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FINAL REPORT

BASELINE SEDIMENT STUDIES TO DETERMINE DISTRIBUTION, PHYSICAL PROPERTIES, SEDIMENTATION BUDGETS AND RATES IN THE VIRGINIA PORTION OF THE CHESAPEAKE BAY

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ABSTRACT

The distribution of the physical properties, patterns of deposition and rates of accumulation of sediments provide an integrating framework for investigations of the concentration and distribution of toxic substances. Over 2,000 grab samples of surface-sediment (1.4 km grid) reveal that the bottom of the Virginia portion of Chesapeake Bay is significantly sandier than hitherto reported. About 65% of the area is sand. The number of samples in this study is an order to magnitude greater (2,000 versus 200) then previous studies allowing a significantly better delineation of sedimentary characteristics.

Distribution of sediment size is, in large part, a function of geomorphology, there being an apparently good correlation between depth and sediment type; the finer grained sediments are usually confined to the deeper channels. The exceptions to the depth:size relationship are the presence of fines in the shallow, marginal embayments such as Mobjack Bay and the absence of fines in the deep channel in the southeastern section of the Bay. The occurrence of sands here is a function of infilling with sands from the area of the Bay mouth and, perhaps, of scour into older (Pliocene?) materials. Sediment distribution also reflects the local source with the shallow-water, marginal sands derived from erosion of the banks and relict features.

Several large geomorphic features are distinguishable on the maps of sediment characteristics. These features include the deep channels, a large sand-shield near Tangier Island, relict spits, and the zone of influence of the Bay mouth.

Nine hundred samples, selected to avoid the coarser sands, were analyzed for total carbon, organic carbon, and sulfur contents. There are strong correlations between these characteristics and sediment type, especially weight-percent clay. Additionally, there is a good relationship between the organic carbon and sulfur contents. Although total carbon content reached 10% in some samples; the average was 1.5%. Average organic carbon and sulfur contents were 1.0 and 0.34%.

Comparisons of the bathymetry on boat sheets from the 1850's and 1950's were used to delineate the patterns and volumes of cut and fill in the Virginia portion of the Chesapeake Bay. The comparisons were adjusted for relative sea level change and monthly variations in mean tide level. In addition, propagation of the error was evaluated and the results applied. Coupled with the data concerning the character of the surface sediments and adjusted for water content, the volumes of sediment shown by the bathymetric changes to have been deposited were converted to the masses

of sand, silt, and clay deposited in a 100-year period. The patterns of deposition and erosion, particularly when coupled with grain-size information, provide very important insights into the sedimentation processes within the Bay. The main Bay-axial channel from Maryland and the transition to the Virginia basin are the principal deposition sites for clay. Silt-sized materials are somewhat more uniformly distributed throughout the stem; however, about 33% of the silt accumulates in the transition region, an area of relatively low tidal-current energy. The Bay mouth may be a principal source. The pattern of deposition of sand suggests that the Bay mouth source is very significant as very fine sands penetrate much further into the Bay than has heretofore been suspected. The patterns are consistent with present understanding of circulation within the Bay.

The project includes an attempt at constructing a sediment budget using published values for silt and clay estuarine advection and contributions from shore erosion measured against the bottom residual accumulations. The residual accumulation of silt and clay is an order of magnitude larger than previously estimated. No previous work has considered the sand budget but the general assumption has been that the contribution from shore erosion would be the principal source. This study indicates the residue bottom accumulation of sand is greater than the shore erosion contribution by a factor of 40. It is evident that additional understanding of the flux of sediment through the Bay mouth and the mouths flanking of the tributaries is required.

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ACKNOWLEDGEMENTS

In a project as large as this, it is impossible to credit even all the major contributors as authors. We thank the following individuals and acknowledge that the project could not have been completed without their labors. J. Zeigler wrote the section on the Geologic History of the Chesapeake Bay and was constantly available for discussion. P. Peebles wrote the section on the statistical comparison of the Rapid Sediment Analyzers. Additionally, she drafted most of the maps and figures and participated in several other program areas. O. Bricker, originally with the Maryland Geological Survey, later our E.P.A. Project Monitor, and now of the U.S. Geological Survey, provided much assistance and encouragement. R. Kerhin, J. Halka, and J. Hill of the Maryland Geological Survey assisted with technical development, inter-state coordination, and general discussion. C. Sutton and D. Owen did much of the computer work. G. Thomas, L. Morgan, D. Owen, S. Fenstermacher, K. Worrell, J. Cumbee, S. Synder, M. Mitchell, A. Frisch, K. Farrell, and G. Chianakas collected the samples. W. Athearn did much of the early logistical work. G. Pongonis and D. Ward, Captain and Mate of the R/V Captain John Smith, provided encouragement, assistance, and excellent service under often trying circumstances. A. Haywood, E. Travelstead, C. Fischler, M. Mitchell, L. Zellmer, R. Bowles, G. Chianakas, C. Lukin, M. Fedosh, B. Savage, H. Byrne, and B. Comyns did laboratory analyses and data reduction. L. Kilch assisted with the quality assurance program for carbon and sulfur analyses. J. Boon provided guidance and discussion on error analysis. M. Nichols and B. Nelson provided valuable assistance and discussion. B. Marshall, C. Gaskins, and the staff of the V.I.M.S. Word Processing Center prepared the various drafts. J. Gilley drafted some of the maps and figures. O. Bricker, C. Strobel, J. Klein, and D. Wilding, among others at E.P.A., assisted with technical coordination. The Chesapeake Bay Program, U.S. Environmental Protection Agency funded the program.

I

INTRODUCTION

The basic reason for the study of the physical characteristics of the bottom sediments of the Chesapeake Bay is that the sediment is the locus of interaction between toxic substances that have been introduced into the Bay system and the biological communities that use the same system. Whether the biological elements make permanent use of the Bay by residing in it, or temporary use through migration or seasonal habitation, they all are to some extent dependent on the sediments and the sediment-formed strata which form the physical structure over and through which the biota are distributed. If, as often has been postulated, there are discrete relationships between the substances of concern and specific types of sediment, knowledge of the sediments is critical to the understanding of the toxic substances problem. Thus, the first objective was to discern the sedimentological characteristics of the bottom sediment at a sufficient sample density so that reasonable interpolations may be made from a sample subset which is analyzed for various toxic substances and other related parameters.

Other tasks within the Environmental Protection Agency's Chesapeake Bay Program are concerned with the transport and transformation of toxic substances and upon the recent sedimentation history of the Bay. A very important element in the analyses of these problems are detailed maps of the characterization of the surface sediments. Thus, a second objective was to supply maps of the characteristics of the bottom sediments to support interpretations made in other phases of the EPA-Chesapeake Bay Program, specifically those phases dealing with the transportation of materials and with the history of recent sedimentation.

As one of the long term goals of the entire Chesapeake Bay Program is to develop a system by which changes in the status of the Bay could be monitored, a third objective of this project was to provide a comprehensive statement of the "condition" of the bottom sediments of the Virginia portion of the Chesapeake Bay against which future sediment samples and characteristics could be compared.

Similarly, the study of sedimentation budgets and rates benefits both the theoretical and practical understanding of the Bay's workings. Areas of deposition might be expected to be reservoirs of existing or potential pollutants which are related to the sediment. Areas of bottom erosion would be very poor sites for disposal of dredged materials.

Thus the objectives of Sediment Budgets and Rates subtask were

1. to identify the principal sites of deposition in the Virginia portion of the Bay,
2. to establish sedimentation rate as a function of position in the Virginia portion of the Bay, and
3. to formulate a sediment budget for the Virginia portion of the Bay which incorporates the sedimentation rates from 2 and available estimates of sediment supply from the tributaries of the Bay, the ocean, and from shoreline erosion.

The attainment of the objectives of both subtasks should be of benefit in making management decisions concerning the fate of the entire Chesapeake Bay. This study was integrated with a similar study in the Maryland portion of the Bay conducted by the Maryland Geological Survey, thus compatible Bay-wide data will be available to those persons making interpretations and decisions affecting the region. An equally important product of the project(s) is information leading to further basic research problems which will augment the ultimate thrust of the EPA-Chesapeake Bay Program and the general understanding of estuaries.

This report is organized with separate, generally complete discussions of the sedimentology of the Virginia portion of the Bay and of the volumetric cut and fill within that area. The discussion of the overall sediment budget draws the sedimentology together with the volumetric changes in the quantity of the surface sediment and additional information in an attempt to determine and to rank the various sediment sources. The several large sets of data which were created during the life of the project and which were used in the intrepretations are included as separate appendices or are available from Virginia's State Water Control Board and its files in E.P.A.'s STORET data system.

II

CONCLUSIONS

1.) The bottom sediments of the Virginia portion of the Chesapeake Bay are significantly sandier than has been previously reported. The difference is attributed to the much higher sampling density used in this study rather than to gross changes in sediment characteristics through time. However, there are locations where transitions may have occurred during extreme events.

The high sampling density disclosed that grain-size gradients are very steep in the transverse sections, generally a reflection of bathymetry. The very fine grained sediments (mud) are generally restricted to the deeper channels or the lower energy environments associated with shallow, marginal embayments. The principal floor areas with mud sediments are the axial channel and basin between the Potomac and Rappahannock tributary estuaries. In addition the channels leading to the James and York tributaries are mud as are the entrance channels and basins of the embayments of Mobjack, and Pocomoke, and Tangier Sounds.

This study corroborates the strong correlations between total carbon, organic carbon, and sulfur content of the sediment and the weight-percent clay as previously has been found.

2.) The patterns of deposition and erosion, calculated by comparing bathymetric data of the 1850's with that of the 1950's, provide very important insights into the sedimentation processes within the Bay, particularly when coupled with grain-size information. The deposition patterns suggest that there is appreciable advection of fine sand from the Bay-mouth region to at least thirty-five kilometers up the Bay. This is represented by significant fine-sand and silt deposition in the Wolf Trap Light region. This locus of deposition is argued to occur as a consequence of net up-Bay estuarine circulation through the deep channel along the Eastern Shore (Cape Charles Deep) mediated by the relatively strong tidal current energies. As well, the contribution of fine and very fine sand to the broad central basin north of this region is most reasonably attributable to a Bay mouth source. Thus, the Bay mouth <u>may</u> contribute very fine sand to as far north as the latitude of the Rappahannock River entrance.

The immediate Bay mouth region, known to be a zone of active bedload movement, is characterized by a pattern of "alternating" erosion and deposition areas as expressed by slowly shifting shoals and intershoal deeps. This pattern is consistent with earlier studies of individual components of the system.

The second region of particular interest is the transition area between Potomac and Rappahannock tributaries. This region contains the junction of the deep axial channel leading from Maryland waters which flares into the central basin of the Virginia Bay, and the junction of the channels leading to Tangier and Pocomoke Sounds. The main axial channel and the channel system of the Sounds are separated by the sand shield containing Tangier and Smith Islands. The western and southern fringes of the sand shield exhibit appreciable deposition. This is attributed to sand encroachment over the "edge" of the shield induced by net down-bay circulation of the surface water layer augmented by wind drift currents and wave driven resuspension accompanying strong north and northwest winds, a dominant component in fall and winter.

The main Bay axial channel from Maryland and the transition to the Virginia basin is the principal deposition site for clay in the Virginia portion of the Bay. The clay/silt deposition area is pronounced where the axial channel flares in cross-section leading into the broad central basin. Approximately 50% of the total clay accumulation in the Virginia Bay occurs between the Potomac and Rappahannock tributaries. Silt-sized materials are somewhat more uniformly distributed throughout the stem; however, about 33% of the silt accumulates in this transition region, an area of relatively low tidal-current energy.

The distribution of the fractional accumulations of sand, silt and clay suggest that the principal clay sources are from the northern Bay followed by the Bay mouth, that the principal sources of silt are the Bay mouth followed by the northern Bay, and that the Bay mouth is the principal sand source.

3.) The estimates of a sediment budget were constructed for the Virginia portion of the Bay using measured values for the contribution from shore erosion and residual bottom accumulation, and literature values for silt and clay importation from Maryland waters. The residual bottom accumulation of silt and clay exceeds the values from the estimated sources by a factor of 12. The measured values of the silt and clay contribution from shore erosion are an order of magnitude less than previously estimated. Bottom accumulation of sand exceeds that contributed from shore erosion by a factor of 40.

Previous attempts at constructing a sediment budget have dealt solely with suspended sediments and with shore erosion as the sole contributor of sand. The patterns of deposition and the magnitudes of the sand accumulation clearly indicate that there is a strong advection of nearshore sands into the Bay mouth and up the Bay stem. Previous estimates of the sediment budget using only the suspended component have concluded, using salt budget arguments, that the tributaries are sinks for materials transported from the Bay. If indeed the tributaries are sinks for materials transported from the Bay, then the apparent discrepancies between bottom accumulation and the previous estimates of source strength are enlarged. If the tributaries are sources rather than sinks, and if the Bay mouth is a stronger source than hitherto estimated, then the order of magnitude discrepancy for silt and clay accumulation would be reduced.

III

RECOMMENDATIONS

A. MANAGEMENT RECOMMENDATIONS.

The parameters addressed in this report are not amenable to control by environmental management agencies. Rather, this study has provided baseline information on the character of the sediments of the Bay stem, an identification of the patterns of deposition with an interpretation of the transporting agents involved, and, finally, an attempt at balancing the residual sediment accumulation on the Bay floor with potential sources. However, this does not mean the information portrayed is without utility to management agencies. Quite the contrary, these results form a foundation from which many management decisions will be founded when used in conjunction with other components of the EPA/Bay Program. In particular, the integration of the results of grain-size patterns and bottom mass accumulation patterns will allow determination of the spatial accumulation of trace metals and toxic organic compounds and estimates of their mass accumulation.

In addition, the results of this study, when coupled with other components of the EPA/Bay Program, should appreciably improve the management of the disposal of dredged material.

Heretofore, the selection of sites for the disposal of dredge material within the Bay stem has been made on economic considerations and on very scanty information concerning the environmental character and operative processes. As a result of the EPA/Bay Program, several very important elements may be integrated to choose disposal sites:

1.) The patterns of deposition may be used to identify areas of natural accumulation and therein sites where the dredged materials are likely to be relatively stable.

2.) The bottom-sediment grain-size information may be compared with that expected for the dredged material and the sites may then be evaluated as to whether the benthic community colonizing the disposal area have greater or lesser resource values.

3.) The expected tidal currents and residual circulation at the potential sites may be estimated from the finite element hydrodynamic model generated in the Eutrophication Program. When the aforementioned elements are combined with bottom slope, salinity, water depth and expected wave energy, potential disposal sites may be ranked relative to expected short and long term stability, and whether the areas, when recolonized, are likely to have an altered benthic community as well as their relative resource value.

B. RESEARCH NEEDS

1.) It is evident that considerable additional study is needed to gain improvements in construction of a sediment budget. In particular, research must be focused on the question of the flux suspended sediment through the mouths of the major tributary estuaries with emphasis on fate of materials discharged from the Potomac and the Rappahannock. The results reported herein suggest that the Bay mouth may be a strong source for silt as well as fine sand; further study is needed to evaluate the strength of this source.

2.) To date there have been three major studies on the grain size characteristics of bottom sediments of the Virginia portion of the Bay stem. This report provides a comparison of these studies with a resulting interpretation that the gross patterns are generally invariant with time. Since the previous studies utilized very sparse sampling densities, additional periodic sampling at a subset of the grid sites sampled in this study should be undertaken to test the hypothesis that the patterns are stable. Since it is the reservoir characteristics of the fine-grained sediment are of principal interest, the subset of stations should be focused in the areas of primarily fine-grained sediments.

Particular attention is warranted on flood events as deposition of fine-grained sediments may be more widespread during these events. If such widespread deposition does occur, then follow-on sampling should be conducted to investigate the fate of the "thin" layer. The object would be to determine how much of the material is "folded" into the sediment column by bioturbation and how much is simply resuspended and advected into the principal regions of deposition of muddy sediments.

3.) The interpretation of patterns of deposition and associated grain-size characteristics has been based upon heuristic arguments about estuarine circulation and dominant pathways of flow. Such interpretation is tenuous until tested with a comprehensive set of measurements of the vertical distribution of currents and density. An important contribution toward that goal will be met through the ongoing study of circulation in Bay conducted by NOAA/NOS. Analysis of this data set will provide the framework to test the interpretation of the gross patterns. As well, it will provide the background necessary to design further specific studies of particulate resuspension and transportation in the various subareas.

IV

BACKGROUND OF THE STUDY

The main stem of the Bay and its tributary estuaries form a system; the physical characteristics of the system have evolved through time with the current circumstances representative of conditions only slowly changing over the last two or three thousand years. As viewed today the system represents a trap for sediments entering the system from the fluvial drainage and, as well, for materials entering the mouth of the Bay by an impressed estuarine circulation.

It is important that the management strategies formulated for the Bay incorporate the realization of a naturally changing system. The purpose of this chapter is to review the geologic history of the Bay region and to review the status of understanding of its sedimentological characteristics prior to this study.

A. GEOLOGIC HISTORY OF THE CHESAPEAKE BAY REGION

The geologic history of the Chesapeake Bay spans time scales that differ by orders of magnitude. The region is related to happenings hundreds of million years ago and to modern sedimentation that sometimes is governed by man-induced changes that occur within a decade. Nevertheless, the parts can be fitted into a single, internally consistent narrative.

Five to six hundred million years ago North America consisted only of a low continent centered around what is now Hudsons Bay. The shoreline ran approximately through the present day Great Lakes and southern Ontario. The region that was to become the Chesapeake Bay lay hundreds of miles offshore near the edge of the continental shelf where thick sequences of muds and sands were being deposited (Hallam, 1974).

While this was taking place the continents of North America, Africa, and Europe were drifting together. By the end of Permian time, approximately 225 million years ago, the continents had been forced together. The sediments caught between these huge plates were folded, faulted, and metamorphosed into the schists, gneisses, slates, and other crystalline rocks which now form the Piedmont and on which the coastal plain sediments have since been deposited.

The collision was to be temporary, for during the Triassic the continents began to drift apart. Huge faults cracked the continental edges dropping blocks of the continental downward to form enormous rift valleys, similar to those in east Africa today, where the same process is taking place. Sediments worn from the mountains, lava flows and ash poured into the basins and, in some cases such as the basin which had formed near what is now Richmond, coal swamps formed. These deposits, stacked in their ancient valleys, are the Triassic "red beds" which can be found in basins from the Maritime Provinces and New England to the Carolinas.

Ultimately the cracks between continents widened and the sea invaded to form the beginning of the Atlantic Ocean. Rivers from the Appalachian regions spread fresh water deposits over the low area at the continental edge. These are the non-marine sands and silts of the Potomac Group of Cretaceous age.

The widening continued. Local and regional uplifting and downwarping took place as the continent adjusted to new loads of sediment and to forces associated with continental drift. The sea inundated the area of the mid-Atlantic states with the result that the non-marine sediments of the Cretaceous grade upward into the younger marine late Cretaceous and early Tertiary materials from about 65 million years to perhaps 25 million years age.

As formations of early Miocene age are missing, we infer that the sea must have withdrawn until about the middle Miocene, perhaps 15 to 18 million years ago, after which time the sea returned and layers of marine sands, sandy clays, clays, and shell beds were deposited as the Chesapeake Group (Calvert, Choptank, St. Marys, and Yorktown formations of Miocene-Pliocene age). This continued until perhaps 2 million years before the present.

It is during this middle Miocene-Pliocene episode that the broad outlines of the Chesapeake Bay are thought to have formed. Stephenson, Cooke, and Mansfield (1933) pointed out that uplift took place during Calvert time beginning in, or north of, Maryland, and spread southward until the seas of Yorktown time receded. Contemporaneously with the tipping-off of the seas, sands and gravels poured from the Delaware, Susquehanna, and Potomac Rivers over the newly emerged coastal plain, forming the land mass of what is now New Jersey and the Eastern-Shore of Maryland, and Delaware. The rivers themselves adjusted their courses around the sands and gravels, the Delaware ultimately flowing between the coarse outwash plains of New Jersey and Maryland-Delaware, and the Susquehanna and Potomac into the basin between the Maryland Eastern Shore and the eroded uplands of the western shore.

We have sketched a history which shows that the basin which was to become the Chesapeake Bay had formed before the Pleistocene and extended at least as far seaward as the last Pliocene sea. The Virginia's Eastern Shore, the lower portion of the Delmarva Peninsula, had not yet formed.

This brings us to the most recent geologic acts which formed the Bay; namely, the glacially induced sea-level changes of the Pleistocene. The Chesapeake Bay fills a broad, shallow valley which was cut, or in our opinion modified, by Pleistocene rivers during multiple lowered sea levels and subsequently flooded by the rise of the sea during the past ten thousand years to produce the modern Bay. This clearly seems to have happened. However, the complete story is more complicated.

In general, sea level remained reasonably close to present sea level between 2 x 10^6 and 1.5 x 10^6 years ago when a very high stand approximately 30 meters (100 feet) above the present occurred. This elevation coincides with that of the Surry Scarp, a prominent geomorphic feature in Virginia's coastal plain. Following that very high stand, the sea was close to or slightly above the present level for the next 500,000 years. Belknap and Wehmiller (1980) believe the core of lower Delmarva formed during this million years between 2 x 10^6 and 1 x 10^6 years B.P. If this be true, then the basin enclosing the Chesapeake Bay was virtually formed and was filled with marine water to approximately its modern shores by about 1 million years ago. Figure 1 is a composite of sea-level changes based upon the work of Shackelton an Opdyke (1973) and van Donk (1976), as modified by Zellmer (1979).

It is not the purpose of this paper to attempt to unravel the details of these multiple lowerings except in a general way. However it is clear that when sea level was so low that the entire Bay was drained, the basin must have been occupied by rivers in deep channels. Each time sea level rose above these channel margins the rivers were essentially lifted out of their channels. When sea level dropped the rivers did not necessarily settle back into their old channels but to one side or the other, except where the basin was narrow.

The evidence for this is widespread. Schubel and Zabawa (1972, 1973) reported a major buried channel they took to be an old channel of the Susquehanna which connects the lower reaches of the Chester, Miles, and Choptank estuaries. Drilling and seismic studies connected with construction of the Bay-mouth bridge-tunnel reported by Harrison et al. (1965) showed three large buried channels. Later a cross-section of the bridge-tunnel crossing was refined and presented by Meisburger (1972). Carron (1979) presented a map showing his interpretation of the old drainage lines (Figure 2). Inasmuch as our main interest is in the most recent or Holocene blanket of sediment, we need not concern ourselves with unravelling the drainage network of the Pleistocene unless in some way it impacts modern sedimentation.

A knowledge of the most recent rise of sea level is an important tool in the understanding of the Holocene sedimentation. Approximately 17,500 years ago the shoreline of the Atlantic Ocean was about 100 km (65 miles) east of the Chesapeake Bay mouth along the break in slope of the continental shelf. Sea level was approximately 100 meters (300 feet) below the present level. Much of the shelf was dry land or swamp over which the river systems draining the Bay area spread sand and gravels. The basin of the Bay was traversed by rivers confined within their valleys.

If we accept the erosion-deposition model of river activity by Jordan (1974), the height of the glacial advance would have been a time of river stability with a tendency for deposition as the glacial age began to end.

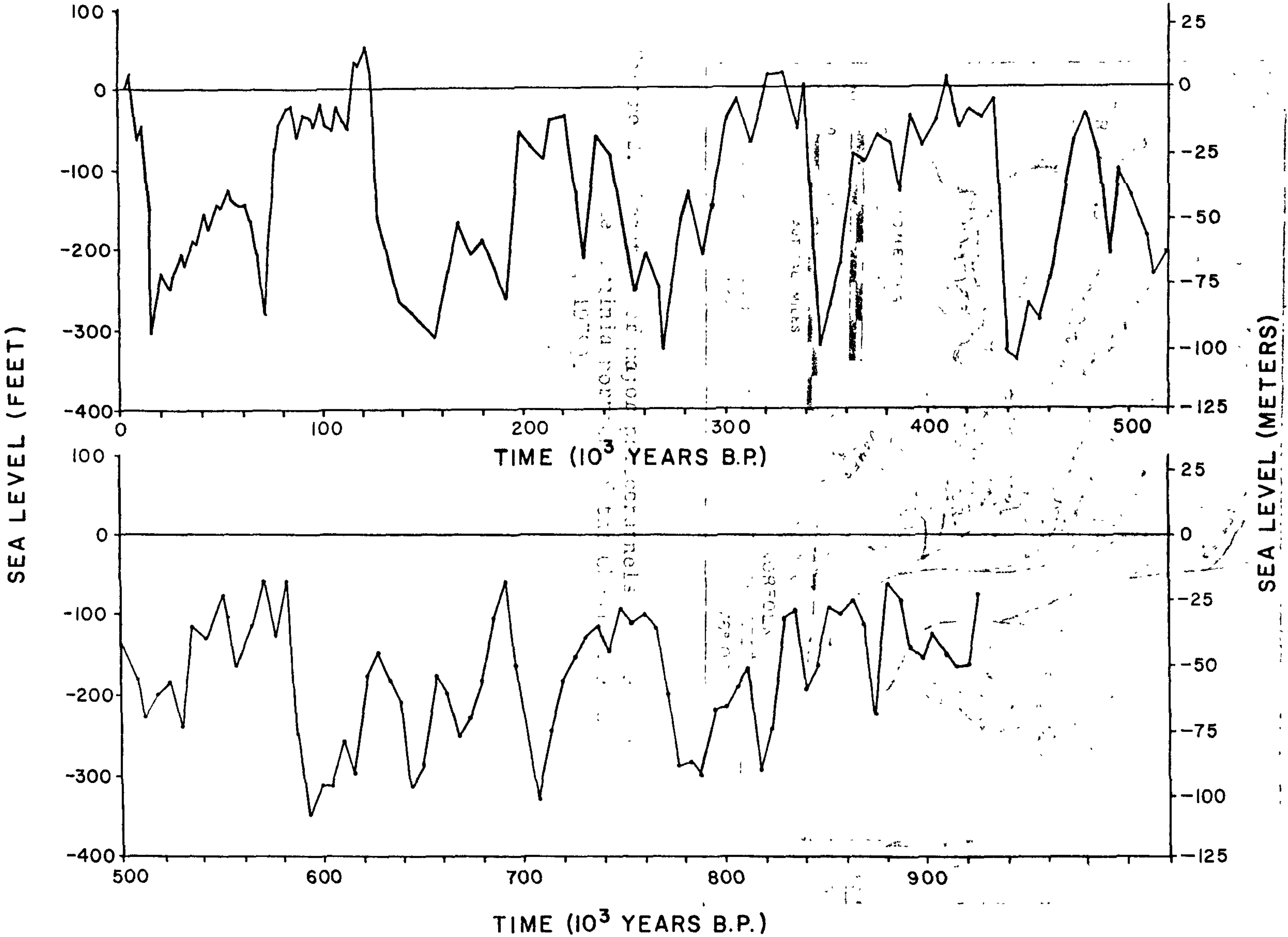


Figure 1. A plot of sea-level fluctuations during the Quaternary (from Zellmer, 1979).

Sea level rose approximately 80 meters (250 feet) in the first 7500 years of deglaciation (17,500-10,000 B.P.), or 1 meter (3.3 feet) per century (Shackleton and Updyke, 1973). The Bay would have started to flood at a sea level of minus 15 meters (50 feet) and sediments would have begun to fill the old channels rapidly. Although the rate of rise of sea level slowed during the next 6500 years, from 10,000 B.P. to 3500 years B.P., it still rose approximately 12 meters (40 feet), or about 18 cm (0.6 feet) per century. The Bay 3500 years ago must have been very nearly the size it is today. Sea level at that time was about 3 meters (10 feet) below the present. Sea level has risen at an average rate of only 10 cm (0.3 feet) per century in the past 3500 years (Newman and Rusnack, 1965).

It is perhaps self-evident that the level of the sea with respect to the land can change because the volume of the sea increases or decreases, or because the land rises or falls, or because of some combination of the two. On the other hand, it is usually impossible to know which is the mechanism at any one place, unless of course eustatic or world wide sea-level is unchanging. For purposes of this discussion it is not critical that we know the cause but it is very important to know the rate. Marmer (1949) reported that sea level, as reported on tide gauges, was rising along the entire east coast. Hicks and Crosby (1974) reported that sea level at Hampton Roads and Portsmouth, Virginia, had been rising at a rate of approximately 30 cm (1 foot) per century, 3 mm (0.01 foot) per year, since 1928. Further confirmation that sea level is rising over the region of the Chesapeake Bay comes from precise re-levelling between first order benchmarks in the Bay area coupled with tidegage data, Figure 3 (Hohldahl and Morrison, 1974). The authors attempted to remove the eustatic effects by substracting an assumed world wide rise of 1.0 mm per year from their measurements. If correct, the entire Bay area appears to be sinking tectonically but not everywhere at the same rate.

B. RECENT SEDIMENTOLOGICAL WORK

The earliest survey of the bottom sediment characteristics was that of Ryan (1953) wherein he obtained 209 samples along transverse sections of the Bay and the river mouths. Eighty-six of those stations were in the Virginia section of the Bay. From the skeleton framework Ryan inferred the spatial patterns of texture on the basis of an implied depth-texture association. An improved portrayal of the spatial patterns in the Virginia part of the Bay resulted from the work of Shideler (1975) who occupied 200 stations, again along transverse sections. This work provided clearer definition of the areas dominated by mud. He observed the sands to be relatively coarse in shallow water and to be very fine in deeper water in association with mud. The differentiation of the sand sizes was interpreted to be the result of wave energy with the coarser, fringing sands representing a lag deposit from shoreline erosion and the very fine sand in deeper waters representing the wave-winnowed fraction transported into deeper water. In the lower portion of the Bay, from the York River to the Bay mouth, were stringers of medium-grained sands which did not appear to be depth controlled. These deposits were interpreted as being partially reworked relict materials.

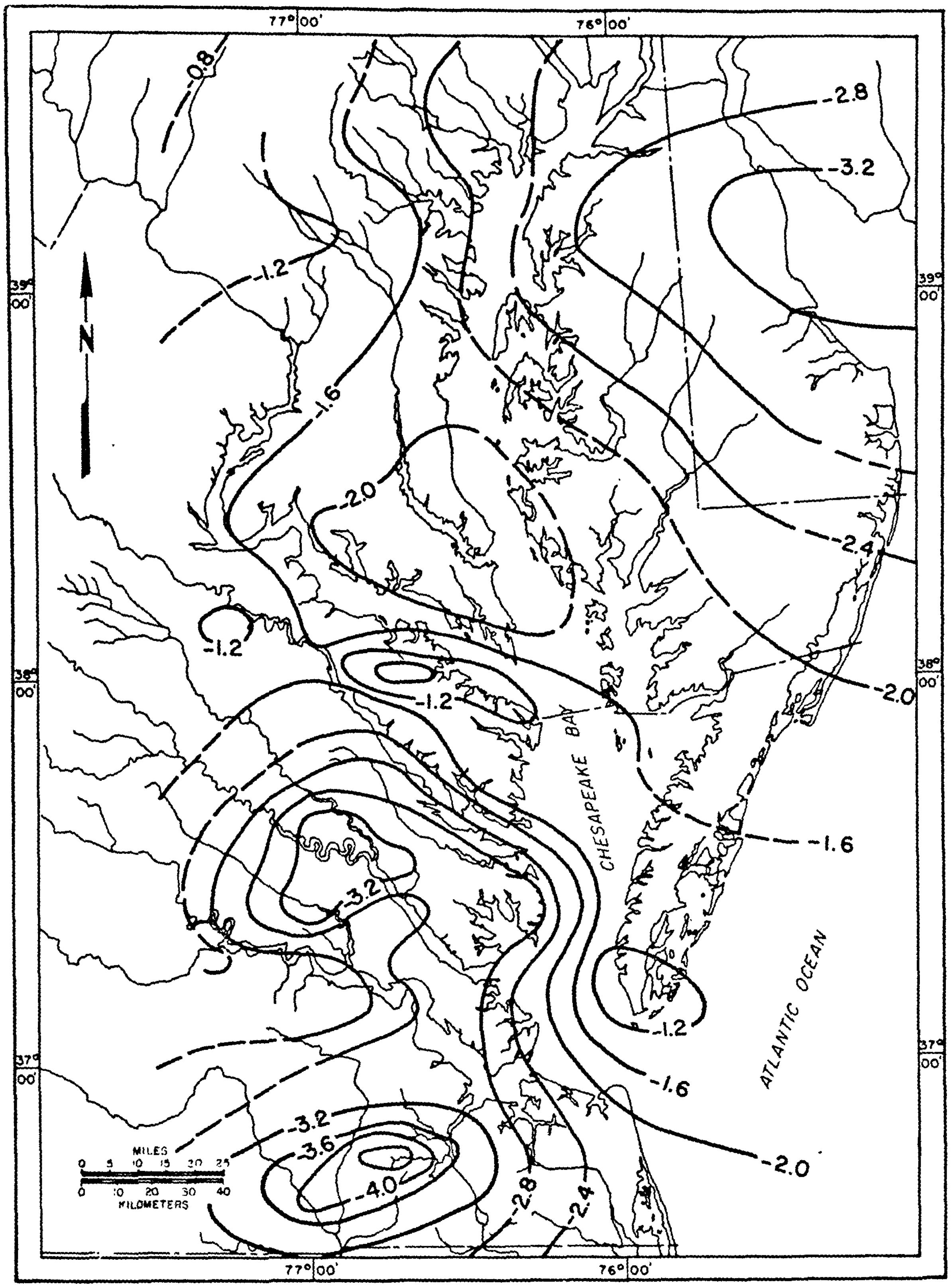


Figure 3. Rates of change in crustal elevation (mm/yr) in the Chesapeake Bay region (from Holdahl and Morrison, 1974).

There are no previous attempts at constructing a sediment budget which includes the sand component for the Virginia portion of the Chesapeake Bay. Schubel and Carter (1976) formulated a suspended sediment budget for the entire Bay stem utilizing a salt budget argument and field measurements of Bay axial suspended sediment distributions during 1969-1970. They argued that in the lower Bay shore erosion may be the largest source of inorganic sediment. In addition they calculated that the input of suspended sediment through the Bay mouth was a strong source and that the tributary estuaries were, in fact, sinks for sediment materials in the Bay.

V

METHODS

The methods used in this study matched, to the extent possible, those of the Maryland Geological Survey's (MGS) parallel study of the Maryland portion of the Bay. The two studies used essentially identical protocols for the analyses of sediment characteristics and chemistry. However, the treatment of the rates of deposition and the information derived therefrom were somewhat different due to differences in the availability of data from bathymetric surveys and in the formatting for automatic data processing.

A. CHARACTERIZATION OF SEDIMENTS

1. Sample Collection. Two basic considerations, providing sufficient coverage to delineate gradients in grain size and efficient utilization of the time available, drove the design of the sampling density and pattern. Moreover, the Virginia grid was designed to be as compatible as with the 1 square kilometer grid that the MGS already had established for their project. The resulting "diamond shaped" sampling pattern in Virginia is based upon the Universal Transverse Mercator (UTM) 1,000 meter grid. The sample sites were at the intersections of even numbered rows with even numbered columns and odd numbered rows with odd numbered columns. This plan resulted in a nominal, minimum spacing of 1.4 km. The total field collection was 2,172 sample sets from 2,018 locations (Figure 4).

Bottom samples were acquired with a stainless steel Smith-MacIntyre grab sampler which has a volume of approximately 0.01 m^3. When the sampler was on deck at least two subsamples were taken from the sediment surface. Surface samples were skimmed from the top centimeter for the carbon-sulfur analysis. These were placed in a labeled plastic vial and promptly refrigerated or iced. The second subsamples were several hundred grams of material from the top 4 to 6 centimeters. These were placed in large plastic envelopes with top fasteners and, although not refrigerated, care was taken to avoid long exposure to environmental extremes. Special scoops were designed and fabricated (Figure 5) for the two sample sets so that a uniform rectangular cross-section was plugged from the larger sample. Using these devices avoided the bias introduced by inserting a circular cross-section sampler into a sediment with vertical gradients in any parameter of interest.

As part of the Quality Assurance Program, discussed later, so as to minimize the possibility of losing the sampling information, two logs were maintained. A "sample log" contained the date, sample code number as recorded on the sample container, and nominal site location. The "cruise

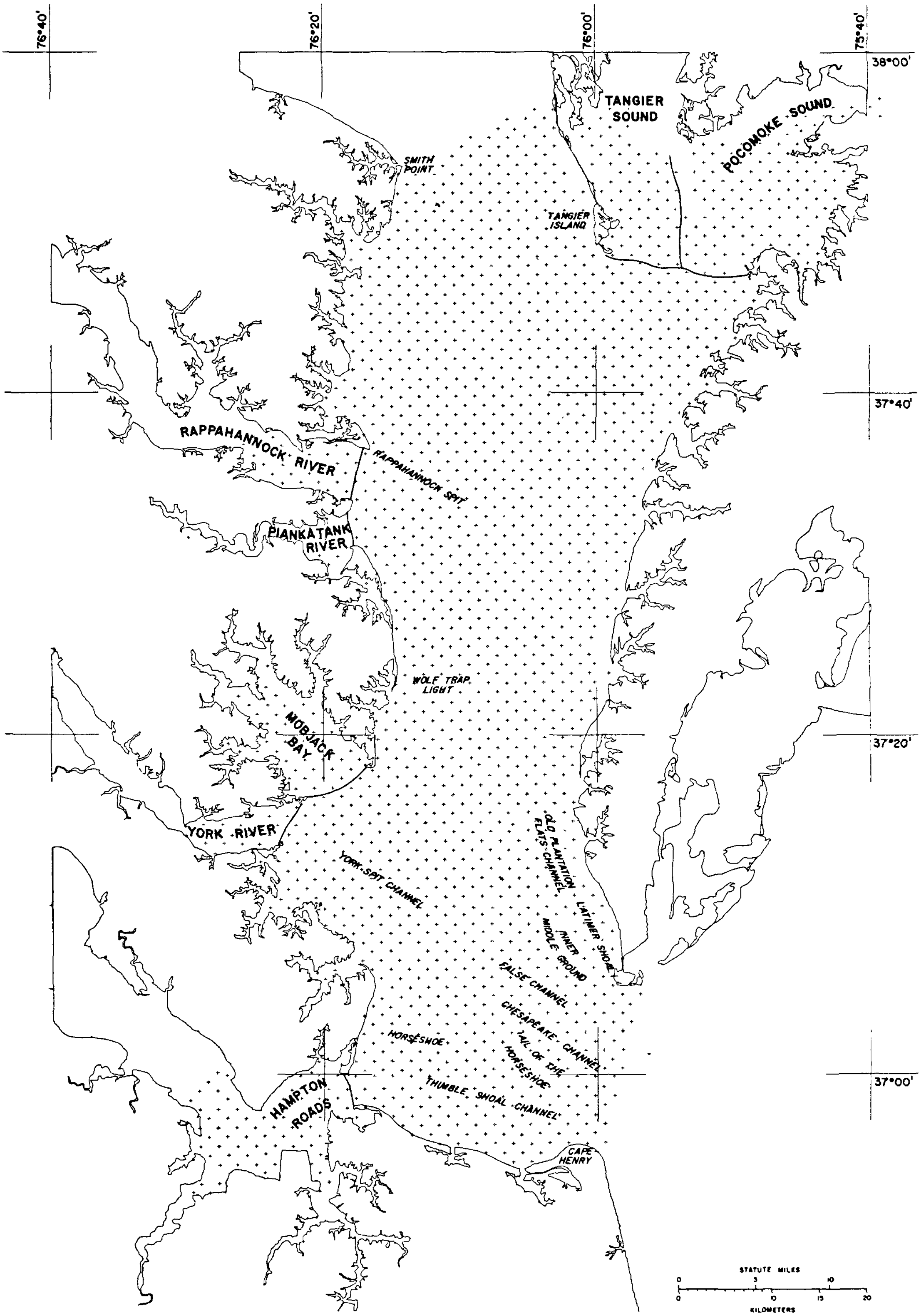


Figure 4. A map of the Virginia portion of the Chesapeake Bay showing the location of subareas and sample stations.

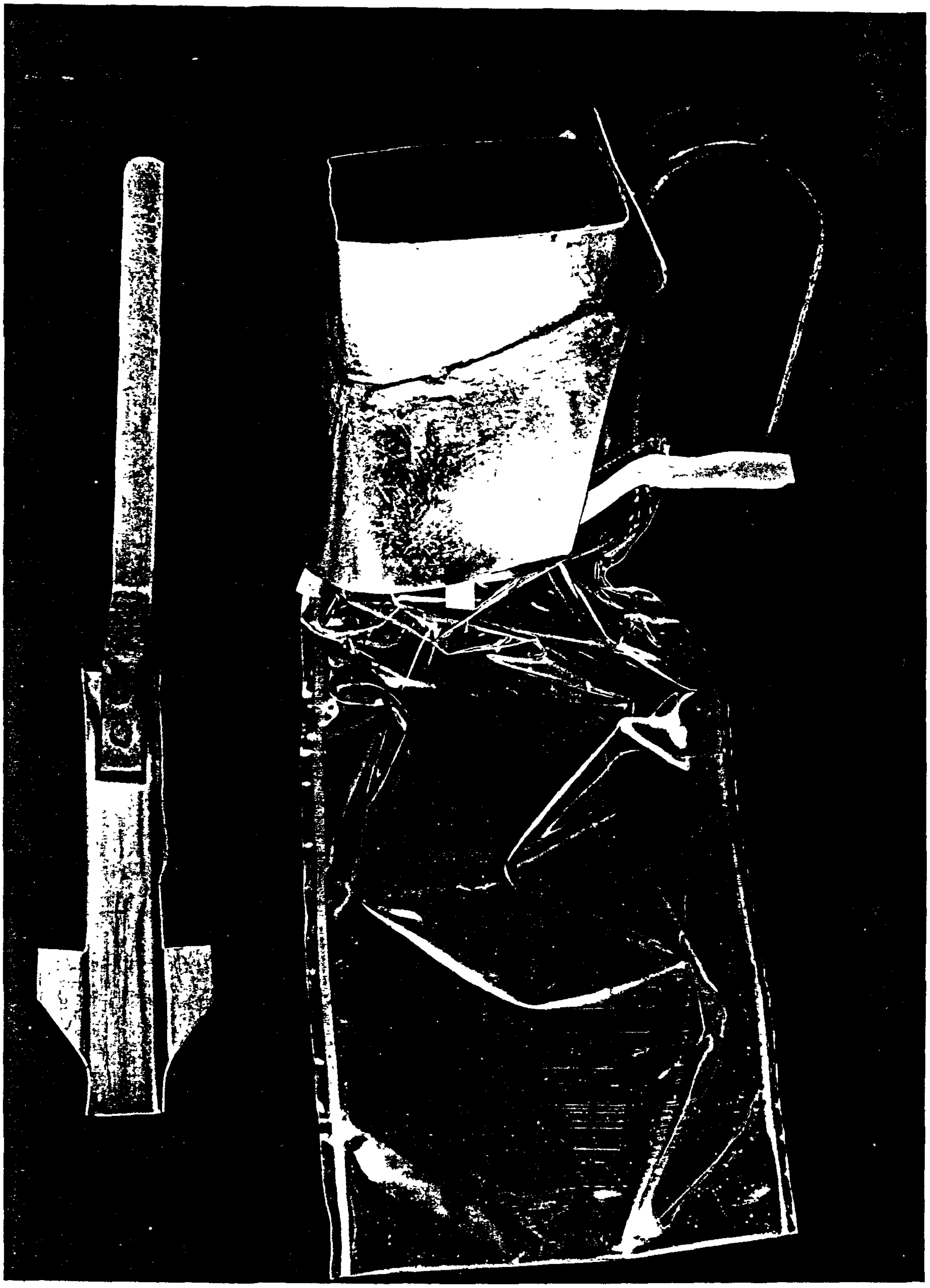


Figure 5. Photograph of sample scoops that were fabricated for use in this project. The larger device, shown with sample bag, was used to collect the large, bulk sample of the top 6 cm of sediment for grain-size and water-content analyses. The smaller device was used to skim a sample from the top 1 cm of the sample for carbon and sulfur analyses.

log" contained, in addition to this information, the time of collection, water depth from an echosounder, name of the sampler, and a description of the sediment surface and of the materials recovered. All sampling was conducted from the Research Vessel Captain John Smith (Figure 6).

