1986

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Proceedings of the Seventh Symposium

on

Coastal Sedimentology

4 April 1986

Memphis, Tennessee

Suite Statistics and Sediment History

Edited by William F. Tanner

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Tallahassee, Florida 32306-3026 U.S.A.

1986

ISBN: 0-938426-05-2

Sandy Estuarine Fill Transported into the Mouth of Chesapeake Bay

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Abstract

The landward flux of sand into an estuary is a process that is seldom documented or quantified, yet is important to the sedimentary dynamics of a maturing estuary. Data from three recent studies converge to demonstrate the transport of sand into Chesapeake Bay from the adjacent shelf. A 100-year sediment budget, distributions of heavy minerals, and seismic-reflection data all point to the bay mouth as a gate through which a significant quantity of sand enters the estuarine system.

Construction of a sediment budget that attempts to balance the mass of material deposited during the past century, as determined by bathymetric comparisons, with the quantity of material available from documentable sources (shoreline erosion and fluvial discharge) reveals that 6 to 20 times more sand has been deposited than those sources have provided. Most of this excess deposition occurs in the region dominated by bay-mouth processes.

Seismic-reflection data indicate that the bay-mouth sand bodies are part of a thick package of beds that dip into the estuary. This extensive package, more than 10 m thick, began to form several thousand years ago, as sea level approached its present position. Although it has built vertically in response to continued sea-level rise, its primary growth has been by progradation into the estuary.

Factor analysis of heavy mineral assemblages from the bay and adjacent shelf demonstrates a mixing of populations. Sample composition gradients indicate transport and sources

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Contribution 1309 of the Virginia Institute of Marine Science.

Tanner, W.F. (editor), 1986. Suite statistics and sediment history. Proceedings, Seventh Symposium on Coastal Sedimentology; Geology Department, Florida State University, Tallahassee, Fla. 32306-3026 U.S.A.

of sediment both in and out of the bay mouth. These analyses in the context of the seismic and budget data demonstrate a landward transport vector.

In sum, the combined studies describe a major process leading to the filling of a coastal-plain estuary, Chesapeake Bay.

Introduction

Estuaries are ephemeral features that blossom during periods of rising sea-level, fill with sediments, and die as sea level falls. The common assumptions are that most of the filling sediment is brought in by fluvial processess or is derived locally from erosion of the shore. Although some consideration is given to the influx of suspended material from the sea (Meade, 1969, 1972), except for Pilkey and Field (1972) and Roy and others (1980), there is little discussion of the upstream flux of coarser material through the mouth of an estuary. Our work indicates that a significant portion of the total quantity of the material deposited in a drowned-river, coastal-plain estuary enters through the mouth. As much as forty percent of the sediment that has been deposited within Chesapeake Bay during the past century may be sand that has been transported landward between the Virginia Capes. Using elements of a sediment budget for the bay, a study of the distribution of minerals near the bay's mouth, and shallow, seismic-reflection data, this paper will characterize the flux of sediment into the mouth of Chesapeake Bay so that it might serve as a partial model for the filling of other drowned-river estuaries.

Chesapeake Bay is a large drowned river-valley, coastal plain estuary that extends approximately 300 km from the mouth of the Susquehanna River to the Virginia Capes (fig. 1). The bay's drainage basin, which includes the Susquehanna, Potomac, James, and Rapahannock Rivers as major tributaries, has an area greater than 166,000 sq. km (Seitz, 1971). The bay, although varying in width from 5 to 56 km, is quite shallow; its average depth is 8.4 m (Cronin, 1971). Depths in the flooded channels, however, commonly reach 30 m and have a maximum greater than 40 m. Shoreline erosion is a significant process. Byrne and Anderson (1977) determined that the average rate of shoreline retreat in Virginia was 20 cm per year with some areas experiencing average losses as great as 3 m per year.

Chesapeake Bay has evolved as the rivers that cut into the shelf during the last Pleistocene low stand of sea level have been drowned by the Holocene rise in sea level. Marine waters probably reached the vicinity of the bay's present mouth in the bottoms of the narrow river valleys by 10,000 years B.P. when sea level was 15 to 20 m lower than today. As the local rate of sea-level rise slowed, about 3,000

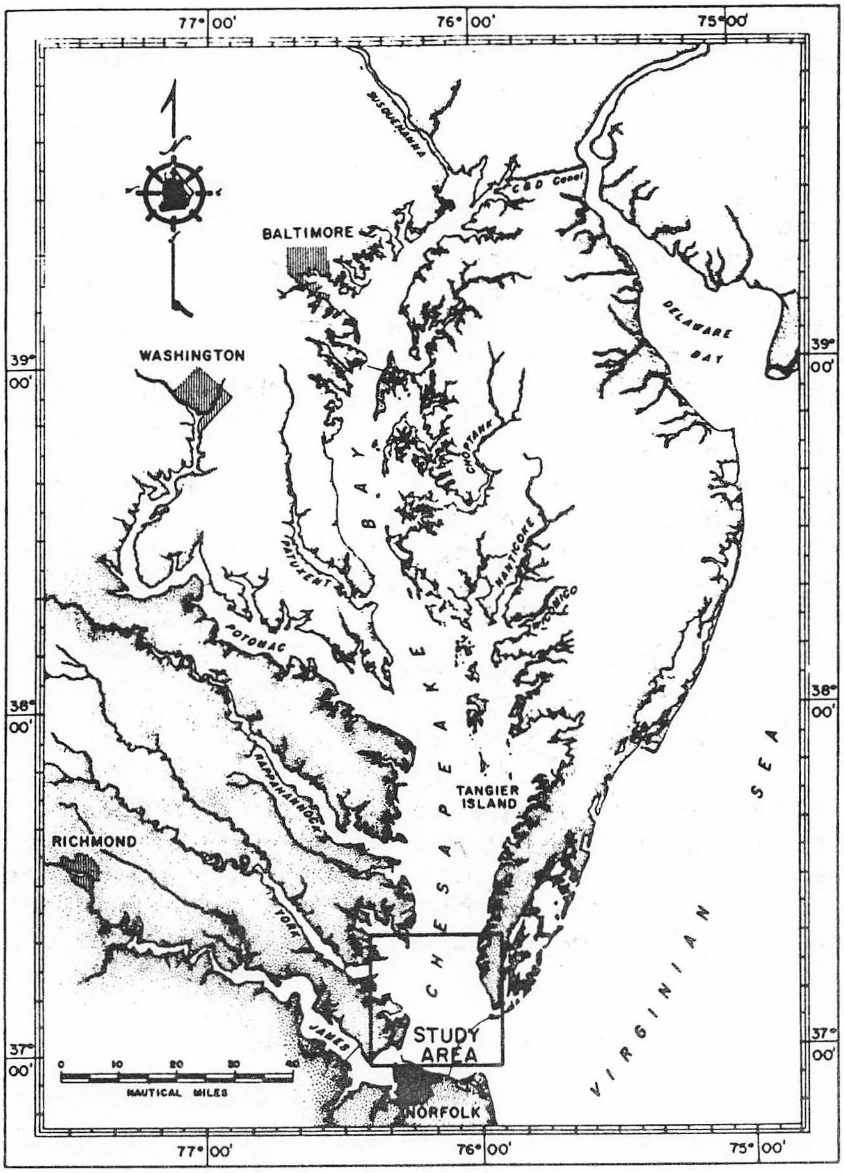

Figure 1. Map of sediment type according to Shepard's (1954) classification in the southern portion of Chesapeake Bay.

