPENDIX A: FIELD METHODS

Boomer reflection techniques were utilized by Leith and Welby (1967) to map the surface underlying the organic-rich mud of the Pamlico River estuary. Attenuation of the soundings by the mud resulted in very poor reflections, making interpretation of the data questionable.

In order to map the distribution and thickness of the mud for this study, a galvanized pipe sediment probe was used. Penetration of the sediments with the calibrated probe allowed the thickness of the mud and the topography of the pre-mud surface to be measured. Location of traverses are shown in figure 5. Results were recorded on United States Coast and Geodetic Survey Navigational Chart no. 537.

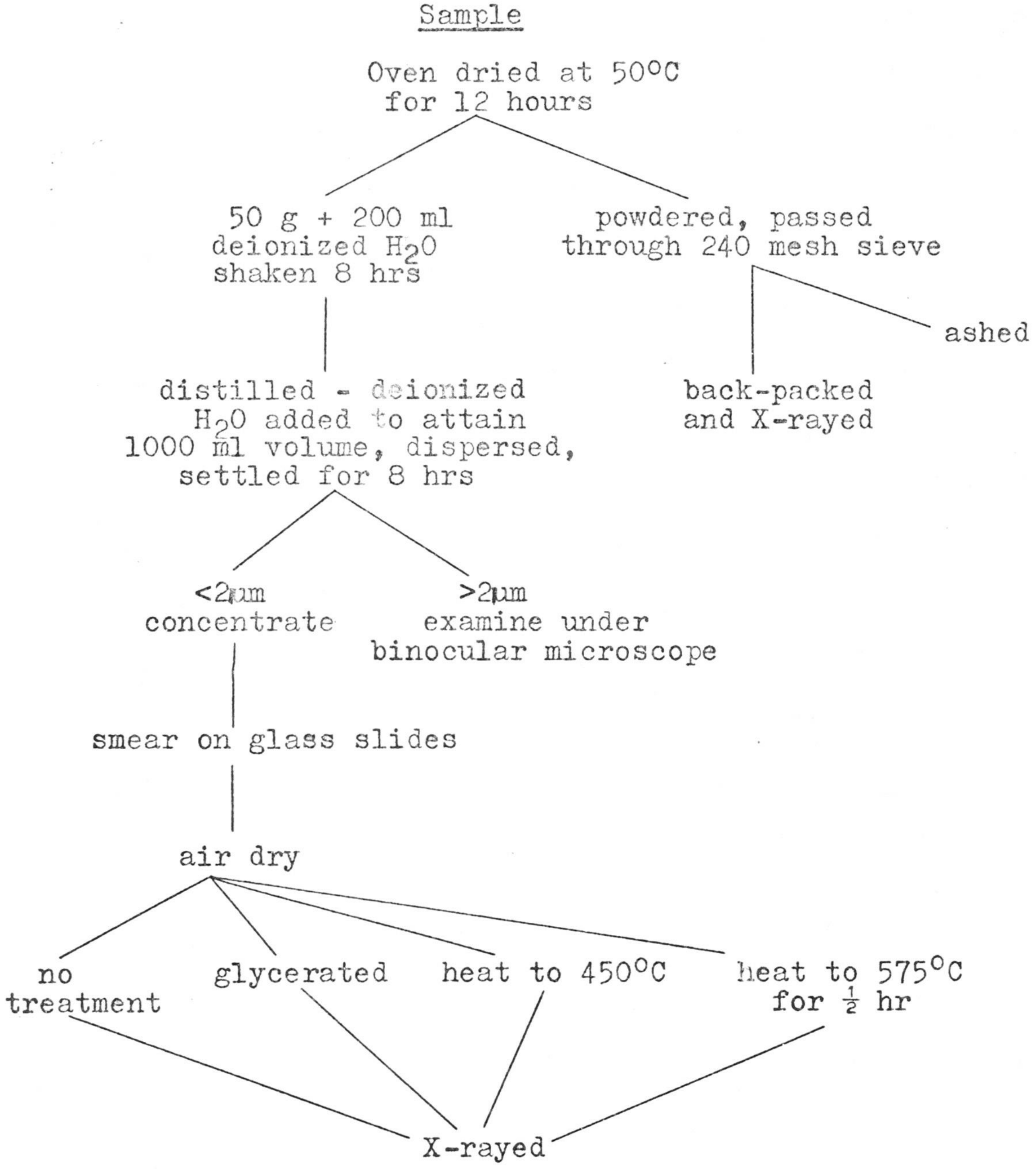
Sediment cores were taken with a 3" PVC pipe from aboard the East Carolina University Geology Department barge, "Beggar Tom". In order to assure that "pile-driving" of the mud did not occur during coring, the length of the mud core in the core pipe was measured and compared to the actual depth of the core. Since the core sample normally compacted in excess of 50% upon extrusion from the core barrel, stratigraphic sampling was limited to the uppermost and lowermost portions of the core. The extruded core was sectioned into 0.3 m samples, labeled, and stored in plastic bags. Upon return to the laboratory, the uppermost and lowermost sections of each core were immediately analyzed.