Sample stations were located by navigating the research vessel to points defined by LORAN C signals; the predetermined values for the LORAN C signals being obtained from tables supplied by the Defense Mapping Agency through EPA and by applying a "Bias Correction Factor" to the listed values. The tabulated values are theoretical and do not consider variations in electromagnetic signal propagation across land masses and across the land-water interface. Bias correction values were determined by comparing the observed LORAN C values for known points with the theoretical values for the same locations. The correction data is given in Appendix 1. Once on station, LORAN C readings were automatically printed on paper tape. The tapes were attached to the sample log-sheets. Later the readings for each station were averaged, "un-corrected", and entered into a computer program which yielded the latitude and longitude of the actual station.

In order to check the ability to return to actual sample sites, at the conclusion of the sampling program, nineteen sample sites were relocated to the averaged LORAN coordinates. Comparison of the calculated latitudes and longitudes for the nineteen pairs of stations yielded an average return to within 30 meters of the original location. With the ability to return to sample sites as located by the observed LORAN or by latitude and longitude as determined by other means, future researchers should be able to very closely approximate the locations of the sites sampled.

Samples were collected on 75 days spread over eight months in 1978 and 1979. Sampling was very slow during the winter months when days were short, windy, and icy. Milder spring weather brought with it a great increase in productivity; Table 1 details the specifics of sampling.

TABLE 1

Schedule of Sampling

Year	Month	Days	Samples Per Month
1978	November	13	160
	December	5	104
1979	January	10	238
	February	5	112
	March	12	462
	April	13	525
	May	15	547
	June	2	26

2. Analysis of the Sediments. As mentioned previously, two sample subsets were collected at each station (aside from replicates). The smaller subsample, for carbon and sulfur analyses, was taken from the

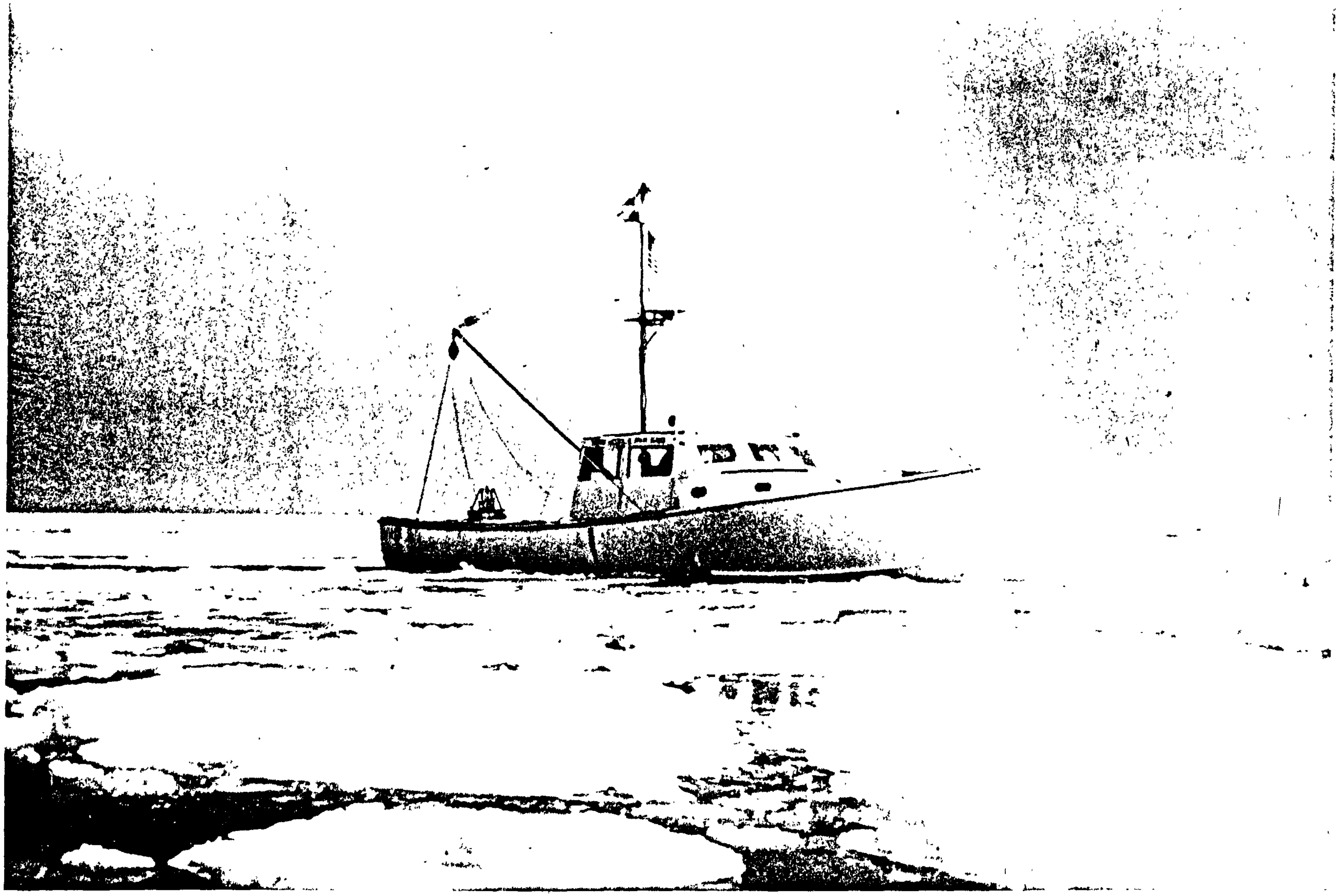


Figure 6. R/V Captain John Smith on the Chesapeake Bay, February, 1979.

cruise on ice and then frozen and held until pretreatment for analysis. The larger subsample, secured for water content and size analyses, upon delivery to the laboratory was mixed and split into at least three subsamples. One was labeled for the archive, another was stored pending granulometric analysis, and the third was promptly analyzed for bulk water content. Figure 7 is a flow chart of the analytical procedures.

a. Water Content. The water contents were determined by placing the sample in a preweighed beaker, weighing it, drying it at 65°C and weighing again; the weight difference being the weight of the water. The percent water content was calculated with the formula

$$W_C = \frac{W_W}{W_T} \times 100,$$

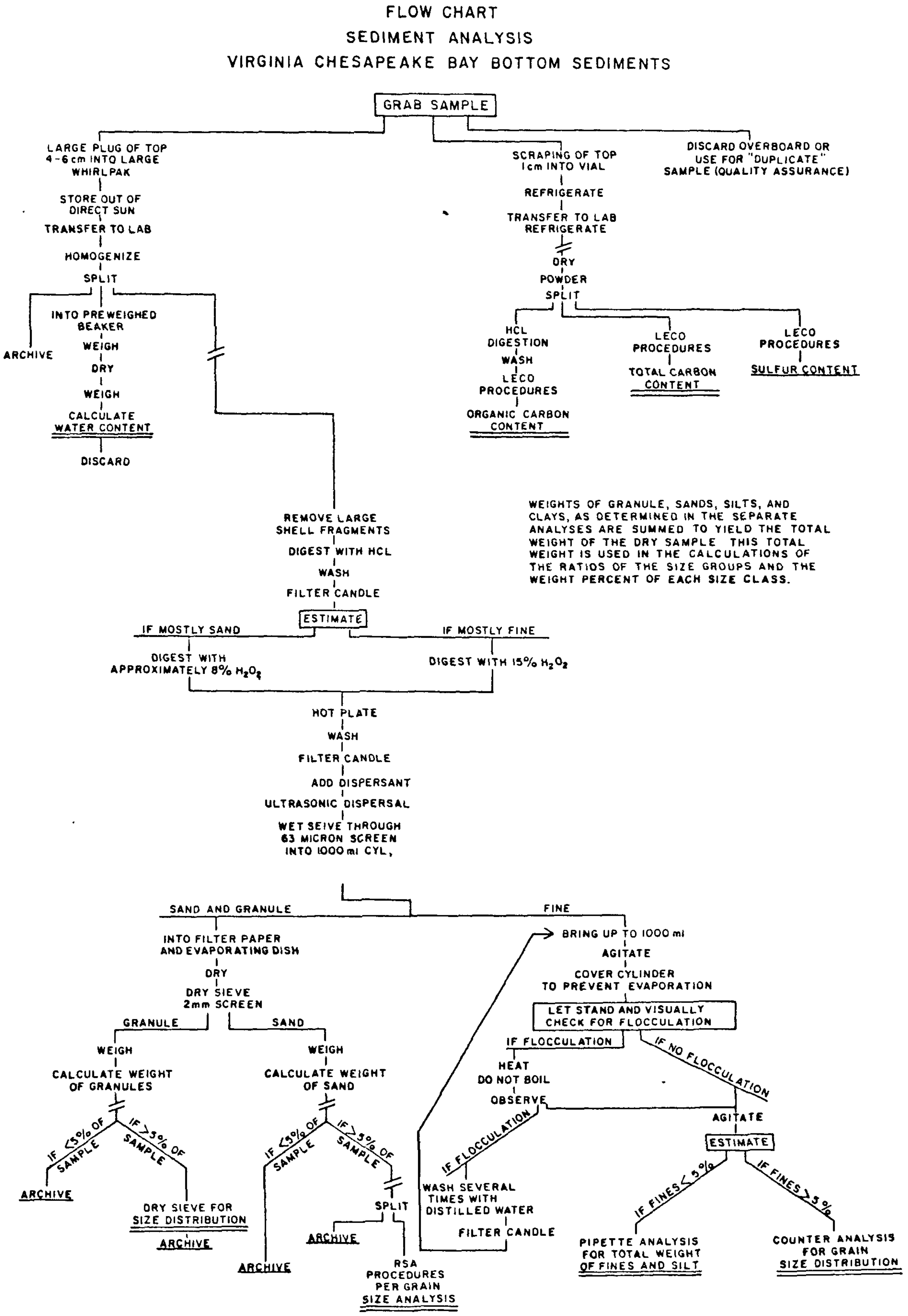
where W_C is percent water content, W_W weight of the water, and W_T the weight of the sediment-water mixture. No attempt was made to compensate for the weight of salts from evaporation.

b. Grain-Size Analysis. As the sediments range from granules to clays, it is necessary to employ different analytical techniques on different fractions of the sample. The sand fraction was analyzed in a Rapid Sediment Analyzer (settling tube), the granules by conventional sieving, and the fines by Coulter Counter. The different data sets from each sample were then joined in a miscegnatious marriage by the computer.

All the samples received the same pretreatment, separate digestions with HCl and H_2O_2, washing, fluid removal through filter candles, dispersal in an ultrasonic bath, and wet sieving through a 4 ϕ (63 μm) screen.

Table 2 is a listing of phi, ϕ, classes and the equivalent metric sizes. Phi, a logarithmic transformation of the linear metric measurement, is calculated with the formula $\phi = -\log_2$ (diameter in millimeters). Because phi is logarithmic and is, in one sense, a measure of the interval between classes (McManus, 1982) it is inappropriate to compare phi and metric standard deviations.

The material passing the screen was transferred to a 1,000 ml cylinder and processed by conventional pipette techniques, including dispersants, for total weight of material, and percents silt and clay. An additional withdrawal of the total sample was taken and kept for analysis on a Coulter Counter Model TA or, later in the project, TA II. This analysis was performed using standard 2-tube (140 μm and 30 μm apertures) techniques (Coulter Electronics, 1975 and revisions). Shideler (1976) discusses the differences between standard pipette data and Coulter Counter data. Further discussion is provided in the section on Quality Assurance. It should, however, be remembered that neither pipette nor Coulter methods give direct measurement of grain size. The former yields grain by equivalence in fall velocities of the natural particles and spheres of a given specific weight. The latter converts electronically estimated particle volumes to spheres of equal volume.



WEIGHTS OF GRANULE, SANDS, SILTS, AND CLAYS, AS DETERMINED IN THE SEPARATE ANALYSES ARE SUMMED TO YIELD THE TOTAL WEIGHT OF THE DRY SAMPLE THIS TOTAL WEIGHT IS USED IN THE CALCULATIONS OF THE RATIOS OF THE SIZE GROUPS AND THE WEIGHT PERCENT OF EACH SIZE CLASS.

Figure 7. The flow chart for the analysis of sediments.

Table 2

Grain-Size Nomenclature

Ø		mm	m
-2		4	
-1		2	
0		1	
1	1/2	0.5	500
1.5		0.35	350
2	1/4	0.25	250
2.5		0.177	177
3	1/8	0.125	125
3.5		0.088	88
4	1/16	0.0625	625
4.5		0.044	44
5	1/32		31
6	1/64		15.6
7	1/128		7.8
8	1/256		3.9
9	1/512		20
10	1/1024		0.98

Granule	-2Ø - -1Ø
Very coarse sand	-1Ø - 0Ø
Coarse sand	0Ø - 1Ø
Medium sand	1Ø - 2Ø
Fine sand	2Ø - 3Ø
Very fine sand	3Ø - 4Ø
Silt	4Ø - 8Ø
Clay	8Ø

Some researchers use 9Ø as the silt-clay boundary.

Sediments finer than 4Ø, that is both silt and clay, are muds.

If the sample were less than 10% mud (silt + clay), the analysis by Coulter Counter was omitted, leaving only the 4 Ø and 8 Ø pipette data to describe the distribution of the fine tail of the distribution. The 10% cutoff was used for the first thousand or so samples; 5% was used for the remainder.

The sand-size portions of the samples, that is the material held on the 4 Ø wet sieve and passing a -1 Ø dry-sieve, were weighed, and passed through a microsplitter until a 0.5 to 1.0 gram subsample was obtained. This subsample was for analysis on the Rapid Sediment Analyzer (RSA) (Figure 8). The remainder was packaged and stored to be available for other researchers. The RSA has a 1.5 m fall distance and is similar in design to that described by Gibbs (1974) and is essentially identical to the device used by the Maryland Geological Survey. The data delivered by the RSA is in the form of a strip chart depicting proportion of sediment fallen versus time since introduction of the sample to the system. The strip chart was then processed on a Numonics 1224 Graphics Calculator which served to put the fall velocity data onto computer compatible magnetic tape. This information was converted to size data by a computer application of the Gibbs, Mathews, and Link (1971) formula

$$r = \frac{0.055804\ V^2\ \rho f + [0.003114\ V^4\ \rho f^2 + (g(\rho s - \rho f)\ (4.5\ V + 0.008705\ V^2 \rho s))]^{1/2}}{g\ (\rho s - \rho f)}$$

where r is sphere radius in cm,

V is fall velocity in cm/sec.,

ρf is fluid density in g/cm^3,

ρs is density of the sphere in g/cm^3, 2.65 gm/cm^3 was assumed,

g is the acceleration of gravity in cm/sec.^{2}, 980 cm/sec^2 was used,

η is the dynamic viscosity of the fluid in poises.

As the fluid density and dynamic viscosity vary with temperature, appropriate values from tables for distilled water were used.

If the sample were more than 5% granule, the particles coarser than -1 Ø were sieved at 1/4 Ø intervals in the conventional manner.

All the procedures and methods were, in so far as possible, standardized with those used in a parallel project conducted by the Maryland Geological Survey.

The weights of each major size class, granule, sand, silt, clay, were summed and the ratios were calculated. As each separate class analysis, Coulter Counter, RSA, sieve, was referenced to 100%, it was necessary to multiply each separate phi-class by the respective granule, sand, or mud

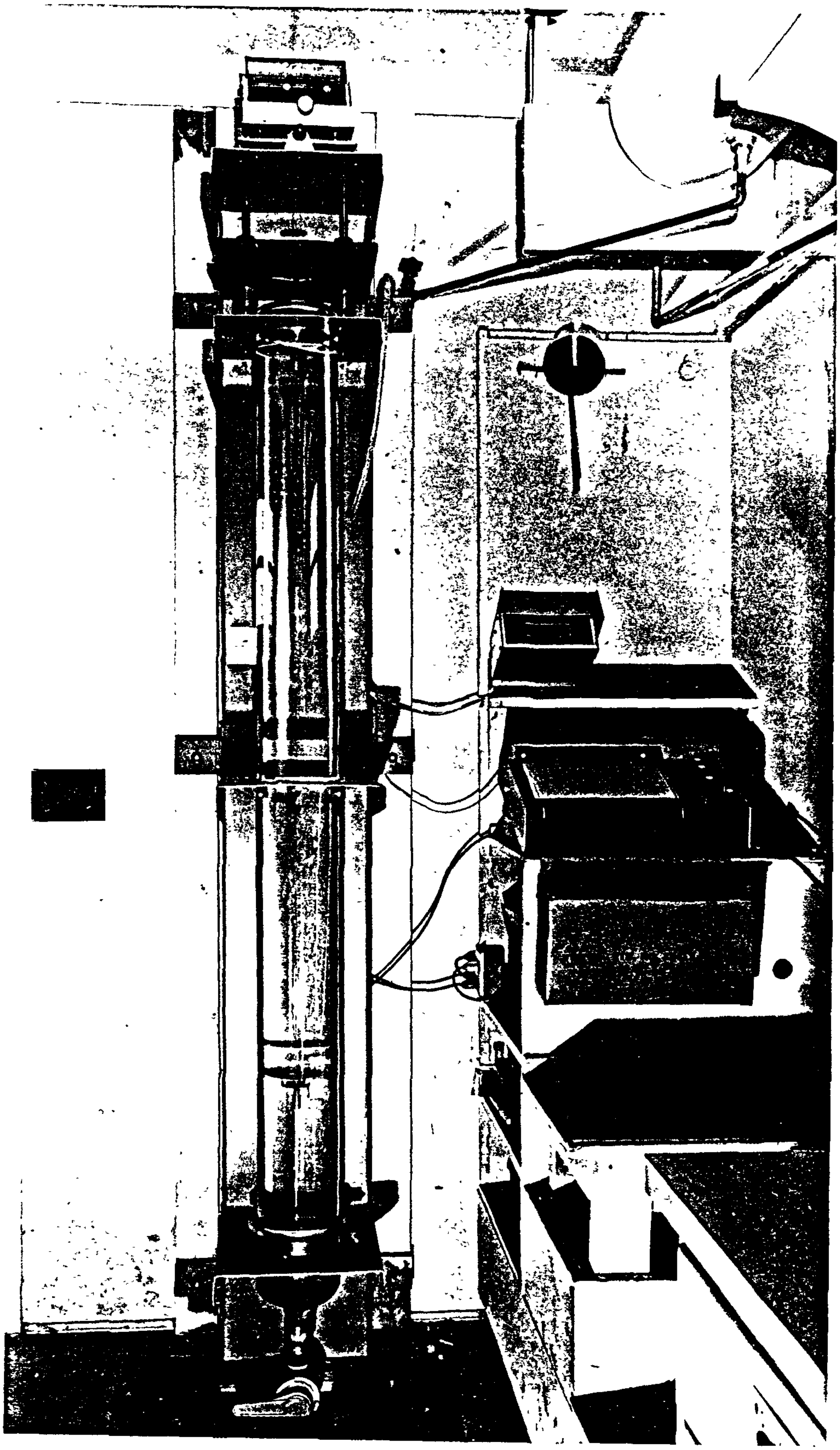


Figure 8. The Rapid Sediment Analyzer (RSA) as constructed at V.I.M.S.

ratio to obtain the proportion of each class relative to the entire sample. Similarly, phi classes common to two modes of analysis were algebraically summed in a form of splined fit.

The standard graphic measures of Folk or Folk and Ward (Folk, 1974) and the first four moments plus moment skewness and moment kurtosis were computer calculated for each sample.

Graphic Measures

Median = $\emptyset_{50}$

Graphic Mean

$$M_Z = \frac{\emptyset 16 + \emptyset 50 + \emptyset 84}{3}$$

Graphic Standard Deviation

$$G = \frac{\emptyset 84 - \emptyset 16}{2}$$

Inclusive Graphic Standard Deviation

$$I = \frac{\emptyset 84 - \emptyset 16}{4} + \frac{\emptyset 95 - \emptyset 5}{6.6}$$

Inclusive Graphic Skewness

$$S_{K_I} = \frac{\emptyset 16 + \emptyset 84 - 2\emptyset 50}{2(\emptyset 84 - \emptyset 16)} + \frac{\emptyset 5 + \emptyset 95 - 2\emptyset 50}{2(\emptyset 95 - \emptyset 5)}$$

Graphic Kurtosis

$$K_G = \frac{\emptyset 95 - \emptyset 5}{2.44(\emptyset 75 - \emptyset 25)}$$

Moment Measures

$\underline{1st}$ Moment $= \frac{fm\emptyset}{100}$

where f is frequency percent of each $\emptyset$ class, $m\emptyset$ is midpoint of each class. By definition the first moment equals the mean, $\bar{X}$, of the distribution.

$\underline{2nd}$ Moment $= \frac{f(m\emptyset - \bar{X})^2}{100}$

The 2nd moment is the square of the standard deviation.

3rd Moment (mean cubed deviation) = $\frac{f(m\phi - \bar{X})^3}{100}$

4th Moment = $\frac{f(m\phi - \bar{X})^4}{100}$

Moment Skewness = $\frac{\text{3rd Moment}}{\text{standard deviation cubed}}$

Moment Kurtosis = $\frac{\text{4th Moment}}{\text{standard deviation to the 4th power}}$

c. Clay Mineralogy. The methods used for the semi-quantitative determination of the clay mineral contents of the sediment were quite simple. A subset of the 2 µm (9 ϕ) and smaller sediments was obtained by standard pipette methods based on Stokes' Law fall velocity. The particles were concentrated by centrifuge. This material was pipetted onto glass slides and dried at 60°C. Another set of slides was dried then heated over glycol. Finally, a third set of some slides was heated to higher temperatures. The slides were analyzed in a General Electric X-Ray diffractometer at approximately 43 KV and 30 ma. The analyses used a 2° aperture silt and a 2° 2θ per minute scan speed. Each slide was scanned from 2° 2θ to approximately 28° 2θ. The data was recorded on 10-inch wide chart paper at 1° 2 per inch. The relative proportions of the various major clay minerals was estimated by the ratios of the heights of the diffraction peaks for each mineral.

d. Carbon and Sulfur Analysis. Approximately 900 samples were selected for carbon and sulfur analyses. As the primary interest was in the chemical alliances with the finer grained sediments, the samples were selected on the basis of an inferred minimum of 15% mud by weight. It was necessary to use percent water content to infer mud content because while the water content analyses were complete for most samples, the granulometric work had just begun. On the basis of 500 samples there was a strong correlation, r = 0.96, between mud and water contents. Also, as all the carbon and sulfur analyses were to be in at least duplicate, it was necessary to reduce the number of samples to a manageable level.

The frozen samples were thawed, oven dried at 50°C, powdered with a mortar and pestle, and divided into several aliquots with a microsplitter. The aliquots were weighed and placed in small vials. The subsamples for sulfur and total carbon analysis received no additional pretreatment. The samples to be analyzed for organic carbon were treated with 10% HCl until evidence of continuing reaction ceased, then they were washed with distilled, deionized water, decanted, oven dried, and weighed. Final analyses were done in at least duplicate on a LECO Gasometric Carbon Analyzer, Model 572-100 and a LECO 532-000 Titrator for sulfur. Both analytical instruments were operated in conjunction with a LECO 523-300 Induction Furnace. The averages of the duplicate analyses are the reported values. Inorganic carbon may be calculated as the difference between total and organic carbon. Samples with differences between paired readings that were outside acceptable limits were re-analyzed with the result of the multiple values showing less variation than the initial pair.

The LECO carbon analysis equipment is relatively common and has been discussed elsewhere in the literature (Leventhal and Shaw, 1980). The method for determination of sulfur, however, is not so common, and is described as follows (LECO, 1975).

> "The sample is burned in a stream of oxygen at a sufficiently high temperature to convert about 90 to 97 percent of the sulfur to sulfur dioxide. A standardization factor is employed to obtain accurate results. The combustion products are passed into a dilute acid solution containing potassium iodate, potassium iodide and starch indicator. The blue starch iodine complex thus formed is bleached by the SO_2. As combustion proceeds, bleaching the blue color, more iodate is added to return to the original blue color. The amount of standard iodate consumed during the combustion is a measure of the sulfur content of the sample."

3. Quality Assurance. All aspects of the laboratory work were subjected to a quality assurance program. The following text describes some of that program.

a. Shared and Duplicate Samples. Several samples were split so that analyses could be performed in the sediment laboratories of both the Maryland Geological Survey and the Virginia Institute of Marine Science. The primary data, sand:silt:clay ratios agree quite closely (Table 3A&B and Figure 9). In all cases except one, No. 7, VCB 1626, the samples fall in the same class. In the single exception, the ratios are very close, but fall along the sand:silty-sand boundary. With the samples for which there are graphic data from both labs, the measures generally agree quite closely. The exceptions are the very fine grained samples, No. 2, VCB 784 and No. 3, VCB 785, where very minor differences in measurement, in both cases 0.003 mm in the graphic mean, appear disproportionately large on the Ø scale.

Additionally duplicate samples were collected at 135 stations. These samples were packaged as ordinary samples and returned to the laboratory for routine analysis; the laboratory staff not being aware which samples were the check samples. Although the data on the duplicates have not been subjected to a rigorous statistical examination, a qualitative review indicates a very close and satisfactory agreement between duplicate analysis.

b. Calibration of the Rapid Sediment Analyzer. The calibration of the RSA constructed at VIMS followed procedures that were described by the Maryland Geological Survey (Halka, et al.). The MGS provided VIMS with a set of glass beads of known diameters and densities. Members of the staff at the MGS had inspected the beads for sphericity, sieved them at 1/4 Ø intervals for size classification, and floated them in various heavy liquids to

Table 3A

Samples from the Virginia Portion of the Bay Analyzed by Both VIMS and MGS

Sample	Plotted as	% Gran.	% Sand	% Silt	% Clay	Graphic ∅	Mean mm	Graphic ∅	Std Dev mm
783 M	1	-	39.3	31.5	29.2	6.3	0.013	3.3	0.10
V		-	33.5	36.5	29.9	5.7	0.019	2.3	0.20
784 M	2	-	-	42.3	57.7	8.7	0.0024	2.7	0.15
V		0.5	4.0	44.9	50.6	7.5	0.0055	1.8	0.29
785 M	3	-	-	41.4	58.6	8.9	0.0021	2.8	0.14
V		-	1.5	42.0	56.5	7.5	0.0055	1.8	0.29
786 M	4	-	92.2	3.3	4.5	2.2	0.22	1.1	0.47
V		-	87.9	4.8	7.2	2.3	0.20	1.3	0.41
1624 M	5	-	97.5	2.0	0.6	1.9	0.27	0.6	0.66
V		-	97.3	1.3	1.3	1.9	0.27	0.5	0.71
1625 M	6	-	88.2	6.3	5.5	1.3	0.41	1.9	0.27
V		7.3	82.3	6.2	4.2	1.2	0.44	1.7	0.31
1626 M	7	-	74.0	14.2	11.8	4.3	0.051	2.0	0.25
V		0.4	72.9	17.8	8.9	3.9	0.067	1.3	0.41
1627 M	8	-	67.2	2.3	9.8	4.2	0.054	2.0	0.25
V		1.2	57.0	31.6	10.1	4.1	0.058	1.5	0.35

Table 3B

Samples from the Maryland Portion of the Bay Analyzed by Both VIMS and MGS

Sample		Plotted	%	%	%	%
R	G	as	Gran.	Sand	Silt	Clay
1148.51	1908.50 M	9	-	2.1	23.2	74.7
	V		4.7	1.8	24.8	68.7
1162.52	1912.50 M	10	-	0.5	24.2	75.3
	V		-	0.4	24.6	75.0
1138.03	1922.02 M	11	0	6.1	23.7	70.2
	V		1.0	1.7	24.6	72.7
1175.85	1846.02 M	12	-	15.5	29.4	55.1
	V			11.0	39.5	49.5
1191.14	1853.56 M	13	-	7.8	39.7	52.5
	V			6.6	44.5	48.9
1164.09	1861.80 M	14	-	5.3	31.6	63.1
	V		-	4.2	37.3	58.5
1269.09	1831.49 M	15	-	78.9	15.9	5.2
	V		-	83.1	9.8	7.1
1180.58	1867.00 M	16	-	83.7	5.8	10.5
	V		-	83.4	6.4	10.1
1113.06	1815.95 M	17	-	89.9	- 10.0 -	
	V		-	90.4	4.1	5.6
1092.45	1845.50 M	18	-	94.0	- 6.0 -	
	V		-	93.5	2.1	4.3
1071.10	1764.94 M	19	-	95.8	- 4.2 -	
	V		-	90.7	0.2	3.2
1253.96	1825.15 M	20	-	99.2	- 0.8 -	
	V		-	97.9	0.7	1.3

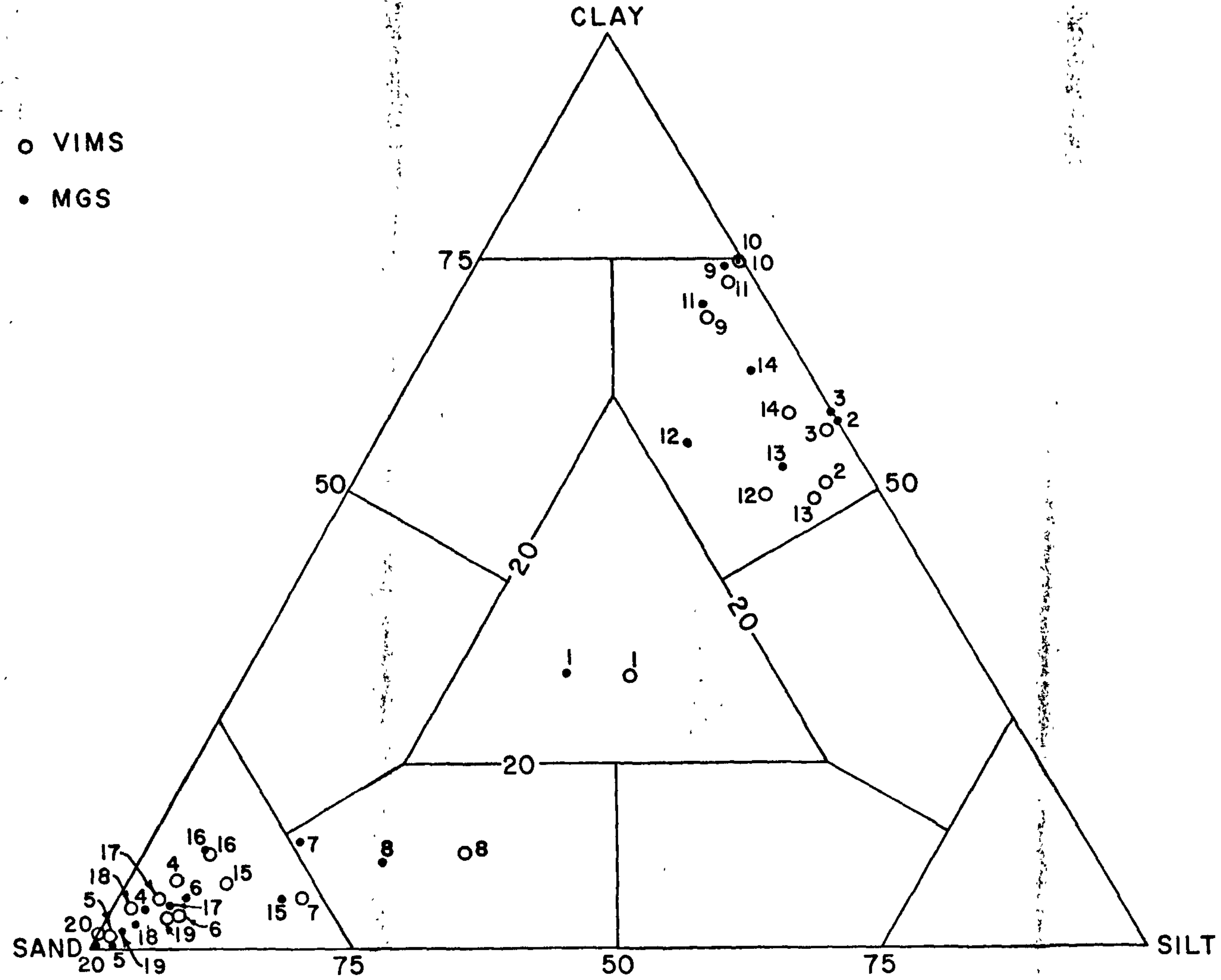


Figure 9. Plot of sand:silt:clay ratios for duplicate analyses at V.I.M.S. and the Maryland Geological Survey of 20 samples.

determine their density. The expected fall velocity of the spheres, as predicted by the equation published by Gibbs, Mathews, and Link (1971), served as a standard to which the observed velocities could be compared. Several aliquots of very nearly 0.5 gram of each separate size class of spheres were processed through the RSA. (Because of a limited quantity, the aliquots of the 4 0 spheres were roughly 0.45 and 0.28 gram.) The elapsed fall time for 50% by weight of the sample to fall through the column was used as the time for the calculation of the observed velocity of the mid-class size. Table 4 is a summary of those comparisons. The data from the test samples of the range 0.25 0 through 2.25 0 agree quite satisfactorily with the expected values and appear to have good repeatability. The very coarse and very fine particles, however, pose a question as the differences between observed and expected values are significant. The greatest errors occur with the 3.25 0 and 4.0 0 spheres.

Aside from operator and machine errors, there are three possible sources of error associated with the spheres themselves: 1) that the size distribution of the sphere within a size class is not as assumed, 2) that the particle density is not as specified, and 3) that size distribution errors were introduced in "splitting" the collection of spheres into smaller samples for analysis. The following example demonstrates the impact of small differences in size and density on fall velocity as predicted by the equation referred to above.

In the 3.25 0 class, the radius of the mid-class particle is 3.125 0, 0.00578 cm, and the given density is 2.49 g/cm^3. The expected fall velocity is 0.88 cm/sec., the observed 1.127 cm/sec. for a 28 "percent error." If the mid-class size were 1/8 0 different, 3.0 0 instead of 3.125 0, the expected velocity would be 1.01 cm/sec. and the error a more respectable 11.6%. Or if the size assumptions were correct but the density was 2.92 g/cm^3 instead of the given 2.49 g/cm^3, the expected velocity would be 1.09 cm/sec. and the error 2.9%. Similar examples of the roles played by density and size assumptions can be demonstrated with the other size classes. It should be noted that the size class with the greatest error, 4.00 0, is the one most subject to errors in density measurement due to particle-surface air bubbles, and to size distribution assumptions. At small particle sizes, a small diameter change yields a large relative change in fall velocity.

As a partial test of the likelihood of a size error, optical measurements were made of the diameters of 10 spheres from each size class. Table 5 is a listing of the data. Although 10 observations probably is not a sufficiently large sample to give a highly significant mean, the sign of the difference most likely is correct. Table 6 is a comparison of the percent errors, or differences, between expected and observed fall velocities and sphere diameters. As can be seen, in most cases, the sense of the errors are the same, perhaps explaining some of the discrepancies in fall velocity.

Although machine and operator errors are very difficult to assess, there are specific mechanical problems in introducing the larger test spheres into the RSA. The size and extreme spherecity of the particles, as

Table 4

Summary of Calibration Data for the VIMS RSA

Ø	Mid-Class Radius cm	Temperature °C	Particle Density gm/cm^3	Expected Velocity cm/sec	Average Observed Velocity cm/sec	Standard Deviation	Percent Error	Number of Observations
-1.00	0.1095	23 1/2	2.92	31.91	27.63	2.27	13.41	5
-0.75	0.0917	19 3/4	2.92	27.76	24.36	0.94	12.24	5
-0.50	0.0771	20 3/4	2.92	24.20	22.48	-	7.11	1
-0.25	0.065	24	2.92	21.12	19.17	-	9.20	2
0.25	0.046	23	2.49	13.49	13.35	-	1.04	3
0.50	0.0387	23	2.49	11.43	11.60	-	1.49	2
1.25	0.023	23 3/4	2.49	6.62	6.87	0.036	3.78	5
1.75	0.01625	23 3/4	2.49	4.41	4.48	0.012	1.59	5
2.25	0.0115	21 1/2	2.49	2.73	2.82	0.02	3.30	5
"	"	24	2.49	2.81	2.95	-	4.98	1
3.25	0.00578	19 3/4	2.49	0.88	1.127	0.008	28.07	5
4.00	0.00341	21 1/2	2.49	0.362	0.540	-	49.0	2
"	"	23 3/4	2.49	0.379	0.535	-	41.1	2

NOTES: Calibration particles and densities were suplied by the Maryland Geological Survey.

Expected velocities were calculated using the formula of Gibbs and others, 1971.

Expected velocities were calculated for particles of a size midway between sieve screens spaced at 1/4 Ø intervals and assuming a normal distribution within the interval.

Percent error was calculated as $(100(V_{\text{expected}} - V_{\text{avg. observed}})/V \text{ expected})$.

Standard deviations were not calculated for data sets consisting of fewer than five runs.

Table 5

Comparison of Expected and Observed Diameter of Calibration Spheres

Ø	Expected Diameter (mm)	Observer Mean (mm)	Standard Deviation (mm)	% Error
-1.0	2.190	2.1008	0.0784	4.1
-0.75	1.840	1.7248	0.0544	6.3
-0.5	1.545	1.5408	0.0830	0.3
-0.25	1.30	1.2224	0.1026	5.8
0.25	0.920	0.9048	0.0334	1.7
0.5	0.775	0.7956	0.0262	2.7
1.25	0.460	0.4684	0.0204	1.8
1.75	0.325	0.3192	0.0110	1.8
2.25	0.230	0.2348	0.0103	2.1
3.25	0.115	0.1148	0.0103	0.2
4.0	0.06825	0.0684	0.0091	0.2

NOTES: Predicted diameter is taken as the mid-point for each Ø interval.

Percent errors was calculated as $(100(V_{expected} - V_{observed})/V_{expected})$.

Column 3 is the mean of 10 measurements.

-1 Ø through 1.75 Ø 45 x magnification.

2.25 Ø through 4.0 Ø 90 x magnification.

Table 6

Comparison of Percent Errors

In Fall Velocity and Mid-Class Diameter

Ø Class	% Error Fall Velocity		% Error Mid-Class Diameter
	MGS	VIMS	
-1.00	1.9	13.4	4.1
-0.75	4.9	12.2	6.3
-0.50	1.8	7.1	0.3
-0.25	1.5	9.2	5.8
0.25	3.7*	1.0	1.7
0.50	3.8*	1.5*	2.7*
1.25	0.9	3.8*	1.8*
1.75	5.2	1.6	1.8
2.25	2.2	3.3*	2.1*
3.25	3.2*	28.1*	0.2
4.0	19.1*	45.1*	0.2*

* Observed greater than expected.

NOTES: 4 Ø velocity error, VIMS, is average of 2 sets of observations.

MGS fall velocity erro data from draft reports by Kerhin, Halka, and others.

compared to natural sediments, severely limits the retention of the spheres on the wetted, convex plate used to introduce the sample in the analytical procedure. Additionally, there are possible errors associated with the values for fluid density and viscosity. The values used were published, tabulated values for pure water, not values measured from the water in the RSA. Thus, while maintaining a continuing check on the reproducibility of the RSA data, we accept the RSA calibration and data as satisfactory.

Even though rapid sediment analyzers or settling tubes have been used for over two decades (Zeigler, Whitney, and Hayes, 1960) to determine the grain-size frequency distribution of sands, questions still arise concerning the comparison of analyses done by RSA and by sieves. Because the two measure different properties, one resulting from a set of variables concerning both grain and fluid, and other resulting from various facets of both grain and mesh sizes and shapes, it would be expected that the distributions depicted by each would differ. This does not state that one method if better than the other, just that they differ. Sanford and Swift (1971) published a comparison of data from sieving and settling techniques in which they found that the results of the two techniques were quite similar. As a check of the Chesapeake Bay samples, cumulative frequency plots were made of data from both sieve and RSA of splits of each of 20 sand samples. Figure 10 is an example of one of the comparative plots.

In general, the plot of the RSA data indicates a slightly better sorted sample than does the sieve data. This difference primarily occurs in the "tails" of the distributions, usually the first and last 5% or less, and would note be reflected in the calculated graphic-measures. In the Chesapeake Bay samples there is no consistent relationship of coarser or finer as was found by Sanford and Swift. This probably is due to the differences between the methods used to convert fall velocity, which is what an RSA measures, to equivalent hydraulic diameter. Sanford and Swift used Schlee's (1966) fall times as a basis for their work whereas the present study used Gibbs, Mathews and Links' (1971) formula.