years ago (Newmand and Rusnak, 1965; Ellison and Nichols, 1976), the lateral rate of shoreline erosion increased (Rosen, 1976). Today, the deeper portions of the bay are the flooded river channels and the shallower margins are areas that have been eroded and/or flooded by a slowly rising sea. Thus, while sea level was rising rapidly, the estuary remained relatively narrow, confined to the former river channels, and the mouth moved upstream as the rising sea swiftly transgressed the gently sloping coastal plain. Since the rate of sea-level rise has slowed, the bay has become wider, through erosion and flooding, and the location of the bay's mouth has been more stable.

During the past 35 years, there have been many studies of Chesapeake Bay's modern sediments. Most are reviewed in Byrne and others (1982) and Kerhin and others (1983). Ryan's (1953) 200 sample reconnaissance study generally demonstrated that the bay's shallow margins are sandy and the deeper areas muddy. Shideler (1975) also used about 200 samples but from only the Virginia portion of the bay and further refined the interpretation of the bottom sediments. The combined studies of Byrne and others (1982) and Kerhin and others (1983) used over 5,000 samples from thoughout the bay to characterize the bottom sediments. This very large set of data provided much more detailed information on the distribution of sediment types within Chesapeake Bay and, thus, allowed better interpretations of the pathways of sediment movement within the system. These studies also determined that the bay's bottom is much sandier than previously had been thought, 57 percent by area being "sand" in Shepard's (1954) ternary classification or 66 percent being the sum of sand, silty sand, and clayey sand. The region of the bay's mouth is almost entirely sand(Fig. 2).

Sediment Budget

Taken together, Byrne and others (1982) and Kerhin and others (1983) have developed a sediment budget for the whole of Chesapeake Bay. These works attempt to balance the mass of material deposited during a 100-year period with the amount estimated to be available from numerous quantifiable sources.

The mass of material deposited was estimated from volumetric changes as determined by bathymetric comparisons. The chart-to-chart comparisons were made using the longest time interval between surveys available and normalized to 100 years. The work included appropriate adjustments for the shifts in latitude and longitude datums. The comparisons used the grid-point method of Sallenger and others (1975) which requires recasting the plotted depths on a new grid and averaging the depths within each cell of the grid. By subtracting the average water-depth in each recent cell from its older mate, the result is the simple change in water-depth, a measure of deposition or erosion. The data

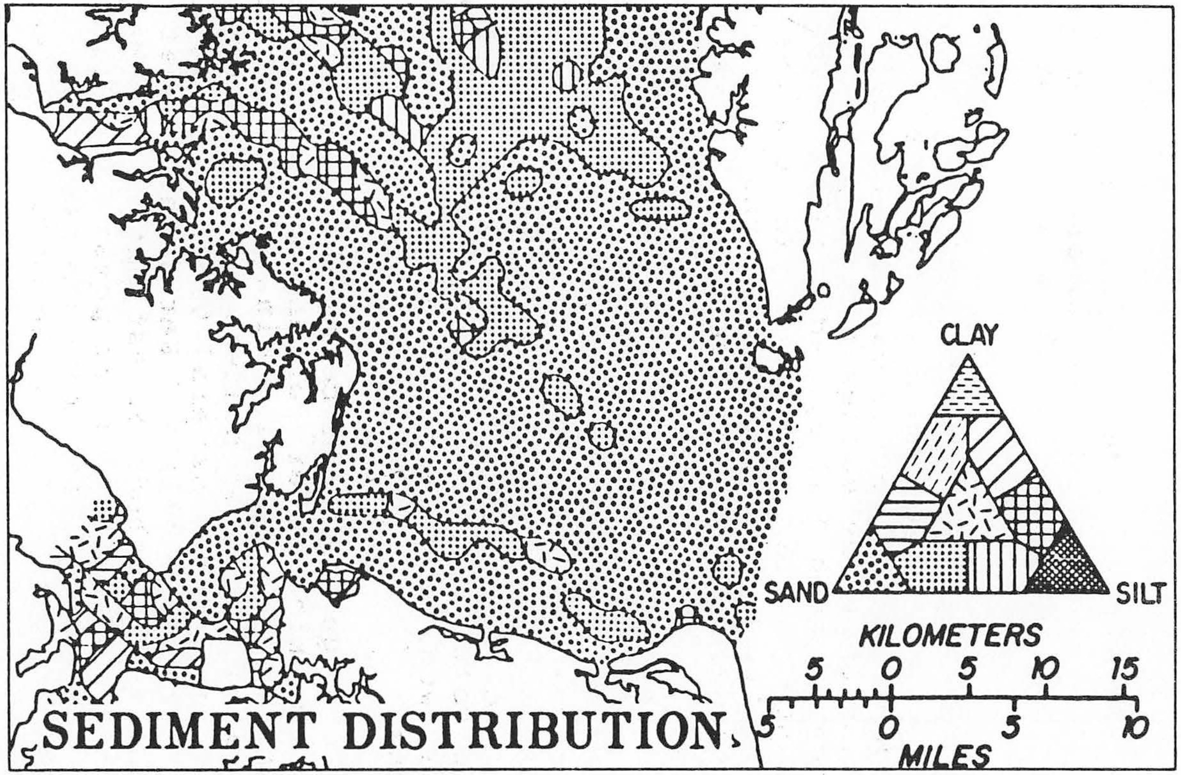

Figure 2. Map depicting the patterns and rates of deposition and erosion within the southern portion of Chesapeake Bay.

were corrected for the local rise of sea level. Data were interpolated or projected for those cells for which paired measurements were not available.