APPENDIX B: LABORATORY PROCEDURE

1. Separation of <2 µm fraction

The extremely slow rate of dessication of the mud samples at room conditions necessitated the heating of the mud to attain a dry sample (Table 2). Samples were oven-dried at 50°C for 12 hours. Fifty grams of the dried sample were then disaggregated to a powder and placed in a 600 ml flask with 200 ml distilled and deionized water, and agitated for 8 hours in a wrist-action shaker. The resultant slurry was transferred to a 1000 ml beaker with deionized water added to attain a 1000 ml sediment-water suspension. A blender was then used to thoroughly mix the suspension. If flocculation of the sample was observed, then the sediment-suspension was washed in order to remove the remaining cations from the sample. Washing of the sample was performed by concentrating the sediments through use of a porcelain filter. The sample was then returned to a 1000 ml beaker and distilled-deionized water added to make the total sediment-water suspension volume 1000 ml. The blender was then used to thoroughly re-mix the sediment-water

Table 2. Lab flow chart



suspension. The sample was washed up to four times in order to attain complete dispersion. Once the sediment-water suspension was dispersed, the <2 μm fraction was obtained by allowing the sediment-water suspension to settle for 8 hours and decanted according to Stokes' Law.

2. Slide preparation of <2 μm fractions

Once the <2 μm fraction of the sediment-water suspension was obtained, the clay-water suspension was then placed in a 600 ml beaker and concentrated through the use of a porcelain filter. The <2 μm clay concentrate was then transferred to a 50 ml beaker and thoroughly mixed by use of a blender. The thoroughly mixed clay paste was smeared on glass slides utilizing a smearing device described by Tien (1974), and dried at room conditions. Five slides were prepared with special treatment as follows: 1) One slide was suspended in an aluminum container with glycerine. The container was then heated, causing the glycerine to vaporize and coat the surface of the slide. A slide smeared with swinefordite was placed in the container with the samples during heating to serve as a monitor for complete absorption of glycerine by expandable clay minerals in the samples. When the swinefordite sample was observed (through X-ray treatment) to have reacted to the treatment, the samples were considered treated. 2) The second slide was heated in a box-furnace to 450°C and allowed to cool in the furnace. 3) A third slide was heated to 575°C for ½ hour, and allowed to cool in the furnace. 4) A fourth slide was untreated. 5) The fifth slide was preserved as a back-up sample in case something went wrong with one of the other slides.

3. <u>Whole rock preparation for X-ray diffraction analysis</u>

Approximately 50 g of dried sample were crushed and passed through a 240 mesh sieve. The crushed and sieved sample was then back-packed in an aluminum sample holder. Packing techniques were kept consistant in order to negate the possibility of reflection variations due to sample preparation procedures.

4. <u>Preparation of samples for low temperature ashing</u>

Approximately 0.1 g of the dried, crushed, and sieved sample was placed in a glass weigh-boat and subjected to ashing treatment. The weight of the sample was measured before and after treatment, thus obtaining the percentage weight loss due to the ashing process.

5. Radiometric dating

Mud samples taken from sections of core no. 1 were sent to Westwood Laboratories for carbon-14 analysis. Ages of 1605 A.D., 1360 A.D., and 1655 A.D. were reported for the top, middle, and bottom sections of the core respectively. No interpretation of these results was attempted since the mud samples were seemingly contaminated due to the effects of burrowing organisms, bacteria, or by some other process.

APPENDIX C: INSTRUMENTATION

1. X-ray diffraction

A General Electric XRD-6 diffractometer using LiF monochromatized CuK_α radiation was utilized for all X-ray analyses. The unit was operated at 45 kv and 20 mA with a scanning rate of $4^\circ 2\theta$ per minute.

Whole rock back-packed samples were scanned between 3° and $85^\circ 2\theta$, and oriented slides between 3° and $45^\circ 2\theta$. A quartz standard was run before and after each sample as a check for variance in X-ray performance and as a reference for reflection intensity comparisons.

2. Low temperature ashing

An LFE low temperature asher was used for obtaining volatile contents of the sample. An oxygen flow rate of 200 cc/minute with 300 watts power for 30 minutes was used for the processing of each sample. Complete ashing of the sample was spot-checked through the use of a 5% solution of hydrogen peroxide. None of the ashed samples checked reacted with the peroxide, indicating that ashing was complete.