Although the plots do differ, they are quite similar, showing inflections in slope at similar grain sizes when plotted on probability paper. This indicates that each method discerns similar mixings of sediment populations with only minor differences in interpreting the means and modes of those distributions.

c. Comparison of RSA's at VIMS and MGS. In order to determine whether or not the measurements made on the RSA at the Maryland Geological Survey, it was necessary to develop a method for characterizing the precision of an RSA. It should be remembered that precision is not the same as accuracy. EPA (1979) defines precision as "the degree of mutual agreement among individual measurements made under prescribed, like conditions," whereas accuracy is a measure of the proximity of a measurement to a true value. The problem at hand is compounded by the fact that there is a neither a standard sediment nor a standard RSA agains which to gauge accuracy. The individual calibration process for each RSA, described elsewhere, is an approximation of an accuracy determination. This section presents a

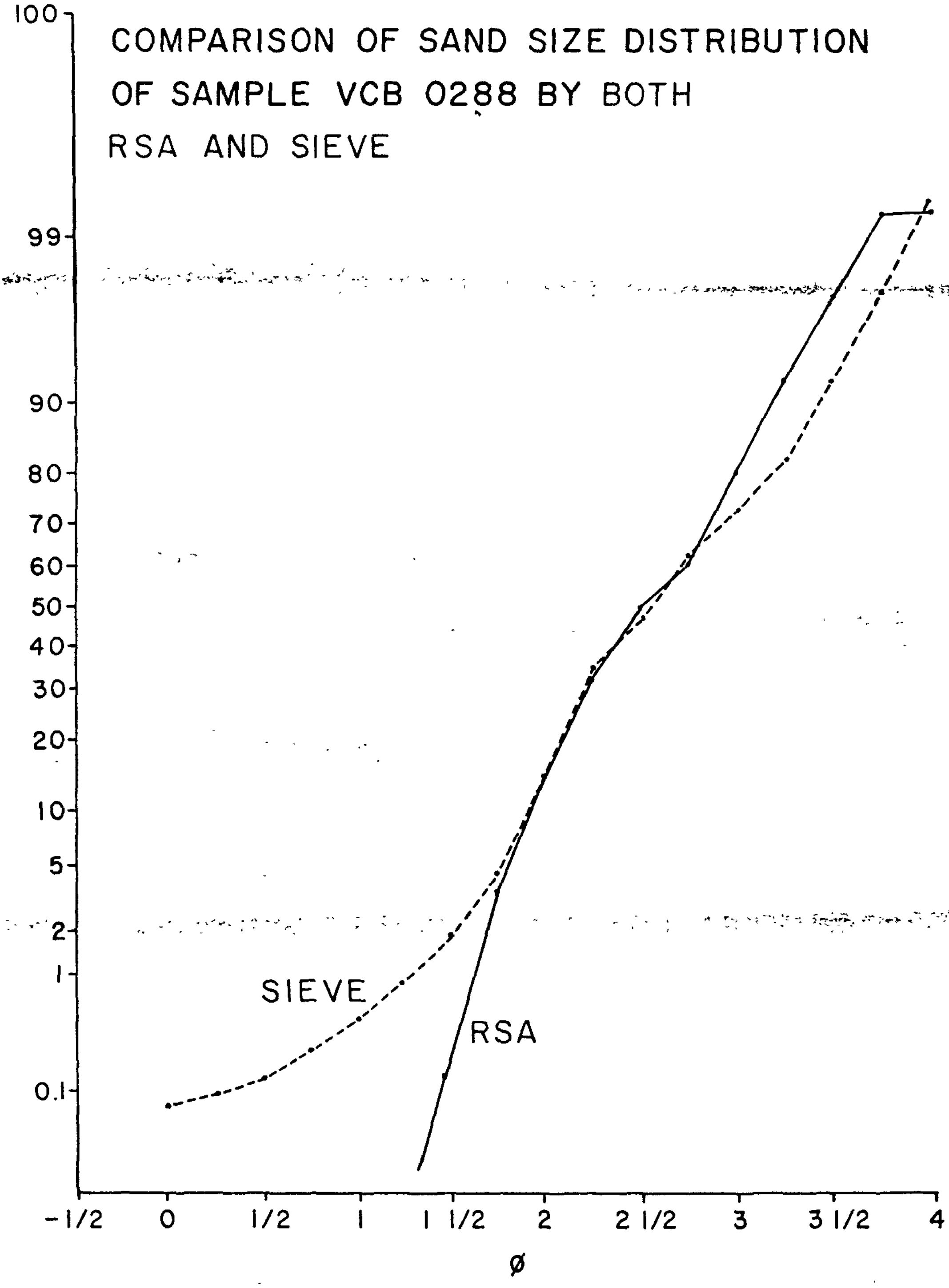


Figure 10. Plots of cumulative grain-size frequency distributions of the sand portion of a sample as determined by both sieve and RSA techniques.

characterization of the precision of the RSAs based upon the traditional model of normal grain size frequency distributions.

To accomplish this characterization, 42 aliquots of the same sandy sediment (Whitemarsh No. 2 quarry sand, supplied by the MGS) were analyzed on each RSA. The resulting quarter-phi grain-size-frequency distribution data were used to calculate the first and second moments of each of the 84 separate grain size distributions. The mean vectors of these two parameters for each RSA were determined and compared. The method of comparison was the Hotelling T^2 test which is a statistical test of the equality of mean vectors.

The formulae for the calculation of the moment measures, where the mean is equal to the first moment and the standard deviation equal to the square root of the second moment, were taken from Friedman and Sanders (1978). The first moment is calculated as

$$M_1 = \frac{\Sigma f M\emptyset}{100},$$

where f is the frequency percent in each 1/4 Ø size class, and MØ is the mid-point of the class. The second moment, M_2, is

$$\frac{\Sigma f(M_{\emptyset} - \bar{X})}{100}$$

where the mean, $\bar{X}$, is the first moment. This then is a distribution with two variables (bivariate) on each of many samples from the larger overall sample.

For all practical purposes, the RSAs at VIMS and at the MGS are mechanically identical. The methods of treating the data vary slightly. At the MGS, the instrument is wired to a microprocessor and the conversion of cumulative weight percent and fall time to grain size is "instantaneous," whereas at VIMS it is a two step procedure. The data product of the RSA is a paper strip chart which has to be digitized in order to allow computer transformation of distance to time, to velocity, to grain size.

Eighty-four subsamples, each of approximately 0.5 gram, were split from a homogeneous "archive" sample, half were analyzed at each sediment lab. The frequency distribution data for the quarter phi classes from -1.0 Ø through 4.0 Ø (very coarse through very fine sand) were used to calculate moment means and moment standard deviations of each subsample.

The measurement error, precision, herein considered is that which occurs within each variate among all the samples measured. Because there are many samples, we can assume the measurement error follows the central limit thereon, which states, "If random samples of fixed size are drawn from a population whose theoretical distribution is of arbitrary shape, but with a finite mean and variance, the distribution of the sample mean tends more and more toward a normal frequency distribution as the size of the sample increases" (Koch and Link, 1970). Thus, one can use the Hotelling T^2 test as a statistical means of comparison between the population of measurements generated by each RSA. This test is used to judge the hypothesis that the two mean vectors are equal. The mean vectors of each variate of the data from the RSA at VIMS is tested against the corresponding mean vector of the MGS data.

The Hotelling T^2 statistic is calculated as

$$T^2 = \frac{n_1 n_2}{n_1 + n_2} [\bar{X}_1 - \bar{X}_2] \cdot [S_p^2]-1 \cdot [\bar{X}_1 - \bar{X}_2]$$

with $(n_1 + n_2 - 2)$ degress of freedom. $[\bar{X}_1 - \bar{X}_2]$ is the difference between the two mean vectors. $[\bar{X}_1 - \bar{X}_2]^1$ is the transpose of that difference and $[S_p^2]^{-1}$ is the inverse of the pooled estimate of the variance-covariance matrix. The test is the multivariant equivalent of the univariate t test,

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_p \quad (1/n_1) + (1/n_2)}$$

where $\bar{X}_1$ and $\bar{X}_2$ are sample means, S_p is the pooled estimate of the standard deviation (based on both samples), and n_1 and n_2 are the number of observations in each sample.

For the Hotelling test, the calculated T^2 is compared to tables of T^2 distribution for a particular level of significance, based upon the number of variates and the degrees of freedom. If the calculated value exceeds the tabulated value, the test supports rejection of the hypothesis of equivalence. If the calculated T^2 is less than the listed value, the Hotelling T^2 test supports the acceptance of the hypothesis that the mean vectors are equivalent at the specified level of significance. If this is the case, the information yielded by the two RSAs can be considered equivalent.

Computer programs in the Statistical Analysis System and SAS Users Guide (1979) were used to determine the variance-covariance matrices and the Hotelling T^2. The difference of the two mean vectors was computed by determining the mean of each of the two variates, and arranging those means in a 1 x 2 matrix (a vector) for each data set, and finally subtracting the VIMS mean vector from the MGS mean vector.

The Hotelling T^2 statistic was computed to be 0.442. The value listed in tables of T^2 distribution (Kramer, 1972) at the 0.05 level of significance with $p = 2$ and 82 degrees of freedom is 6.303. Therefore, as the calculated value is less than the tabulated value, the Hotelling T^2 test indicates equivalence between the precision of MGS and VIMS Rapid Sediment Analyzers. In turn this encourages the acceptance of the assumption that data from the two RSAs may be used interchangeably.

d. Comparison of Analyses by Pipette and Coulter Counter. As most of the grain size distribution analyses reported in the literature for silt and clay particles utilize the pipette-Stokes Law procedures (Folk, 1974; Galehouse, 1971), it is advantageous to this report to compare the results obtained using a Coulter Counter with those of the more traditional method. Swift, Schubel, and Sheldon (1972), Shideler (1976), and Behrens (1978) all present dicussions bearing on the subject.

Results obtained by the two methods are not expected to be identical. Each measures a different characteristic and uses that to infer the diameter of a sphere having the same characteristic. The pipette method indirectly measures fall velocity which, when with certain assumptions is used in the equation for Stokes' Law, yields the diameter (or radius) of a sphere that has the same fall velocity. Fall velocity is influenced by, among other things, both the specific gravity and shape of the particle. As fine particles are platelike, the shape factor is quite important as it results in fall velocities much lower than that of a sphere of equivalent volume. The Coulter Counter makes an indirect measurement of particle volume and assuming that as the volume of a sphere, determines the diameter. The other significant difference between the methods is the nature of the distribution each observes. The pipette distribution is open ended; that is, given proper laboratory conditions, it is possible to analyze through the full range of silt and clay sizes. Pipette results yield the cumulative percent-coarser-than, thus if the procedure is not carried to completion, the results may terminate at appreciably less than 100 percent. The Coulter Counter uses only a limited size range (approximately 4 Ø through 10 Ø in this study) and the results are given relative to the range used. The contribution of the particles outside the machine's range is omitted from consideration. Thus the distribution as defined by the Coulter Counter always closes at 100 percent.

With these considerations, one would expect that the distribution depicted by the Coulter Counter would be coarser and better sorted than that shown by pipette analysis. Indeed this is noted by both Shideler and Behrens and is apparent in comparisons made for this study (Figure 11). In addition to the two reasons just discussed, Shideler offers a third factor contributing to the Coulter-pipette difference. This is the error that occurs when two or more particles simultaneously pass through the Coulter Counter's aperture and are sensed as a single, larger particle. With proper sediment concentrations, this "coincidence error" should be less than 3 percent. Behrens maintains that the most significant contribution to the difference in results between the two methods is the omission artifact resulting from the arbitrary truncation of the distribution by the Coulter Counter.

Analysis of 20, or approximately 1 percent, of the Chesapeake Bay sediment samples by both methods yields results which display the expected differences. Figure 11 depicts the grain size distributions as determined by both methods of the mud portion of one of the samples. The figure also shows a plot of the pipette data adjusted or normalized to the Coulter Counter end point. The Coulter Counter and adjusted pipette data are nearly identical, agreeing with Behren's statement. Although not all of

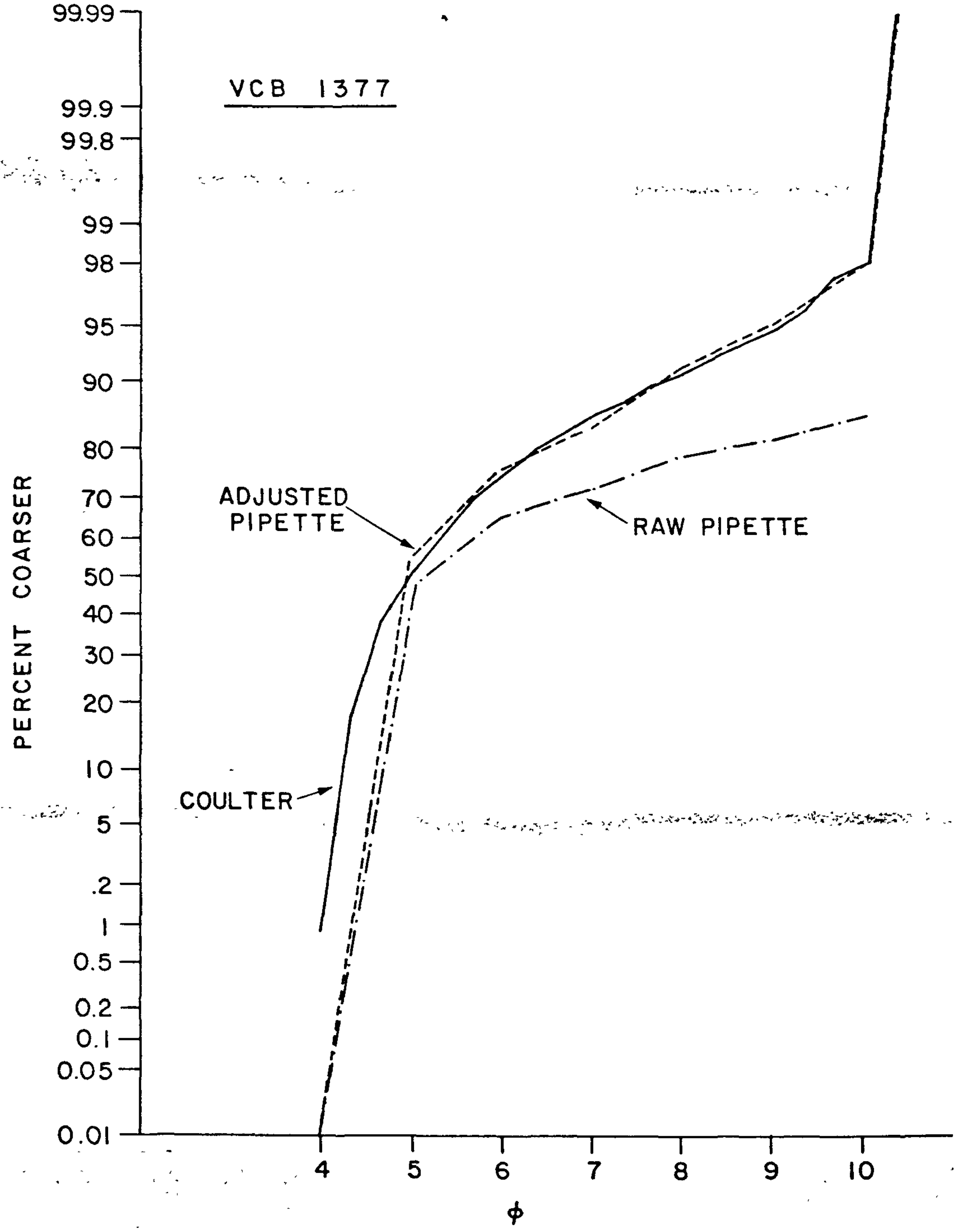


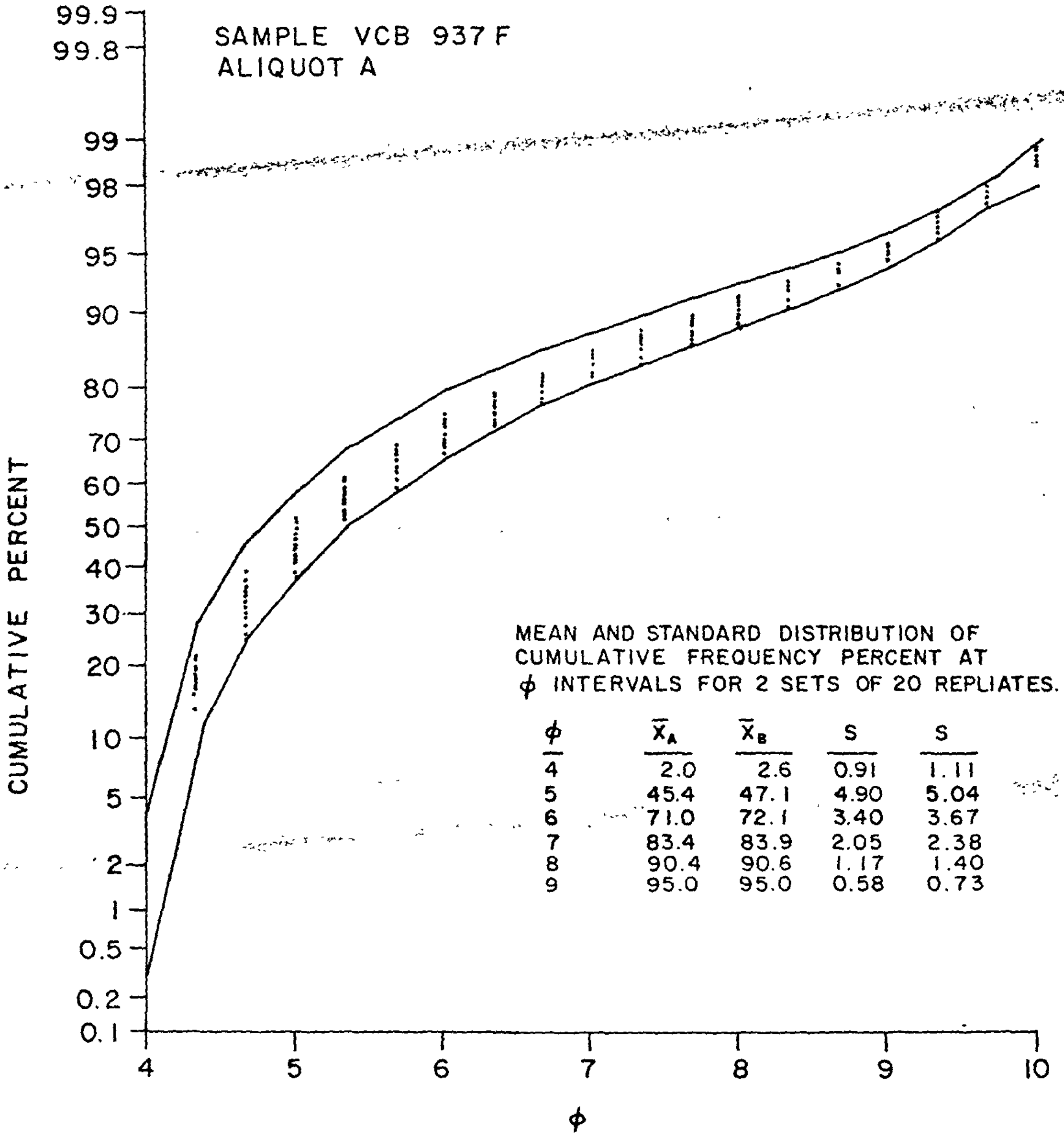
Figure 11. Comparison of frequency distributions as determined by pipette and Coulter Counter techniques. The distribution as determined by pipette but adjusted or normalized to the Coulter Counter's end point is also shown.

the plots for the 20 pairs are as close as the example, none vary significantly. Assumedly, the difference between the end of the unaltered pipette data and 100 percent is the material finer than 10 Ø.

The reasons for using the Coulter Counter in preference to the more traditional pipette method are several. Using the Coulter Counter, individual analyses can be completed in a fraction of an hour, whereas the pipette method is much more time-consuming. Although several pipette analyses can be run concurrently, analysis to 10 Ø takes upwards of 15 hours with dramatically greater times required for finer sizes. Galehouse (1971) states that pipette analysis probably should be ended at 8 or 9 Ø unless laboratory conditions can be maintained stable for long periods. Swift, Schubel, and Sheldon (1972) speak of the advantage of the short time required for complete analyses by Coulter Counter. It is possible to interpolate the distribution from the end point of the pipette analysis to 100 percent at 14 Ø (Folk; 1974), there is question as to the validity of the data so obtained (Galehouse, 1971). Also, as the pipette analysis requires a great number of finely timed, carefully executed steps, there are a number of opportunities for error. Although the Coulter Counter also is subject to operator error, there are few separate phases in the analysis and possibly a lesser opportunity for operator caused errors. Shideler makes reference to other studies (Interagency Committee on Water Resources, 1964; Allen, 1968) which "indicate that the accuracy of electronic sensing is probably superior to that of any other commonly used technique suitable for routine analysis." If the Coulter Counter were not available, it would have been impossible to perform the number of analyses reported for this study.

e. Coulter Counter Precision. The precision, or reproducibility, of the Coulter Counter is, within limits, quite acceptable. Shideler (1976) stated that comparison of the curves from triplicate analyses of two samples each analyzed by both Coulter Counter and pipette suggested a greater precision for the more modern technique. A similar procedure, 20 replicates of each of two aliquots of the same sample, also indicates the relative precision of the technique. Figure 12 is a plot of the envelope of one set. When superimposed on the similar plot for the other 20 replicates, the two are indistinguishable from one another, indicating a high degree of reproducibility. The thickness of the envelopes, however, detracts somewhat from the confidence one might have in the precision.

This aspect of the precision perhaps is explained by the data in Figure 13. For the first 10 or so replicates, the reproducibility appears very satisfactory with no apparent trends in the data. The later observations, however, tend towards decreasing values, especially for the coarser particles. This most likely is an artifact of the sample size and not of the instrument or operator. As successive small quantities of the dilute sediment-water mixture are withdrawn from the vial for analysis, the remaining suspension is progressively less representative of the whole. Also, as the coarser particles are relatively fewer in number, their progressive depletion may have a pronounced impact on the overall remaining particle-size distribution.



MEAN AND STANDARD DISTRIBUTION OF CUMULATIVE FREQUENCY PERCENT AT ϕ INTERVALS FOR 2 SETS OF 20 REPLIATES.

ϕ	$\bar{X}_A$	$\bar{X}_B$	S	S
4	2.0	2.6	0.91	1.11
5	45.4	47.1	4.90	5.04
6	71.0	72.1	3.40	3.67
7	83.4	83.9	2.05	2.38
8	90.4	90.6	1.17	1.40
9	95.0	95.0	0.58	0.73

Figure 12. Plot of the envelope described by the cumulative frequency distribution of 20 replicate Coulter Counter analyses and a table of the means and standard deviations of the cumulative frequency at whole ϕ intervals for 2 sets of 20 replicates of the same sample.

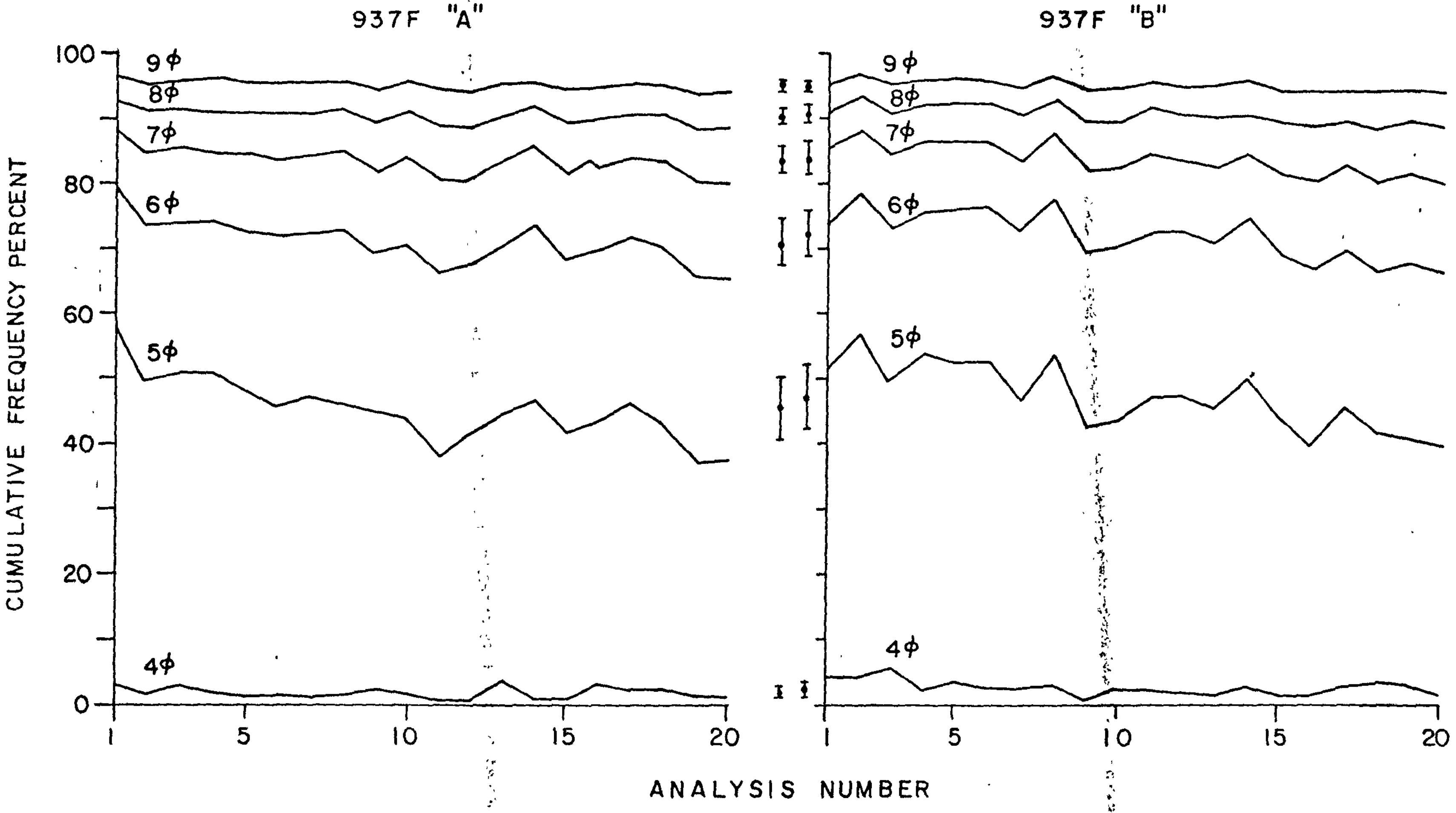


Figure 13. Plot of the cumulative frequency percents at 1 ϕ intervals for 20 replicates of each of 2 aliquots of the same sample. The vertical bars between the plots represent the means ± 1 standard deviation of the adjacent data.

Therefore, it appears that the precision of the Coulter Counter analyses is quite satisfactory as long as care is maintained to assure that the sample analyzed is representative of the whole.

f. Quality Assurance - Carbon and Sulfur Analyses. There were four major elements to the quality assurance program which was developed and implemented for the analyses of the carbon and sulfur content of sediments. These elements were 1) personnel and procedures, 2) reagents and other supplies, 3) records, and 4) the statistical interpretation of the quality assurance statistics. A brief discussion of each of these areas follows.

Personnel: The majority of the analytical work was performed by technicians and/or graduate assistants. Prior to initiating analyses, all the equipment operators reviewed both the manufacturer's operations manuals and the laboratory's protocol and operating guides.
Then they followed a "hands on" learning process working directly with experienced technicians.

Reagents and Supplies: All reagents, chemicals, gases, and standards used were of analytical quality and were purchased from appropriate manufacturers or supply houses.

Records: Several, sometimes redundant, formats were used to record and track the hundreds of samples and analyses. A master log was used to list each sample and record the various procedures or analyses that had been performed on each sample. A second set of records was kept to record the specific analytical data and results for each sample. Additionally, another log was kept to record the results of instrument calibrations and standards. Finally the statistical comparisons of sample pairs were calculated and plotted to see if the duplicate analyses fall within satisfactory limits.

Interpretation: Statistical interpretation of the quality assurance information was accomplished in two forms. Accuracy was checked using a percent recovery technique which utilized known standards. Precision, or the ability to obtain consistent results, was monitored with an industrial control statistic,

$$I = \frac{/A - B/}{/A + B/},$$

where A and B are the values from duplicate analyses of aliquots of the same sample. As the total carbon and organic carbon analyses are identical, only total carbon and sulfur were tracked for accuracy. Both procedures follows EPA (1979) formats.

The percent recovery was calculated as the ratio of the observed value to the actual value of the commercially purchased standards. The results of the first 50 analyses of standards were used to establish the general control limits for future analyses. The mean and standard deviation of the carbon analyses were 98.5% and 1.4% respectively. The EPA (1979) procedures set the control limits as plus or minus 3 standard deviations about the mean; hence the accuracy control limits for the carbon analyses were 102.7 and 94.3 percent recovery. Less than 10% of the observations were outside the control limits. The majority of these observations were traced to procedural errors or instrument malfunction. All observations were plotted promptly and there were no consistencies or trends apparent in the out-of-control samples.

The average percent recovery of the first 50 sulfur standards was 90.2% with a standard deviation of 5.5%; thus the control limits were 106.7% and 73.7%. All observations fell within two standard deviations of the mean, well within the control limits.

The control limit for the industrial statistics used in the evaluation of precision is equal to the average range of the absolute value of the differences between duplicate determinations multiplied by 3.27, the Shubart factor calculated for duplicate analyses. If the difference between duplicates of a particular sample exceed the control limit, the analysis is repeated until duplicate determinations are within control limits. The control limits, calculated on the basis of the first 25 duplicates, were 0.339 for total carbon, 0.268 for organic carbon, and 0.095 for sulfur. Due to the great number of analyses, several persons assisted with the visual examinations of the graphs of the industrial statistic for each set of analyses in order to assure that all out-of-control samples were noticed and corrected.

B. FORMULATION OF SEDIMENT BUDGET

The estimation of the sediment budget for the Virginia portion of the main-stem of the Chesapeake Bay involves the comparison of the residual sediment mass as determined for a 100-year period. This estimation treats the Bay as a "sink" for sediments derived from various "sources." The determination of the residual sediment mass utilizes the method of comparing corrected bathymetric data from the 100-year interval of (approximately) 1850 to 1950 to discern the patterns of sedimentation and erosion. This information, coupled with the data obtained from the 2,000 samples of the surface sediment, enables one to estimate the mass of sediment deposited in the Bay, both in total and in terms of the separate masses of sand, silt, and clay. The calculations require the synthesis of several sets of data and the acceptance of several assumptions. The most important of these assumptions are:

1. That the surficial sediments sampled are representative of the sediment column beneath. As such, we assume the sand:silt:clay ratios observed at the surface are constant over the sedimentation lengths calculated for the 100-year period. This is a <u>necessary</u> assumption for the estimation of residual sediment mass.

2. That the <u>sense</u> of the depth difference reflected in the bathymetric comparison are representative of conditions at the time of sediment sampling (1979-1980). For example, at a given point the bathymetric comparisons between 1850 and 1950 may indicate a net loss of sediment (a net erosional condition). In such a circumstance we would expect a reduced water content in a surface sediment sample due to

compaction. In fact, however, we may find that the sample station exhibited a high water content indicative of recent deposition. This is ignored in our calculations as the conversion from sediment volume to mass would use the "high" water content and thus underestimated the mass of sediment "eroded". Again, we have utilized a necessary assumption. It is particularly noteworthy that the sedimentation dynamics associated with the passage of the high, fresh water discharge due to Hurricane Agnes in 1972 may have temporarily switched an area of erosion to one of deposition. Or, even more dramatically, there may have been erosion followed by deposition at a given site during the respective onset and relaxation of the event.

In order to array the bathymetric and sedimentological data at a common level, the information was smoothed to a 0.5 minute grid using a pseudo-two-dimensional, bicubic, spline-fitting program. This program was used separately with the roughly 40,000 corrected bathymetric-comparisons (Figure 14) and with the sediment information from the 2,000 or so sediment samples.

Thus, at the center of each 0.5 minute grid cell there were interpolated values of sedimentation rates (based upon corrected water depth comparison), surface sediment water content, and percentages of sand, gravel, silt, and clay. The surface water content was used to estimate the average water content over the sedimentation distance. Then the average water content was used to convert the sedimentation rate to total mass accumulation rate which, in turn, could be partitioned to component values of sand, silt, and clay. The depositional patterns of the sand, silt, clay components might be expected to be depth dependent and, as well, latitudinally variable. Accordingly the final tabulation was arrayed into 66 one-minute north-south intervals (38°00' to 37°59' = zone 1) with depth stratification into eight depth zones (0-6 ft., 6-12 ft., 12-18 ft. 18-24 ft., 24-30 ft., 30-36 ft., 36-42 ft., and > 42 ft.).* Finally, as the western part of the Bay may exhibit different behavior than the eastern part, the array was further divided into six sub-segments: the western shore and eastern shore divided by the Bay thalweg, eastern and western sides of Smith-Tangier Islands, Pocomoke Sound, and Mobjack Bay (Figure 14).

Within a given one-minute, depth-bounded latitude slice:

a. the area was approximated as the sume of the elemental 0.5 minute cells with centerpoints within the depth limits.

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*Because the original bathymetry is in feet, or fathoms, many of the calculations were performed using feet. Thus some of the intermediate results discussed in this report are presented in English units, 1 meter equals 3.28 feet, 1 inch equals 2.54 centimeters, 1 metric ton equals 1.1 English tons.

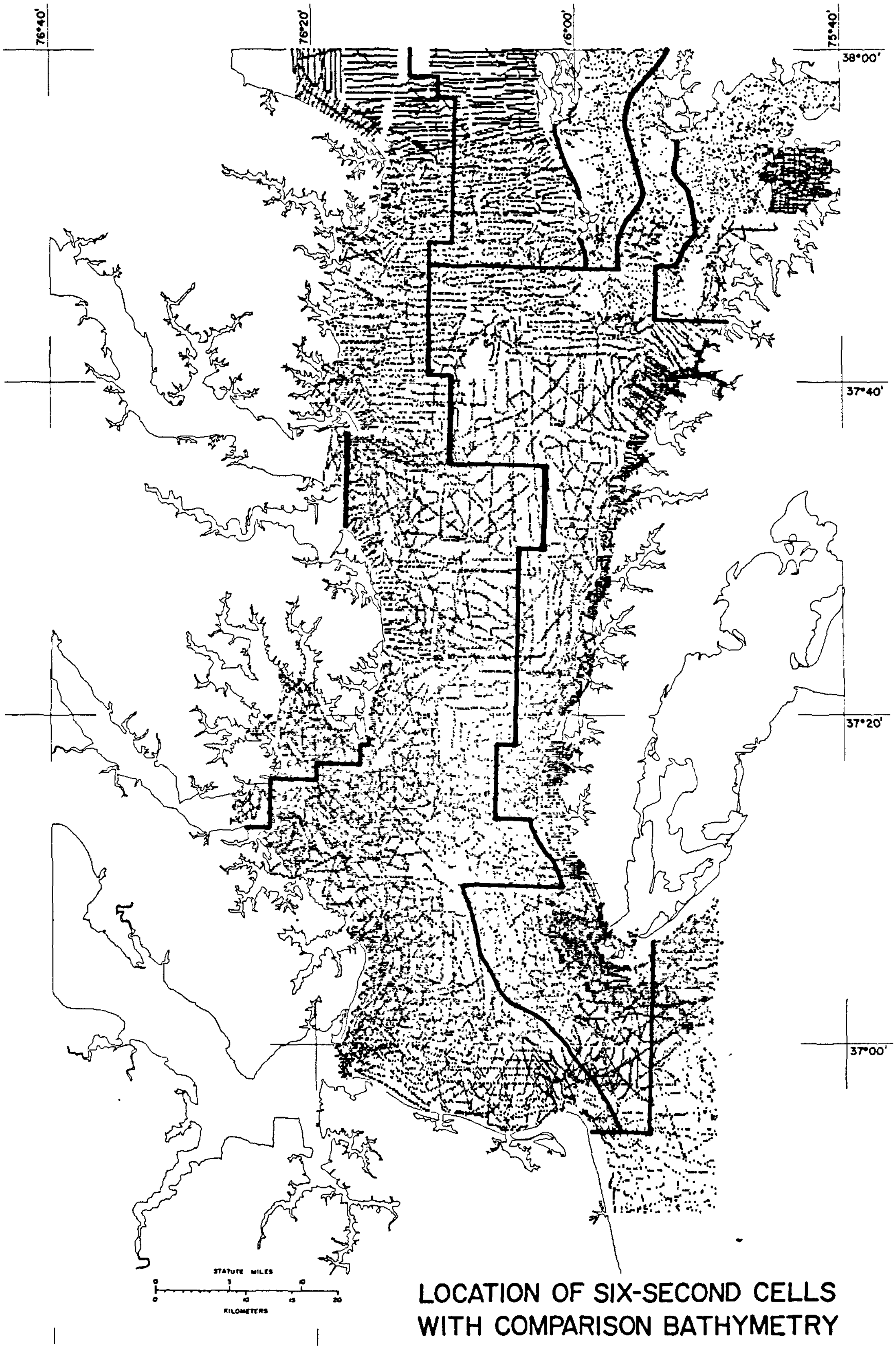


Figure 14. Location of 6-second cells with bathymetric comparisons and bay sub-segments.

b. the average sedimentation length (and rate) was computed by dividing the cumulative 5.0 minute cell volumes, prorated to 100 years, by the total area.

c. the accumulated masses of sand, silt, and clay were calculated from the sum of the contributions from each 0.5 minute call to yield mass of sand (and gravel), silt, and clay per 100 years.

The process flow chart is shown in Figure 15 and the details of the calculations of depth difference, and conversion of sediment volume to sediment mass follow.

1. Bathymetric Comparisons. The elemental information available consisted of the most recent bathymetric information (circa 1950) available from NOAA (EDS) wherein the average depth within six-second (approximately 150 x 200 m) cells were listed on magnetic tape, and the bathymetric "boat sheets" of circa 1850. The latter were partitioned into identical six-second rectangles and the depths within were algebraically averaged. Thus, the basic data set for bathymetric comparisons were those six-second cells for which there were recorded depth data for both survey periods. The boundaries of the respective surveys are shown in Figures 16 and 17. Approximately 40,000 grid points (out of a possible 420,000) were obtained (Figure 14). The time difference between surveys ranged from 85 to 110 years but the preponderance was between 95 and 100 years.

In order to rectify the two data sets to the same mean-low-water datum, it was necessary to consider three corrections (Carron, 1979);

a. eustatic sea level change,

b. crustal changes, and

c. semi-annual and annual tidal variations.

Eustatic sea level change was assumed to be 1 mm per year. The correction was applied to the number of years between the center of the 1950 tidal epoch (1950) and the survey date for the 1850 series survey.

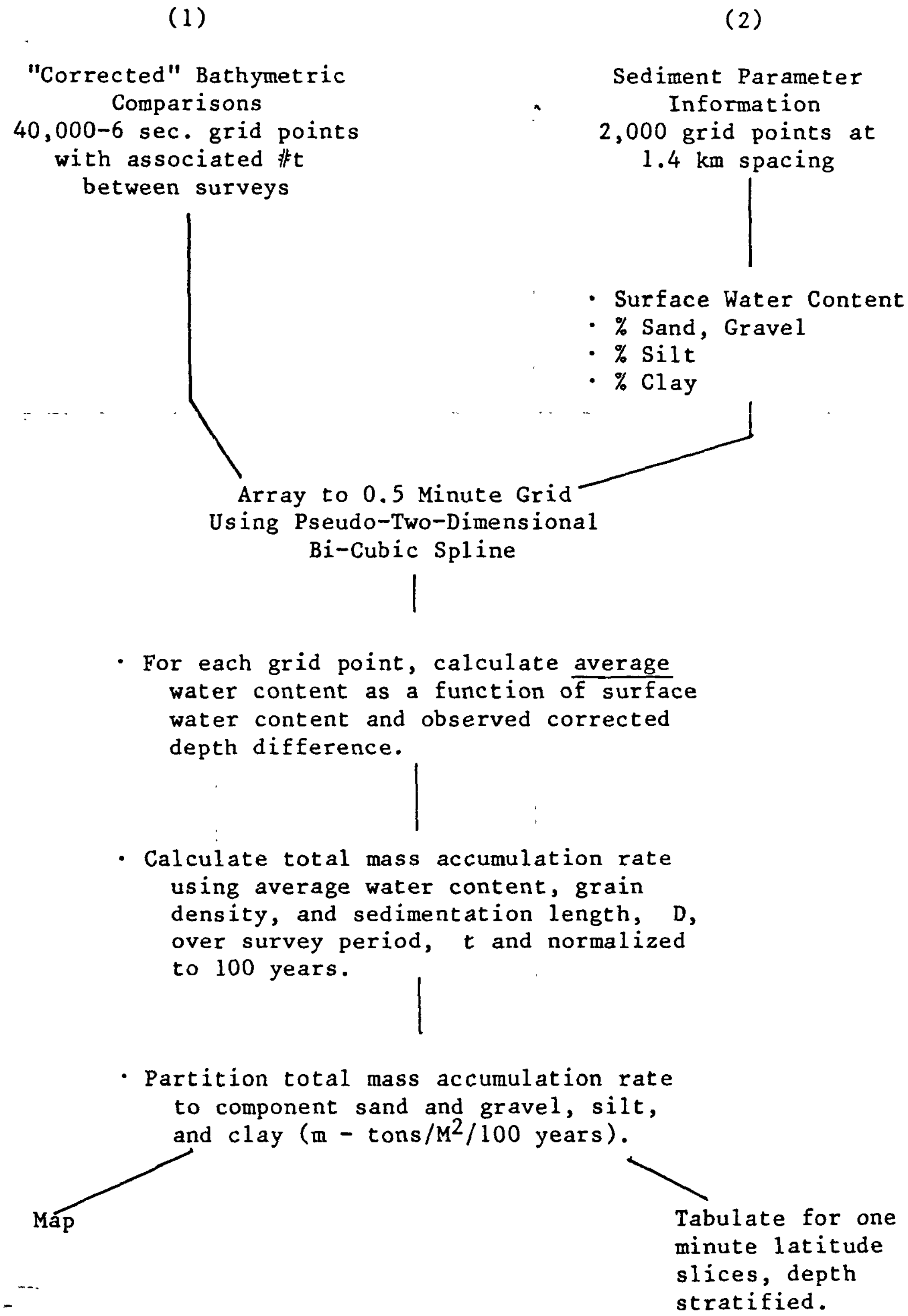
Crustal changes which would appear to be bottom erosion (all changes were downward), when in fact no mass balance change took place, were accounted for by applying a fifth order trend surface equation to the data of Holdahl and Morrison (1974) (Figure 3), giving vertical crustal movement rates for the same period used in this sedimentation and erosion study.

Semi-annual and annual tidal variation (Figure 18) corrections were applied to the 1850-series data to correct for seasonal deviations of observed mean low water from long-term mean low-water.

However, it is important ot note that no corrections were attempted to estimate the depth differences solely due to compaction of the bottom sediments. While negligible for sandy sediments, the effect of compaction in fine-grained sediments over one hundred years could be significant.

FIGURE 15

FLOW CHART FOR RESIDUAL MASS ESTIMATES



(1)

"Corrected" Bathymetric
Comparisons
40,000-6 sec. grid points
with associated #t
between surveys

(2)

Sediment Parameter
Information
2,000 grid points at
1.4 km spacing

- Surface Water Content
- % Sand, Gravel
- % Silt
- % Clay

Array to 0.5 Minute Grid
Using Pseudo-Two-Dimensional
Bi-Cubic Spline

- For each grid point, calculate average water content as a function of surface water content and observed corrected depth difference.

- Calculate total mass accumulation rate using average water content, grain density, and sedimentation length, D, over survey period, t and normalized to 100 years.

- Partition total mass accumulation rate to component sand and gravel, silt, and clay (m - tons/M^2/100 years).

Map

Tabulate for one
minute latitude
slices, depth
stratified.