Obviously, the bathymetric comparisons incorporate and propagate the errors within the two surveys that are compared; in order to quantify the error embodied within the comparisons, Byrne and others (1982) examined the difference in depth values at crossing of lines of soundings on individual surveys from a subset of the comparative surveys and performed a statistical analysis of the combined, or pooled, errors. The standard deviation determined from the pooled variance of the comparisons of individual soundings at given locations is 0.57 m, with a 95% confidence interval about the measure of 1.1 m.

In order to indicate the magnitude of the potential error, the calculations of volume of change in the Virginia section were calculated, then the calculation was repeated using only the values of change where the difference was greater than 0.57 m, and finally using only the areas of change greater than 1.1 m. In the last two, changes less than the standard deviation and 95% confidence level were considered within the error band and were not included.

The calculation of volumetric change from the areas and changes in depths was relatively simple. Volumetric changes, however, do not provide a true measure, let alone comparable quantities, of erosion and deposition as they take no account of degree of compaction. The problem lies in the volume of the void spaces, the porosity. Although the volume would change with erosion and redeposition, the mass would not as the void spaces essentially are without mass.

In general, the conversion from volume to mass was made by equating water content with porosity and assuming a density for the solid mineral constituents (Hobbs, 1983). Data on the water content for the sediments were available for each of the several thousand surficial samples; Byrne and others (1982) and Kerhin and others (1983) developed empirical methods of estimating changes of water content with depth. Thus, it is possible to calculate an estimate of the mass of sediment deposited in Chesapeake Bay or a portion thereof during the nominal 100-year period.

The mass of sediment deposited is balanced by the sum of material available from the several measured or measurable sources, the Susquehanna River, shoreline erosion, and suspended sediment from the waters of the continental shelf.

Table 1 presents the net quantity of sediment broken down by sand,silt and clay deposited within Chesapeake Bay during a 100-year period ending in the mid-1950's. The total ranges between 2.9×10^9 and 1.0×10^9 metric tons

TABLE 1

NET DEPOSITION IN CHESAPEAKE BAY
Millions of Metric Tons per Century

Confidence Interval	Sand	Silt	Clay	Total
± 0	2,237.66	374.20	260.20	2,872.06
± 0.57 m	1,718.02	350.56	224.59	2,293.17
± 1.10 m	744.13	154.79	167.90	1,006.82

Bathymetric changes less than indicated by the confidence value were not included in the calculation of sedimentation in the Virginia portion of the Bay.

TABLE 2

SOURCES OF SEDIMENT SUPPLIES TO CHESAPEAKE BAY
Millions of Metric Tons per Century

Source	Sand	Mud	Total
Suspended sed. from Susquehanna R.[1]	--	107.0	107.0
Shoreline erosion, Maryland[1]	74.0	137.0	211.0
Shoreline erosion, Virginia[2,3]	40.0	2.5	42.5
Biogenic silica, Virginia[4]	--	0.8	0.8
Suspended sediment from ocean	--	22.0	22.0
Total	114.8	269.3	384.1

1. After Schubel and Carter, 1976
2. After Byrne and Anderson, 1977
3. After Byrne and others, 1982
4. After Jacobs, 1978

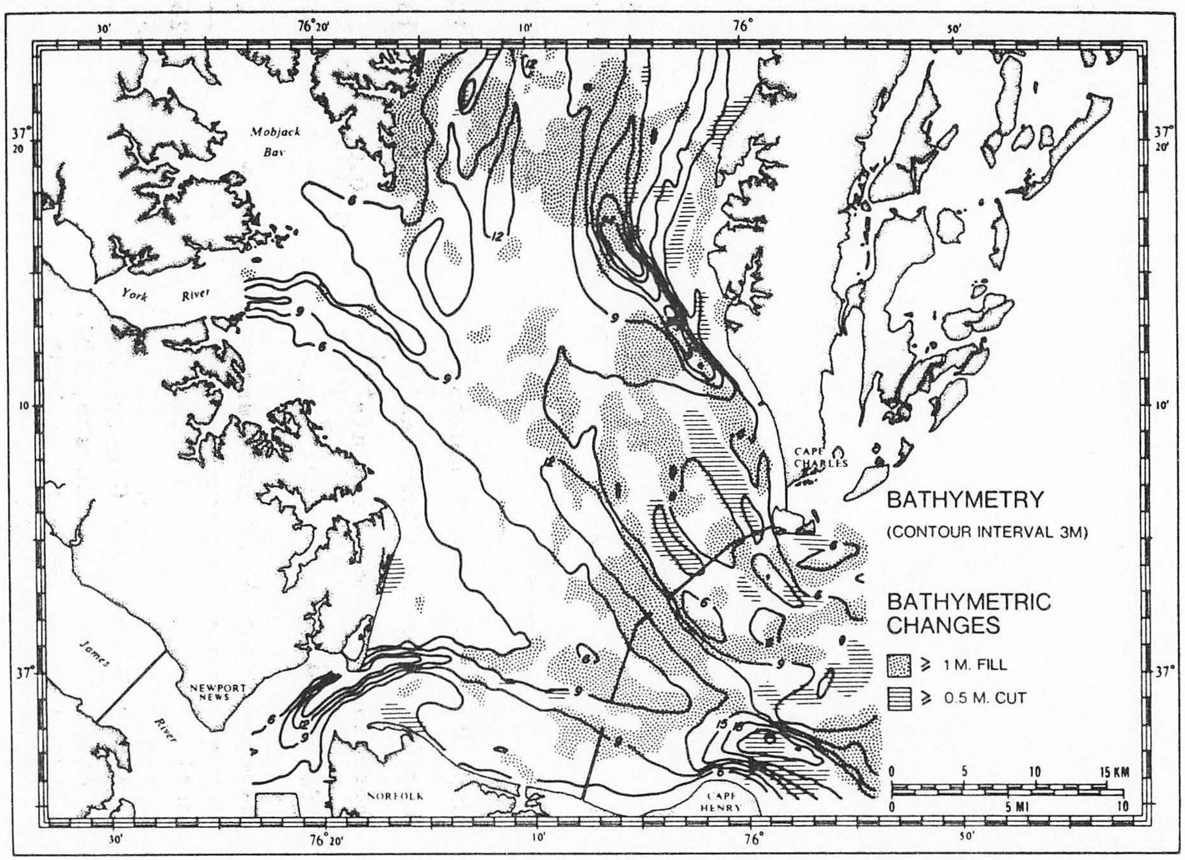

Figure 3. Map depicting the rate of deposition of sand in the southern portion of Chesapeake Bay; units in metric tons per square meter per century.

depending upon the confidence level of the measurement. Regardless of the specific measurement, approximately three-quarters of the sediment deposited was sand. Figure 3 depicts the rates of deposition across the southernmost portion of Chesapeake Bay.