APPENDIX D: RAW DATA

Table 3: Field data

Core #	Water depth (m)	Core depth below river bottom(m)	Core compaction (m)	% compaction
1	1.5	1.2	0.15	13
2	1.5	1.2	0.30	25
3	1.8	1.5	0.91	60
4	1.5	1.8	0.91	50
5	3.7	0.6	0.30	50
6	3.9	1.5	0.45	30
7	3.7	3.3	2.40	72
8	4.3	1.2	0.30	25
9	4.3	0.6	0	0
10	5.2	1.2	0.30	25
11	3.9	3.4	2.10	62
12	5.5	2.4	1.50	63
13	4.6	1.2	0.60	50
14	5.2	2.3	1.50	65
15	5.5	3.4	2.10	62
16	5.5	2.7	1.80	67
17	1.5	1.5	0.90	60
18	1.2	1.5	0.50	33
19	0.6	2.4	1.20	50
20	2.4	3.7	2.60	70
21	3.0	3.0	1.40	47
22	2.7	3.2	2.00	63
23	2.4	2.3	1.50	65
24	2.7	4.9	3.70	76
25	2.1	3.7	2.30	62

Table 4: Lab data Lab Data

Sample #[1]	Sample location in extruded core (m)[2]	% organics	$I_{clay}/I_{standard}$[3] K	D.V.	I	S
1A	0-0.3	8.0	1.70	0.70	---	---
B	0.15-1.05	26.6	1.00	0.60	---	---
2A	0-0.3	12.1	1.20	0.60	---	---
B	0.6-0.9	12.5	2.00	0.70	---	---
3A	0-0.3	15.5	1.50	0.80	---	---
B	0.3-0.59	18.0	1.49	0.62	---	---
4A	0-0.3	6.2	1.80	1.00	0.14	0.15
B	0.59-0.69	10.8	0.90	0.40	0.14	0.12
5A	0-0.15	8.4	1.80	1.00	0.13	0.14
B	0.15-0.3	3.7	2.10	0.70	0.15	0.15
6A	0-0.3	12.8	2.00	0.60	0.13	0.13
B	0.75-1.05	22.4	1.00	0.40	0.12	0.12
7A	0-0.3	10.8	1.20	0.80	0.23	0.15
B	0.6-0.9	17.0	1.20	0.40	0.20	0.11
8A	0-0.3	9.3	1.60	0.26	0.26	0.21
B	0.6-0.9	12.6	0.90	0.32	0.20	0.14
9A	0-0.3	13.9	0.90	0.34	0.23	0.14
B	0.3-0.6	5.8	0.80	0.29	0.24	0.21
10A	0-0.3	10.7	1.50	0.29	0.26	0.17
B	0.6-0.9	11.9	0.90	0.30	0.21	0.23
11A	0-0.3	13.0	0.90	0.34	0.27	0.21
B	1.0-1.3	14.5	1.30	0.21	0.21	0.23
12A	0-0.3	15.0	0.70	0.21	0.27	0.21
B	0.6-0.9	11.1	1.00	0.18	0.21	0.23
13A	0-0.3	11.5	1.80	0.41	0.27	0.14
B	0.3-0.6	9.5	0.68	0.16	0.37	0.19
14A	0-0.3	17.1	0.69	0.18	0.52	0.31
B	0.5-0.8	9.4	0.87	0.21	0.33	0.14
15A	0-0.3	13.0	0.71	0.16	0.29	0.21
B	1.0-1.3	14.5	0.63	0.14	0.27	0.26
16A	0-0.3	15.0	0.63	0.11	0.33	0.48
B	0.6-0.9	14.5	0.68	0.11	0.25	0.18
17A	0-0.3	18.0	1.10	0.60	0.03	0.07
B	0.3-0.6	20.0	0.54	0.43	0.02	0.05
18A	0-0.3	9.7	0.88	0.43	0.08	0.07
B	0.7-1.0	18.0	0.48	0.52	0.30	0.72
19A	0-0.3	10.2	0.86	0.14	0.16	0.25
B	0.9-1.2	11.3	0.62	0.25	0.10	0.19
20A	0-0.3	22.0	0.50	0.11	0.16	0.20
B	0.8-1.1	30.0	0.48	0.34	0.08	0.22
21A	0-0.3	12.0	0.70	0.25	0.30	0.19
B	1.3-1.6	23.7	0.53	0.30	0.25	0.25
22A	0-0.3	16.8	0.47	0.32	0.27	0.14
B	0.9-1.2	23.6	0.38	0.16	0.12	0.09
23A	0-0.3	16.1	0.29	0.12	0.16	0.10
B	0.5-0.8	10.2	0.22	0.11	0.13	0.09
24A	0-0.3	14.5	0.57	0.20	0.22	0.19
B	0.9-1.2	15.3	0.72	0.11	0.17	0.16
25A	0-0.3	14.2	0.49	0.19	0.23	0.11
B	1.1-1.4	28.7	0.36	0.18	0.11	0.17

1--"A" collected from top of core, "B" collected from bottom of core.

2--Location measured from top of extruded core.

3--Intensity of X-ray diffractogram reflection of the sample divided by the intensity of X-ray diffractogram of the quartz standard. K=kaolinite, D.V.=dioctohedral vermiculite, S=smectite, I =illite.

FIGURE 3. ISOPACH MAP OF ORGANIC-RICH MUD, PAMLICO RIVER ESTUARY, N.C.

FIGURE 4. STRUCTURE CONTOUR MAP OF THE PRE-MUD SURFACE.

FIGURE 5. STRUCTURE SECTIONS OF THE ORGANIC – RICH MUD UNIT.