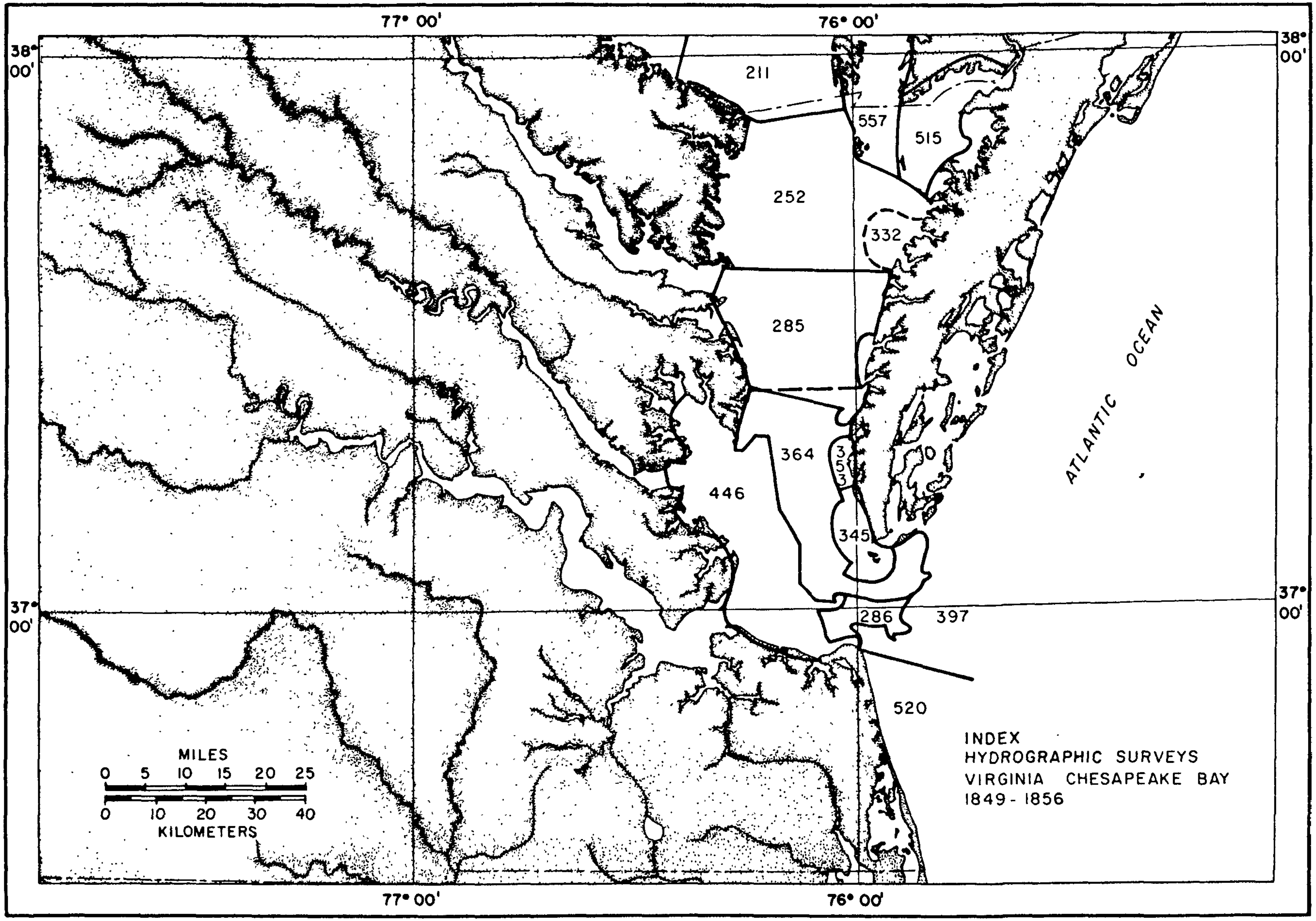


Figure 16. Index map of the bathymetric surveys from 1849-1856.

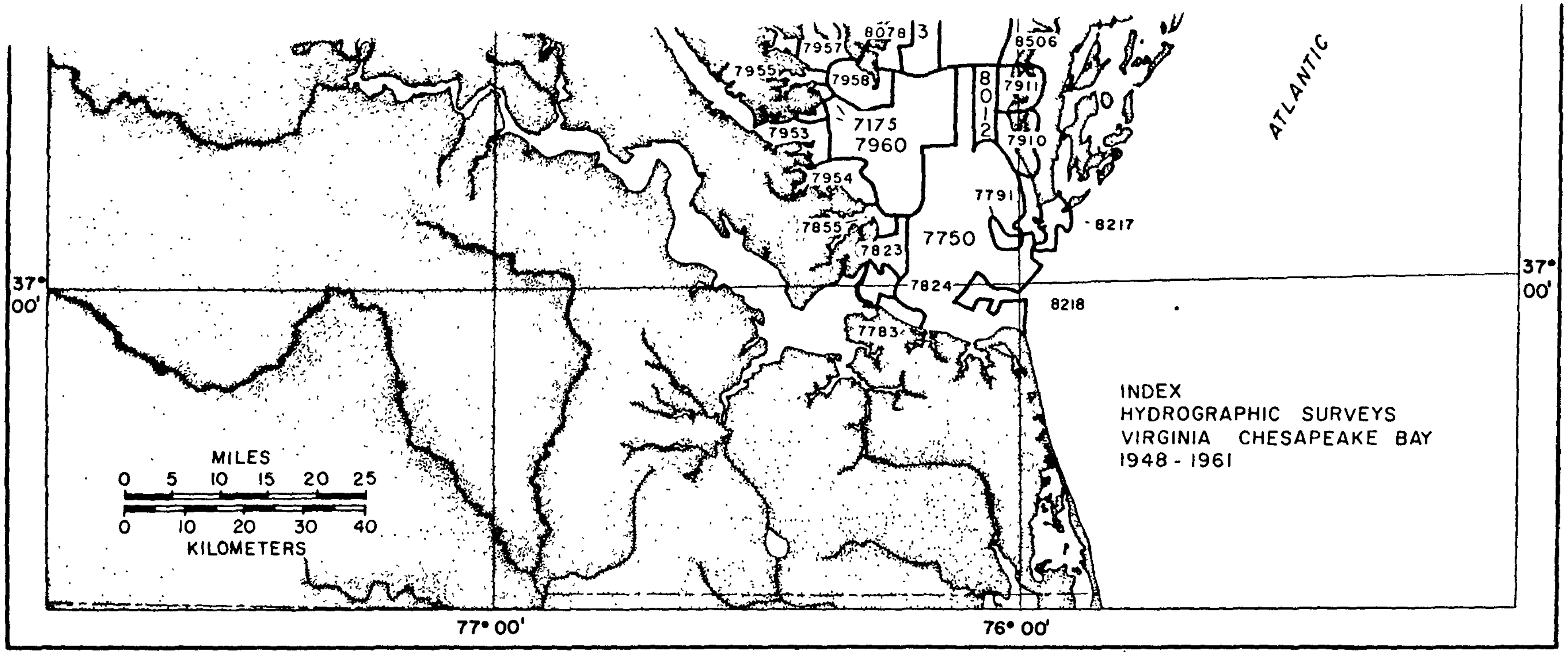


Figure 17. Index map of the bathymetric surveys from 1948-1961.

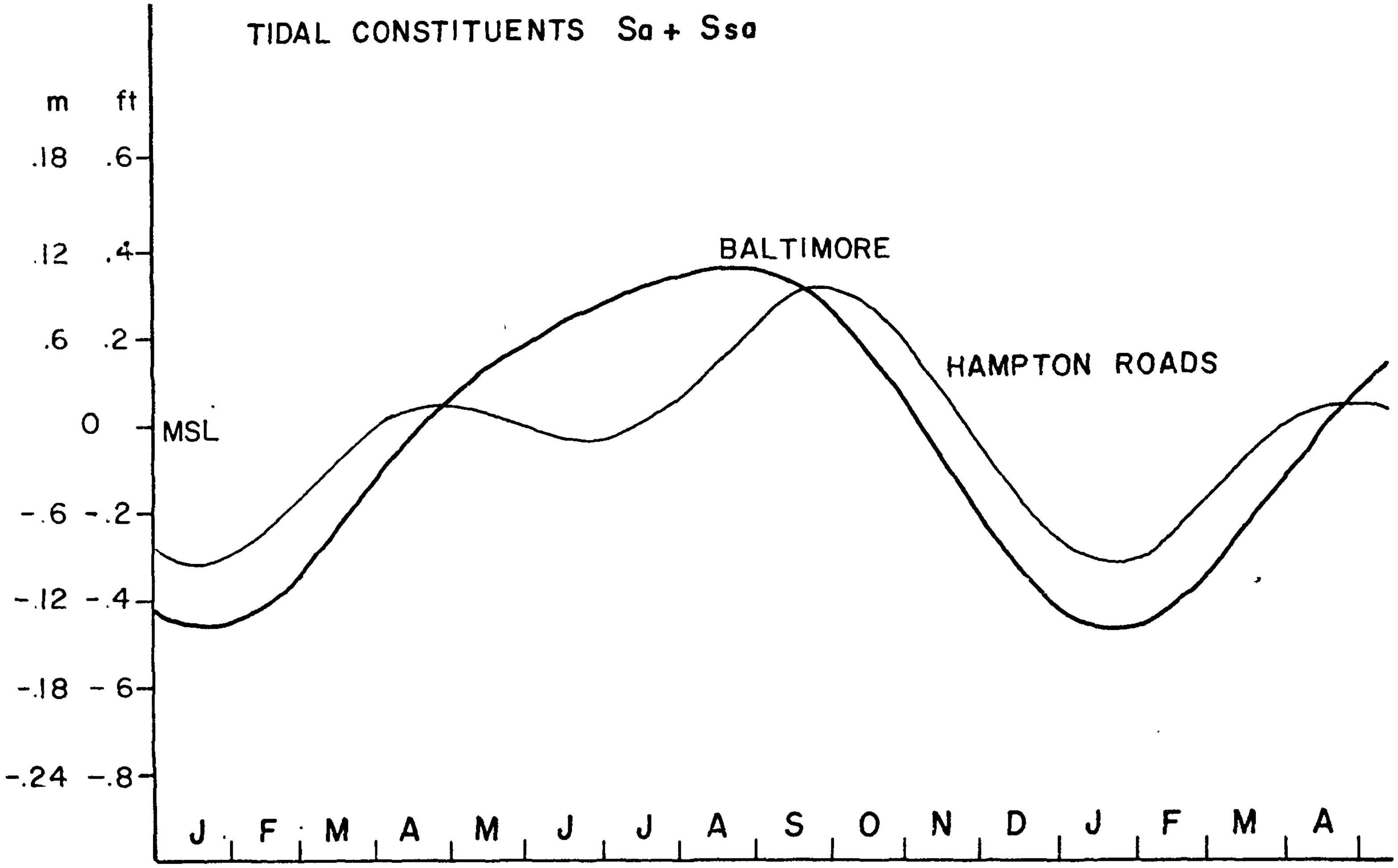


Figure 18. Tidal variation used in the reduction of sea-level data (from Carron, 1979).

In addition, no corrections were attempted to compensate for the fact that lead-line methods were used in the surveys of the 1800s whereas echo sounding techniques were employed in the 1950s surveys. Again the difference would depend upon the grain-size characteristics of the bottom sediments. In sandy materials and at shallow to moderate depths, the two techniques would be comparable. In muddy sediments, significant differences might exist (Watts, 1954), and these errors would be particularly sensitive in areas of very high water content, such as where fluid muds are encountered. Other studies have not disclosed such conditions within the main stem of the Bay in Virginia (Nichols, personal communication). Moreover, as the larger survey vessels calibrate the echo sounder against lead-line determinations, the differences would be partially rectified in sediments with intermediate water contents.

The corrections applied are shown schematically in Figure 19 and given as follows:

a. We assume the 1850 surveys have not been rectified for monthly variation in MTL (or MLW). This correction is applied from Figure 18 as follows (Figure 19A):

$$D_o = D_o' - T \tag{1}$$

where D_o' is measured old depth, D_o is corrected depth for monthly variation in MTL (MLW) relative to annual MTL (or MLW).

b. The new depth, D_n, may then be cast in terms of then old depth, D_o', as follows (Figure 19A):

$$D_n = D_o + E \cdot \Delta t + (C \cdot \Delta t - \Delta D),$$

since $D_o = D_o' - T$

$$D_n = D_o' - T + E \cdot \Delta t + C \cdot \Delta t - \Delta D \tag{2}$$

where D_n = measured new depth,

D_o' = measured old depth,

T = correction for monthly variation from annual datum,

E = eustatic sea level rise rate,

C = subsidence rate,

Δt = period between surveys,

ΔD = sedimentation distance over period Δt.

Solving Equation (2) for ΔD yields

$$D = D_o' - D_n + E \cdot \Delta t + C \cdot \Delta t - T. \tag{3}$$

The sedimentation rate, S, normalized to a 100-year period is then

$$S = \frac{D}{t} \cdot 100 = \frac{D_o' - D_n + E \cdot \Delta t + C \cdot \Delta t - T}{\Delta t} \qquad (4)$$

The above noted "corrections" take into account depth difference biases which may amount to about 0.6 meter.

As previously mentioned, the corrections do not include the effects of sediment compaction as shown in Figure 19B for an otherwise rectified situaiton. Layer 1, deposited in 1850, may have become thinner due to expulsion of water through time and due to overburden of new sediment. The bathymetric comparison would yield ΔD and thereby underestimate the total sedimentation by ΔS, the component due to compaction. The thickness of the layer Δ would depend upon the vertical, water-content profile and the rate of sedimentation.

In addition to the corrections noted above, the propagation of error in the sounding comparisons must be considered. Each of the separate surveys contains error, and, as well, the comparison between surveys embodies error. For a given survey, the principal errors are in accuracy of locating a hypothetical site, and the variability of repetitive soundings at a fixed site.

The surveyors were aware of the problem of accuracy and, as a check on their data, ran crossing survey lines. If the differences of the crossing vlues for particular water depths were within given limits (Sallenger *et al.*, 1975), the bathymetry was acceptable. For example, criteria adopted in 1955 quote a maximum allowable difference between depth measurements at 0.3 m for water depth less than 20 m.

As a means of quantifying absolute sounding error, we examined the crossing differences from both the 1850s and 1950s data. The crossing differences are the absolute values of the differences in depth from two lines of bathymetry where the lines cross. Because soundings from separate lines were seldom coincidental, crossing values were derived from linear interpolation along the separate lines. In neither survey were crossing differences related to depth.

For two soundings at the "same location" (*i.e.* a crossing) we have

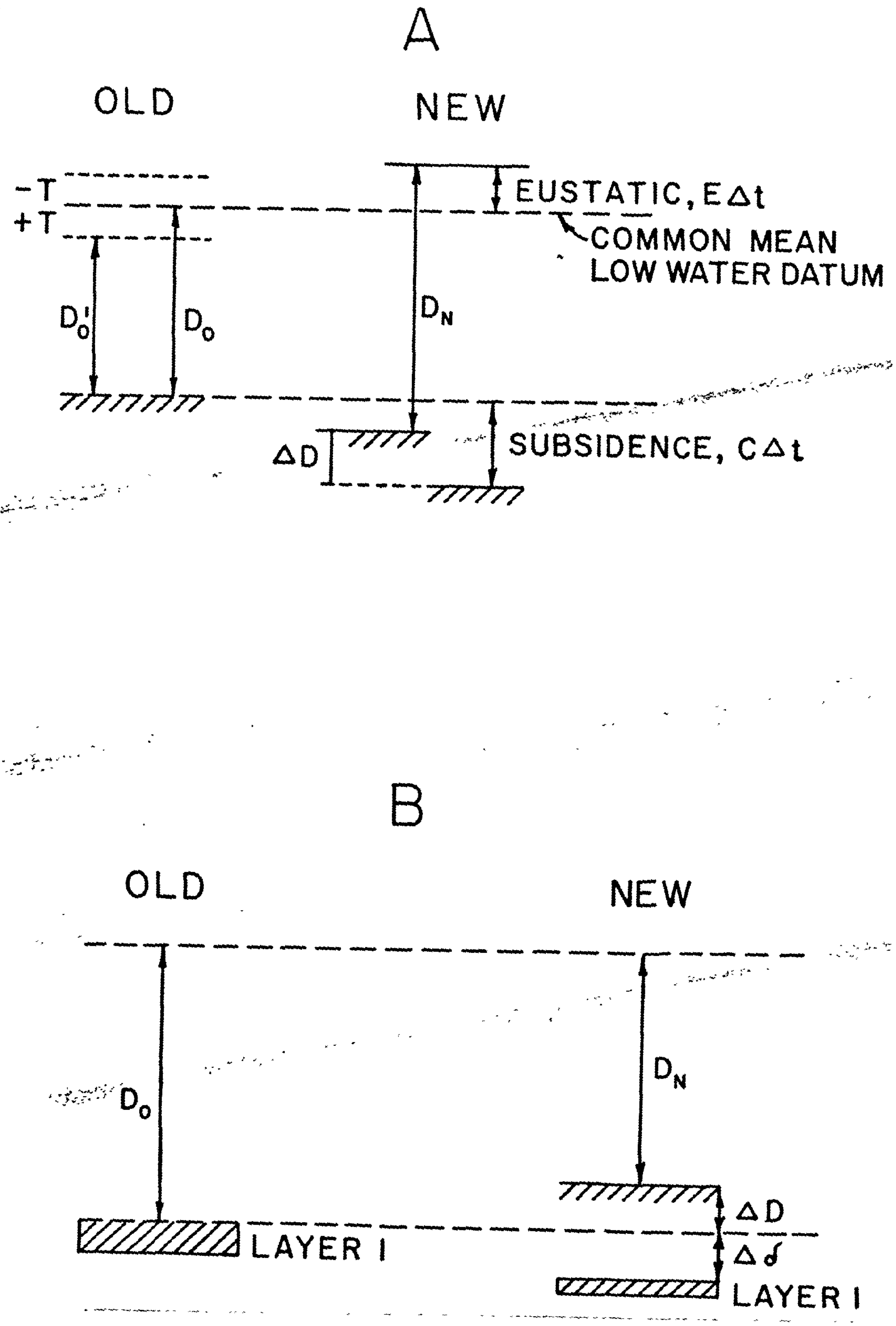
$$a = d + E_a$$

$$b = d + E_b$$

where a and be are the soundings at a crossing, d is the true depth, and E_a, E_b are the respective errors from d. The difference is

$$a - b = E_a - E_b \text{ and}$$

$$(a - b)^2 = E_a^2 - 2E_aE_b + E_b^2$$



Schematic diagram of corrections applied to bathymetric change data.

For comparisons at a large number of locations we assume E_aE_b is small compared to the squared terms and that $\sigma E_a^2 \approx \Sigma E_b^2$. Furthermore, if E_a and E_b are random deviations with zero mean and the same standard deviation then the variance is approximated as:

$$\sigma^2 = (1/2)\overline{(a - b)^2}$$

Calculations for the 1850's and 1950's survey series give, respectively, $\sigma_1^2 = 3.03$ ft^2 and $\sigma_2^2 = 0.52$ ft^2 for sample sizes of $N_i = 351$ and $N_2 = 691$.

The pooled variance arising from the comparison of individual soundings at a given location is:

$$\sigma_{1,2}^2 = \sigma_1^2 + \sigma_2^2 = 3.55 \text{ ft}^2, \text{ and}$$

the standard deviation

$$S_{1,2} = \pm 1.88 \text{ ft } (\pm 0.57 \text{ m})$$

The 95% confidence interval is 1.96 $S_{1,2}$ or ± 3.68 ft (± 1.12 m). Thus, for a comparison between co-located individual depths on separate surveys, a depth difference greater ± 1.12 m has a 5% probability of being to survey error.

While the above applies to the comparison of individual co-located depths, our comparison procedures should reduce the error as the average depths within co-located six-second sedon grid cells are compared. Furthermore, this grid cell sampling density is further smoothed by application of the bi-cubic spline. However, the degree of potential error reduction has not been evaluated.

2. Conversion of Sedimentation Rate to Mass Accumulation Rate. Recall that each 0.5 minute grid point had interpolated values of the sedimentation length (≡ corrected comparative depth difference), surface water content, and the percentages of sand, silt, and clay. The sedimentation length (+ as accumulation, - as erosion) when applied to unit area, a square meter, yields cubic meters of change in sediment volume per square meter of surface. Once the volume of deposition or erosion per unit area at a site has been calculated, the problem is to convert the volume, a mix of solid (mineral) sediments, shell, organic sediments, and water to the mass of dry, mineral sediment. In order to arrive at the number of metric tons of dry, non-organic sediment deposited per square meter, it is necessary to discount the volume of water and the mass of organic material from the volume of material deposited.

The most significant problem in the procedure for conversion from wet volume to dry mass is estimation of a value for the average water content over the estimated sedimentation length when given only the surface water content. Although an exponential-like decrease in water content with depth may be expected for uniform sediment material, the exact form of the equation cannot generally be stated since the water content (or porosity) gradient is also dependent upon the uniformity and rate of sediment accumulation.

In this study, the water content gradient with depth, as a function of surface-sediment water-content, was estimated using approximately fifty (50) short (1 meter) gravity cores obtained in 1978 and 1979 by the MGS for study of interstitial water chemistry (Figure 20). Their analysis included determination of the water content gradient and a log of sediment type. The surface water content of these cores varied from over 80% to less than 20%. The water content profiles were then grouped into 10 percentum surface water content classes. These class groupings are exemplified in Figure 21 where it may be noticed that most of the profiles fall within an envelope monotonically decreasing values of water content with depth. However, some of the profiles depart from the envelope with either a dramatically nonmonotonic behavior or otherwise wide departure from the general grouping (i.e. VA 78).

The second step was to shift all of the profiles exhibiting "normal" behavior within a class group to a common surface origin (Figure 22). An "average" profile for the class group was then drawn. At this stage in the process any profile with a surface water content within a particular 10 percentum class interval would be estimated by the averaged profile for that class.

The depth averaged water content was then determined at 10 cm depth increments for each "average" water content profile. For any given depth in the core, the depth-averaged water content of the overlying material could then be expressed as a deficit relative to the value of the surface water content. A nomogram (Figure 23) was prepared for this purpose. Values for water content at between 1 and 2 meters are extrapolations. Observation indicated that when the surface water content in a core was less than about 30% there was little variation with depth, and have thus been treated as constant.

Again, recall that each 0.5 minute grid point had an associated value for sedimentation length (+ or -), and a value for surface water content. The nomogram (Figure 23) was applied in tabular form (Table 7) at each point wherein the sedimentation length, ΔD, and surface water content, were used to calculate an average water content for the pertinent ΔD, value.

If we assume zero gas content and ignore the salt evaporate, the dry mass of sediment per unit volume of wet sediment may be expressed as:

$$M = \frac{\rho s\ (1 - \bar{W}_c)}{(\rho s - \rho f)(W_c + 1)}$$

where ρs = sediment grain density,

ρs = water density,

$\bar{W}_c$ = average water content.

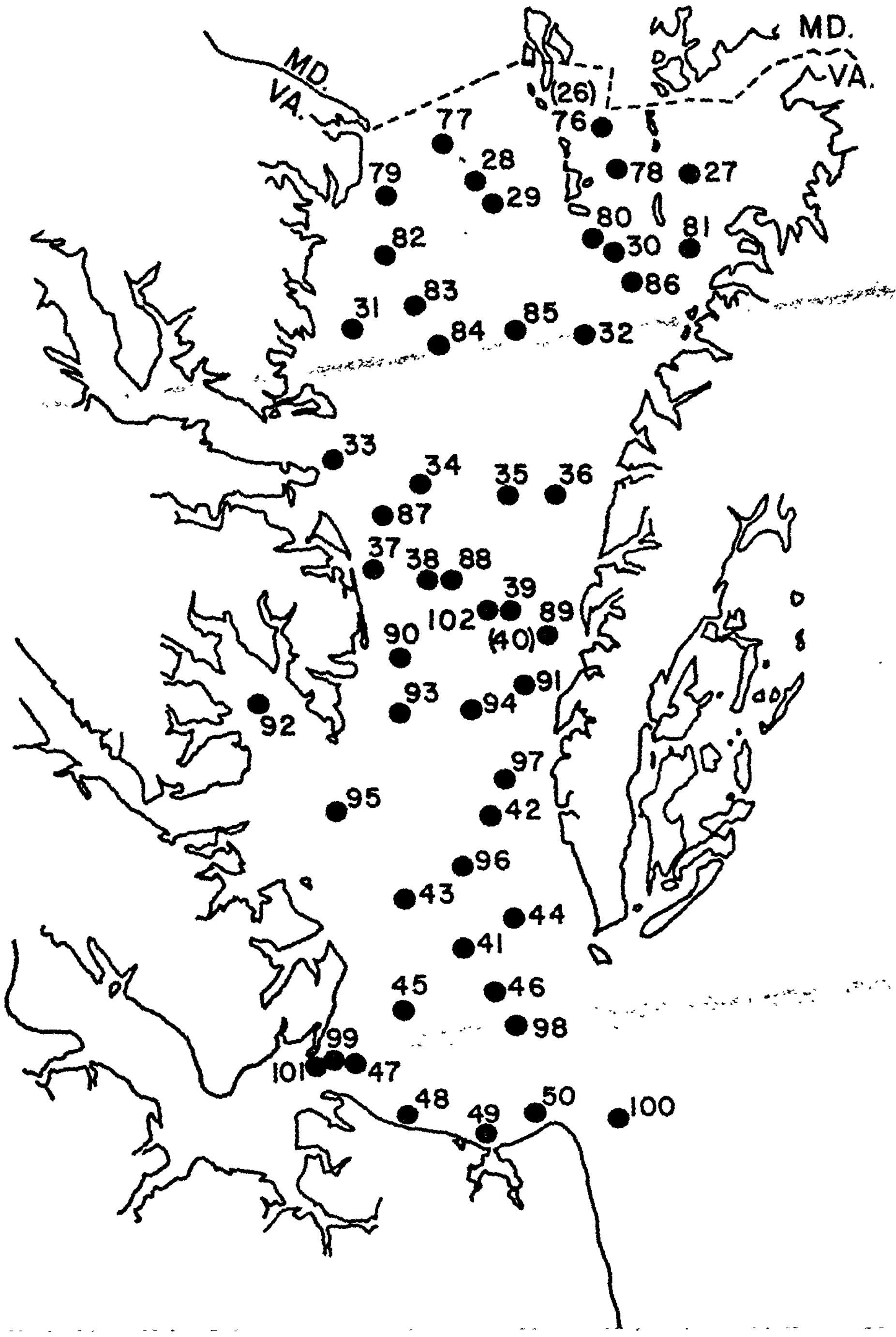
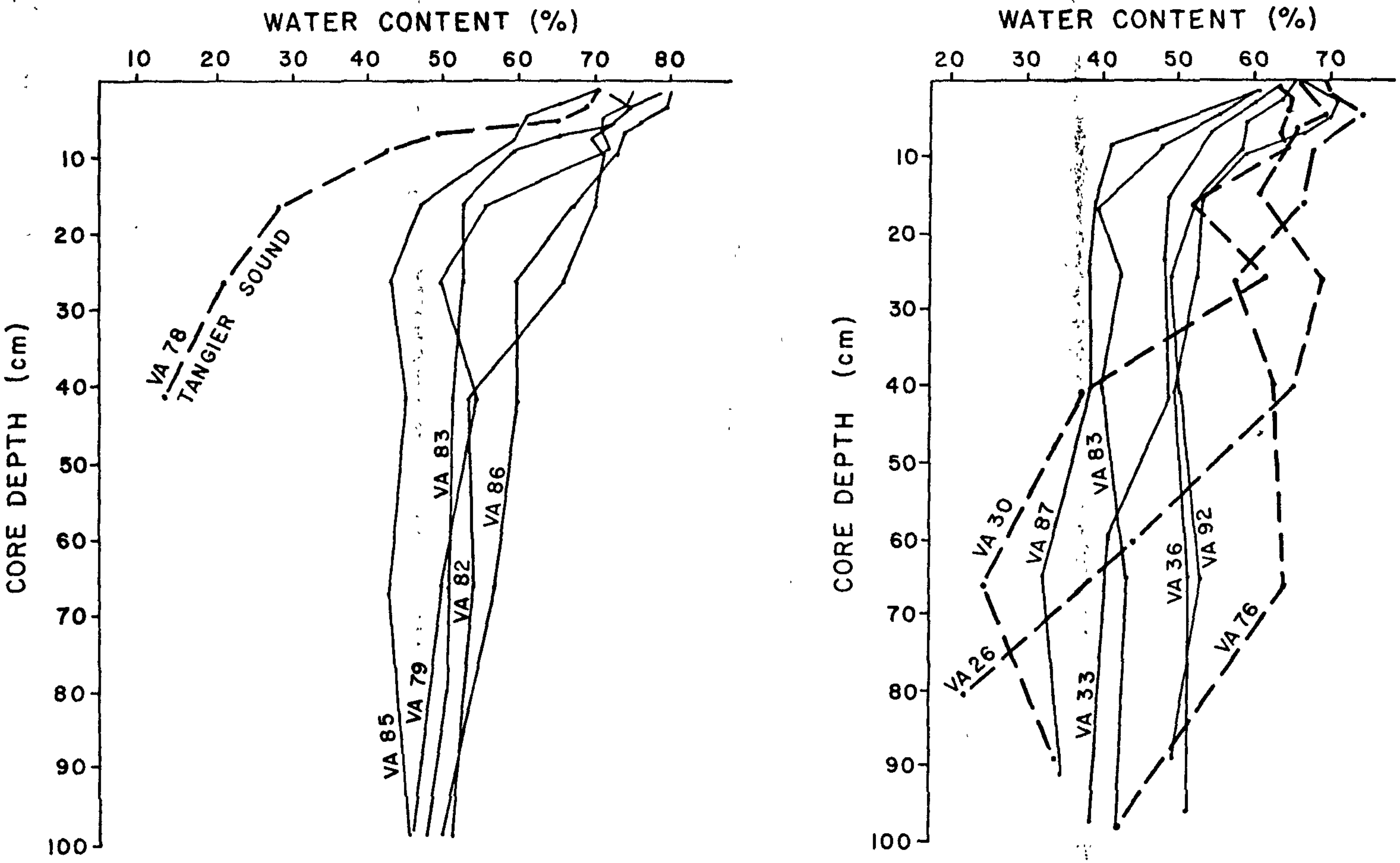


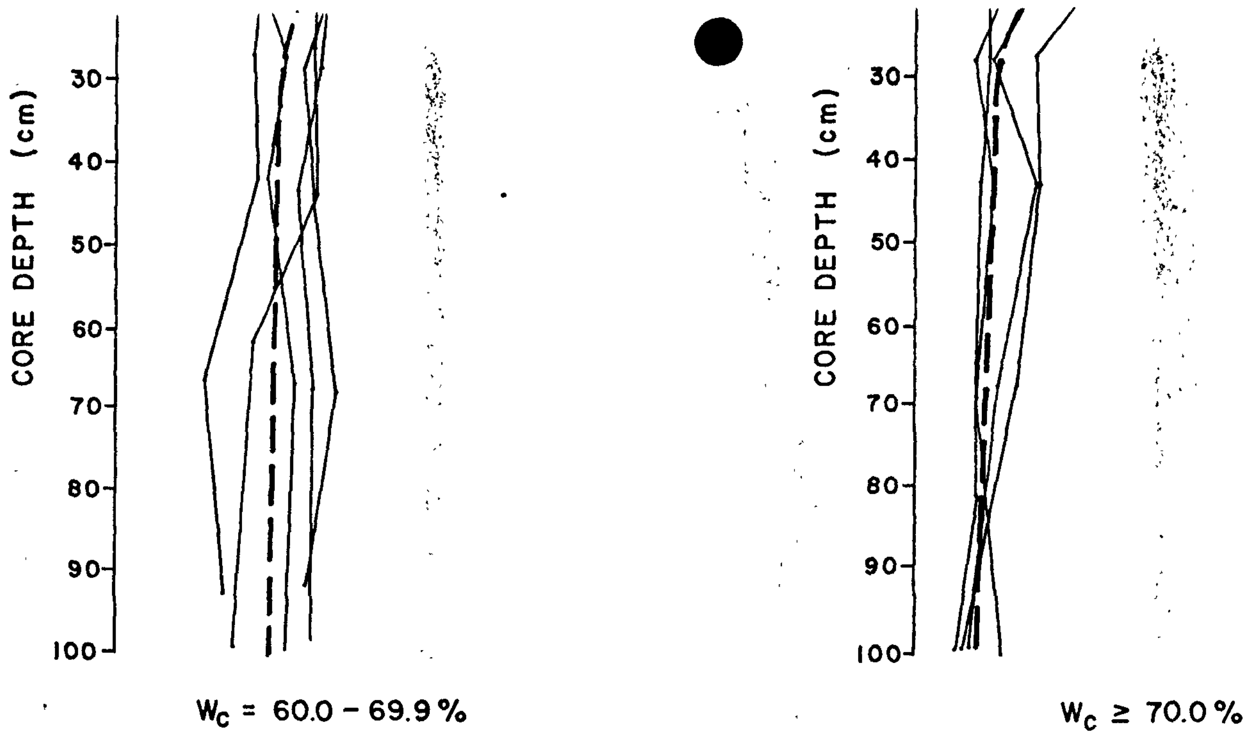
Figure 20. Map showing the location of short cores used in the formulation of water content profiles.



$W_c \geq 70.0\%$

$W_c = 60.0 - 69.9\%$

Figure 21. Vertical profile of water content for cores with surface water — contents of 70% and greater at 60-69.9%.



W_c = 60.0 – 69.9 %

$W_c \geq$ 70.0 %

Figure 22. The water-content profiles depicted in Figure 21, normalized to a common origin.

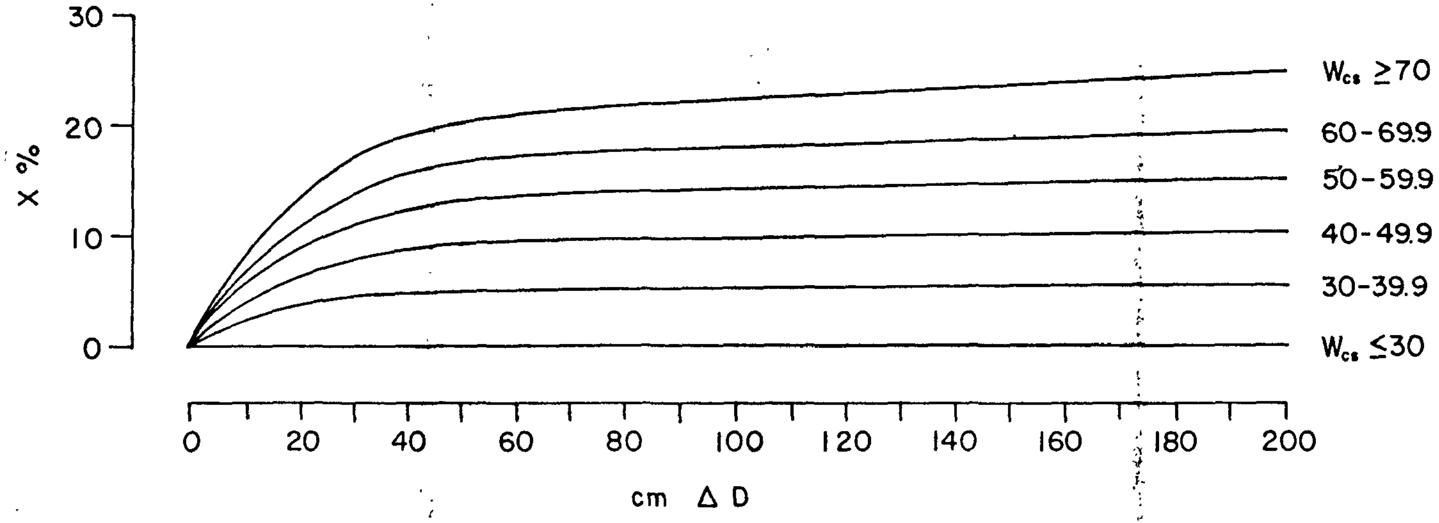


Figure 23. Nomogram for the determination of the depth averaged water content of a core based upon surface water content.

Table 7

Determination of Average Water Content with Depth

Surface Water Content	x, Deficit in water content relative to surface water content.					
ΔD in cm	< 30	30-39.9	40-49.9	50-59.9	60-69.9	> 70
10	0	2.5	4.5	6.0	7.0	8.0
20	0	4.0	6.5	9.0	11.0	13.0
30	0	4.5	8.0	11.0	14.0	17.0
40	0	5.0	8.5	12.5	16.0	19.0
50	0	5.0	9.0	13.0	17.0	20.0
60	0	5.0	9.5	13.5	17.5	21.0
70	0	5.0	9.5	14.0	17.0	21.5
80	0	5.0	9.5	14.0	17.5	21.5
90	0	5.0	9.5	14.0	18.0	22.0
100	0	5.0	9.5	14.0	18.0	22.0
110	0	5.0	10.0	14.0	18.0	22.5
120	0	5.0	10.0	14.5	18.5	22.5
130	0	5.0	10.0	14.5	18.5	23.0
140	0	5.0	10.0	14.5	18.5	23.0
150	0	5.0	10.0	14.5	18.5	23.5
160	0	5.0	10.0	14.5	19.0	24.0
170	0	5.0	10.0	15.0	19.0	24.0
180	0	5.5	10.0	15.0	19.0	24.0
190	0	5.5	10.0	15.0	19.5	24.5
200+	0	5.5	10.0	15.0	19.5	24.5

For a given ΔD and surface water content, W_c, subtract the values taken from the table from the surface water-content to obtain the depth averaged water content, $\bar{W}_c$: $\bar{W}_c = W_c - x$.

It should be noted that this expression differs from the saturated unit weight generally used in geotechnical studies (Bennett and Lambert, 1971). Consistent with the assumption of zero salt evaporate, we have assumed the density of pore water is 1.0 g per cm^3. The range of salinities in the pore water of cores from the Virginia portion of the Bay ranges from 12 to 32 $^o/oo$ (James Hill, Maryland Geologial Survey, personal communication). At 0°C, these salinities yield densities of 1.0096 and 1.025 g per cm^3 (Knudsen, 1959). Dry grain density was taken as 2.7 g per cm^3 following the findings of Harrison, Lynch and Altschaeffle (1964). This assumption is valid for the mineral component, and nearly so for shell, but invalid for the small component of other organic materials. A sensitivity analysis indicates about a 2% error in dry mass calculation for the extreme of ρf = 1.02 g per cm^3 and ρs varying between 2.65 and 2.75 g per cm^3. Figure 24 displays the graph of dry mass (m-tons per m^3) as a function average water content.

The preceding paragraphs explained the procedures for determination of the average water content, $\overline{W}_c$, over the sedimentation length, and the determination of dry mass of sediment per cubic meter given the average water content. Multiplication of the latter value by the length of the sedimentation column, ΔD, then gives the mass accumulation between the survey periods, Δt. Further multiplication by $100/\Delta t$ then gives the final result of total sediment mass accumulation normalized to a 100 year period.

3. Sources

a. Sediment Mass Derived From Shoreline Erosion. The estimation of the mass of material supplied to the Virginia portion of the Chesapeake Bay from erosion of the shoreline utilized published data concerning areal loss (Byrne and Anderson, 1977), field observations of shoreline geology and geomorphology, and sediment samples. Byrne and Anderson determined the area of shoreline change by comparing shoreline positions for the period 1850-1950. These estimates of area were converted to volume by multiplying them by observed shoreline heights. The volumes, in turn, were converted to mass using data on the unit dry weight of different sediment types from Terzaghi and Peck (1948). The most frequently used values were 90 lb/ft^3 (1.43 gm/cm^3) and 99 lb/ft^3 (1.99 gm/cm^3) for uniform and mixed grained, loose sands, respectively.

In addition to the general observation of sediment type, samples were taken at approximately 1 mile intervals along the main shoreline of the Bay. At each site, samples of the beach and and fastland sediments were obtained. The fastland samples were collected so as to be representative of the stratigraphy. Thus, the sand:silt:clay ratios of the samples of the (eroding) sediments, coupled with the calculated mass of the material eroded for each shore segment yielded information on the separate masses of sand, silt, and clay supplied to the Lower Bay. Appendix 2 is a tabulation by minute-of-latitude of the mass of material attributable to shoreline changes. Figure 25 depicts both the mass of sediment per minute-of-latitutde and the areas of the Bay shoreline that were included in the calculation.

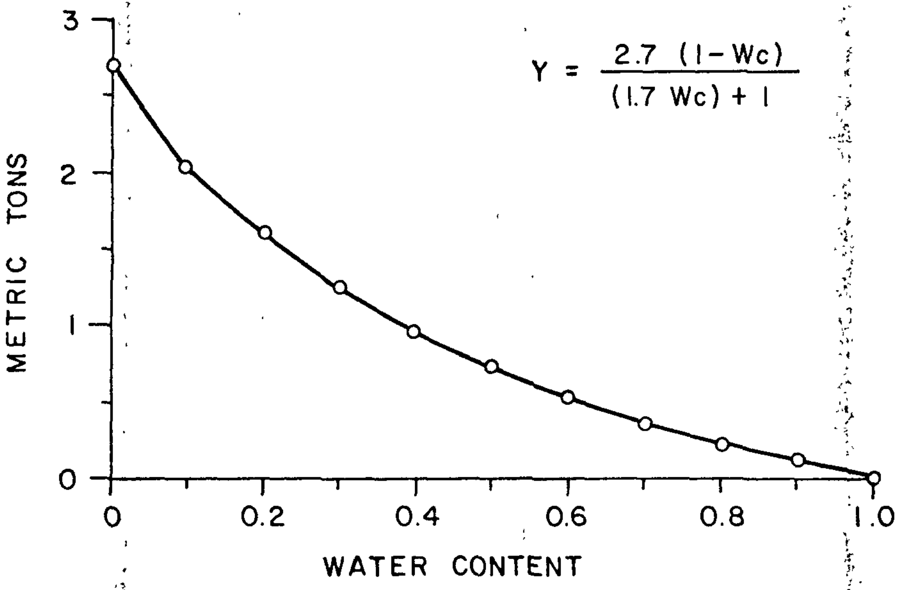


Figure 24. A plot of the mass of dry sediment in one cubic meter of bottom material as a function of water content.