The sum of the independently quantifiable sources (Table 2) accounts for only a seventh to a fourth of the deposited material (Table 3). Most of the discrepancy is in the sand fraction. Furthermore, as much as 40 percent of the deposition occurs south of the York River (Table 4, Fig. 4). The southern portion of Chesapeake Bay, although a significant depocenter, is not exclusively an area of deposition; there are several areas of non-deposition or erosion in the vicinity of the bay's mouth (Figs. 2 and 3).

What is the source of the unaccounted-for sand and what are other pathways and processes of transportation? As most of the sediment deposited in the southern sections of the bay is sand, it is logical to look outside the bay's mouth for a proximal source to explain the discrepancy between the quantified sources and the amount deposited. Furthermore, the patterns of deposition are suggestive of sediment moving into the bay through some of the channels and being distributed through much of the bay's southern portions. Indeed, Harrison and others (1967) recovered inside Chesapeake Bay bottom drifters that were deployed on the inner continental shelf. Many of the drifters were recovered north of the mouth of the York River, a few as far north as Tangier Island.

Seismic-Reflection Data

Seismic-reflection data were collected in October 1984, as part of a high-resolution survey of the entire main part of the bay (Fig. 5). The data were collected along east-west tracklines about 3 km apart and north-south tracklines about 7 km apart using an ORE Geopulse[1] system. The seismic signals were filtered between about 300 and 5000 Hz and were recorded at a one-quarter second sweep rate. Penetration into the subbottom sediments averaged 100m.

The seismic-reflection data indicate that the bay-mouth sand bodies are part of a thick package of beds that prograde or dip into the estuary. This package, here called the bay-mouth sand wedge, is bounded on the northeast by the Delmarva Peninsula and on the southwest by the Chesapeake Channel, the modern axial channel of the bay. Bayward, the deposit grades into estuarine sediments of Holocene age,

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[1]The use of trade name is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey, the Virginia Institute of Marine Science, or the Virginia Division of Mineral Resources.

TABLE 3

MULTIPLE OF TOTAL SOURCE (TABLE 2) REQUIRED TO YIELD TOTAL DEPOSITED (TABLE 1)

Confidence Interval	Sand	Mud	Total
± 0 m	19.5	2.3	7.5
± 0.57 m	15	2.1	6
± 1.1 m	6.5	1.2	2.6

TABLE 4

DEPOSITION IN THE SOUTHERN PORTION OF CHESAPEAKE BAY

A:

DEPOSITION SOUTH OF
Millions of Metric Tons per Century

Confidence Interval	37°16′	37°11′	37°06′	37°01′
± 0 m	1212.07	970.80	732.39	601.63
± 0.57 m	844.43	693.27	596.48	346.74
± 1.1 m	478.19	405.72	371.04	281.29

B:

DEPOSITION IN EACH EAST-WEST SEGMENT
Millions of Metric Tons per Century

Confidence Interval	37°16′-11′	11′-06′	06′-01′	south of 37°01′
± 0 m	241.27	238.41	130.76	601.63
± 0.57 m	151.15	96.79	249.74	346.74
± 1.1 m	72.47	34.68	89.78	281.26

C:

PERCENTAGE OF TOTAL DEPOSITION SOUTH OF

Confidence Interval	37°16′	37°11′	37°06′	37°01′
± 0 m	42	33	25	21
± 0.57 m	37	30	26	15
± 1.1 m	47	40	37	28

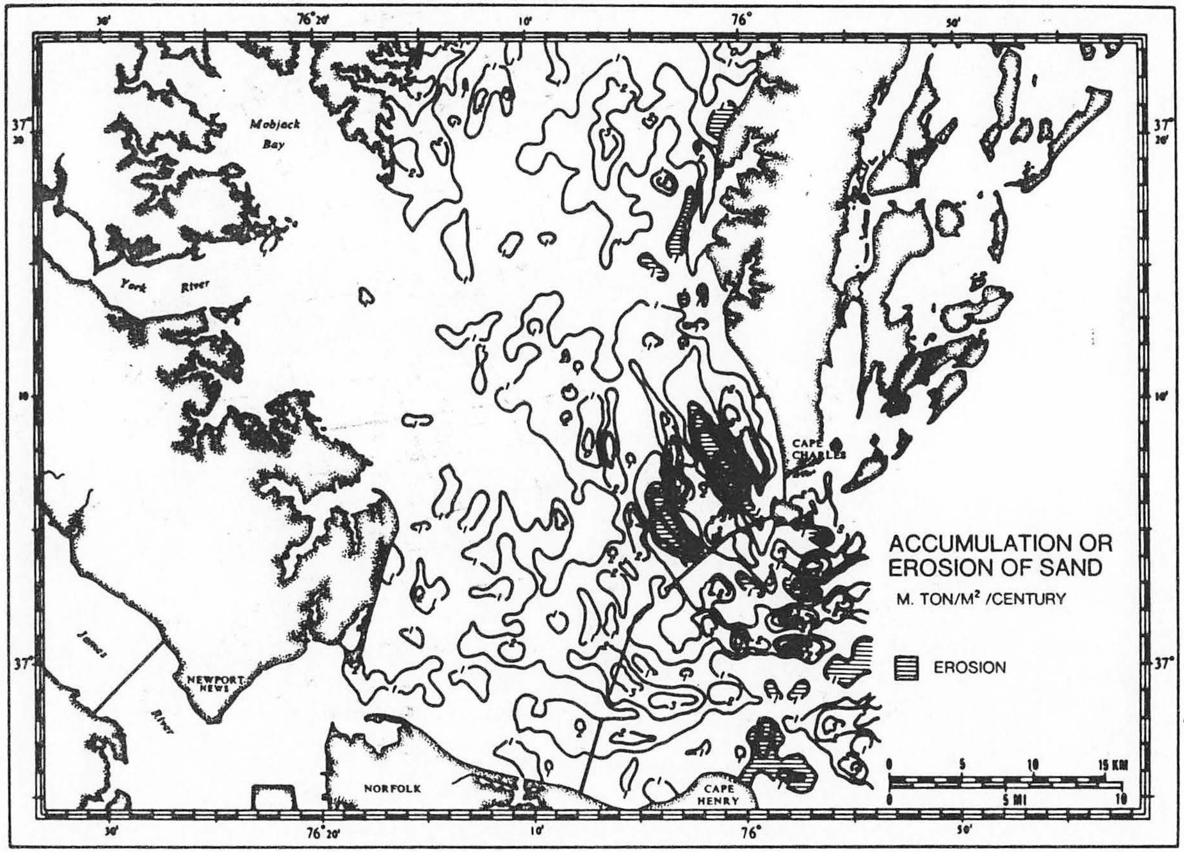

Figure 4. Map of the geophysical ("boomer") track lines run in October, 1984.