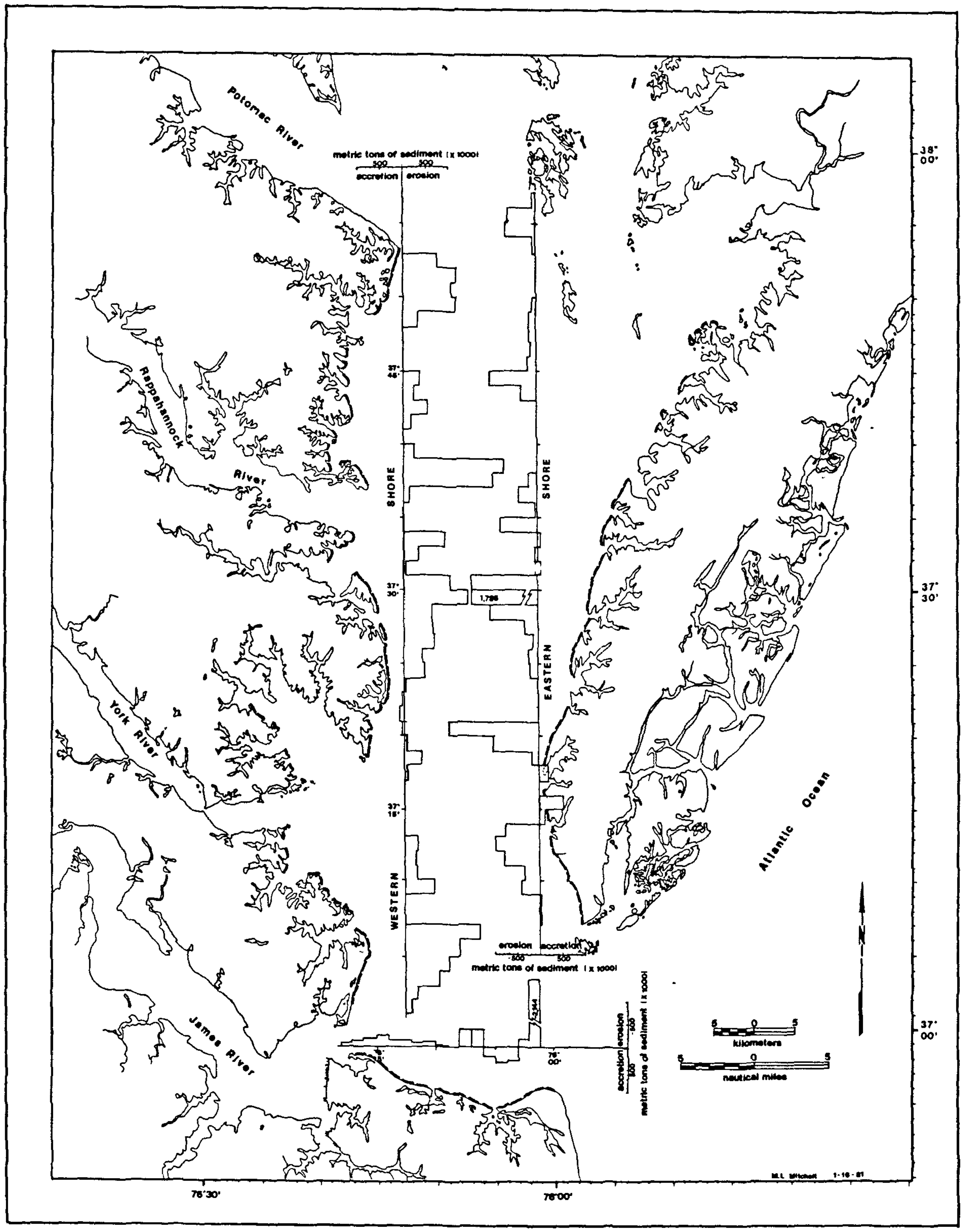


Figure 25. Histogram of the mass of material eroded from the shoreline for each minute of latitude. The areas used in the calculations are shown on the map with bold lines.

The sum, approximately 42.3 x 10^6 metric tons, 90% of which is sand, is probably a conservative, or low, figure. The calculated areas and volumes of shore change use only data from approximately mean high water and above. Sediment eroded from below MHW as part of normal shoreline retreat is not included in the calculations (Figure 26). The quantity of this material is a function of both the rate of retreat and tide range. In areas of low shore elevations and gently nearshore slopes, the quantity of material not considered could approach the calculated supratidal amounts.

b. Calculation of the Mass of Biogenic Sediment. Jacobs (1978) presented basic data on the distribution of zooplankton through a large portion of the Lower Chesapeake Bay. His data stems from two years of monthly samples from each of eight subareas. The samples were collected by careful tows of 202 µm mesh nets and were later concentrated through 110 µm strainers in order to retain broken specimens. Hence the mass of material deposited from zooplankton and phytoplankton less than 202 µm in life size is not included. Because this data is to be integrated with data on sediments that have been digested in HCl and H_2O_2, only the ash weights of the plankton samples are used in the calculations as the ash weight is representative of the mass that would remain after the digestion process.

Table 8 shows the path of the calculations from the determination of the monthly average ash weight of the zooplankton in a cubic meter of water in each of the eight subareas through the total ash weight for a 100-year period. The calculations use the assumption that all the potential, zooplankton derived, ash material settles to the bottom and is incorporated in the sediment. Figure 27 depicts the subareas. It should be noted that subareas G and H extend north only to 37°40' latitude, not to the state line, approximately 38°00'.

The calculated total ash, from Table 8 is 81.4 x 10^4 metric tons per 100 years. If the contribution of subareas G and H are doubled, to extend the area to include all of the Virginia portion of the Bay, the total of the ash weight of the fraction of the biogenic sediment in the study area is 1.252 x 10^6 metric tons.

C. DATA STORAGE

Several very large data sets were constructed to provide for the logical storage of the information derived as part of this project. These data sets can be divided into two groups. The first is the data associated with the bathymetric changes. The other is the information concerned with the two thousand bottom samples.

The raw bathymetric data is available on magnetic tape at the Virginia Institute of Marine Science. This data includes digitized sounding data from both the 1850 and 1950 bathymetric survey series. The latter informaiton was obtained from NOAA. Additionally, bathymetric changes, adjusted to compensate for the parameters noted section also are available on tape.

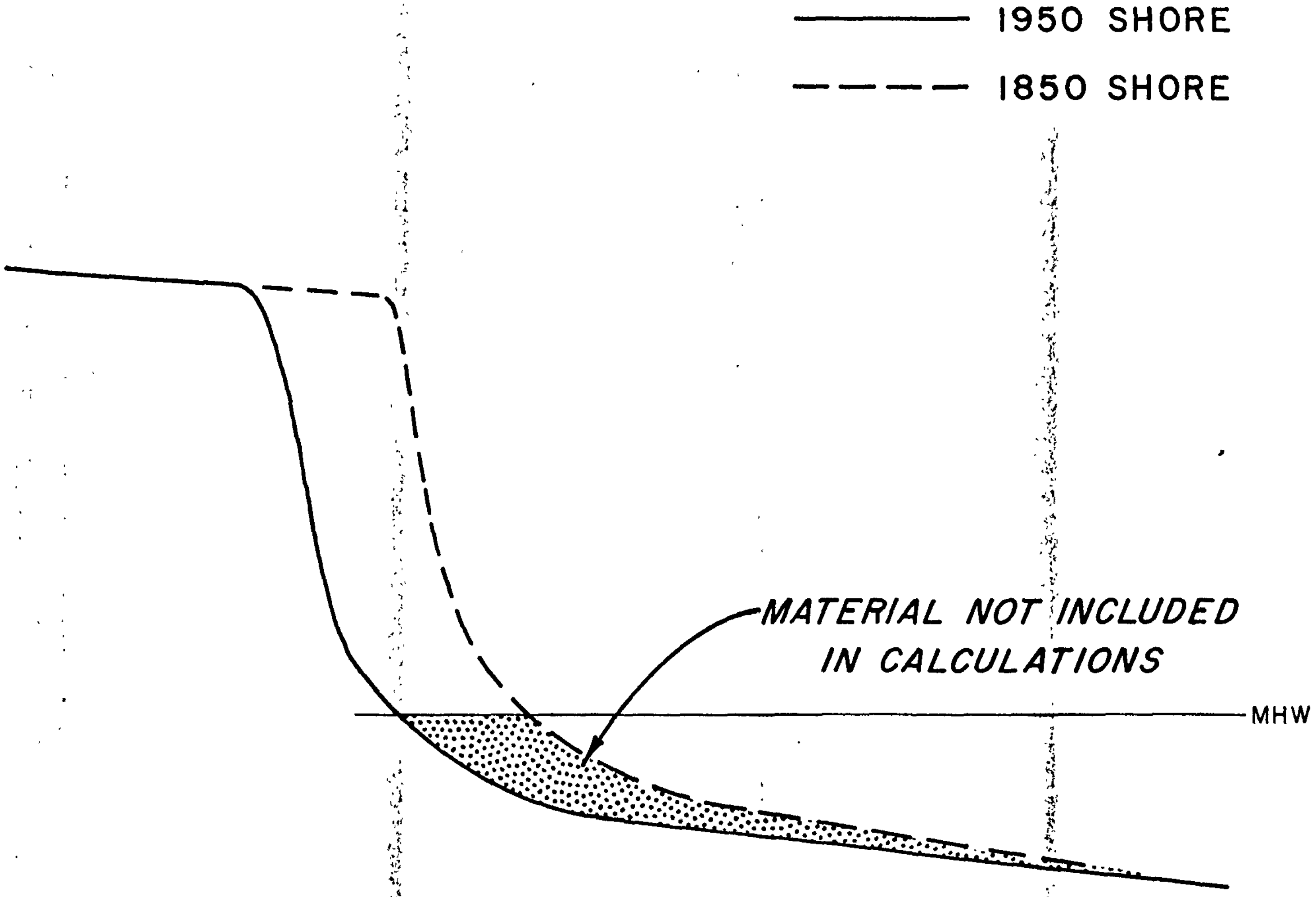


Figure 26. Sketch of the profile of an eroding shore depicting material not included in the calculation.

Table 8

Calculation of the Ash Weight of the Biogenic Sediment

Produced in the Lower Chesepeake Bay During a 100-Year Period

	Subarea							
	A	B	C	D	E	F	G	H
1) Monthly Average Dry Weight mg/m^3	54.62	98.05	56.08	79.65	95.79	97.13	83.98	143.84
2) Monthly Average Ash Free Dry Weight mg/m^3	37.24	68.41	44.31	51.99	64.70	68.81	63.26	76.07
3) Monthly Average Ash Weight (1 - 3) mg/m^3	17.38	29.64	11.77	27.66	31.09	28.32	20.72	67.77
4) 100-Year Ash Weight (3 x 1200 ÷ 1000) g	20.856	35.568	14.124	33.192	37.308	33.984	24.864	81.324
5) Estimated Average Depth m	6.7	9.1	12.0	5.5	9.7	10.3	9.1	9.7
6) Ash Weight Per m^2 of Bottom (4 x 5) g	138.73	324.49	169.49	182.56	361.89	350.03	226.26	788.85
7) Area m^2	327.7×10^6	278.4×10^6	106.9×10^6	386.4×10^6	246.0×10^6	159.3×10^6	491.6×10^6	441.9×10^6
8) Grams of Ash Per 100 Years (6 x 7)	5.2×10^{10}	9.0×10^{10}	1.8×10^{10}	7.1×10^{10}	8.9×10^{10}	5.6×10^{10}	11.1×10^{10}	32.7×10^{10}
9) Metric Tons	5.2×10^4	9.0×10^4	1.8×10^4	7.1×10^4	8.9×10^4	5.6×10^4	11.1×10^4	32.7×10^4
TOTAL	81.4×10^4 Metric Tons							

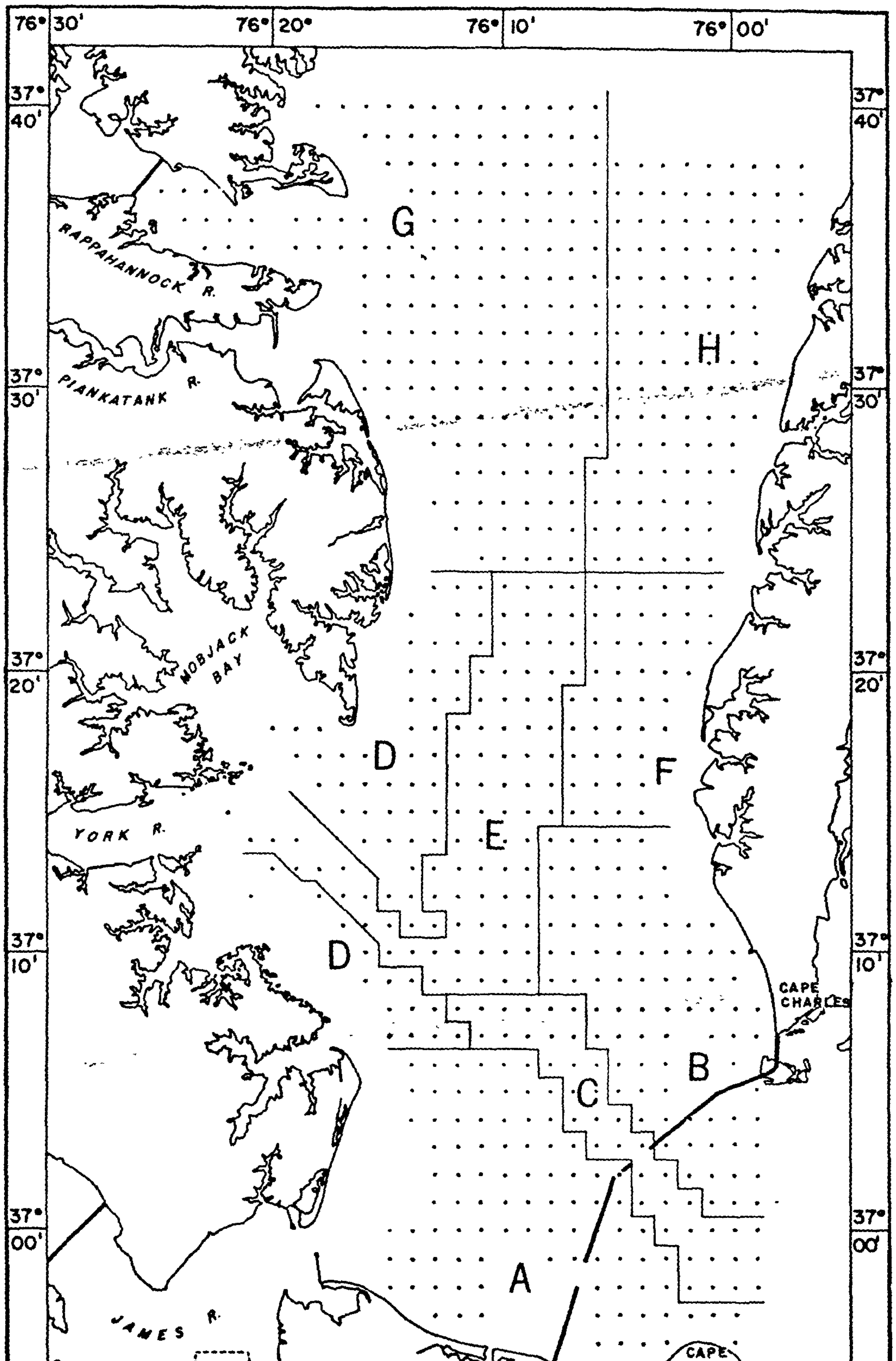


Figure 27. Subareas from Jacobs (1978) used in determining the zooplankton contribution to the sediment.

The data on the individual sediment samples are comprehensive and are available from several sources. The data include the latitude and longitude, water depth, water content, weight percents total carbon, organic carbon, and sulfur (not all samples), weight percents gravel, sand, silt, and clay, tabulated, 1/4 Ø interval grain-size-frequency distribution, and the several calculated statistics. This information was submitted on magnetic tape to the Virginia State Water Control Board for transferral to the EPA STORET data system and should be available through both agencies. Additionally, both magnetic tape and paper tabulations of the data are filed at VIMS.

VI

RESULTS AND DISCUSSION

A. SEDIMENTOLOGY

1. Description of Sedimentology. One of the most striking attributes of the bottom sediments of the Virginia portion of the Chesapeake Bay is the dominance of sand over mud. Over 65% of the samples are 75% or more sand (Table 9). The mean of the graphic mean grain size for over 2,000 samples is 3.17 ø (0.11 mm). Table 9 displays sediment type from Shepard's (1954) ternary classification. The data is grouped by 5 minute bands of latitude for the main stem and by fringing subarea. On most maps of sediment characteristics, such as weight percent sand, mean grain size, or sediment type (Figures 28, 29, and 30), the great extent of the sands is clear. With few exceptions, the finer-grained sediments are confined to the deeper portions of the Bay. Indeed the patterns of the various sediment maps echo the bathymetry. However so little of the Bay is deep, approximately 80% of the study area is less than 42 feet (13 meters) deep (Figures 31 and 32) that silts and clays in shallow areas such as Mobjack Bay and the sands in the deep channel near the lower Eastern Shore destroy any significant correlation between grain size and depth. R^2 for 2,018 depth versus percent mud samples is 0.13. Figure 33 depicts clay content. Although the visual correlation between depth and clay content is strong, the R^2 value is only 0.11 for the entire suite of samples. Again this poor quantitative relationship is, in part, a function of the hypsometric distribution.

On all the above sediment characteristic maps the channels into Pocomoke and Tangier Sound, the channel in the main stem that runs north from near the mouth of the Rappahannock, and the York and Rappahannock channels are clearly shown. Only the deep channel in the southeastern Bay is lost. The presence of coarser grained sediments in this deep portion probably is due to erosion of a sand substrate, or, locally, to the transport of sediment into the channel from the region of the Bay mouth.

The qualitative depth versus grain size relationship is very well depicted in Figure 34 which is a map of the graphic mean of the sand portion of the samples. The distribution of the very fine sands, 3 to 4 ø (0.125 to 0.0625 mm), marks all the deeper areas of the Lower Bay including the channel near Cape Charles. This map, as well as the others, depicts a band of finer-grained sediments running southeast from the mouth of Mobjack Bay. Although this area is in slightly deeper water than the surrounding region, the bathymetry is not nearly so pronounced as with the York River channel which the Mobjack band parallels. It is possible that this band is

Table 9

Distribuiton of Sediment Types

	Number of Samples	Percent of Samples									
		Sand	Silt	Clay	Sand Silt Clay	Sandy Clay	Silty Clay	Clayey Silt	Sandy Silt	Silty Sand	Clayey Sand
SUBAREA											
Rappahannock River	11	55	-	-	-	-	18	27	-	-	-
Mobjack Bay	50	42	-	-	2	-	16	28	-	10	2
York River	19	42	-	5	11	-	26	11	-	5	-
Hampton Roads	77	38	-	-	26	-	12	9	-	10	5
Tangier Sound	69	62	-	-	10	-	-	12	-	14	1
Pocomoke Sound	109	61	-	-	8	-	-	22	1	8	-
Piankatank River	29	38	-	-	17	-	14	28	-	3	-
MAIN STEM OF BAY BY LATITUDE											
38°00' - 37°55'	14	100	-	-	-	-	-	-	-	-	-
37°55' - 37°50'	84	87	-	-	5	-	7	-	-	1	-
37°45'	156	83	1	-	3	-	4	3	1	4	2
37°40'	188	68	-	-	6	-	6	13	1	4	2
37°35'	166	53	-	-	10	-	1	25	6	5	-
37°30'	145	34	-	-	5	-	-	17	12	32	1
37°25'	111	53	-	-	4	-	-	4	7	32	1
37°20'	104	69	-	-	2	-	-	4	1	24	-
37°15'	120	52	-	-	3	-	-	2	3	38	1
37°10'	167	61	-	-	3	-	-	7	2	26	-
37°05'	131	90	-	-	1	-	-	1	-	8	-
37°05' - 37°00'	141	95	-	-	1	-	-	-	-	4	-
37°00' - 36°55'	103	85	-	-	2	-	-	1	-	12	-
TOTAL	1994	65.2	0.1	0.1	5.4		2.7	9.3	2.4	14.2	0.8

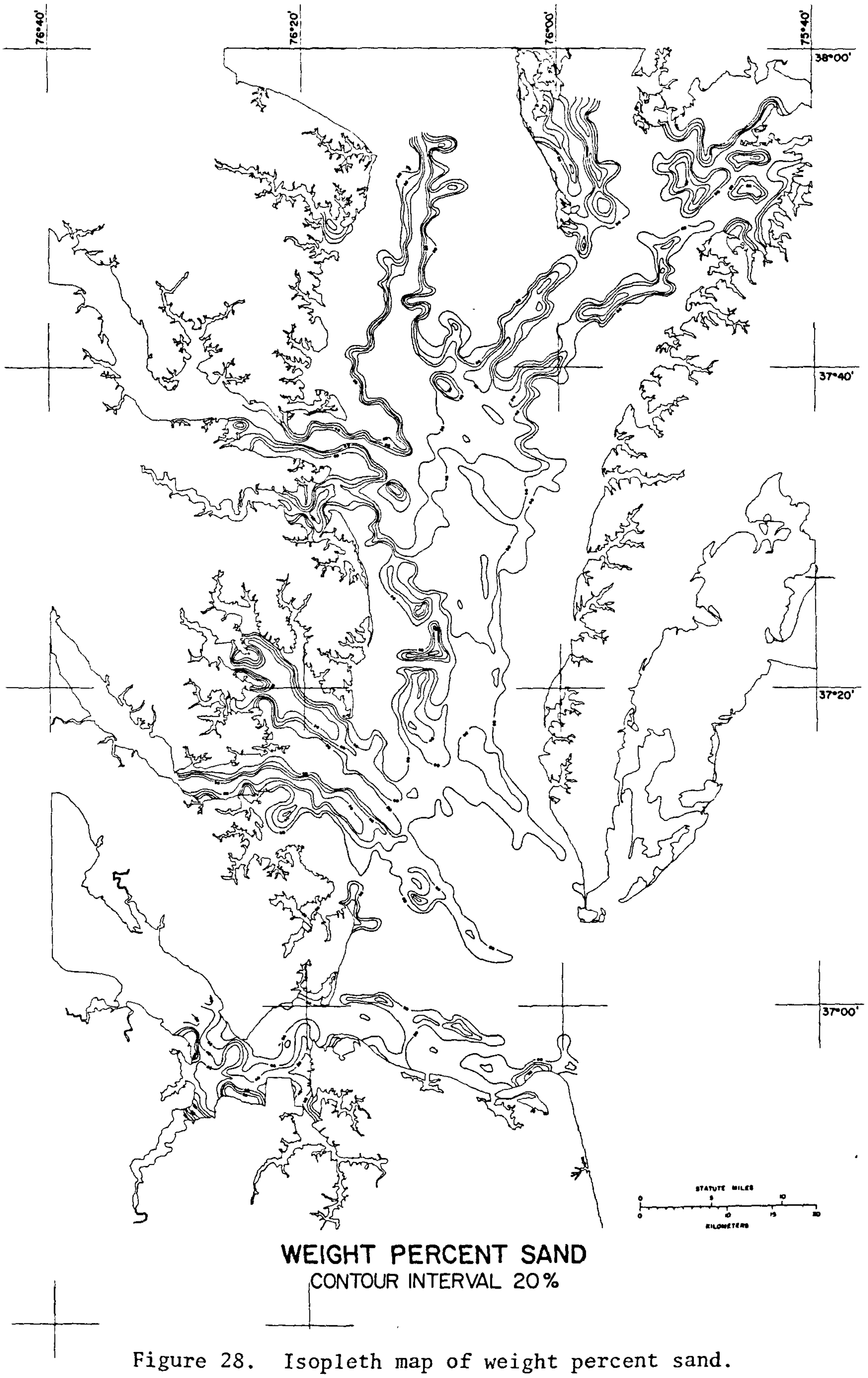


Figure 28. Isopleth map of weight percent sand.

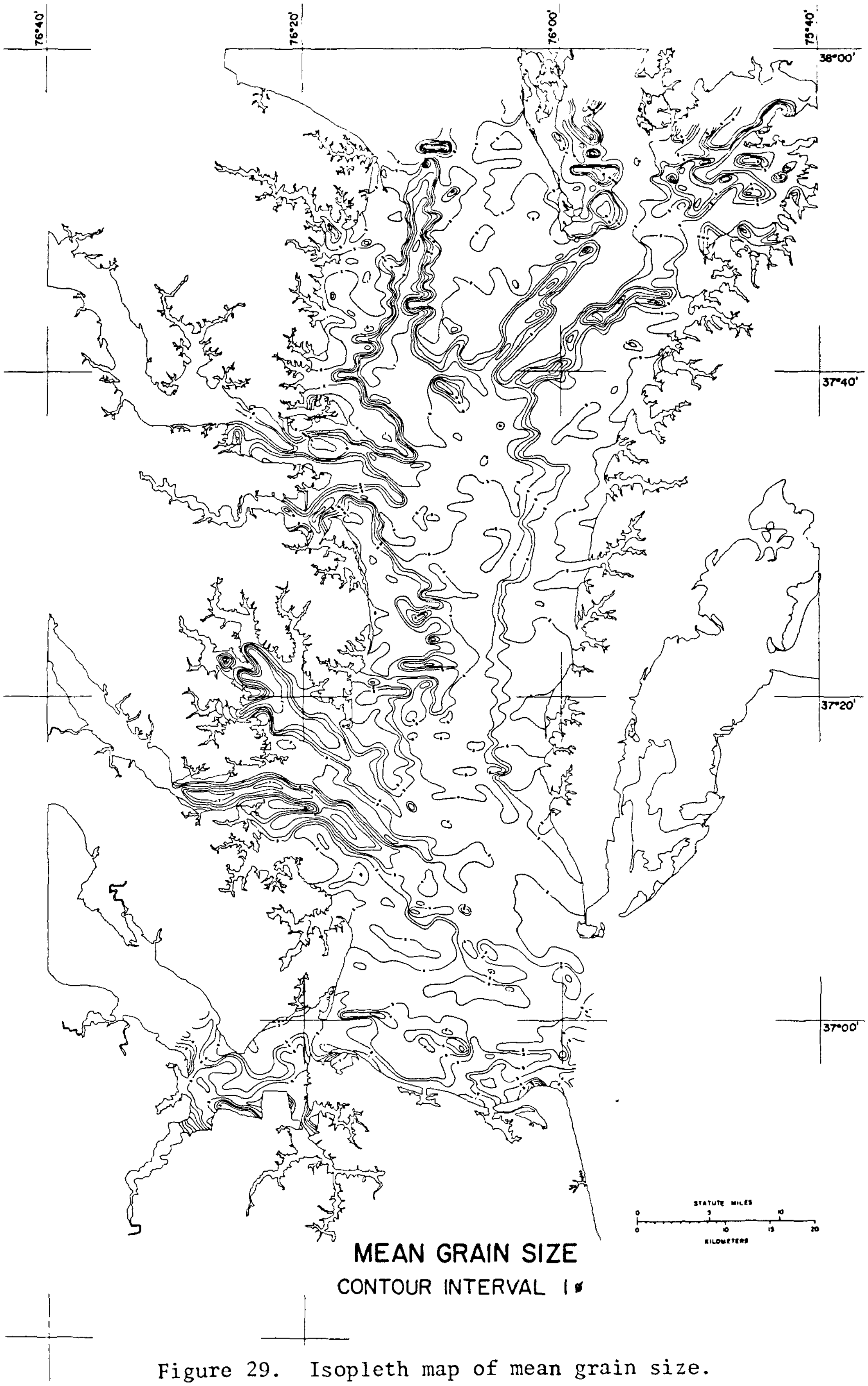


Figure 29. Isopleth map of mean grain size.

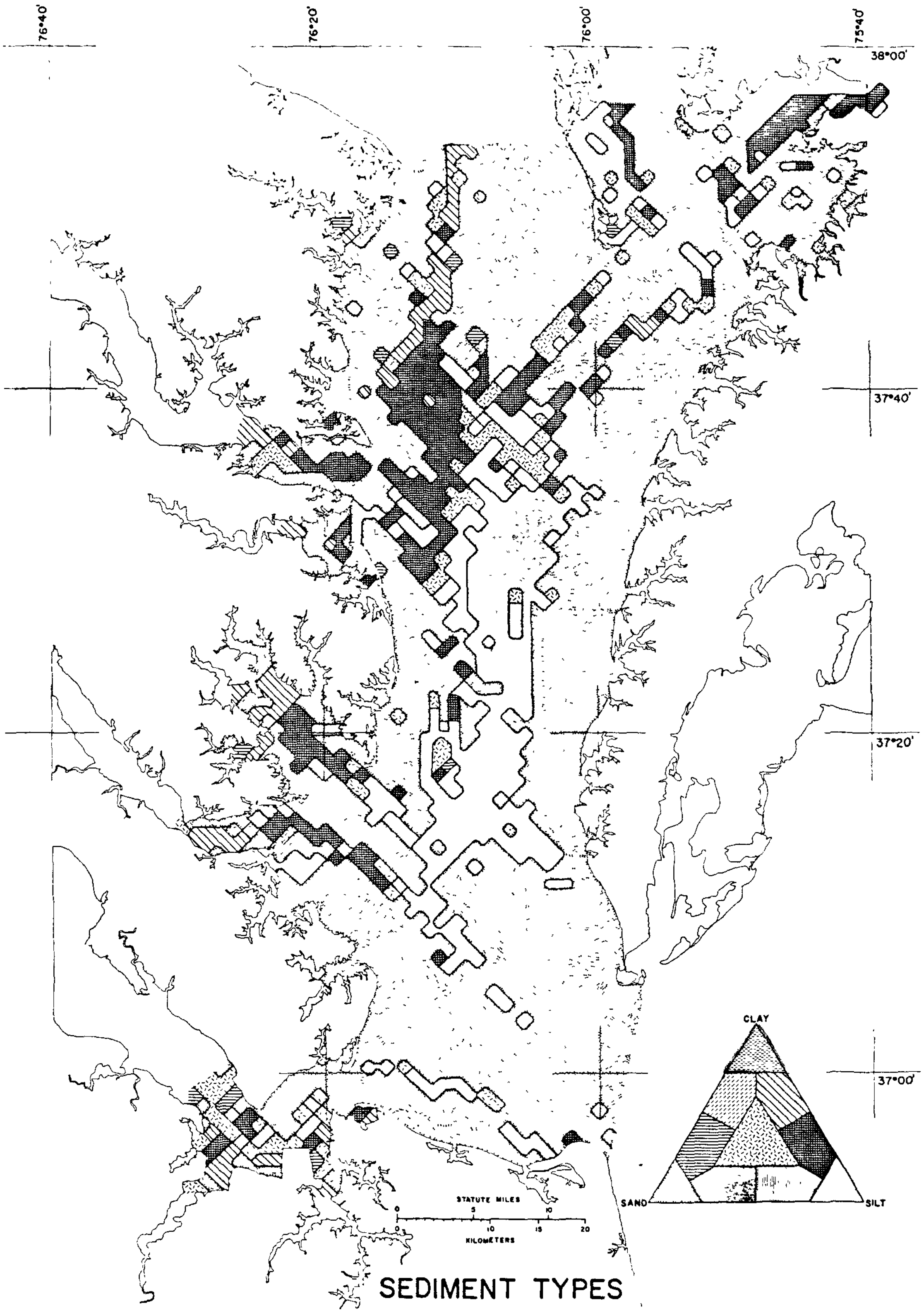


Figure 30. Map of the distribution of sediment types.

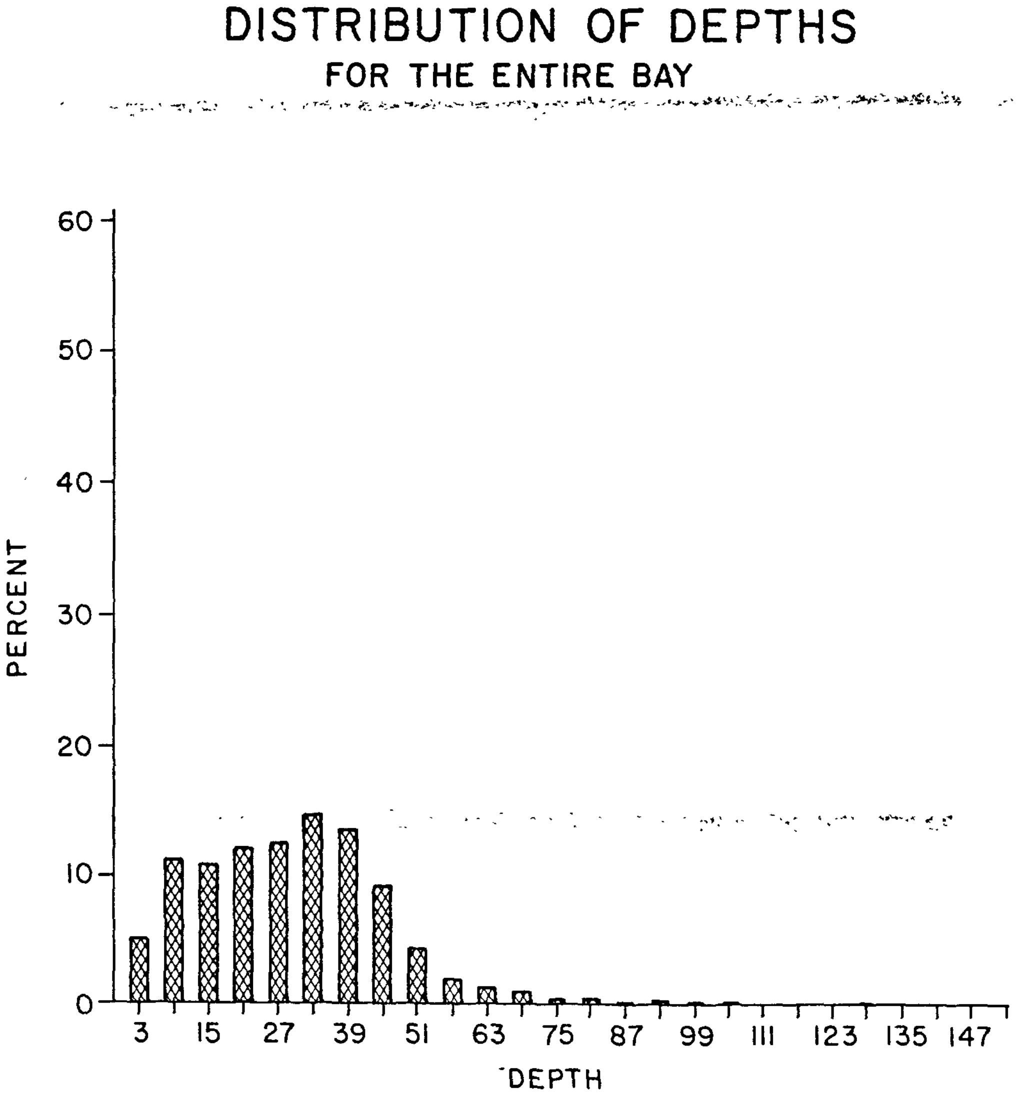


Figure 31. Histogram of depths at sample locations.

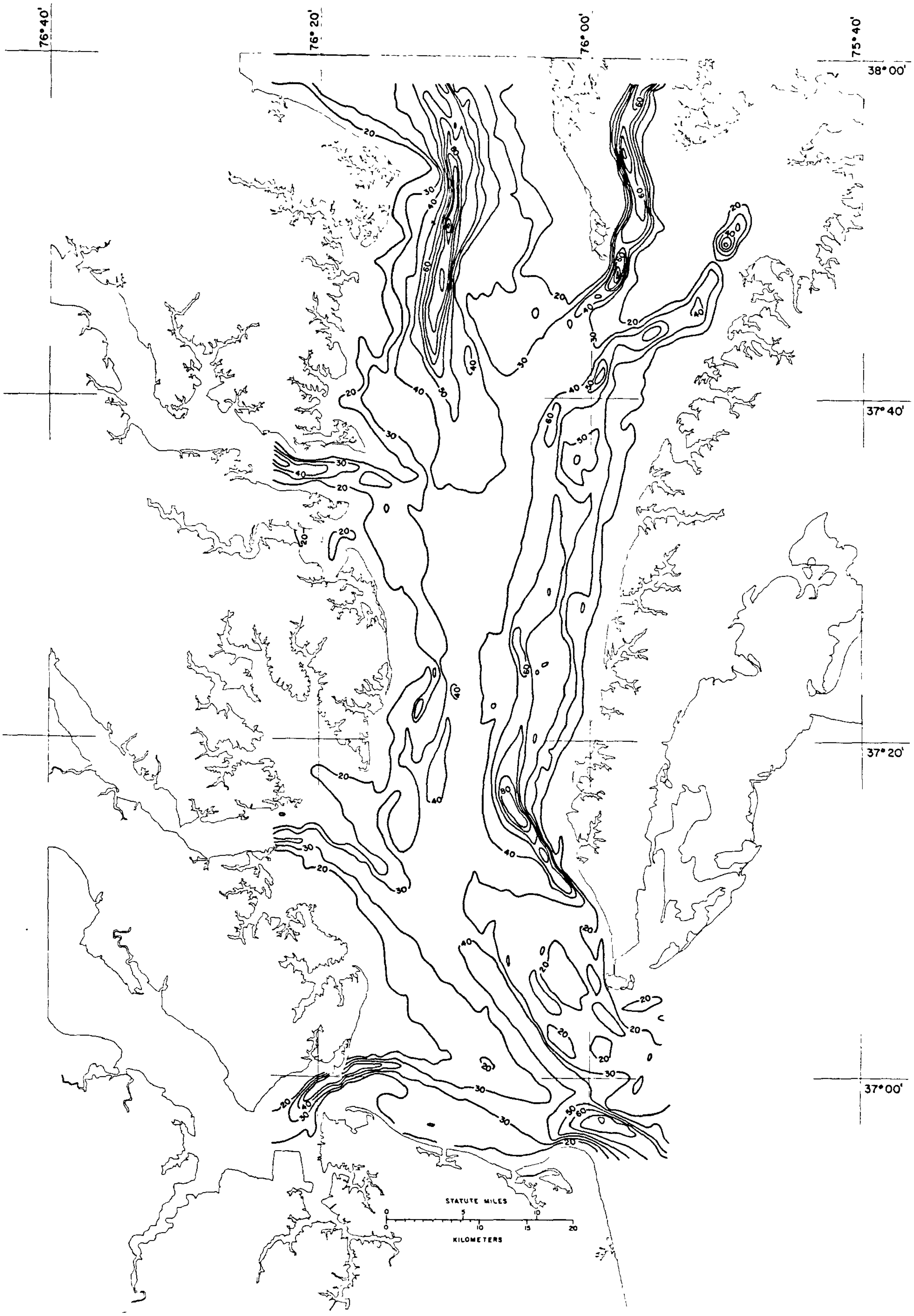


Figure 32. Map showing the bathymetry of the Virginia portion of the Chesapeake Bay, 10-foot contour interval.

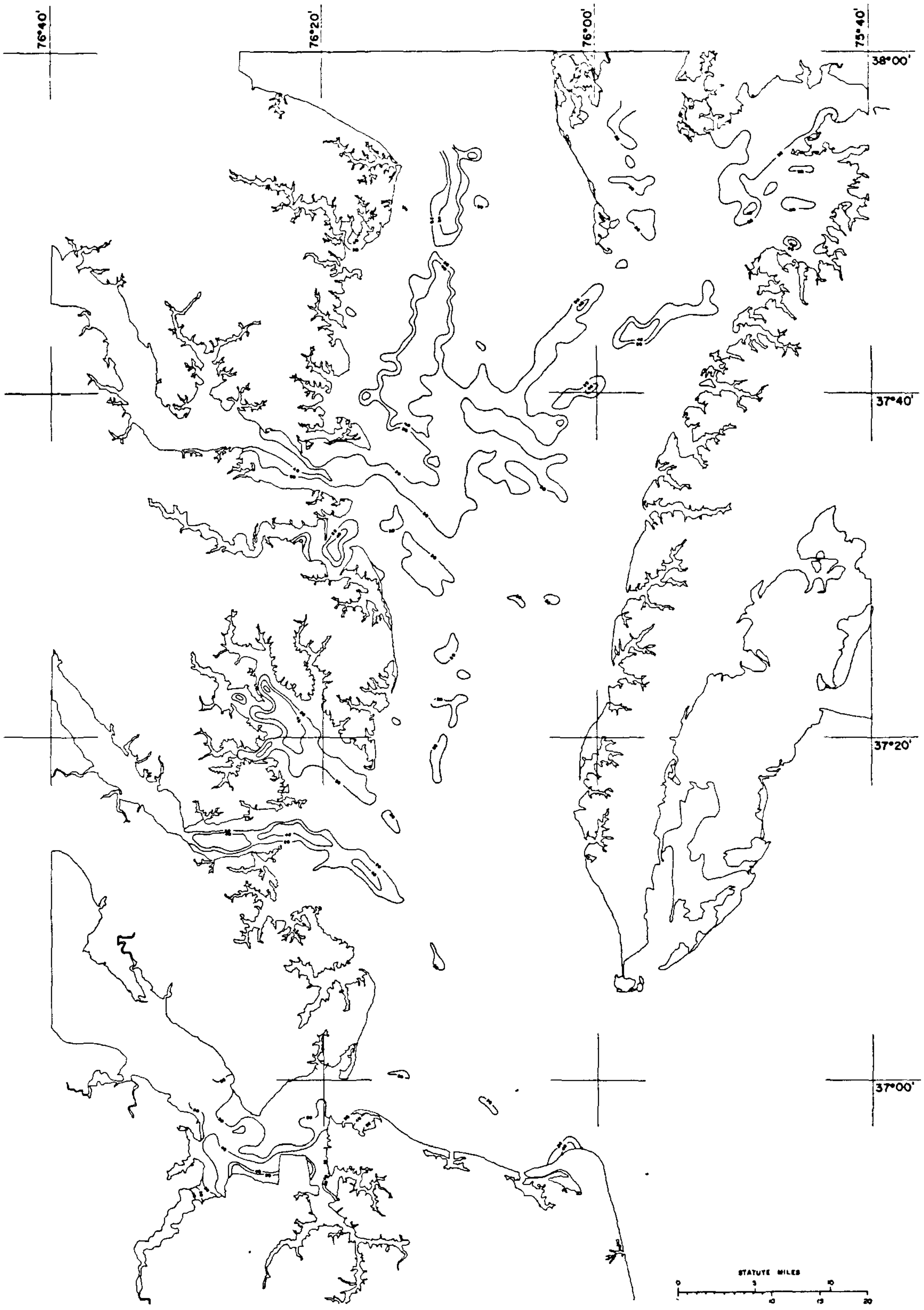


Figure 33. Isopleth map of weight percent clay.