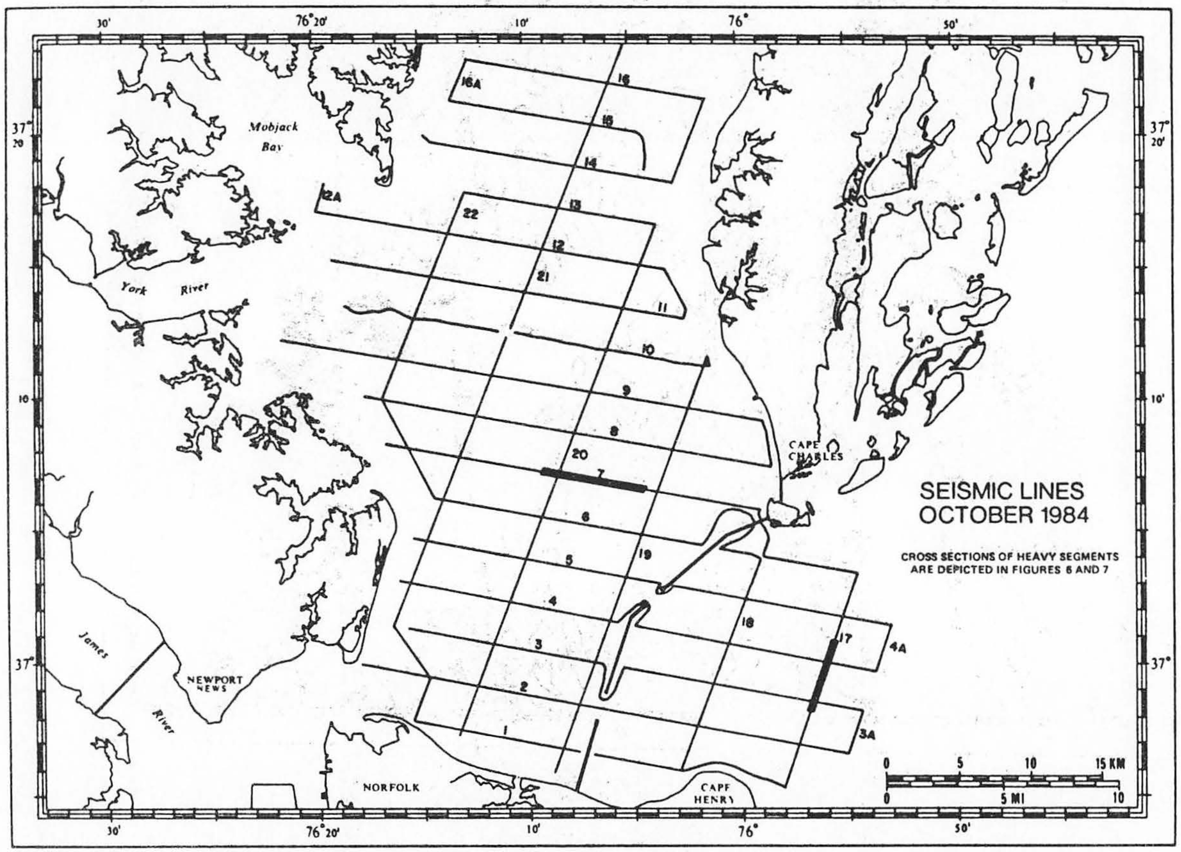

Figure 5. Bathymetry of the southern portion of Chesapeake Bay.

whereas seaward, it grades into the Holocene sand sheet on the inner continentl shelf. The surface of the bay mouth sand wedge in the bay entrance area is irregular and consists of alternating shoals 1-4 m below mean low water, discussed by Ludwick (1974), and tidal channels 10-15 m deep (Fig. 5). The surface becomes smooth and nearly planar inside the bay at a depth of 8-9 m. The base of the bay-mouth sand wedge is smooth and nearly planar thoughout most of its area, although locally it descends into partially filled late Pleistocene paleochannels. The base of the unit slopes slightly to the northeast, seaward, and from Chesapeake Channel toward the late Pleistocene fluvial paleochannel along the eastern margin of the bay. Its altitude ranges from about -18 to -32 m and averages about -25 m. The thickness of the bay-mouth sand wedge mirrors the pattern of the altitude of its base, so that the thickest parts of the unit occur at the entrance to the bay and near the late Pleistocene paleochannel. The thickness ranges from about 8 to 22 m and averages about 15 m.

Inside the bay's entrance, seismic-reflection profiles (Figs. 6 and 7) show that, to the north and east of Chesapeake Channel, the bay-mouth sand wedge overlies a planar, truncated surface cut on Tertiary marine sediments and upper Pleistocene channel-fill deposits, whereas to the south and west of the channel, only thin, bay-bottom sediments cover an irregular Tertiary surface. The modern axial channel of the bay is cut almost directly on Tertiary deposits. The bay-mouth sand wedge contains long, continuous, prograding reflectors that extend from near the base to near the surface of the deposit. These reflectors are sub-parallel to and dip toward the channel margin at low angles, generally less than 2^{o} (Figs. 6 and 7). Near the bay entrance, seismic profiles across the mouth of the bay (Fig. 7) show similar relations, especially the southward prograding reflectors in the bay-mouth sand wedge.

These relations indicate that the bay-mouth sand wedge and Chesapeake Channel are closely related. The channel apparently is actively migrating to the south and west, leaving a prograding wedge of sediment on an early planar surface in its wake. The modern channel has migrated from its former position over the late Pleistocene fluvial paleochannel along the eastern margin of the present bay to its modern axial position. The impetus for the channel migration and the source of sediments deposited in the wedge is primarily southerly longshore drift along the east shore of the Delmarva Peninsula. The sediment is brought into the bay by apparently landward (bayward) net transport. The morphology of the surface of the bay-mouth sand wedge (Fig. 5), the patterns of modern erosion and deposition (Fig. 2) (Byrne and others, 1982), and modern sediment transport (Ludwick, 1972, 1974, and 1975) in the bay-mouth area are all complex. The detailed surface morphology has been described as that of a series of small tidal deltas (Ludwick, 1975). However, the seismic data indicate that