CONTOUR INTERVAL 20%

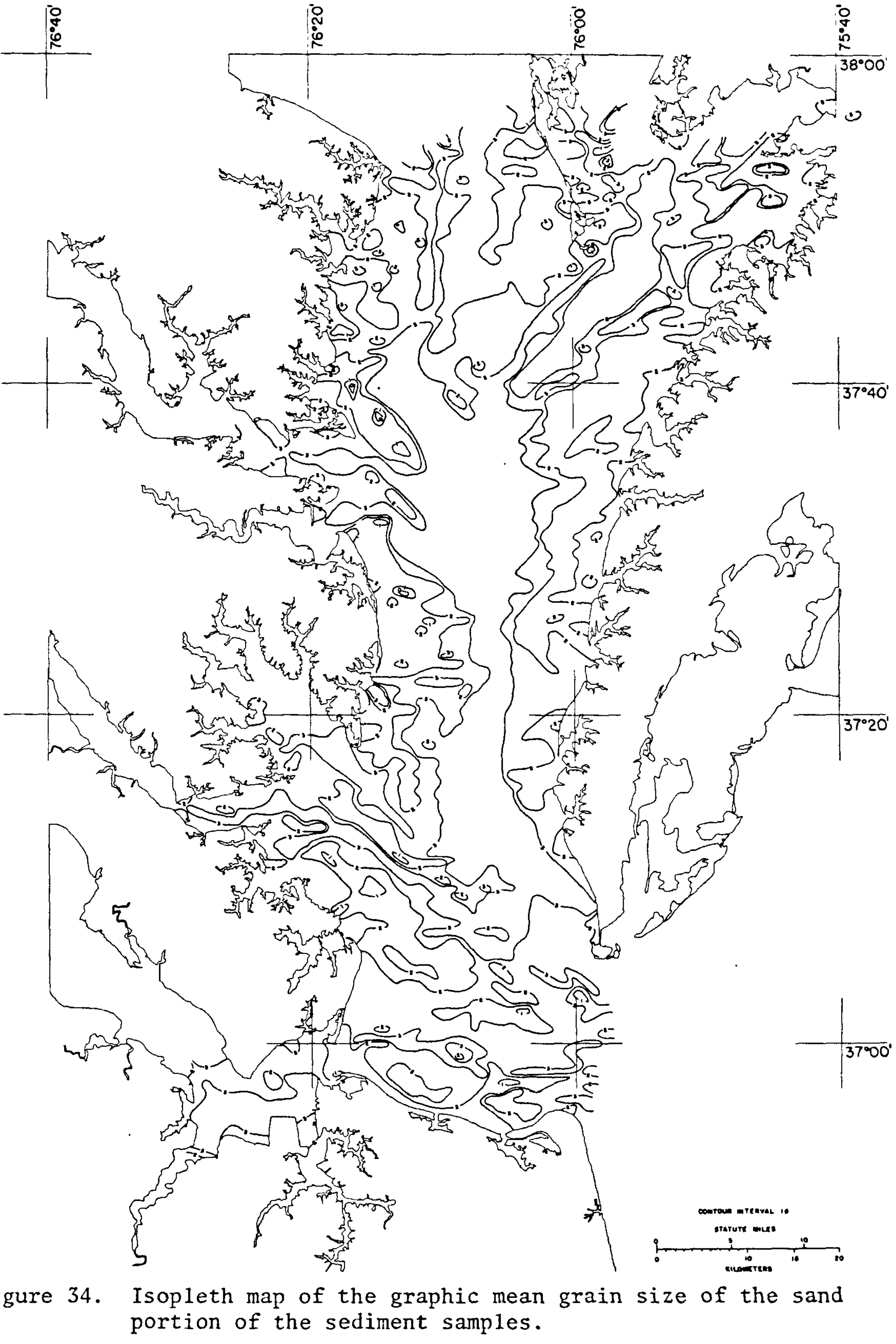


Figure 34. Isopleth map of the graphic mean grain size of the sand portion of the sediment samples.

the surface representation of a channel filling with material derived from the Mobjack Bay upland drainage.

The explanation of the distribution of the medium and coarse sands is complementary to that for the very fine sands. Whereas the very fine sands are deposited in the deeper portions of the Bay, the medium and coarse sands are found in the shallower areas that are subject to agitation by waves. It is arguable from site to site whether the coarser sands are the lag deposit left behind as the shallow sediments have been reworked and winnowed of the fines by waves or are relict, palimpsest, materials. Indeed the two explanations are not mutually exclusive and often may both be true. Dramatic shoreline retreat has accompanied the Holocene rise or sea level. Rosen (1976) cited evidence for the shallow, 3.6 meters (12 foot) and less, flat terraces being the erosional platform created during the relatively slow sea level rise of the past 3,000 years. Using the work of Brunn (1962), Rosen related the change in bottom slope to the change in the rate of sea-level rise that occurred approximately thirty centuries ago. Thus the roughly shore-parallel zones of coarser sediment adjacent to Accomack and Mathews Counties may be the lag deposits of Rosen's erosional terraces. The southeast-northwest trending coarse zones adjacent to the York River channel, extending from southern Mathews County, and just north of Windmill Point at the mouth of the Rapphannock may be the sediment of the eroded morphology and not exclusively a "lag" material. These features are likely to be the remnants of fossil spits formed during an earlier, lower stand of sea level. The large sandy-shield around Tangier and Smith Islands also probably is a relict feature as there are insufficient modern sources for this material.

The classification of sediments according to Shepard's (1954) ternary scheme provides additional data. Figure 30, clearly shows the dominance of sands and silty sands. The finer sediments, particularly the sandy- and clayey-silts, describe the major channels and, as previously noted, Mobjack Bay. The thin band of fines extending southeast from Mobjack Bay also appears on this map.

The sample data, when plotted on sand:silt:clay ternary diagrams (Figure 35) also illustrate the depth-sediment relationship. The samples all fall in a swath running from pure sand to clayer silt. Although the width of the swath remains nearly constant from depth to depth, indicating a mixture of the same general sediment types, the distribution within the swaths changes with the proportion of fines increasing with depth. This pattern is very similar to that shown by Kerhin, Halka, and Wells (1979) in the Maryland portion of the Bay except that the trend of their swath is somewhat finer, running from sands to silty clays and having a greater percentage of the samples falling on the silt-clay axis with little or no sand. They also show the general trend of an increasing percentage of fines with depth.

The generally finer nature of the sediments upstream in the Bay is not surprising. The proximity to the mouth of the Susquehanna and the presence of the turbidity maximum in the upper Bay work toward the resultant presence of an abundance of fines. Also the general phenomenon of

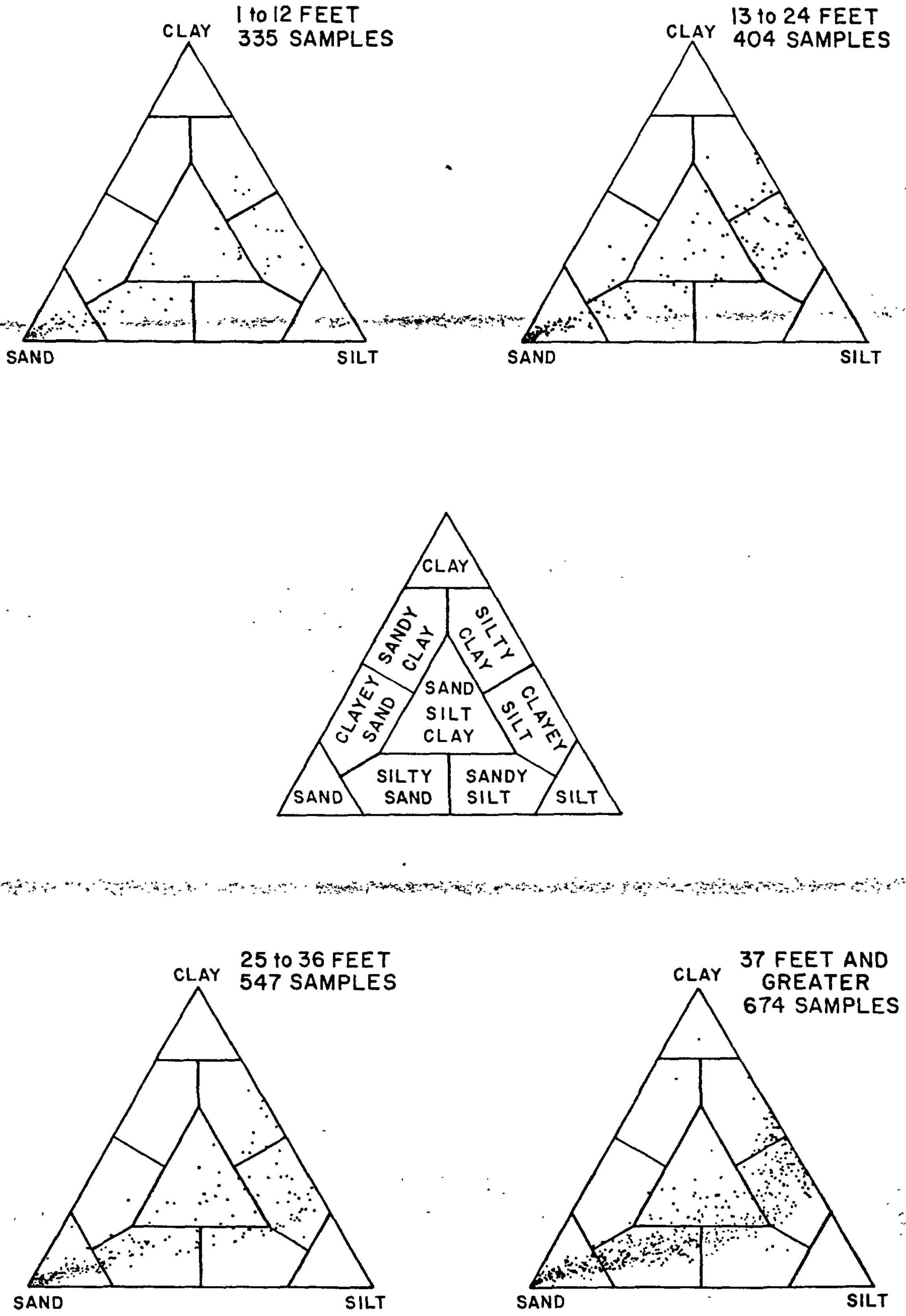


Figure 35. Ternary diagrams of sand:silt:clay ratios of sediments at different depths.

down-estuary coarsening has been noted by Nichols (personal communication) in the James River. Nelson (personal communication) has demonstrated it with successive down stream sand:silt:clay plots of sediments from the Rappahannock.

Water content is closely related to sediment type. For mud (x) versus water content (y) the R^2 for 2,018 samples is 0.91 with the equation $y = 0.459x + 18.6$. The R^2 values for mean grain size versus water content and weight percent clay versus water content are only slightly less significant at 0.881 and 0.879. Figure 36 is a scatter plot of the mud-water data.

As will be discussed later, these descriptions are somewhat similar to those of Ryan (1953) and Shideler (1975). The present study demonstrates that the sands are more widespread than was thought by the earlier works. Although some of the difference may be real, reflecting a change in bottom sediment through time, much of the difference is due to the better detail that results from the near order-of-magnitude greater sampling density of the present study. A comparison of isopleth maps of the mean grain size of the sand fraction (Shideler's Figure 3, this study's Figure 37) demonstrates the different levels of detail. As an example, where Shideler depicts a small shield of very fine sand near the mouth of the York River, the present study shows two discrete band, one from the York connecting with the main, central Bay bands fines, the other running from Mobjack Bay toward, but not connected to, the mid-Bay band.

2. Comparison With Earlier Surveys of Bottom Sediments. As the work done through the course of this study covers some of the same ground that was touched by the work of Ryan (1953), Harrison and others (1964), and Shideler (1975), it is appropriate to discuss the differences in observed characteristics and among results. This is especially important as the major physical events of the 1962 Ash Wednesday storm and the floods of Hurricane Agnes in 1972 occurred during the interval between these studies and it may be possible to discern changes in the bottom sediments results from these events. Broadly speaking there are two distinct types of differences that could exist between studies. The first are real or actual differences that result from true changes in the bottom. The second group is due to such causes as dissimilar sampling and analytical techniques, including sample pretreatment, errors in site location, differences in sample spacing, and differences in the subjective interpretation of the data. Although it is only the changes in bottom sediment which should be compared across studies, it is difficult to isolate these differences from those that are artifacts of the methods and techniques of the individual projects.

Analytical differences can be minimized by using comparisons of the weight percent mud (or sand) as the wet-sieving technique used to separate sand from mud are standard. The major remaining places for variation are in obtaining the sample and pretreatment. In the present study, the top 6 cm of sediment were sampled. Shideler used the top 10 cm, Harrrison *et al.* the top 20 cm, and Ryan the whole "snapper" sample or the top 15 to 20 cm of each core. None of the earlier reports indicated any pretreatment of the samples. The VCB samples were pretreated by digestion with HCl and

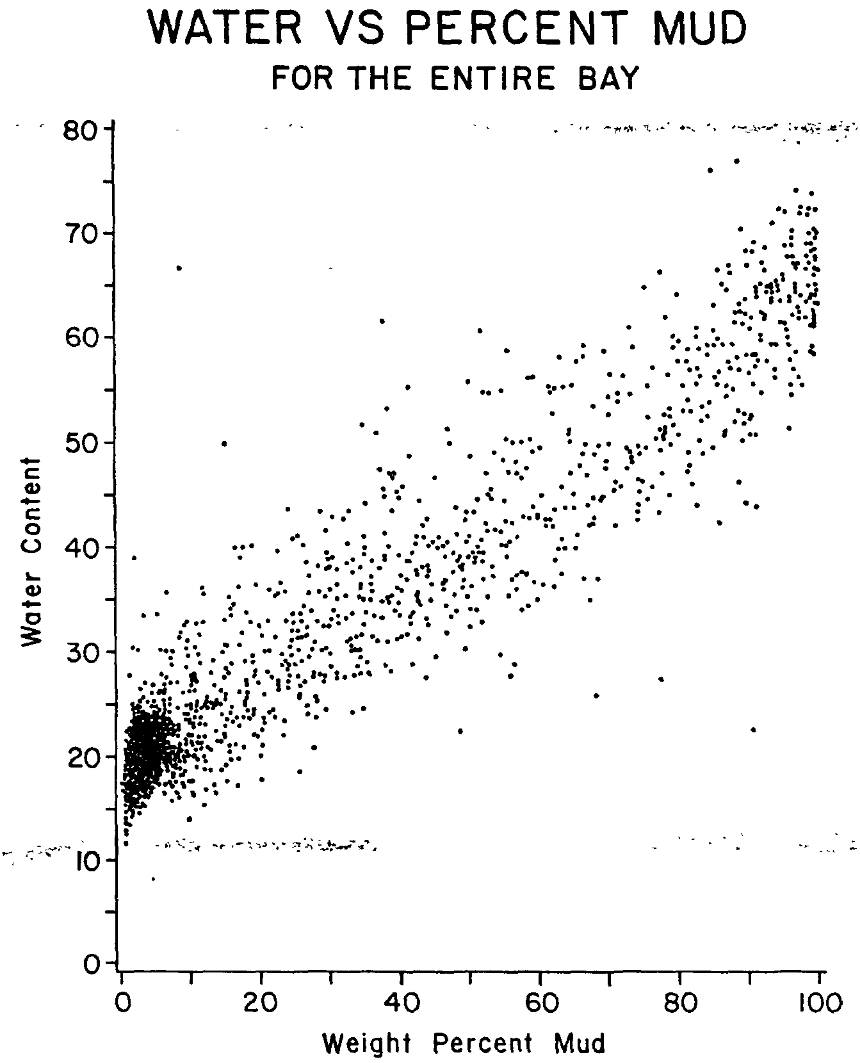


Figure 36. Scatter plot of weight percent mud versus water content.

H_2O_2 to remove carbonate and organics. Although not typical of the VCB samples, a laboratory study of 22 samples from a separate project in the Elizabeth River indicated that the weight percent mud averaged 1.1% greater (weight percent sand 1.1% less) for the digested samples. This suggests that the difference due to the pretreatment is not significant. (The differences in weight percent clay were significant, though, with the digested samples having an average of a 9.3% greater clay content (less silt) than the undigested). The other possible source of variation is the wet sieve itself. Although the 4 Ø separation of sand and mud is 62.5 μm, sieves with nominal openings of 60 to 64 μm are commonly used. This plus variations due to the condition of the sieve contribute to minor differences in the final result. Thus if one accepts that analytical differences are minimal, the remaining differences are due either to sample position, sample thickness or true changes.

Ryan had approximately 200 stations through the entire Chesapeake Bay. Shideler also had about 200 samples, but just from the Virginia portion of the Bay. The present study has over 2,000 samples from the Virginia portion of Bay including Mobjack Bay and Pocomoke and Tangier Sounds. Harrison and others studied only a small section of the area. Figure 38 shows the location of the samples from those three studies and Figure 4 shows the locations of the 2,000 samples analyzed for this study. The profile lines A through G on Figure 38 are the transects along which comparisons of weight percent mud were made. These profile comparisons are shown in Figure 39A,B,C. As samples were seldom exactly on the line, any falling within a half kilometer were used. If the sediment distributions were "patchy", this would be a source of error in the comparison. The profiles shown in the figure depict the west to east variations in weight percent mud for the present study (VCB) and Ryan, Shideler, and Harrison and others where applicable.

The VCB data and Shideler's generally are similar. Profiles E adjacent to the mouth of the York and G near the Bay mouth are especially interesting as they show the differences in gradient that can result from different sample spacings. The VCB data has steeper gradients and more variations than the "smoother" data from Shideler. It is probably a result of this greater detail that the present interpretations show much less fine-grained material than the earlier studies.

Harrison's samples appear only on Profile B and show reasonable correspondence with both Ryan's and the VCB data.

On Profile F the VCB sample which is almost 90% mud has been identified as being taken from a spoil area.

Although in some instances, Profiles A and D, Ryan's data indicate a greater mud content than either the present or Shideler's works, it is difficult to assess the variations as either being due to the "patchiness" of the sediment types or due to an actual change in sediment type through time. As strong gradients of sediment properties are apparent, it is desirable to have a great number of closely spaced samples. However

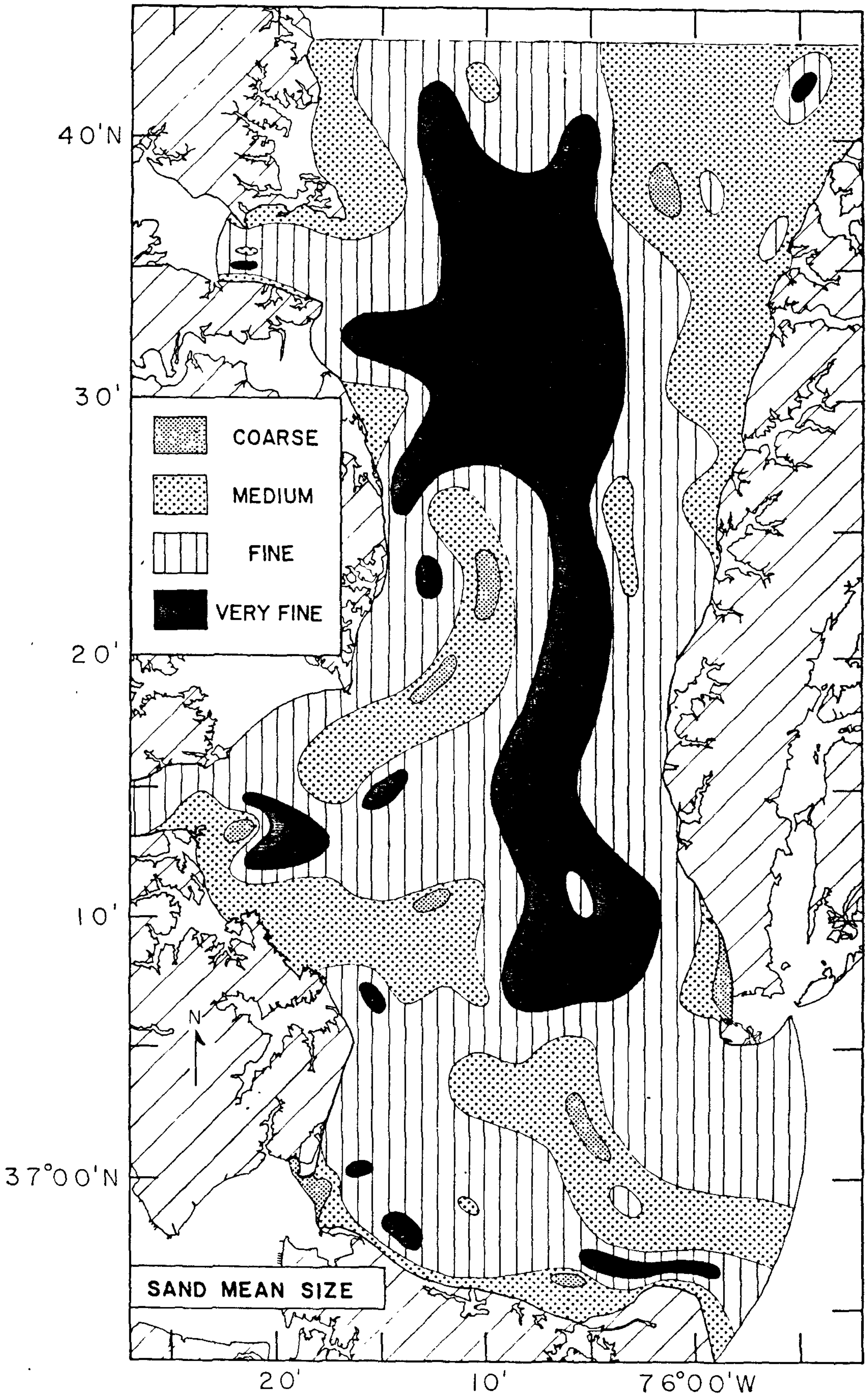


Figure 37. Isopleth map of the mean grain size of the sand fraction. Reprinted, with permission of the publisher, from Shideler, 1975.

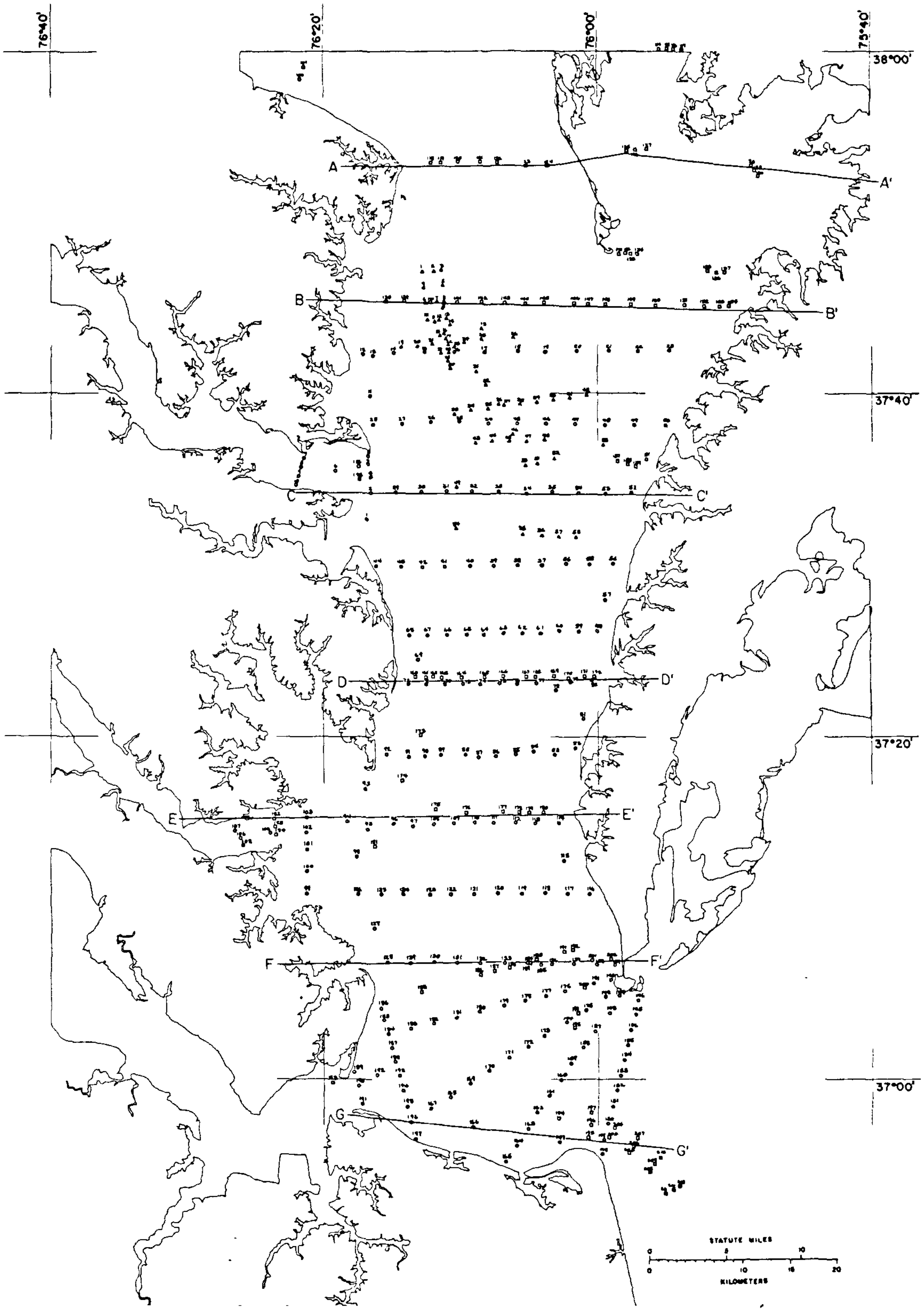


Figure 38. Location of sample stations from Ryan (1953), Harrison and others (1964), and Shideler (1975).

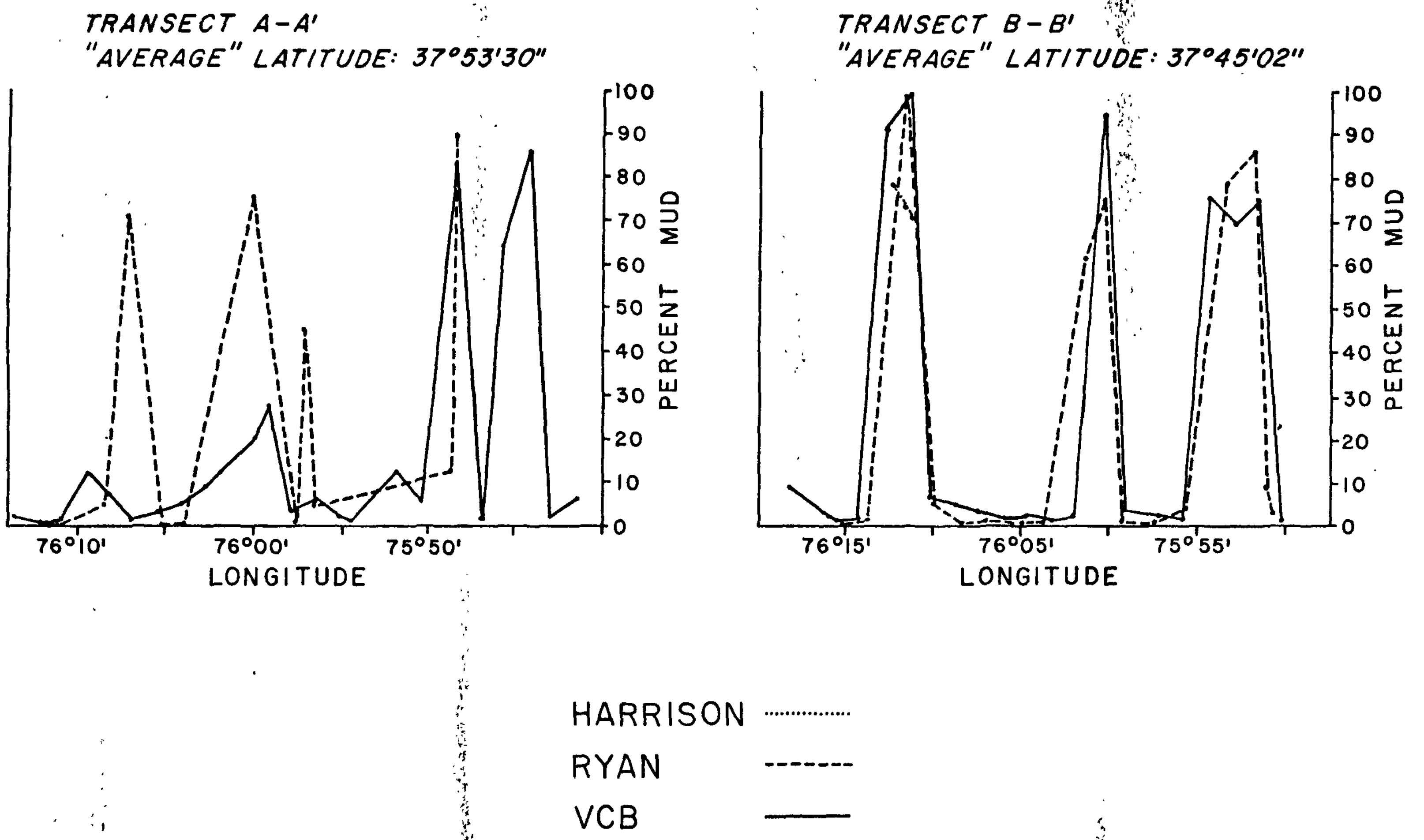


Figure 39a. A comparison of weight percent mud along profiles A and B from the data of Ryan (1953), Harrison and others (1964), and the present study.

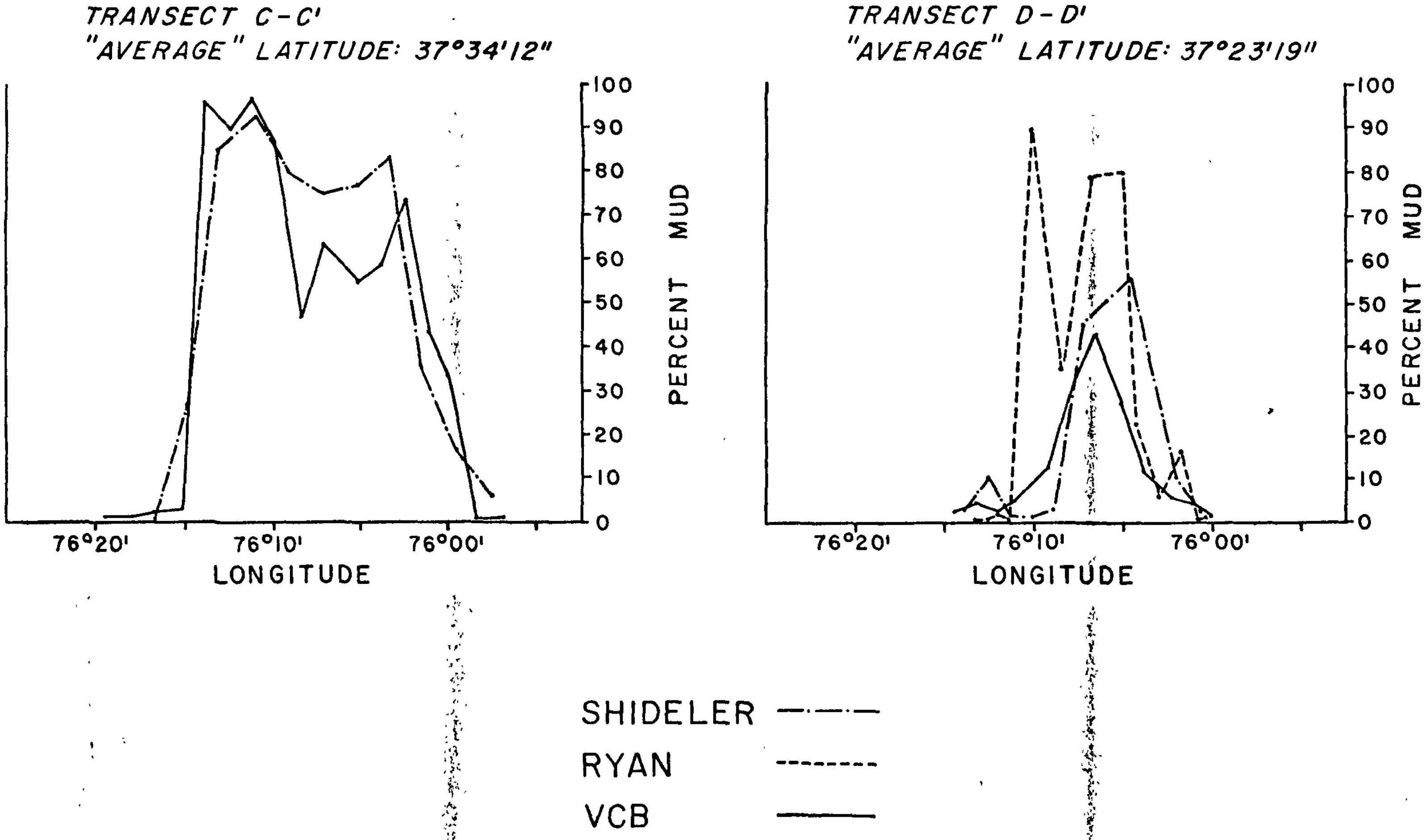


Figure 39b. A comparison of weight percent mud along profiles C and D from the data of Ryan (1953), Shideler (1975), and the present study.

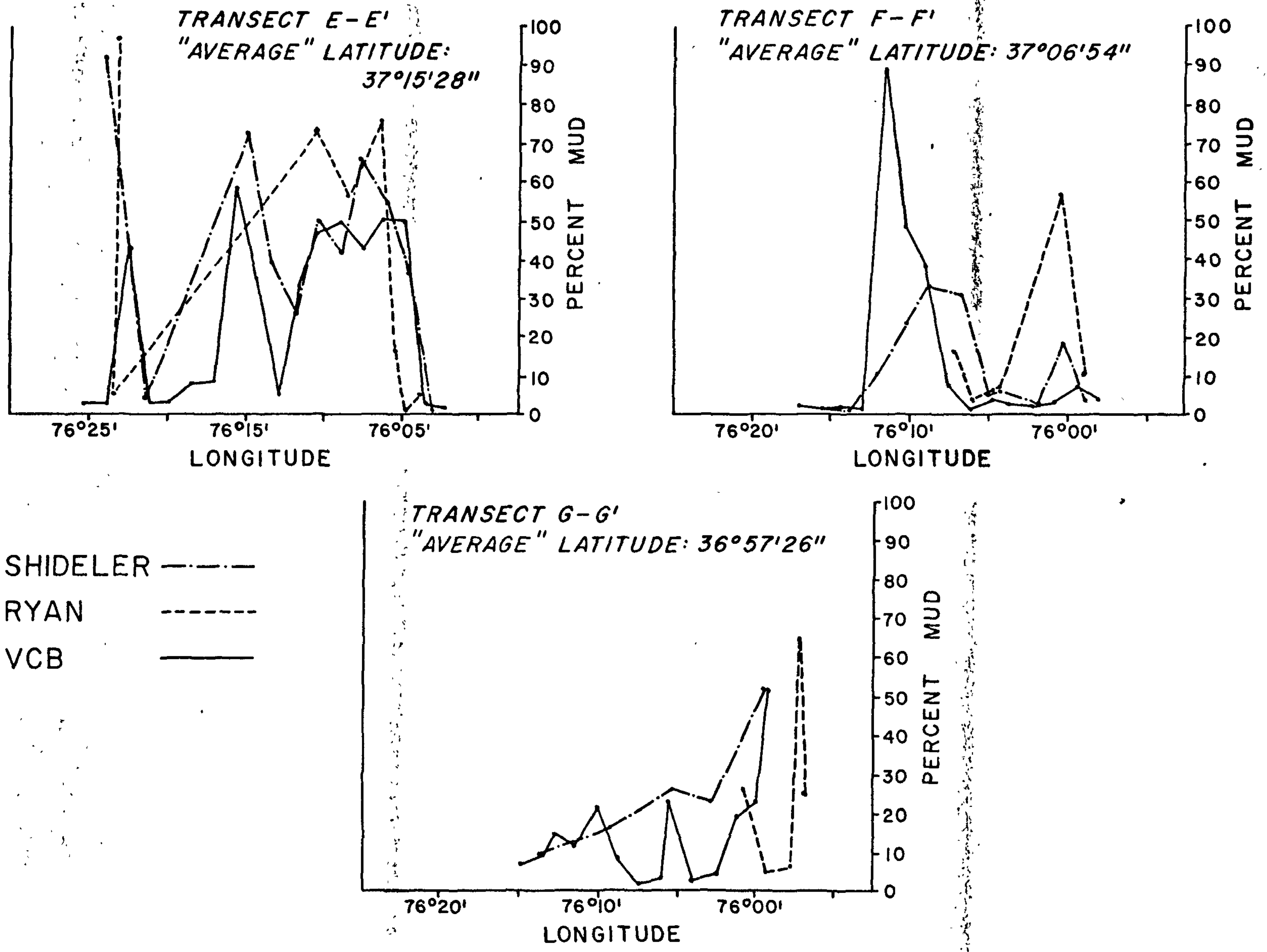


Figure 39c. A comparison of weight percent mud along profiles E, F, and G from the data of Ryan (1953), Shideler (1975), and the present study.

factors such as time, funding level, and logistics often necessitate the acquisition of fewer samples than might otherwise be desirable.

The concept of the nature of the bottom sediments changing with time should not be discounted. In considering this possibility it is worth while to look at the dates of sampling and their relationship to specific physical events:

Ryan (1953)		
Samples collected	1950, 1951	
	March 1962	Ash Wednesday Storm
Harrison *et al*. (1964)		
Samples collected	June 1962, April 1963	
	June 1972	Agnes floods
Shideler (1975)		
Samples collected	April-September 1973	
This study		
Samples collected	November 1978-June 1979	

The Ash Wednesday 1962 storm lasted several days and was accompanied by greatly elevated water levels and heavy wave agitation. Hurricane Agnes, 1972, provided all the elements necessary for the maximum transport of sediments from the upper Bay and tributary rivers into the lower Bay. It should be noted that two studies, Harrison *et al*. and Shideler, follow within a year of the significant storms while the other two studies fall during periods of "normal" processes. This then presents the questions of both the nature and duration of the storm impacts on the bottom sediment.

The profile comparison between the information from Shideler and the present (VCB) studies are somewhat ambiguous. In the profiles and plots of weight percent mud are generally parallel and exhibit the greatest differences in places where sample location, or rather lack of co-location, could account for the differences. That is the "spikes" in one plot occur between samples on the other indicating that, perhaps, the second study failed to sample the "spike" area. However, if in the laboratory, one plots both complete sets of mud-content data on the same map, another interpretation becomes possible. In some areas Shideler observed bottom sediments that were 10 to 15% muddier than the bottom sediments of the most recent study. The greatest differences are immediately south of Tangier Island in Shideler's northernmost line of samples and in the lines adjacent to and below the Rappahannock. A possible explanation is that the muddier sediments are material that entered the Bay as a result of the major floods that followed Hurricane Agnes in 1972. The sediments coming from either the Maryland portion of the Bay the Potomac, and the Rappahannock. During the years between the two studies, the "normal" processes would have altered the immediate post-storm surface sediments by both redistribution and burial. Unfortunately a similar comparison using Harrison et al. post-Ash Wednesday storm data is in-conclusive.

The map comparison of Shideler's with the present study's data suggests that there may have been unusually high loads of fine-grained sediment deposited within the Virginia portion of the Bay as a result of the Agnes floods and that five years of "normal" processes are sufficient to "mask" the event. The profile comparisons of the several data sets demonstrate, or at least very strongly suggest, that the distribution of the sediment is quite patchy and that significant gradients may be lost to a wide sample spacing. Indeed if sediment types can vary across an area of one or two hundred meters width the relatively "close" spacing of the present study gives only a slightly better picture than the less close spacing of Shideler's work.

3. Clay Mineralogy. Little work has been done with the details of the clay mineralogy of the Chesapeake Bay. A quarter century ago Powers (1954) studies the diagenesis of clays in the Bay and reported the formation of a thermally stable, clorite-like mineral that increases with salinity and depth of burial. Hathaway (1972) had fewer than a dozen samples from the lower Bay in his study of east coast clay-mineral facies, although he does indicate the Bay as a transition area between glaciated and non-glaciated sources. Nelson (1960) discussed some of the aspects of the clays of the Rappahannock. Nichols (1972) examined the sediment of a portion of the lower James River. Harrison, Lynch, and Altschaeffl (1964) briefly mention the clay mineralogy of sediments in the portion of the Bay roughly between the Potomac and Rappahannock Rivers. More recently, Feuillet and Fleischer (1980) studies the clay mineralogy of the lower James River and the extreme southern portion of the Bay. There has been no comprehensive investigation of the clay mineralogy of the Chesapeake Bay. This study slightly increases the body of knowledge in two ways. First, it defines the distribution of clays as a size class (Figure 33) and second it reports the clay-mineral composition of approximately 20 samples (Table 10).

The original intent of the investigation was to test three hierarchial or nested hypotheses. 1) That there are mappable variations in the clay-mineral assemblages of the lower Chesapeake Bay, 2) that the major cause of the variations are differences in the material supplied by the several sources, and 3) that the mapped pattern of clay-mineral assemblages can be explained by logical processes, e.g. currents. This set of hypotheses can be recast as the following questions. Do the major sources of sediment to the Bay, the several rivers, the ocean, and shoreline erosion contribute different, definable suites of clay minerals to the Bay? Do those clay-mineral assemblages remain as identifiable units coding deposited sediments as to their source? What processes govern the distribution and physical form of the deposits? The reconaissance work is only semi-quantitative in nature using ratios of peak heights of both untreated glycolated sediment from the 9 Ø (2 μm) and finer fraction of the sample. As with the previous researchers, chlorite, illite, kaolinite and montmorillonite, and vermiculite are the major clay minerals.

Table 10

Approximate Proportions of Specific Clay Minerals as Percentage of Total Clay

Sample Number	General Location	Chlorite	Illite	Kaolinite	Montmorillonite	Vermiculite
VCB0060	York River mouth	30	30	20	15	
VCB0104	Rappahannock River	15	30	20	10	
VCB0105	Rappahannock River	20	30	20	Tr	
VCB0110	Rappahannock River	20	25	25	10	20
VCB0263	Wolf Trap-mid, lower Bay	25	50	10		
VCB0404	Tangier Sound	20	30	15		20
VCB0454	Md.-Va. Line, Smith Point	20	30	15	15	20
VCB1142	Hampton Roads	30	20	20	30	
VCB1145	Hampton Roads	30	40	30		
VCB1474	Md.-Va. Line, Smith Point	20	40			
VCB1479	Md.-Va. Line, Smith Point	15	10	5		15
VCB1480	Md.-Va. Line, Smith Point	10	40	20		
VCB1637	Bay mouth	20	40	15	15	
VCB1890	Tangier Sound	15	30	10	10	10
VCB1954	Watts Island	15	25	10		
VCB1990	Pocomoke Sound	20	30	15		15
VCB2011	Pocomoke Sound	40	30	15	10	
VCB2014	Pocomoke Sound	15	30	25		25
VCB2024	Pocomoke Sound	35	50	15		

However the relative paucity of sediments with even moderate clay contents raises questions about the significance and validity of the data. If the samples analyzed are chosen only from those with appreciable clay contents, the spatial distribution is quite limited, hence greatly restricting the inference of broad processes. If, on the other hand, samples are chosen as a random subset of the large sample grid, the data from samples with minimal clay contents might be sufficiently suspect as to invalidate specific conclusions.

Using both the new and published data though, there is evidence to suggest that the hypotheses may be valid. Much of the published evidence is summarized by Hathaway (1972), but other sources include Powers (1954), Meade (1969), Nelson (1960), Harrison and others (1964), and Feuillet and Fleischer (1980). The Susquehanna River, the Bay's major tributary, is the only one of the Bay's tributaries which drains a glaciated region. The potential availability of rock flour in addition to the clay products of more conventional weathered bedrock should give the Susquehanna borne clay assemblage different and differentiable characteristics. Similarly the rivers draining non-glaciated areas transport sediment eroded from more deeply weathered bedrock of the piedmont. Although Hathaway's (1972) map of kaolinite distribution in the Chesapeake Bay shows a mid-Bay peak, this would be expected as a result of the upstream estuarine bottom circulation. Indeed, Hathaway indicates that the kaolinite concentration of the James, York, and Rappahannock Rivers is 4 to 5 parts in 10, with far and away the greatest quantity contributed by the James, whereas the Potomac and Susquehanna have 2 to 3 and 1 part in 10 kaolinite respectively. The greatest concentrations in the Bay's clays away from the immediate river mouths, however, are north of the Rappahannock. It should be noted that Hathaway depicts 10 stations in the lower Bay and fewer than a dozen and a half in the entire Chesapeake Bay. The progressively deeper and more intense weathering of the southern areas is perhaps an explanation of the increased kaolinite content of the more southerly rivers.