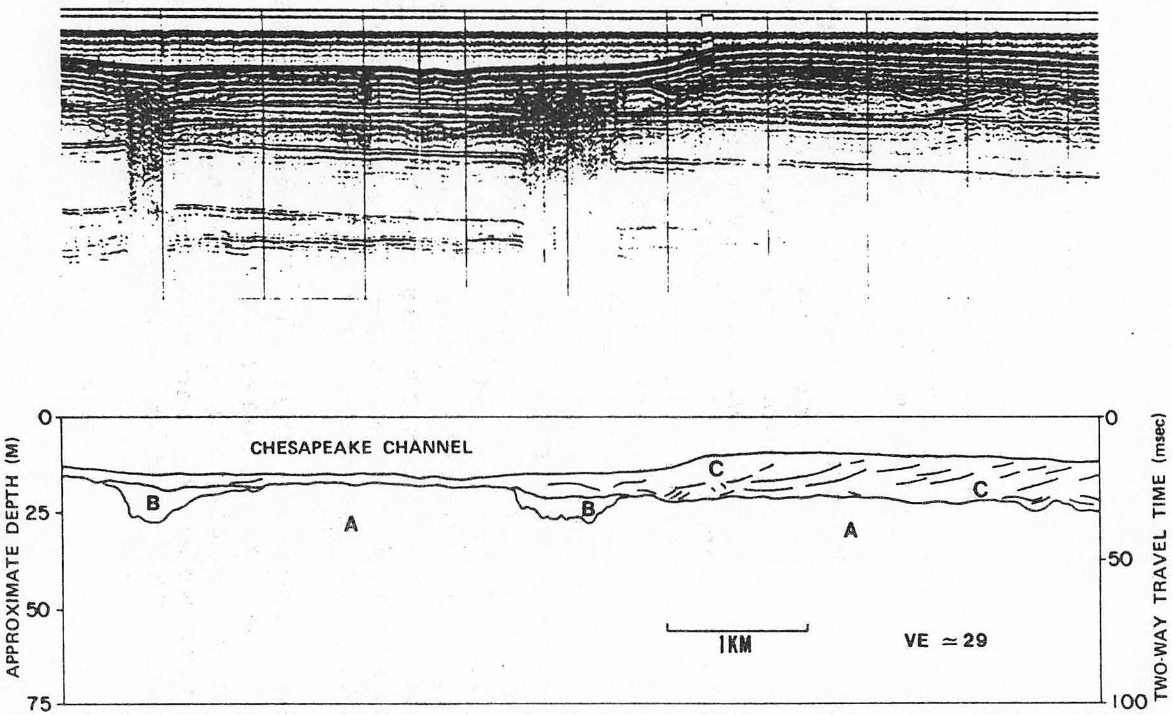

Figure 6. East-west seismic-reflection profile collected just inside the entrance to Chesapeake Bay and line drawing of the profile. A. marine deposits of Tertiary age; B. channel-fill deposits of late Quaternary age; C. bay-mouth sand wedge and coeval deposits of late Holocene age. Internal reflections are traced only for the bay-mouth sand wedge in the line drawing. [line 7, 1055-1147]

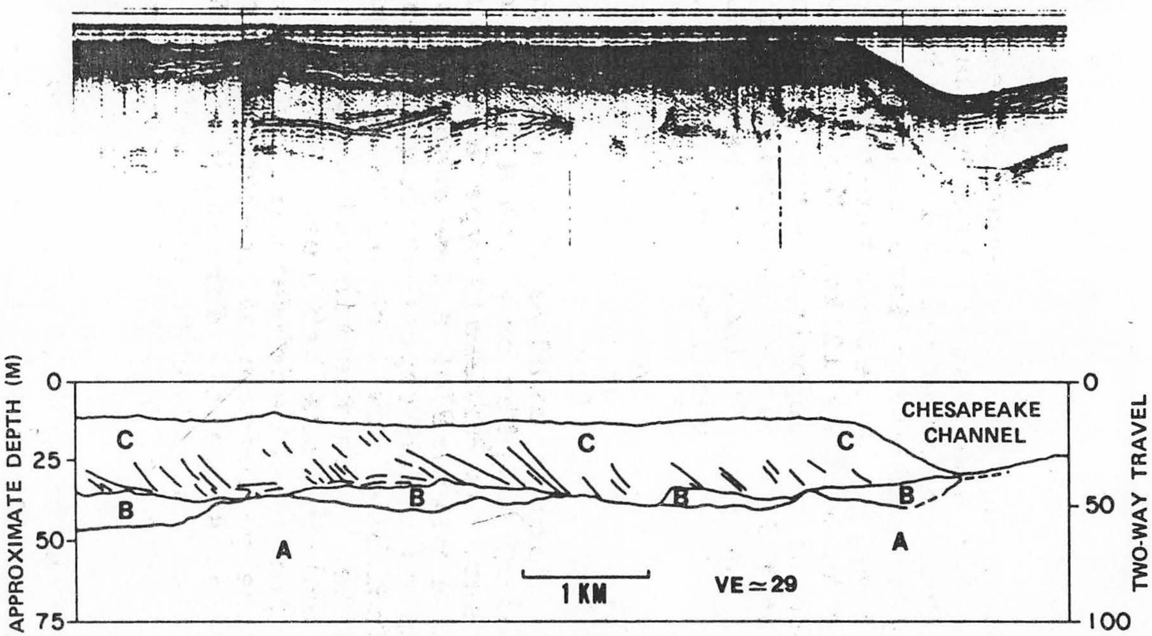

Figure 7. North-south seismic-reflection profile collected just seaward of the entrance to Chesapeake Bay and line drawing of the profile. Explanation as in Figure 6. [line 17, 1445-1545].

the deposit as a whole is a coherent, bayward-prograding sediment body.

Prograding structures within the bay-mouth sand wedge extend from near the surface to near the base of the unit. This observation indicates that much of the unit is related to present or near-present sea level and to a configuration of the bay similar to the present one. Additional information about the age of the bay-mouth sand wedge comes from microfossils in the deposit, which are related to present conditions in the area (Meisburger, 1972). Based on these data, we infer that the bulk of the bay-mouth sand wedge is less than a few thousand years old.

Thus, the age of the bay-mouth sand wedge and its structure indicate that both its deposition and the associated migration of the Chesapeake Channel from the late Wisconsin fluvial channel to its present position have occurred within the last few thousand years. Since it began to form, the bay-mouth sand wedge has built vertically in response to continued sea-level rise, but its main growth has been by progradation into the bay. Along with this growth, the main channel of the bay has migrated to the southwest by as much as 12 km. The processes affecting the upper surface of the deposit and the patterns of erosion and deposition at this surface are complex, but the geometry and structure of the deposit indicate that it is a coherent unit that is prograding bayward and tending to fill the estuary.