Other patterns outlined by Hathaway include increasing montmorillonite content in the rivers away from the Susquehanna, but a relatively uniform distribution in the mid and lower Bay, a definite progressive down-Bay increase in chlorite, even though the mineral was not detected in the rivers south of the Potomac, and an extensive area of illite concentration surrounding a small island of lesser concentration adjacent to the mouth of the Potomac. The present work echos the down Bay chlorite trend. The Bay mouth changes which he notes can be attributed to the contributions of sediment from outside the Chesapeake. Indeed, in a separate figure (his Figure 14), he depicts a definite bottom transport of clay into the Chesapeake during the Holocene.

Powers (1954 and other dates) attributed the lower Bay increase in chlorite to the diagenetic formation of chlorite in increasingly saline waters. Nelson (1960) also reported a downstream increase of chlorinte in the Rappahannock but was unwilling to ignore causes oter than diagenesis and withheld judgment.

Meade (1969) drawing on the works of many others presents a strong case for the "landward transport of bottom sediments." And as noted above, the patterns depicted by Hathaway (1972) infer the presence of such a process.

Harrison *et al.* (1964) state that most of the clays in this area were primarily illite (50%), chlorite (30%), and a mixed layer clay (20%); the later being illite-montmorillonite and chlorite-montmorillonite. They reported only a trace of kaolinite.

Feuillet's and Fleischer's work in the James is primarily concerned with along-river trends in varying concentrations of various clay minerals. In the extreme lower Bay between Hampton Roads and Cape Henry, they record illite (approximately 50%), montmorillonite (12%), chlorite (8%), and lesser quantities of kaolinite, vermiculite, and dioctahedral vermiculite.

4. *Carbon and Sulfur in the Sediments.* The spatial distribution of the carbon, organic carbon, and sulfur contents, as weight percents, of the sediments of the bottom of the Virginia portion of the Chesapeake Bay are the major concern of this section. The delineation of relationships of these distributions with one another and with physical characteristics, such as water depth or sediment type, makes a contribution toward the understanding of the processes active within the Bay.

The gross chemical attributes of the modern sediments provide information of potentially broad use. When compared to the analyses necessary for the determination of the presence of various complex organic pollutants, the cost of the laboratory analyses performed for this study is relatively small. It may possible, when data from the more complex analyses become available, to correlate indices derived from the relatively simple analyses with the different levels or aspects of pollution. If such were the case, index values could be used to screen areas in order to identify zones of possible concentration of contaminants. Additionally, index data developed from samples taken on a tight grid might be used to extend maps of more difficulty obtained data from a coarser grid.

a. *Previous Work.* Shideler (1975) discussed the total organic content of the sand-gravel fractions of the sediments of the Lower Bay. The weight percent organic content as determined by heating the greater than 63 m sediments at 400°C and acid digestion ranged from 0% to 43% with most values less than 5%. Shell material was the dominant component. He mapped areas of concentration adjacent to but offset to the south of the mouths of the Rappahannock and York Rivers, perhaps reflecting areas of sediment enriched in nutrients by material supplied from the rivers. Harrison *et al.* (1964), reporting on an area between the Potomac and Rappahannock Rivers noted organic and inorganic carbon contents ranging up to 1.9% and 0.42% respectively.

Biggs (1967) reported on the organic carbon content of 120 samples taken from the mid-Bay in the vicinity of the mouth of the Patuxent River. The values range from 0.95% to 3.4% (organic) carbon, with the lower values from shallow-water silty-sands, the higher from the finer sediments of the deeper waters. Biggs, working with relatively short cores, also reported a general decrease in organic matter with depth of burial, confirming observations of earlier workers. He related the increase in organic carbon of the surface sediments with increasing water depth to four phenomena: 1) a higher rate of sedimentation in shallow water which would serve to dilute the organic matter with detrital material; 2) the higher oxygen content of the shallow waters and the greater grain size (thus permeability) of the shallow water sediments; 3) the scavenging activity or organisms in shallow areas; and 4) the greater physical energy of the shallow areas.

Folger (1972) related organic carbon content to sediment texture and cited the organic carbon content as an index to the level of pollution. He stated that the organic matter in estuarine sediments is derived from plant detritus carried to the estuary by rivers, from the debris of estuarine plants and animals, and from various anthropogenic effluents. Referring back to the earlier work of Trask (1932), he states, "concentrations of organic matter vary inversely with sediment grain size." As did Biggs (1967), Folger (1972) also found the sediment-organic matter relationship to be a complex one including the settling characteristics of the particles and permeability of the sediment, in addition to water chemistry and microbiology. In a brief discussion of the Chesapeake Bay, he found the organic carbon content to be as would be expected for the grain size; that is, generally below 1% for sands, below 5% for silts and clays. In reviewing the organic carbon content of estuarine sediments in general, citing Whitewater Bay, Florida, and Deep Inlet, Alaska, as examples, he stated that areas where the bottom waters are anaerobic (swamps and fjords) there may be higher concentrations of natural organic carbon.

Although the impact on his paper probably is not great, Folger's (1972) work has a synthesis of the work of several researchers who used a number of different analytical techniques. Leventhal and Shaw (1980), working with a shale, showed that precision within individual techniques to determine carbon content is good (± 3%), but there can be significant (24% or more) variations among techniques. Obviously this necessitates that researchers carefully document and describe analytical procedures.

Mencher et al. (1968) reported very high organic-carbon-contents in the surficial sediments of Boston Harbor, Massachusetts. The enormously high values, however, are explained by the high level of pollution in the harbor. The sandier sediments contained wind-carried fragments of coal and coke; raw sewage was the probable prime contributor to the organic content of the less than 62 m sediments.

Rashid and Reinson (1979) noted the relationship of organic-carbon content and fine-grained sediments with an average 4.8% organic-carbon content in muds and 3.6% in sandy muds of the Miramichi Estuary of New Brunswick. They further state that "The sediments of the Miramichi contain a much higher quantity of organic carbon than would be expected to occur naturally in a shallow, well-mixed estuary", and attribute this apparent anomaly to the discharge of pulpmills.

LORAN-C INTERVALS

9960-X			9960-Y		
Chart	Theoretical	Actual	Chart	Theoretical	Actual
27318.4	27321.56	27318.88	41634.6	41636.81	41636.34
27314.2	27316.99	27314.67	41719.2	41720.41	41720.06
27340.8	27343.38	27341.30	41925.9	41926.90	41926.74
27283.0	27285.93	27283.53	41904.0	41905.88	41905.26
27223.2	27226.48	27223.69	41987.1	41989.74	41988.46
27230.4	27233.39	27230.80	41841.5	41843.29	41842.49
27203.1	27206.18	27203.63	41840.6	41842.76	41842.14
27237.2	27239.91	27237.49	41703.8	41705.67	41705.07
27275.1	27278.01	27275.77	41575.8	41577.68	41577.32
	27228.83	27226.20		41595.64	41594.59
	27221.93	27219.71		41497.59	41497.79
	27306.60	27303.63		41449.50	41448.44
	27271.34	27268.75		41443.50	41442.95
	27192.80	27464.99		41405.09	41404.32
	27260.17	27257.46		41366.01	41365.84
	27244.46	27241.72		41307.17	41306.50
	27255.68	27252.97		41280.57	41280.05
	27296.79	27293.64		41256.82	41255.73
	27190.93	27188.49		41300.78	41300.63
	27208.75	27206.29		41287.70	41287.45
	27222.25	27219.53		41267.81	41267.52
	27272.41	27269.18		41242.21	41241.54
	27194.55	27191.98		41247.25	41246.94
	27250.33	27247.41		41212.49	41212.14

LORAN-C INTERVALS

9930-Y			9930-Z		
Chart	Theoretical	Actual	Chart	Theoretical	Actual
53476.9	53477.72	53475.63	70565.2	70563.26	70564.51
53388.4	53389.54	53387.80	70528.5	70526.59	70527.90
53208.4	53209.45	53207.93	70409.2	70407.26	70408.58
53172.1	53173.02	53171.55	70464.3	70462.35	70463.77
53028.9	53029.71	53028.40	70467.4	70465.40	70466.70
53181.8	53183.07	53181.62	70533.8	70532.14	70533.74
	53156.40	53154.65		70552.11	70553.33
53326.4	53327.22	53325.74	70597.6	70595.61	70597.00
53492.4	53493.30	53491.92	70631.2	70629.16	70630.49
53425.3	53426.16	53424.96	70661.5	70659.70	70661.26
53616.0	53616.54	53614.99	70666.6	70665.19	70666.52
53516.7	53517.31	53515.25	70716.9	70715.41	70715.94
53649.1	53650.06	53648.40	70670.4	70668.84	70670.05
53619.8	53620.81	53619.17	70704.2	70702.52	70703.74
53579.5	53580.68	53578.97	70788.4	70786.73	70788.00
53685.9	53687.13	53684.97	70753.0	70751.88	70752.93
53729.1	53730.27	53728.52	70797.4	70795.95	70797.23
53767.3	53768.08	53766.31	70801.5	70800.23	70801.17
	53832.94	53831.33		70775.83	70777.05
53681.9	53683.12	53681.14	70845.0	70843.61	70844.67
53712.0	53714.02	53712.21	70837.0	70836.12	70837.22
53746.2	53747.41	53745.24	70836.7	70835.49	70836.55
	53823.17	53821.02		70805.54	70806.80
53739.0	53740.27	53738.25	70870.6	70869.36	70870.47
	53830.81	53828.74		70840.76	70841.83

Jones and Jordan (1979) report concentrations of organic carbon in the estuary of the River Liffey, Dublin, ranging from 1.7% at the mouth of the estuary to 25.4%. The River Liffey flows through the urban environment of Dublin and the greatest levels of organic carbon occur at the upper limits of sea-water incursion (the zone of the turbidity maximum), perhaps reflecting the deposition of particulate wastes from paper mills and other sources.

In a discussion of the 1 cm surface sediments from Lakes Ontario, Erie, and Huron, Kemp (1971) reported that carbonate carbon was usually less than 1%. Higher values, up to 5%, were attributed to bottom materials that were locally derived from carbonate sediments. Organic carbon ranged upward to 5%. Kemp also noted the strong relationship between organic carbon and clay contents and an apparently equally strong correlation between organic carbon and nitrogen. As in Chesapeake Bay, basin morphology in the lakes is a factor in the distribution of sediment sizes and, hence, in the spatial distribution of organic carbon.

Thomas (1969) addressed the relationship of organic-carbon content and grain size and suggested that, partially as a function of the great surface area of clays, carbon is associated with clay particles. He further stated that environmental conditions might also have an influence.

Young (1968) addressed the chemistry of the sediments of a portion of the Lower Chesapeake Bay. His reported values or organic carbon, 0.15% to 2.01% agree with the ranges noted in the present study. Young's procedures included using a LECO carbon analyzer to determine carbon content and by digesting the sample in 10% HCl to remove carbonate ("inorganic" carbon). As Young's samples were short cores he provided some information on the vertical trends. At most sites, the highest organic carbon contents were between the 10 and 20 cm depths. In only 1 of the 19 stations was there an increase in organic carbon below 20 cm. He found no trend with depth of burial in the inorganic carbon. The highest organic carbon contents were found in the deep water stations. He found a good correlation ($R = 0.82$) between total iron and organic carbon content and noted that although clayey sediment contained larger amounts of organic carbon than sandier sediments, the percent organic carbon to percent clay correlation was not significant ($R = 0.40$).

The literature on sulfur in estuarine sediments in relatively scant when compared to that on organic carbon. Dunham (1961, cited in Goldhaber and Kaplan, 1974) lists river estuaries and tidal lagoons among a limited set of environments wherein the sediments may contain authigenically formed reduced sulfur compounds. There is, however, a reasonable body of literature on sulfur in marine sediments including, among others, the summary work of Goldhaber and Kaplan (1974) and Berner (1970, 1981, 1982). Goldhaber and Kaplan (1974) in tabulating the work of several other marine researchers show sulfur contents ranging from 0.02% to 2.0% in marine sediments.

The incorporation of sulfur in the sediments depends upon the reduction of sulfate to H_2S and HS^- by bacteria. This process requires anoxic conditions, which, even if not present in the water column may exist below the sediment-water interface. Although the sediments may have been deposited through oxygen-rich water, the dissolved oxygen of the interestial water is removed as it is used by the organisms inhabiting the sediment (Goldhaber and Kaplan, 1974). Berner (1981), in a discussion of sulfidic sediments, states that the occurrance of sulfides in marine sediments is common because of the sulfate available from seawater and nearly universal presence of organic matter in the sediments. Berner (1969), however, sites local differences in the content of organic matter as causing local differences in the sulfur content of anaerobic sediments. Berner (1970), using a field example from the Connecticut shore of Long Island Sound, further states that the availability of organic matter that can be metabolized by sulfate-reducing bacteria is a factor limiting the formation of pyrite in marine sediment. This relationship is depicted in a plot of weight percent organic carbon, a rough indicator of the content of organic matter, versus weight percent sulfur. The data points show very little scatter about a line of best fit. Goldhaber and Kaplan (1974), using data from several sources, present a similar plot. They state that the relationship is approximated by a line with a slope of 0.36 but admit to "a good deal if scatter the data." The scatter is due to a number of causes, including the great range of depths (0 to 500 cm) below the sediment-water interface from which the samples were taken.

b. Results. The ranges of values of total carbon, organic carbon, and sulfur contents (Figure 40) present no anomalies. The values of organic carbon up to a maximum of 3.9% with a mean of 1.0% are consistent with literature values (Shidler, 1975; Folger, 1972; Kemp, 1971). Total carbon contents are slightly greater, with mean 1.3% and are generally under 4% but with a few samples reaching 9 or 10%. These very high values are from areas where shell fragments constitute a significant portion of the sediment. Although little was known to predict the values of sulfur content, the distribution and range are not unreasonable with a maximum of approximately 2% and a mean of 0.35%.

Although the samples were chosen with a bias toward finer sediments, this bias is not significantly represented in the statistical correlations of the various parameters (Table 11). The strongest correlations of the chemical contents with a sedimentological factor are of the organic carbon and sulfur contents with the percentage of clay in the sediments. The table is a listing of R^2 values from the SAS, GLM calculations of regressions of the chemical contents against mean and median grain sizes, mud and clay contents and water depth, and each other. The table has values for the entire sample set and for sets of samples within subareas because study of the spatial distributions (Figures 41, 42 and 43) seemed to indicate a general trend of relationships between carbon or sulfur contents and depth or clay content except in shallow and/or restricted areas such as Mobjack Bay or Pocomoke Sound. In these areas the patterns differed from those in the Chesapeake Bay proper. The several subareas represent different physical environments and deserve separate consideration.

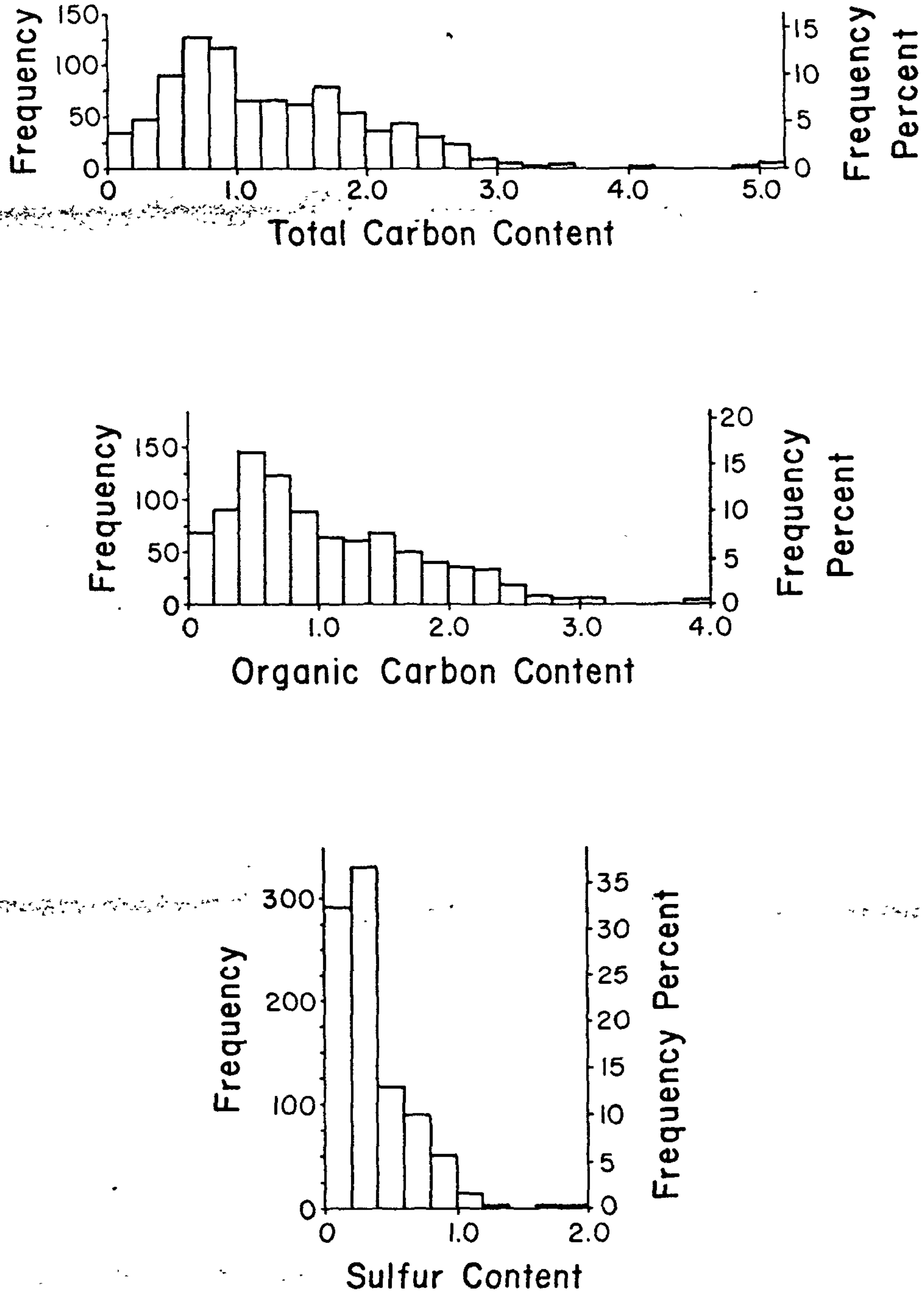


Figure 40. Histograms of the ranges of values of the total carbon, organic carbon, and sulfur contents of the sediments.

Table 11

Table of R^2 Values for Various Regressions and Areas

	Variables		Areas								
	Independent x	Dependent y	Main	Hampton Roads	Mobjack Bay	York River	Rappahannock River	Tangier Sound	Piankatank River	Pocomoke Sound	Entire System
1.	Mud	% Water	0.90	0.88	0.96	0.96	0.92	0.83	0.99	0.94	0.90
2.	Mean	% Water	0.86	0.89	0.97	0.95	0.90	0.77	0.98	0.94	0.88
3.	% Clay	% Water	0.88	0.87	0.92	0.87	0.90	0.78	0.97	0.94	0.88
4.	Depth	% Sand	0.21	0.01	0.57	0.62	0.55	0.34	0.89	0.07	0.13
5.	Depth	% Mud	0.23	0.01	0.57	0.62	0.54	0.35	0.89	0.06	0.13
6.	Depth	% Clay	0.23	0.00	0.52	0.57	0.58	0.35	0.86	0.06	0.11
7.	Depth	Mean	0.23	0.00	0.58	0.59	0.53	0.29	0.90	0.16	0.14
8.	Depth	Median	0.21	0.00	0.50	0.43	0.52	0.31	0.90	0.04	0.12
9.	Mean	T Carb	0.53	0.14	0.88	0.72	0.58	0.04	0.19	0.05	0.33
10.	Median	T Carb	0.53	0.1	0.84	0.63	0.57	0.05	0.15	0.04	0.33
11.	% Mud	T Carb	0.56	0.12	0.79	0.72	0.71	0.02	0.00	0.06	0.34
12.	% Clay	T Carb	0.66	0.15	0.97	0.59	0.73	0.09	0.87	0.11	0.41
13.	Depth	T Carb	0.04	0.00	0.34	0.39	0.42	0.01	0.00	0.04	0.00
14.	Mean	O Carb	0.53	0.67	0.83	0.8	0.74	0.61	0.15	0.43	0.57
15.	Median	O Carb	0.54	0.59	0.81	0.70	0.67	0.57	0.12	0.42	0.57
16.	% Mud	O Carb	0.55	0.53	0.74	0.79	0.79	0.56	0.09	0.49	0.59
17.	% Clay	O Carb	0.70	0.67	0.96	0.64	0.7	0.61	0.98	0.55	0.70
18.	Depth	O Carb	0.05	0.02	0.3	0.33	0.47	0.37	0.01	0.1	0.01
19.	Mean	Sulfur	0.55	0.43	0.91	0.81	0.81	0.67	0.12	0.47	0.57
20.	Median	Sulfur	0.57	0.43	0.88	0.75	0.81	0.62	0.09	0.50	0.59
21.	% Mud	Sulfur	0.57	0.45	0.86	0.87	0.86	0.74	0.32	0.5	0.58
22.	% Clay	Sulfur	0.77	0.46	0.90	0.77	0.93	0.62	0.76	0.60	0.72
23.	Depth	Sulfur	0.05	0.02	0.2	0.26	0.44	0.40	0.04	0.07	0.01
24.	T Carb	O Carb	0.91	0.16	0.97	0.98	0.89	0.27	0.88	0.36	0.58
25.	T Carb	Sulfur	0.72	0.02	0.88	0.73	0.64	0.00	0.48	0.13	0.38
26.	O Carb	Sulfur	0.79	0.27	0.84	0.8	0.63	0.66	0.80	0.73	0.76

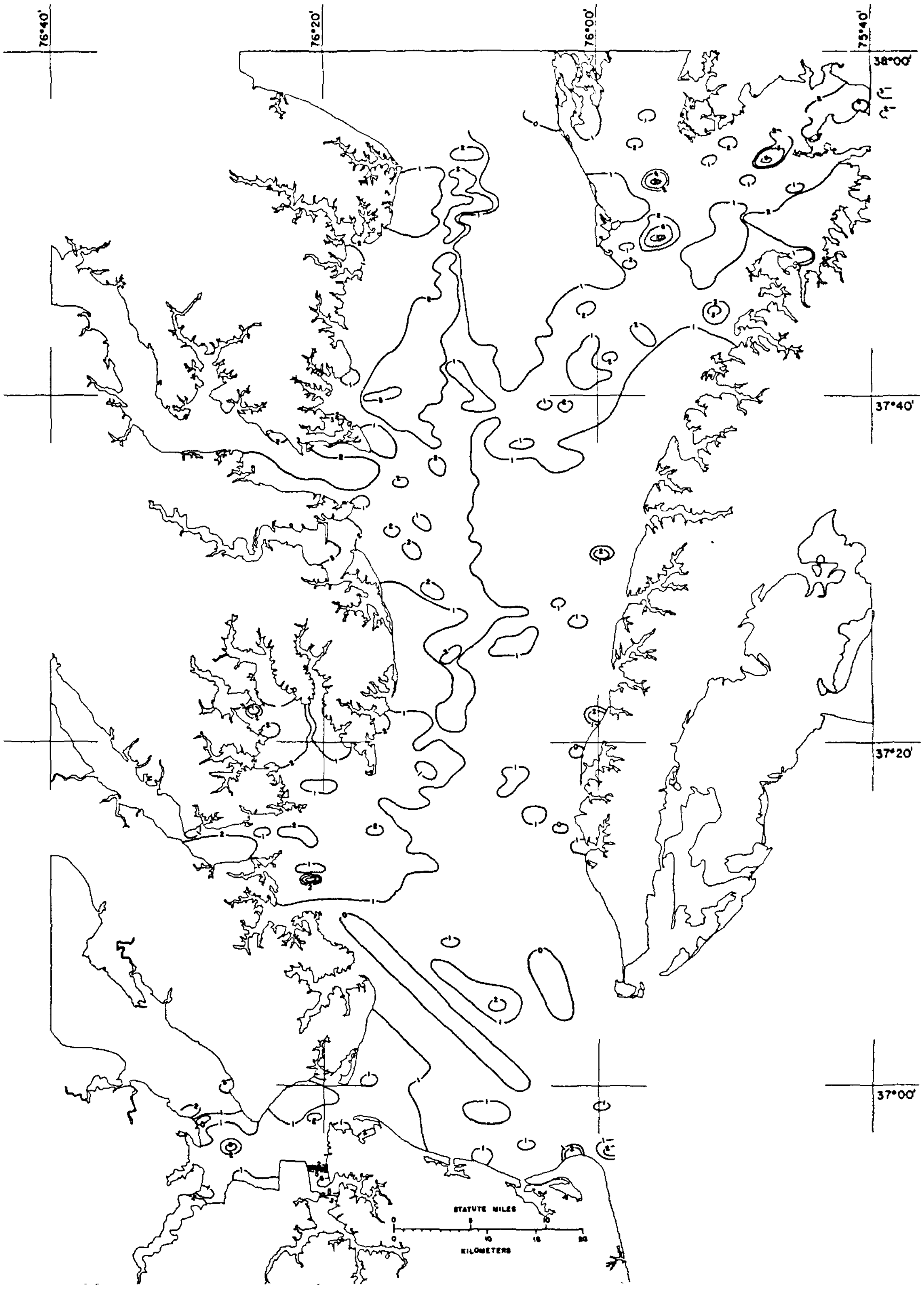


Figure 41. Isopleth map of the total carbon content of the sediments of the Virginia portion of the Chesapeake Bay.

CONTOUR INTERVAL 1%

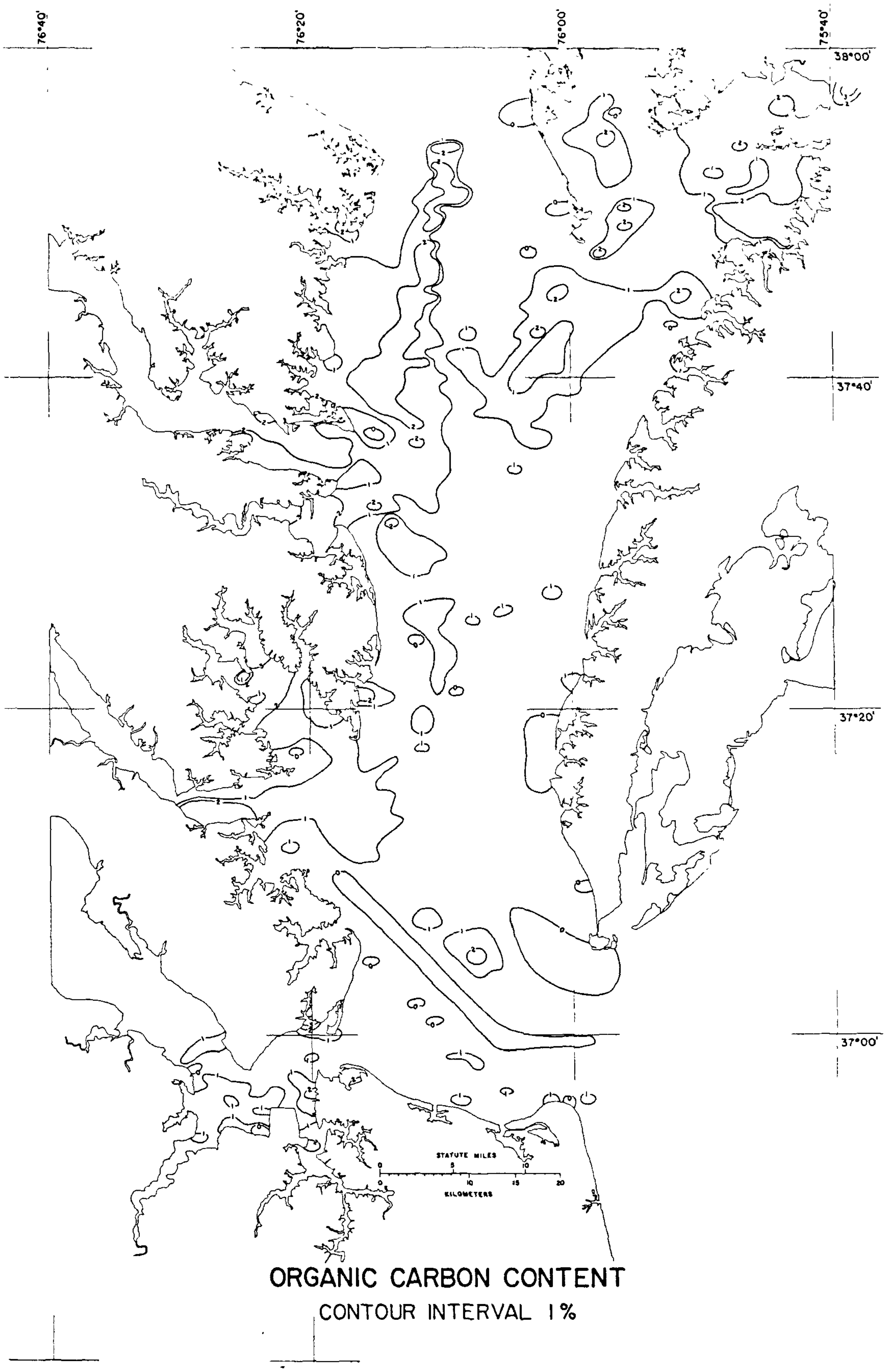
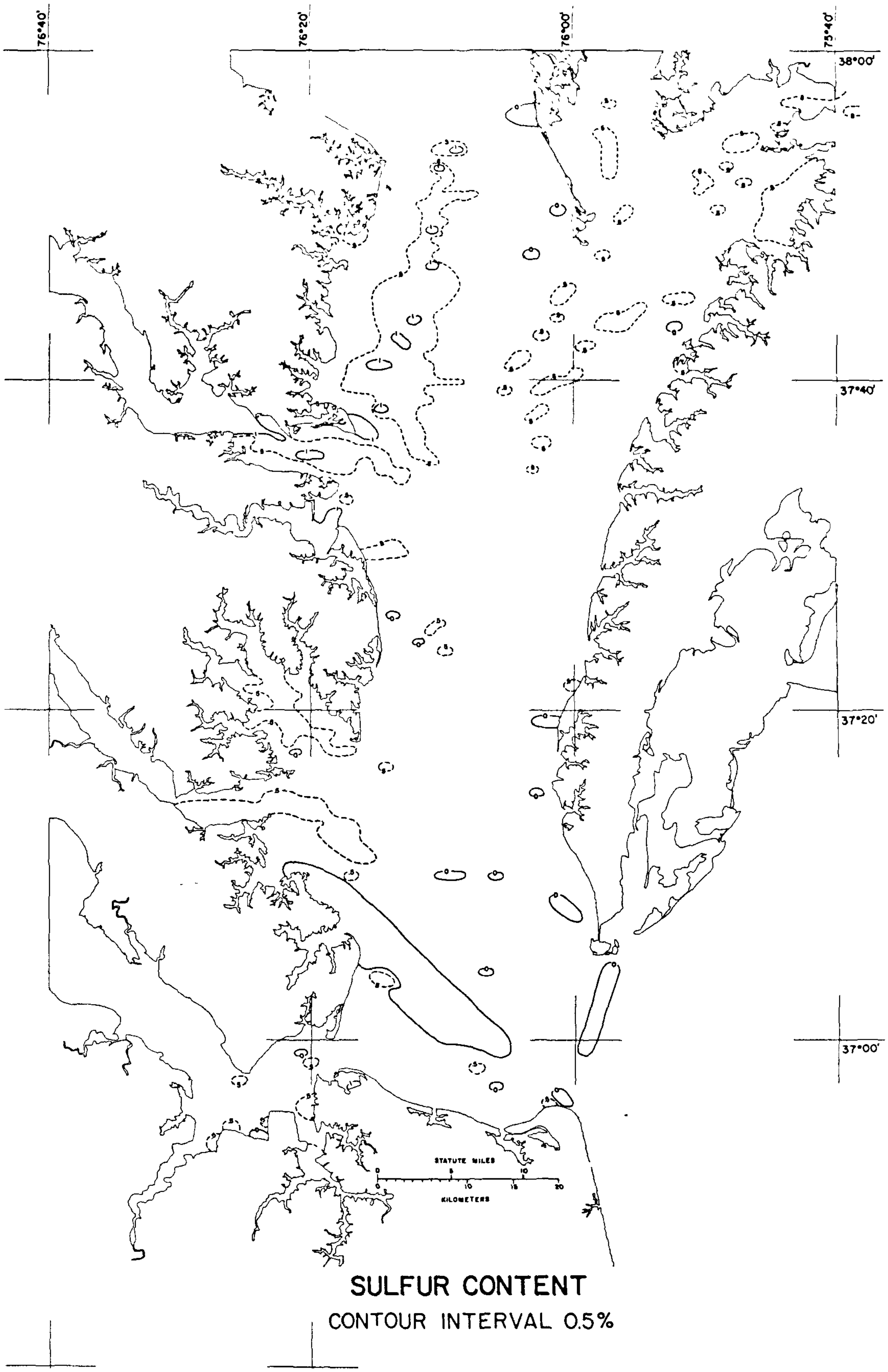


Figure 42. Isopleth map of the organic carbon of the sediments of the Virginia portion of the Chesapeake Bay.



SULFUR CONTENT

CONTOUR INTERVAL 0.5%

Figure 43. Isopleth map of the sulfur of the sediments of the Virginia portion of the Chesapeake Bay.

c. Discussion. Because the visual tie between depth and the various other parameters, both sedimentological and chemical, is so appealing, the very poor statistical correlations, maximum R^2 of 0.47 and common values of 0.1, is surprising. It most probably is explained by the frequency distribution of depths (Figure 44). The distribution is decidedly asymetrical, with most depths being quite shallow. Hence there are very few locations of greater depth with high clay contents to offset the locations of shallow depth and high clay content which results from the very sheltered nature of the location.

Of the several characteristics used to describe the sediment type, the percentage of clay has the most significant relationship to the carbon and sulfur contents. This agrees with the conclusion of Thomas (1969), based on the work of others, that "(organic) carbon is predominantly absorbed by clay particles (Bader, 1962), the quantity of which is related to clay surface area...". The poor percent-clay with total carbon correlation is probably a function of shell material found in sandy sediments. The close parallel between the clay-organic carbon and clay-sulfur relationships is a further expression of the good organic carbon-sulfur (Figure 45) correlation. R^2 for the entire system 0.76, range for subareas exclusive of Hampton Roads, 0.63 to 0.84. Figure 45 is very similar to Goldhaber and Kaplan's (1974) plot. The very low organic carbon-sulfur correlation in Hampton Roads is most likely the result of several factors including the vast quantities of coal moved through the port and the industrial and urban nature of the surrounding lands. The measures of the central tendencies of the grain size distributions, mean and median, and the mud content of the sediment are less well correlated than the percentage of clay. This points out that the governing processes are the great surface area and (potentially) active nature of clay particles and not purely grain size. Hence the quantity of clay in the sediment is more important than an integrating measure of the grain-size distribution.

The interrelationship of the various characteristics within individual subareas is a function of the local, physical environment of the subareas. Relatively shallow, semi-enclosed and little populated Mobjack Bay, from which roughly 35 of a possible 55 samples were selected for chemical analysis is the site of the strongest interrelationships. R^2 values for percent clay versus total carbon, organic carbon, and sulfur contents are 0.97, 0.96, and 0.90 respectively. The quality of the interrelationships reflects the relatively simple nature of the set of processes active within Mobjack Bay. There is only a minimum of fresh water inflow; the mean tidal range is low, approximately 0.75 m; and fetches are limited as the bay is open only to the southeast.

The York and Rappahannock River mouths, with 13 and 21 samples, also exhibit reasonably good correlations reflecting the uniform nature of the processes active across the limited areas of the river mouths. The information from the other subareas indicates some of the differences between them.

Pocomoke Sound is shallow and has a small drainage basin and freshwater inflow when compared to the rivers of the western shore. This

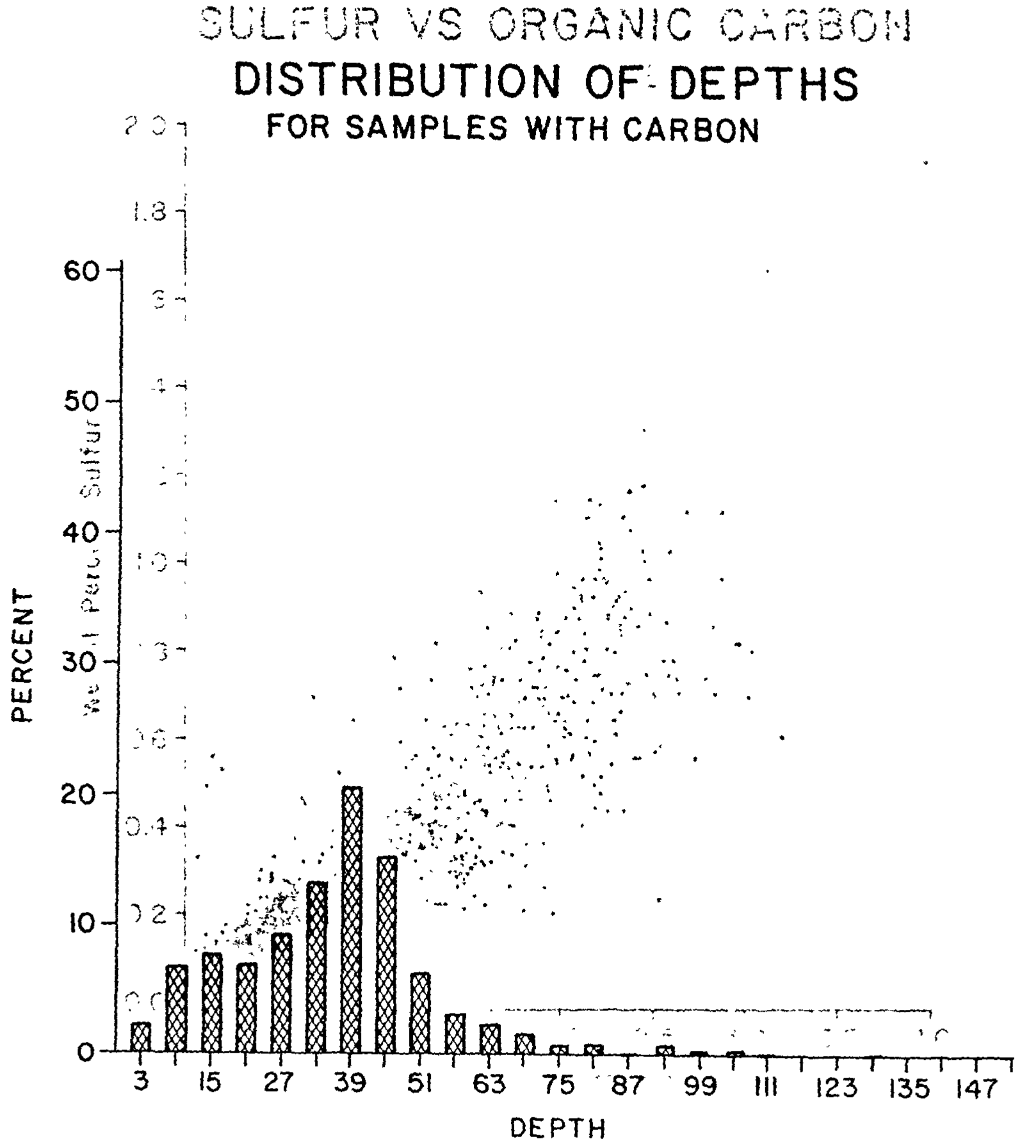


Figure 45. Scatter plot of organic carbon and sulfur contents.

Figure 44. Histogram of depths recorded at sample sites for which carbon contents were determined.

is reflected in the relatively poor relationship of organic to total carbon. This is probably due both to the less polluted waters of Pocomoke Sound and to the abundance of shell material in the clean sediments. Tangier Sound, which has a great range of depths, also has an abundance of shell material. Also there is no freshwater inflow, hence no indirect mechanism for the inward transportation of organic materials derived from terrestrial sources.

d. Conclusions. There is a strong relationship between the clay content and the total carbon, organic carbon, and sulfur contents of the sediments of the lower Chesapeake Bay. This relationship probably is due to the great surface-area presented by a large volume of clay particles and to the chemically active nature of the clays. The ratio of organic to total carbon is most strongly controlled by the presence or absence of shell material and must equal one in the absence of shell.

Several subareas of the Bay are affected by different processes which, in turn, influence the chemical and sedimentological relationships. The urban, industrial surroundings of Hampton Roads create an environment quite different from that in Tangier Sound or Mobjack Bay. The volume of fresh-water inflow, the nature of the drainage basin, and the local energy regime, in the form of waves and currents, all contribute to local variations.

B. PATTERNS AND RATES OF SEDIMENT ACCUMULATION

1. Patterns of Erosion and Deposition. The patterns of erosion and deposition in the Bay fit, with minor modifications, the physiographic segmentation offered by Ryan (1953) based upon the Bay geomorphology:

Northern Bay: Susquehanna River to south of the Patapsco River mouth.

Middle Bay: Patapsco River to the mouth of the Rappahannock River.

Southern Bay: Rappahannock River mouth to the Bay entrance.

Within the Virginia portion of the Bay stem, the patterns of erosion and deposition suggest a further zonation:

Middle Bay:

Lower belt: 37°55' to 37°35'

Southern Bay:

Upper (transitional belt): 37°35' to 37°25'
Central (farfield Bay mouth) belt: 37°25' to 37°15'
Lower (nearfield Bay mouth belt: 37°15' to 36°55'

The principal loci of deposition and erosion are shown in Figure 46. The generalized pattern is superimposed on bathymetry in Figure 47. The patterns of deposition/erosion are displayed in terms of the rate of mass accumulation in Figures 48, 49 and 50 showing, respectively, the sand, silt, and clay components.

a. The Nearfield Bay mouth belt is characterized by a pattern of "alternating" erosion/deposition areas across the Bay mouth entrance, and depositional zones on the flanks of the Tail of the Horseshoe Shoal and Thimble Shoal Channel (Figure 4). Erosion is pronounced off of Cape Henry, and in False Channel and North Channel separating Middle Ground, Inner Middle Ground and Latimer Shoals on the northern part of the entrance. The shoal areas themselves are characteristically depositional, while the location of the alternating cut and fill pattern suggests a migration of the Inner Middle Ground and Middle Ground Shoals to the southwest. The migration is consistent with the results of Granat (1976) who studied Middle Ground Shoal and presented bathymetric comparisons of five surveys between 1852 and 1975. The principal surface sediment type (> 80% by weight) within this zone is fine sand although there are fingers of medium and very fine sand (Figure 48).