Heavy Minerals

Q-mode factor analysis can be used to describe a collection of samples on which a series of attributes or variables such as mineral type and abundance has been measured as a mixture of a few theoretical or real "end-member" samples which represent compositional extremes. The procedure indicates how much of each end-member is present in each sample. Once the mineral composition of a suitable number of end-members has been determined, composition gradients for each end-member can be established by contouring the percentage of the end-member in each sample. These patterns suggest a direction of sediment transport "down gradient" similar to the results of using tracer sediments (Imbrie and Van Andel, 1964; Flores and Shideler, 1978).

Firek and others (1977) used one-way analysis of variance between pairs of arbitrarily defined provinces and R-mode factor analysis on a data base of heavy-mineral compositions obtained from bottom grab samples in lower Chesapeake Bay.Based on the comparisons of minerals among the provinces in the bay and the combination of minerals composing each factor, they supported the notion of sediment transport into the bay from offshore as well as from erosion of surrounding land.

In a study designed to characterize massive sands in the bay, we used Q-mode factor analysis programs developed by Klovan and Imbrie (1971), Klovan and Miesch (1975) and Full and others (1981) on the original data of Firek (1975) and Firek and others (1977). Several analyses were made and some gave different results. First, all data were used (190 samples and 19 variables, or minerals) in 3-4-5 and 6-factor models. The 3-factor solution provided the most geologically reasonable model because end-members uniquely coincided with three of Firek's provinces. Solutions using additional factors partially duplicated the end-member suite of minerals and their locations in the provinces of the 3-factor solution. Plots of the composition loadings of samples on end-members showed geologically reasonable patterns: the gradient of garnet-hornblende composition decreased in the up-bay direcion and confirmed the idea of sand advection into the bay mouth from offshore; the gradient of clinopyroxene-hornblende was opposed to the first plot and probably represented the contribution of sediment from rivers or shoreline erosion; the third plot showed mixing of both factors. Unfortunately, the end-members were characterized by large negative compositions of minerals, so we sought a more realistic solution.

Principal component analysis of Firek's (1975) data using the programs from Davis (1973) determined that seven minerals (hornblende, zircon, garnet, clinopyroxene, sphene, epidote, and staurolite) out of the original 19 accounted for 96% of the variance in the entire set of data. Using only 8 variables (7 minerals and 1 "other", recalculated to constant row-sums of 100%) and 190 samples, we attempted several Q-mode factor solutions with similar results: duplication of provinces and negative end-member compositions. Because the sampled area was so large, there could have been more than 6 Q-mode factors (or sample end-members); a few samples could not be fully explained as a mixing in any proportion of the existing end-members thus suggesting the presence of an external end-member. Another analytical approach gave more realistic results. Using only 87 samples from the lower bay and a row-normalized composition of 7 minerals, a 3-factor solution gave large negative values of end-member compositions, but accounted for 97% of the total variance; a 4-factor solution gave more reasonable results because end-member compositions were essentially positive. Two of the 4-factor plots suggested the dilution of land or river material rich in staurolite and the introduction of hornblende-rich material from offshore and upper bay. These results are plausible because of the complex current structure shown by Ludwick's studies (Ludwick, 1972, 1975; Granat and Ludwick, 1980), and diverse sources in the lower bay area. The other factor plots were similar to those in the 3-factor solution. Figure 8 very clearly depicts the influx of sediment into the bay mouth from offshore. The type end-member sample is located off Cape Charles and is 27% hornblende and 72% garnet; this

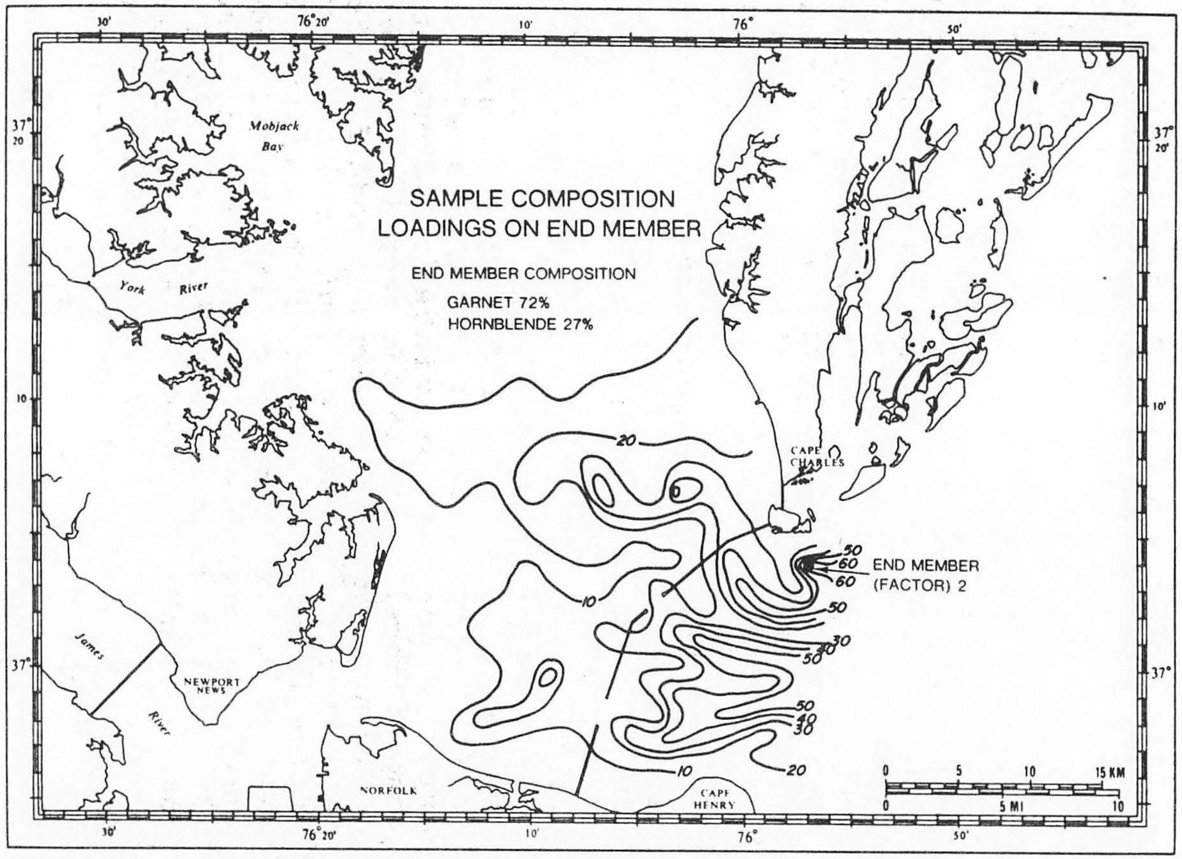

Figure 8. Map of the sample composition loadings on the garnet-hornblende end-member.

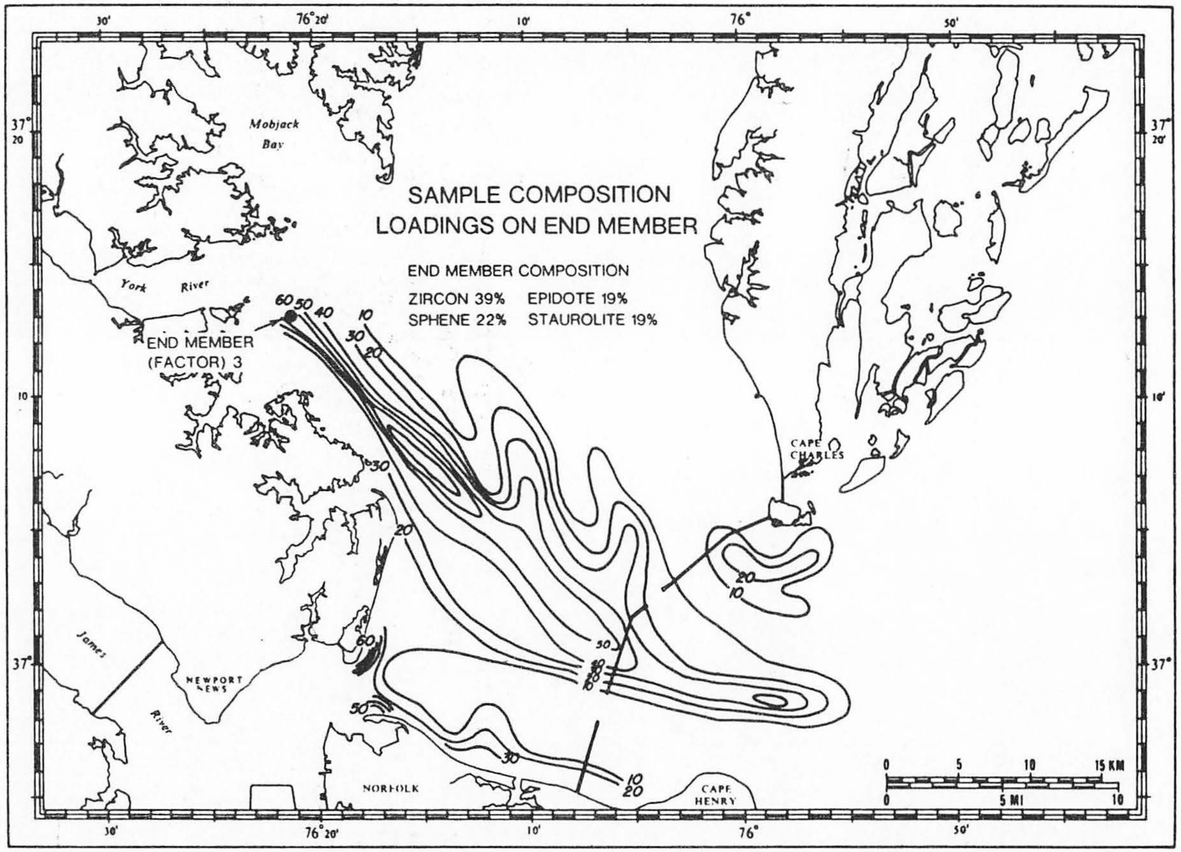

Figure 9. Map of the sample composition loadings on the zircon-sphene-epidote-staurolite end-member.

composition is similar to the mineral compositions on North Carolina's beaches and dunes (Giles and Pilkey, 1965). The existence of a zircon-rich region through the center of the lower bay (Fig. 9) warrants further study partly because heavy mineral data from the surrounding land and tributary estuaries is lacking. The high zircon composition with associated sphene, epidote, and staurolite suggests the combination of a present source composed of moderately young material with much older sediments being reworked by modern processes. Because of the duplication of patterns in a 3- and 4-factor solution with different data sets, we strongly believe that the gradients of mineral compositions substantiate transport processes in the lower bay area.

Summary and Conclusions

It is apparent from the patterns and rates of sediment accumulation and the distribution of sediment types in Chesapeake Bay that a substantial quantity of sandy sediment has entered the bay through its mouth. An analysis of the potential sources of sandy sediments and the quantity of sediment deposited during a 100-year period suggests that on the order of a third of the total quantity of sediment and a much greater portion of the sand deposited during that same period came into the bay from outside the Virginia Capes. This would place the system's depositional regime in a class midway between Rusnak's (1967) positive-filled and inverse-filled basin. The character of the bay's filling approaches that of Roy's and others (1980) Type III, Drowned River Valley modeled on the Broken bay, Port Jackson (Sydney Harbor), and Georges River (Botony Bay) systems in Australia.

Although both Rusnak (1967) and Roy and others (1980) fashion the accumulation of sands at an estuary's mouth as a simple, though perhaps extensive, flood-tide delta, the situation in Chesapeake Bay appears more intricate. However, this may be a function of scale, the mouth of Chesapeake Bay being an order of magnitude wider than Broken Bay's. Nichols and Biggs (1985) termed the region a flood tidal delta complex. The bottom drifter study of Harrison and others (1967) suggests the probable transportation of sand into the Chesapeake far beyond the morphological extent of the tidal-delta-equivalent bay mouth shoals. Also the factor analysis of heavy minerals and Fourier grain-shape analysis (Boon and Frisch, 1983) indicate that the bay mouth sand body contains a mixture of sediments and a strongly coherent pathway following the littoral-drift system around Cape Charles, into the bay, and then detaching from shore. Both sets of analyses describe a major contribution of sand to the bay from the southerly-directed longshore drift system that operates along the Atlantic shore of the Delmarva Peninsula.

Seismic reflection work demonstrates that the package of sediment being deposited in the lowermost portion of Chesapeake Bay is substantial, averaging 15 m in thickness. The bay mouth sand wedge is characterized by gently bayward dipping, prograding reflectors. No discrete sets of steeply dipping reflectors suggestive of tidal deltas were observed. The progradational wedge of sand forms a coherent body tht is advancing into the bay mouth from the ocean side of the Delmarva Peninsula.

Collectively, these several lines of evidence demonstrate that the up-estuary flux of sand into Chesapeake Bay is great. If considered a single source, the estuary's mouth is the largest individual source of sediments filling the main-stem depositional basin. Virtually none of these features or processes likely are unique to Chesapeake Bay. Thus the landward or up-estuary flux of sediment, particularly sands, into an estuary, through its mouth is a significant process that is most important in a maturing, filling estuary.

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