The Chesapeake Channel is indicated as depositional throughout the reach from the entrance to the latitude of Cape Charles. The surface sediments are predominately fine and very fine sand with up to 40% silt.

The lower part of Old Plantation Flats Channel is included in this belt. The deeper areas of the channel are erosional as is the eastern flank; the bottom sediments are very fine sand with up to 30% silt in the deep area while the eastern flank is composed of fine to medium sand. The western flank, indicated as depositional, is very fine sand (> 60% by weight) and silt.

Horseshoe Shoal, which forms the western portion of the Bay mouth nearfield belt, is indicated as an area of relatively low deposition with areas of erosion in the nearshore zone. This sand shield (> 80% sand) is characterized by fine sand on the southern part whereas the region flanking York Spit Channel is medium sand with patches of coarse sand. The latter areas fronting Poquoson Flats are indicated as non-deposition or erosional. This is consistent with independent observations from a coring study which show only a veneer of sand over Pliocene sediments.

The Bay bottom south of Thimble Shoals Channel is indicated as depositional near the seaward part of the channel, and erosional within the inner segment (dredging zone). The Crumps Bank area is expressed as non- to slightly depositional with fine and very fine sand and local areas of silt. The nearshore zone along the southern Bay shore and Willoughby Bank is indicated as being a relatively weak depositional zone with erosional spots in the nearshore. Surface sediments are fine to medium sands.

b. The Central Southern Bay belt is considered a portion of the Bay mouth system because of the presence of a pronounced depositional area (Figures 46 and 47) to which we attribute a Bay mouth source. This depositional

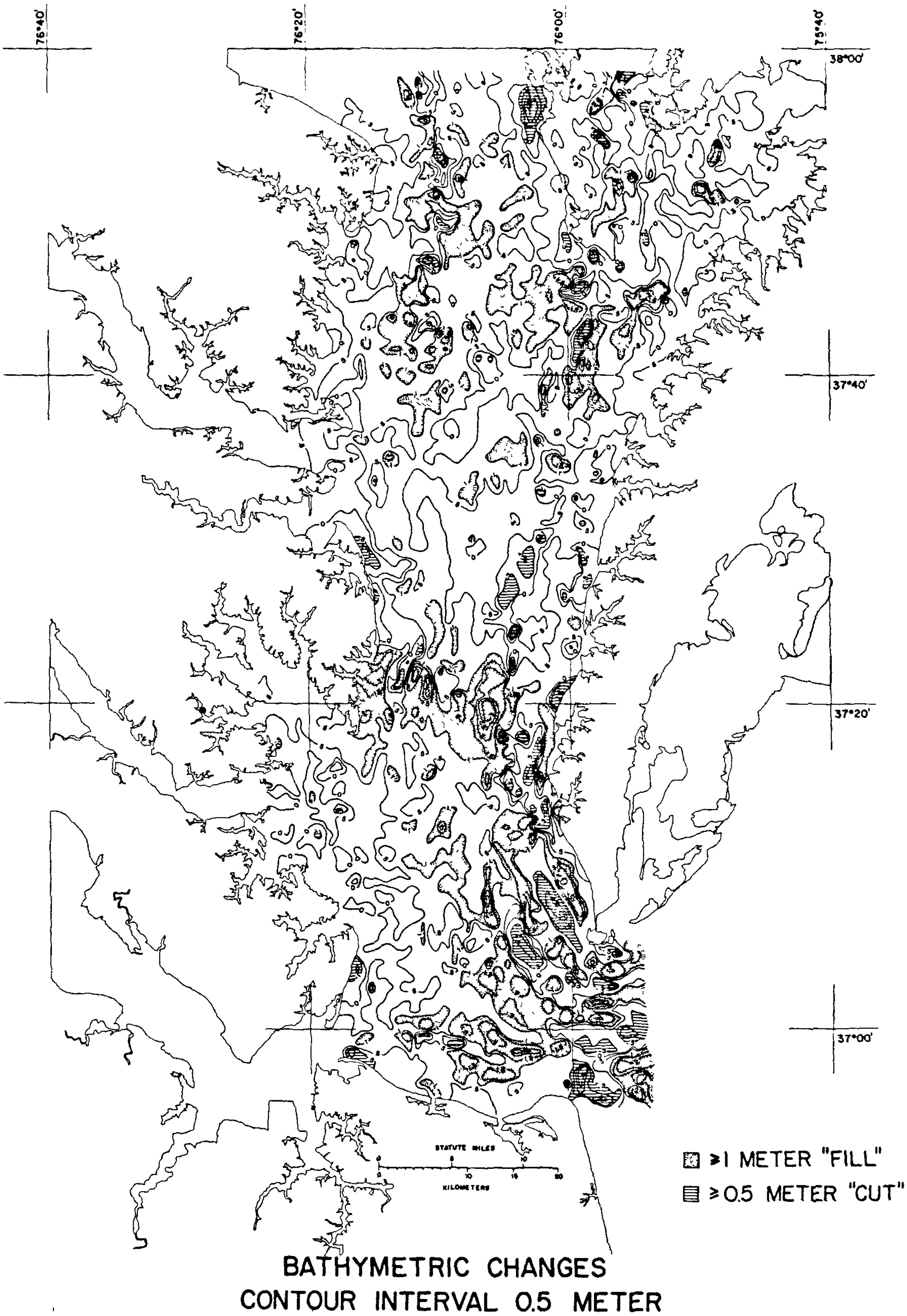


Figure 46. Bathymetric changes during the past 100 years in the Virginia portion of the Chesapeake Bay.

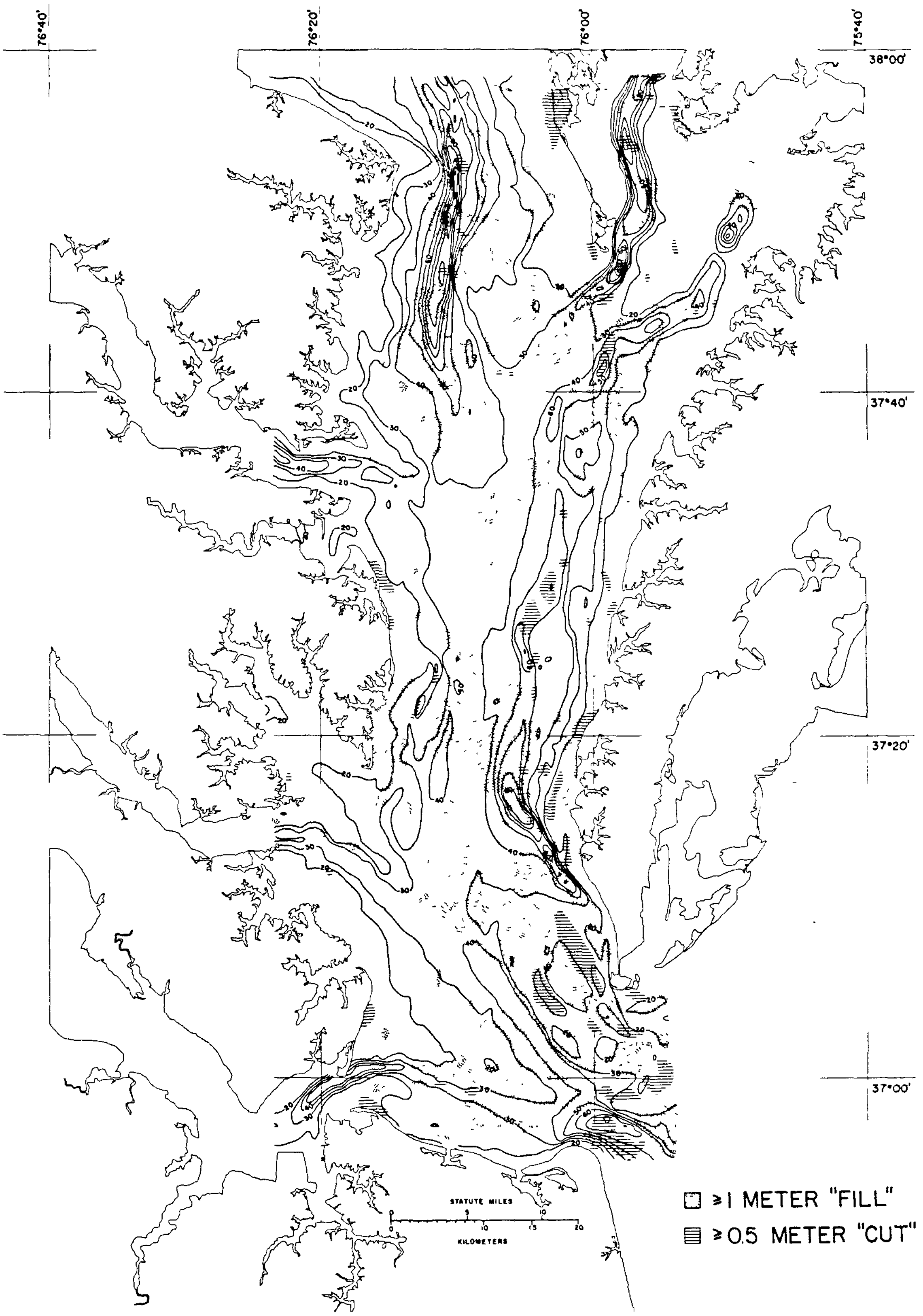
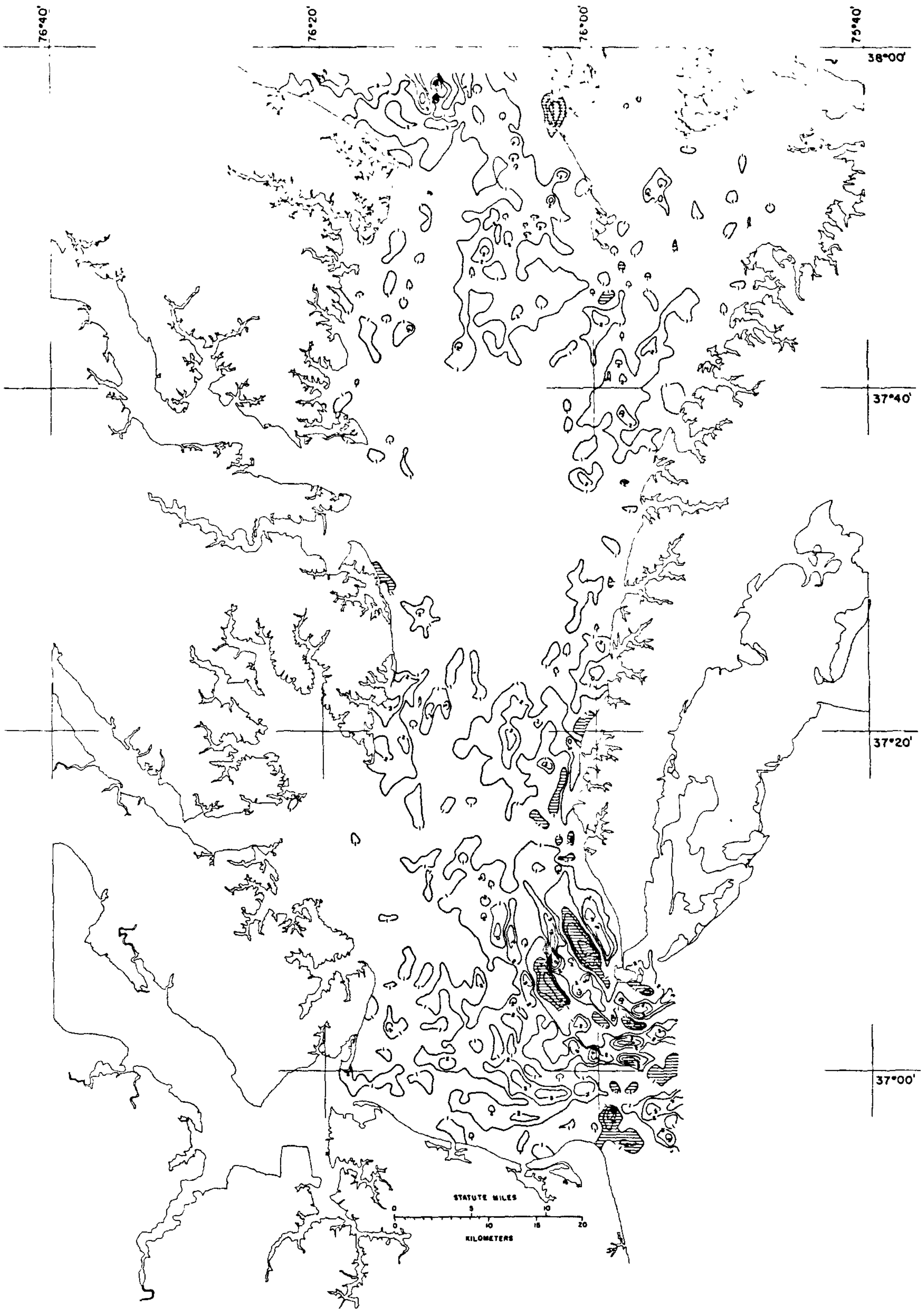


Figure 47. Bathymetry and generalized bathymetric changes in the Virginia portion of the Chesapeake Bay.



MASS ACCUMULATION OF SAND

CONTOUR INTERVAL 1 M-TON / M^2 / CENTURY

Figure 48. The mass of sand accumulation per square meter per century in the Virginia portion of the Chesapeake Bay.

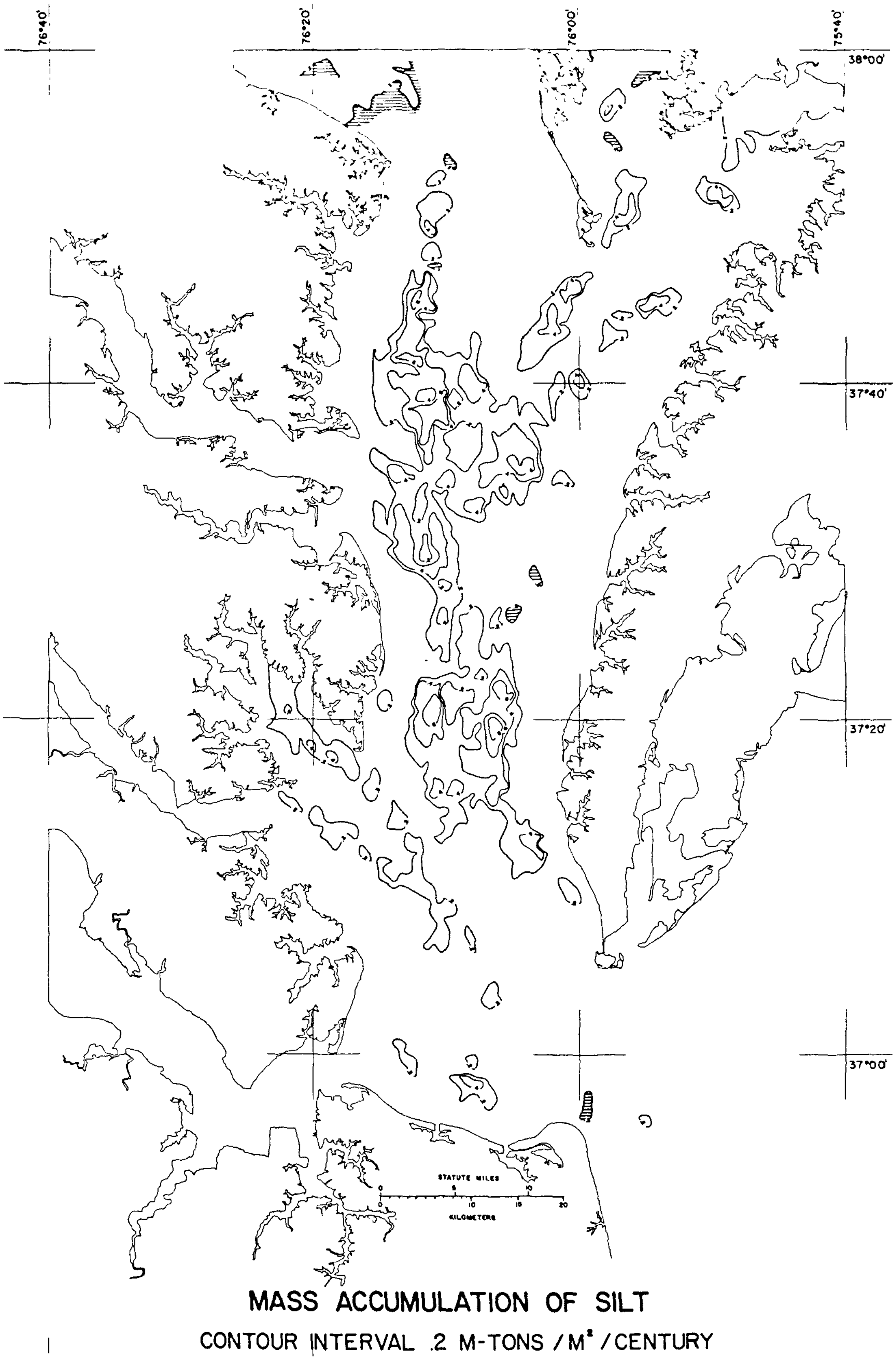


Figure 49. The mass of silt accumulation per square meter per century in the Virginia portion of the Chesapeake Bay.

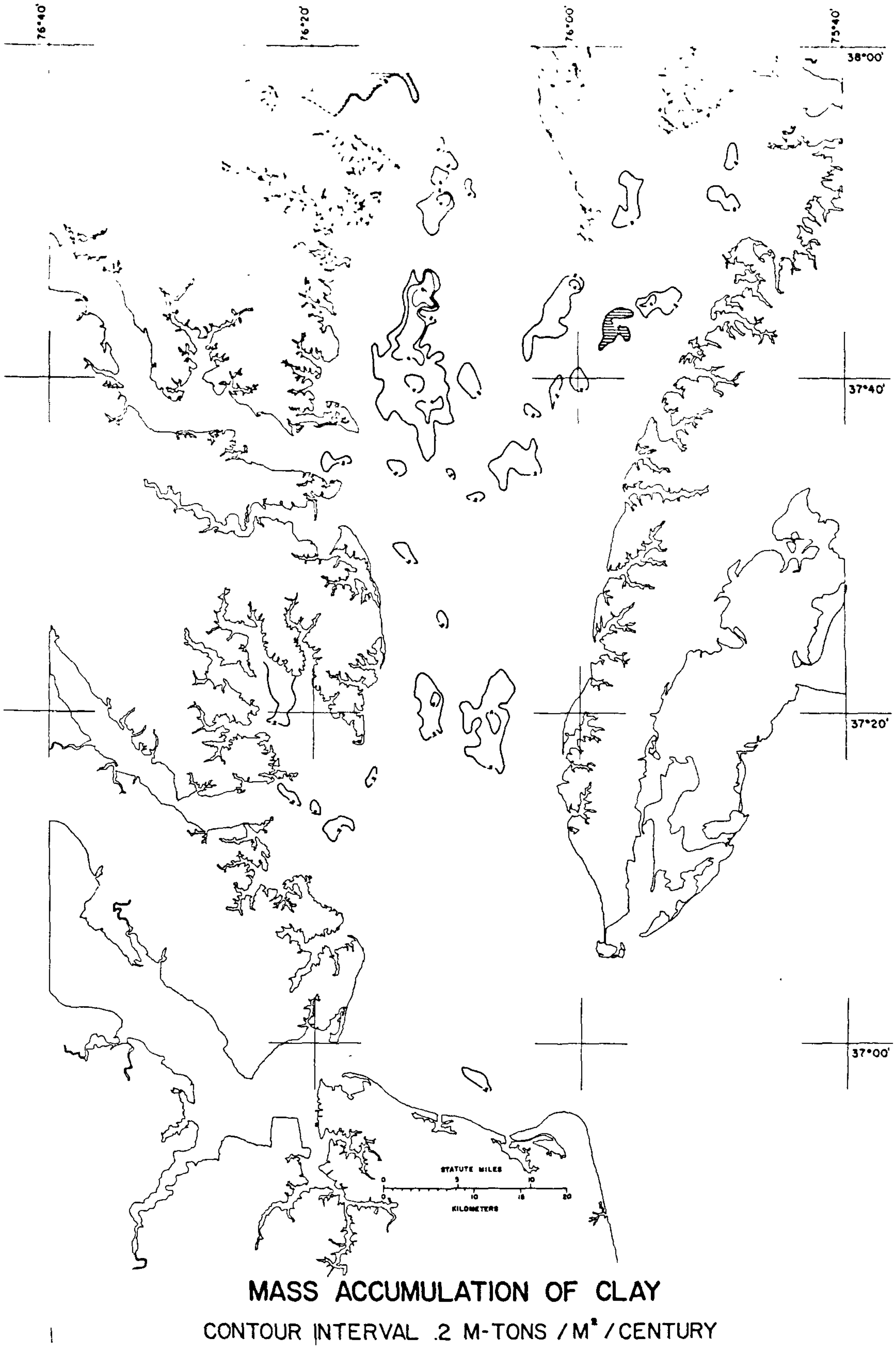


Figure 50. The mass of clay accumulation per square meter per century in the Virginia portion of the Chesapeake Bay.

area, centered at 37°20', includes the northern ramp of the Old Plantation Flats Channel. Our hypothesis is that this depositional lobe (> 60% sand; the remainder silt) results from transport from the Bay entrance through the channel and up onto the ramp as the channel cross-sectional area increases. The driving force for the transport is argued to be the net up-Bay bottom-water circulation which is strongest along the eastern side of the Bay. The recovery of bottom drifters (Harrison, et al., 1967) released in the vicinity of the Bay mouth fortifies the hypothesis; one of the strongest recovery zones within the Bay, and incidentally the northernmost zone, was the shoreline west of the deposition lobe.

The eastern flank of the channel and the adjacent shallow terrace have erosional loci of fine and medium sands (total sand > 80% by weight).

There are two additional zones of deposition in the western part of the belt. The westernmost of the two is the nearshore terrace (water depths generally less than 6 meters (20 feet) fringing Mathews County. For the most part, the bottom sediments are medium sands (Figure 30) which may represent bedload migration from the more northerly nearshore terrace which is indicated, in part, to be erosional. In these shallow waters, the net bottom flows could be expected to be down-bay. During strong northeast wind events, the southerly wind-drift currents and wind wave driven bottom agitation could, as well, play a significant role. To the east of the terrace depositional area is a narrow erosional zone which is coincident with the western flank of the spit-like shoal upon which Wolf Trap Light is situated.

The second locus of deposition on the western side is directly east of the Wolf Trap Shoal. The bottom materials are predominately fine and very fine sand with pockets containing more silt. This depositional lobe may represent an admixture of materials from the adjacent "Bay mouth derived" depositional area and the western terrace. According to Firek (1975) and Firek et al. (1977) the eastern lobe has relatively high concentrations of garnet in the heavy mineral suite compared to the western lobe which has a higher concentration of tourmaline and zircon which he considered to be representative of western shore source.

c. The Upper Southern Bay belt is indicated as being generally depositional (0 to 0.5 m/cent) but no strong depositional loci are expressed. Erosional loci are indicated in the channel trough on the eastern side of the Bay. As well, the nearshore terrace along the Eastern shore has patchy erosional areas. A strong erosional locus is indicated on the western shore terrace below the Rappahannock River. When the depositional patterns are viewed in conjunction with bottom sediment type (Figure 30), this belt appears as a transitional region between the predominately sandy regions to the south and the finer grained sediments to the north.

Within the channel along the Eastern Shore, indicated as erosional, the bottom is composed of fine sands with up to 25% silt. The erosional areas on the western shore terrace are composed of medium and coarse sands. Zircon is a strongly dominate heavy mineral in the fine fraction (Firek, 1975, Firek et al., 1977), which in terms of hydraulic equivalence is consistent with the relatively coarse sand population.

The Bay floor area between the fringing terraces, without strong depositional loci, may be roughly divided longitudinally. The area in the central part is characterized as about 50% very fine sand, less than 20% clay, and the remainder silt. In contrast, the western area, a confluence of the Rappahannock Tributary and the main channel leading to Maryland waters, is characteized by increasing dilution of very fine sand with increasing contributions of clay and silt (Figure 28 and 33).

d. The Lower Middle Bay belt, ranging in latitude from the mouth of the Rappahannock River to the Virginia boundary at the mouth of the Potomac, is the most complex segment in the Virginia portion of the Bay stem. The clearly defined deep channel which extends through most of the Maryland portion of the Bay terminates in this section. The channel is flanked on the east by the large sand-shield containing Tangier and Smith Islands. As well, the segment contains the junction of the channels leading into Tangier and Pocomoke Sounds.

The channel floor, except in the deepest parts and associated flanks, are indicated as depositional. The sand component, very fine sand, is a relatively minor constituent of the channel and lower flank, and the clay fraction exceeds 40%. The deepest parts of the channel, with essentially the same sediment constituents, are erosional loci. These erosional sites include parts of the eastern channel flank where the sediments rapidly grade into sands.

At approximately 37°40' latitude, the channel begins to flare in width and cross-sectional area. The flaring section is associated with sites of pronounced deposition. In this section sand (very fine sand) is a very minor constituent (< 5%) and clay exceeds 40%. The western boundary of this section follows closely the 30-foot (10 meter) bathymetric contour, shoreward of which sand sized materials dominate (> 90%). The Tangier-Smith Island sand shield terminates at 37°40' (following the 10-13 m contours) so the channel flare is not bathymetrically bounded on the eastern side. However, between 37°40' and 37°35' the dilution with the clay constituent rapidly decreases to the east such that the mud component increases to 25-30% with silt generally dominating.

Most of the surface sediments with significant clay fractions (> 20%) are contained within the latitude range 37°35' to 37°55'. This band apparently represents the principal residual deposits of material delivered to the Virginia Bay stem from Maryland waters including the Potomac River and, perhaps, the Rappahannock River.

The sand shield containing Tangier and Smith Islands is indicated as null to mild deposition in water depths less than 7 meters. However, there are erosional loci in very shallow waters. The western and southern limits of the shield have strong depositional loci. On the west, fringing the main Bay channel, deposition extends to water depths of greater than 17 meters (50 feet) while on the southern terminus the depositional lobes extend to depths greater than 12-14 meters (36 feet). The shield is generally greater than 90% sand with the depositional loci composed of fine to medium sand. The depositional nature of the deeper fringes of the belt is attributed to encroachment of sand over the edge of the shield induced by the net down-bay circulation in "surface" waters, augmented (or perhaps dominated) by wind drift current with wave driven resuspension accompanying strong north and northwest winds, a dominant component in fall and winter.

2. Sediment Budget. Previous work addressing sediment budgets for the Bay has dealt only with the suspended sediment component. Moreover, with one notable exception (Schubel and Carter, 1976), attention has previously focused on the Maryland portion of the Bay. Observations of suspended sediment concentrations in the Virginia part of the Bay are relatively scanty.

A complete sediment budget for the inorganic constituents of the Virginia portion of the system would include several terms for sources and sinks:

1.) the Maryland portion of the system (Bay stem and the Potomac estuary) (probably a source),

2.) the principal Virginia tributary estuaries (Rappahannock, Piankatank, York, and James), and minor fringing creeks (could be either sources or sinks),

3.) the Bay mouth and near continental shelf waters (probably sources),

4.) Shore erosion of the margin of the Virginia Bay stem (source),

5.) skeletal remains from primary production (source),

6.) carbonates from shell (source), and

7.) accumulation of material on the Bay floor (treated as a sink).

As ensuing discussion will indicate, current knowledge is insufficiently developed to address all of the requisite contributions. Our attempt at a sediment budget utilizes the reported values for estimates of suspended sediment (clay plus silt) for items 1, 2, 3 (Schubel and Carter, 1976; Biggs, 1970), and 5, and information derived from this study for items 4, 6 and 7. No estimates of influx of sand from the Bay mouth have been reported. The strategy is to ask whether the observed sediment accumulation on the Bay floor is consistent with the existing best estimates of the contributions from various sources.

The most comprehensive evaluation of the relative sources (inorganic and organic) within the Maryland portion of the Bay is that of Biggs (1970). Utilizing estimates for the annual yield of silt and clay from shoreline erosion, of skeletal material derived from plankton, and a comprehensive set of suspended sediment measurements taken over a one-year

(1967) period, he concluded that 10% of the total input of inorganic material was transported, by estuarine circulation, into the regions south of the Patuxent River.

Schubel and Carter (1976) advanced a suspended sediment budget for the entire main stem of the Chesapeake Bay. They formulated this budget from a single-segment, two-layer model using the salt balance equations to infer net movement of suspended sediment. Axial distributions of vertical salinity and inorganic suspended sediments down the Bay stem during a twelve month period, 1969-1970, provided the primary data for the model. They concluded that there is a net movement of suspended sediment <u>into</u> the Bay from the ocean, and that the tributary estuaries are <u>sinks</u> for suspended sediment from the Bay (summarized in Table 12). The results in Table 12 display several interesting points aside from the conclusion that the tributaries act as sinks for sediments from the Bay. In order of rank, the sources of suspended sediment are the Susquehanna River, silt and clay derived from shore erosion, and, then the ocean. The tributaries are relatively weak sinks and, by subtraction, the remainder is deposition onto the Bay bottom.

Whether the Bay stem responds as a <u>net</u> source or sink for suspended sediments to the principal estuaries remains a question demanding detailed investigation. Nichols (1977), in a study of the response of the Rappahannock estuary to the flooding of the 1972 tropical storm, Agnes calculated that over the sixteen days encapsulating the event, 10% (11,000 tons) of the suspended load escaped into the Bay. Officer and Nichols (1980) applied a two dimensional box-model formulation to four sets of suspended sediment concentration in the James and Rappahannock estuaries, one of which was the Rappahannock response to Agnes. In the latter, the estuary was found to export sediment to the Bay. However, in another data set (spring, 1978) the estuary was found to be a sink for Bay materials and the magnitude was the same order of the sediment input from the river. For the James data sets, the estuary was found to be an exporter of sediment during very high discharge but an importer of sediments from the Bay during moderate river discharge conditions. Ludwick (1981) argued that the relatively high deposition rate of fine grained sediments in Thimble Shoals Channel exiting the James estuary is due, in part, to the deposition of sediments from the ebb plume of the James. This in itself does not constitute sufficient evidence that the James is a net sediment exporter, but it does suggest tha James River sediments are deposited in the Bay. The strength of the oceanic source could however be stronger than the amount deposited with a net importation resulting. Feuillet and Fleischer (1980) documented the mixing of clay minerals from the ocean source within the James estuary.

It is important to recognize that none of these studies were specifically designed to address the question of net flux. Rather than investigation of transverse variations in salinity, flow, and sediment concentrations at a cross-section, these studies have emphasized the vertical distribution along the estuary axis. For example, in the 1978 series of measurements at the Rappahannock estuary mouth (Nichols <u>et al.</u>, 1981) a single vertical array of current meters on the northern side of the

Table 12

Suspended Sediment Budget

(after Schubel and Carter, 1976)

Sources	Mass/Year
Susquehanna River	1.07 X 10^6 tons
Shore Erosion, Md.	0.40 X 10^6 tons
Va.	0.20 X 10^6 tons
Ocean	0.22 X 10^6 tons
TOTAL	1.89 X 10^6 tons

Sinks	
Tributaries	
Potomac	0.04 X 10^6 tons
Rappahanncok	0.02 X 10^6 tons
York	0.02 X 10^6 tons
James	0.05 X 10^6 tons
All Others	0.03 X 10^6 tons
TRIBUTARY TOTAL	0.16 X 10^6 tons
Deposition	1.73 X 10^6 tons
TOTAL	1.89 X 10^6 tons

channel indicated a net landward flow at all depths. Prior measurements indicated a net bayward flow at all depths on the south side of the channel. Estimates of the flux at a cross-section would require sufficient sampling to capture these pronounced transverse variations.

While the evidence that the tributary estuaries are effective traps for riverine sediment is incontestable, considerably more detailed measurements will be required to settle the claim that the Bay stem acts as a net source for sediments to the tributary estuaries. The availability of sediments from tidal resuspension would be a controlling factor. The suspended materials "leaking" into the Bay stem from the tributaries may, upon settling, arrive in regions where tidal currents are not strong enough for appreciable resuspension.

The present attempt at a sediment budget does not attempt to resolve whether the tributaries are net sources or sinks. Before venturing into the evaluation of the sources, it is necessary to consider the residual sediment accumulation derived from the treatment of bathymetric comparisons (see section V B for the details of calculation). Taking into consideration the errors in bathymetric comparison, the data are presented at three levels of estimation; for data cells (1 minute, depth bounded, latitude slice) with changes greater than ± 1.10 m, ± 0.57 m, and finally treating the data as if there were no error, that is ± 0.00 m. Application of ± 0.57 m and ± 1.10 m cutoff criteria is very conservative as these values were derived from the error associated with comparison of individual depth measurements. Here they are applied to information which has undergone three levels of smoothing, each of which would be expected to reduce the propagated error of the bathymetric comparison.

There are no reliable independent ways to ascertain the reasonableness of the three levels of estimation. The approach herein used is to make a comparison between sand derived from erosion and the mass of sand "accumulated" in the nearshore zone. The sediment distribution maps show the nearshore to be dominated by coarse sand. The test is applied to the western side of the Bay as it is reasonable to argue that the major tributaries act as barriers to sand transport and that the Bay's western shore is isolated from sand sources other than shore erosion. Table 13 displays the correspondence between the mass of sand derived from shore erosion and the "accumulated" mass for eight relatively isolated coastal segments along the western shore of the Bay. Comparisons are made for two outer-depth limits, 12 feet (3.7 m) and 18 feet (5.5 m). For the wave height and period conditions found in the Bay, the 12 foot (3.7 meter) depth is a reasonable limit for normal active wave induced movement of the bottom sediment. The 18 foot (5.5 meter) depth-limit is taken as the maximum depth to which appreciable sand from shore erosion is likely to be dispersed. Zone 4 displays relatively large sand accumulations out to the 18 foot (5.5 meter) depth and beyond. Previous discussion has noted that this zone, between the Piankatank River and the entrance to Mobjack Bay, is at the latitude of appreciable deposition argued to have a Bay-mouth source. Furthermore, this shore zone was the recovery area for a number of seabed drifters (Harrison, et al., 1967). Comparison within this zone may thus be "contaminated" with sands derived from a source other than shore

Table 13. Comparison between Nearshore Sand Accumulation on Western Shore with Sand from Shore Erosion.

		Accumulated Sand (X 10^6 m-tons/100 years)						Sand From Shore Erosion (X 10^6 m-tons/100 years)
		0 to 18 ft depth			0 to 12 ft depth			
Zone	Shore Segment	± 0 m	± 0.57 m	± 1.10 m	± 0 m	± 0.57 m	± 1.10 m	
1	37°55' to 37°39'	35.40	10.75	1.03	19.13	3.76	1.03	5.49
2	37°39' to 37°35'	9.62	3.75	-0-	6.42	0.69	-0-	3.83
3	37°35' to 37°33'	0.91	0.52	-0-	0.32	-0.45	-0-	1.20
4	37°33' to 37°17'	52.69	49.61	27.20	36.17	33.27	22.37	5.46
5	37°17' to 37°14'	5.34	-0-	-0-	3.75	-0-	-0-	-0-
6	37°14' to 37°10'	2.45	-0.73	-0-	2.54	-0-	-0-	0.74
7	37°10' to 37°07'	6.83	1.50	-0-	3.56	-0-	-0-	0.61
8	37°07' to 37°00'	38.00	16.58	-0-	6.16	4.01	-0-	4.72
	TOTAL	151.24	81.98	28.23	78.05	41.28	23.40	22.07
TOTAL W/O ZONE 4		98.55	32.37	1.03	41.88	8.01	1.03	16.61

erosion. Thus, the total without Zone 4 is of final interest. Both the ± 0.00 m and ± 1.10 m estimation levels for accumulation show poor correspondence with the shore-erosion source. The ± 0.57 m level, however, displays a correspondence within a factor ranging between one-half and to one for the two depth limits. The individual zones show a better correspondence for the 12-foot depth limit. Based upon this comparison, the estimation level using depth changes greater than ± 0.57 m appears to be the most reasonable. Ludwick (1981) used, without explanation, ± 0.61 m as the level of significant change in his study of bathymetric change in the Thimble Shoals area.

The values of accumulated sediment mass of sand, silt, and clay are shown in Table 14 for the three levels of estimation. Only the Bay stem excluding fringing sounds, embayments, and tributary mouths is included in this discussion. Sand-sized materials clearly dominate the sediment mass accumulation. Given the dominance of sand-sized materials in the surficial sediments, and the method of calculating mass accumulation, this result is not surprising. However, the summary values of Table 14 do provide an estimation of the magnitude of the dominance. Given the mass of residual accumulation, we may draw the first comparison between the strength of the known sources and the residual accumulation, a sink, shown in Table 15. The bottom accumulation dramatically exceeds the source terms for both the silt and clay and the sand comparisons. The contribution of silt and clay from Maryland waters (0.147 X 10^8 m-tons/100 years) is taken from Table 12 as the contribution of the Susquehanna and shore erosion reduced by 90% as argued by Biggs (1970). This value is uncompensated for any deposition between the Patuxent River and Smith Point or any source or sink value for the Potomac. The value of 0.025 X 10^8 m-tons/100 years for silt and clay from shore erosion in Virginia, obtained in this study, is an order of magnitude less than that value estimated by Schubel and Carter (1976). The inorganic constituent from zooplankton is relatively small. The value for oceanic source, also taken from Table 12, appears as a stronger source for silt and clay than the estuarine contribution from the Maryland portion of the Bay.

If the $\geq$ 0.57 m average depth change is accepted as the appropriate basis for calculation of mass accumulation, the bottom accumulation of silt and clay (4.9 X 10^8 m-tons/100 years) exceeds the value from the estimated sources (0.4 X 10^8 m-tons/100 years) by a factor of 12. This formulation does not include the major Virginia tributaries as either sources or sinks. Bottom accumulation of sand (16.9 X 10^8 m-tons/100 years) exceeds shore erosion source by a factor of 40. Inspection of the axial trends of sand, silt, and clay bottom accumulation may offer some insight toward explaining the discrepancy.

The patterns of accumulation (Figures 48, 49, and 50) indicate that the principal locus of clay deposition is between the Potomac and Rappahannock Rivers. The silt accumulation occurs throughout the central basin between the York River and the confluence of the channels to Tangier and Pocomoke Sounds as well as within the axial channel leading into the Maryland portion of the Bay. Sand accumulations are most pronounced at the Bay mouth area with secondary loci at about 37°20' latitude, and on the

Table 14

Bottom Deposition of Combined Sand, Silt and Clay; Values are cumulative from north to south

SAND, SILT, AND CLAY

($\times 10^8$ m-tons/100 years)

Zone	Latitude		± 0	± 0.57 m	± 1.10 m	Geographic Location
7	37°54'		.3544	.3291	.0527	Smith Point
10	37°51'		1.5002	1.2860	.2800	
15	37°46'		5.1092	3.6093	1.1247	
20	37°41'		7.6834	6.0761	1.9129	
25	37°36'		10.1408	7.3292	2.0970	Rappahannock Spit
30	37°31'	CUMULATIVE	11.2542	7.7420	2.1527	Cherry Point
35	37°26'		12.2022	8.9009	2.2496	Wolf Trap Light
40	37°21'		15.4840	12.6242	4.1704	
45	37°16'		17.8967	14.1358	4.8951	Entrance Mobjack Bay
50	37°11'		20.2808	15.1037	5.2419	Poquoson River
55	37°06'		21.5884	17.6011	6.1397	Fisherman Island
60	37°01'		26.2558	20.8609	8.4071	Old Point Comfort
64	36°57'		27.6047	21.0685	8.9523	Cape Henry
	TOTALS					
	SAND		22.1038	16.9074	7.1685	
	SILT		3.2958	3.0594	1.1017	
	CLAY		2.2051	1.8409	0.6821	

Table 15

Comparison of Sediment Budget Terms

Source	SILT PLUS CLAY	SAND
	X 10^8 m-tons/100 years	X 10^8 m-tons/100 years
Maryland	0.147	?
Shore Erosion, Va.	0.025	0.400
Zooplankton, Va. ash	0.008	-
Ocean	0.220	?
TOTAL SOURCE	0.400	0.400
BOTTOM RESIDUAL		
± 0 m	5.500	22.104
± 0.57 m	4.900	16.907
± 1.10 m	1.784	7.168

fringes of the Tangier-Smith Island sand-shield. These patterns are rendered in quantitative form in Figure 51 and Table 16 which indicates cumulative mass accumulation as a function of latitude.

The curves for sand accumulation indicate that about 25% of the total accumulation occurs between Smith Point (37°51') and the fringes of the Tangier Smith Islands shield (37°43'). Between 37°43' and 37°25' there is relatively small additional accumulation of sand. For the intermediate level of estimation ($\geq$ 0.57 m) about 65% of the sand accumulation occurs below latitude 37°25' and 38% occurs within the Bay mouth entrance latitudes (37°11' - 36°55'). These results indicate that the Bay mouth acts as a gateway through which very large quantities of sand are advected. As well, the accumulation of sand on the Tangier-Smith sand-shield indicates an advection of sand from the Maryland portion of that feature. The sand contributed from shore erosion is then a relatively weak source.

The calculation of mass accumulation did not compensate for shell content, thus, the "sand" accumulation is an overestimate. If we take a liberal estimate of 10% by weight for shell fragments (Shideler, 1975; also this study, Figures 41 and 42), the results of this study indicate that the Bay mouth acts as a source for sand of the order ranging from 16 X 10^6 to 5 X 10^6 m-tons/year distributed as far north as 37°25'. At the intermediate level of estimation, we find 12 X 10^6 m-tons/year.

The previously postulated sources for silt and clay cannot be readily rectified to explain the disparity between the bottom mass-accumulation and the estimated source-strengths. The bathymetric comparisons are based on a period prior to the sediment influx due to runoff from Hurricane Agnes so we cannot appeal to the anomalously high Agnes input from the Susquenna (31 X 10^6 m-tons, a factor of 25 to 30 greater than the "normal" year; Schubel, 1975). The results suggest that the major Virginia tributaries act as <u>sources</u> for sediment to the Bay. Both the Rappahannock and York tributaries show clayey-silt stringers entering the Bay. As well, Ludwick (1981) presents evidence that there is deposition of muds from the James River estuary in the Thimble Shoals Channel. The relative strength of these potential sources cannot be determined from available information.

Mass accumulation rate as a function of depth interval is shown in Figures 52 and 53a, b, c and Tables 17 and 18 for the $\geq$ 0.57 m (±) level of estimation. The five latitude slices reflect the principal depositional segments dicussed in section VI B 1. In water depths less than 18 feet (5.5 m), the accumulation rate is relatively low. Maximum accumulation generally occurs between 18 feet (5.5 m) and 42 feet (12.8 m) with a relative redution in greater depths. This trend was noted by Carron (1979) in a plot of sedimentation rate (deposition thickness per unit area ÷ time) derived from the same bathymetric comparisons but with different smoothing procedures.

Maximum total sediment-mass-accumulation per unit area (0.968 m-ton/m^2/100 years) occurs in Zone 3. This is particularly notable in the sand and silt components, each exhibiting maximum in this zone. It is germane to contrast the sand, silt, and clay components in Zones 1, 2 and 3

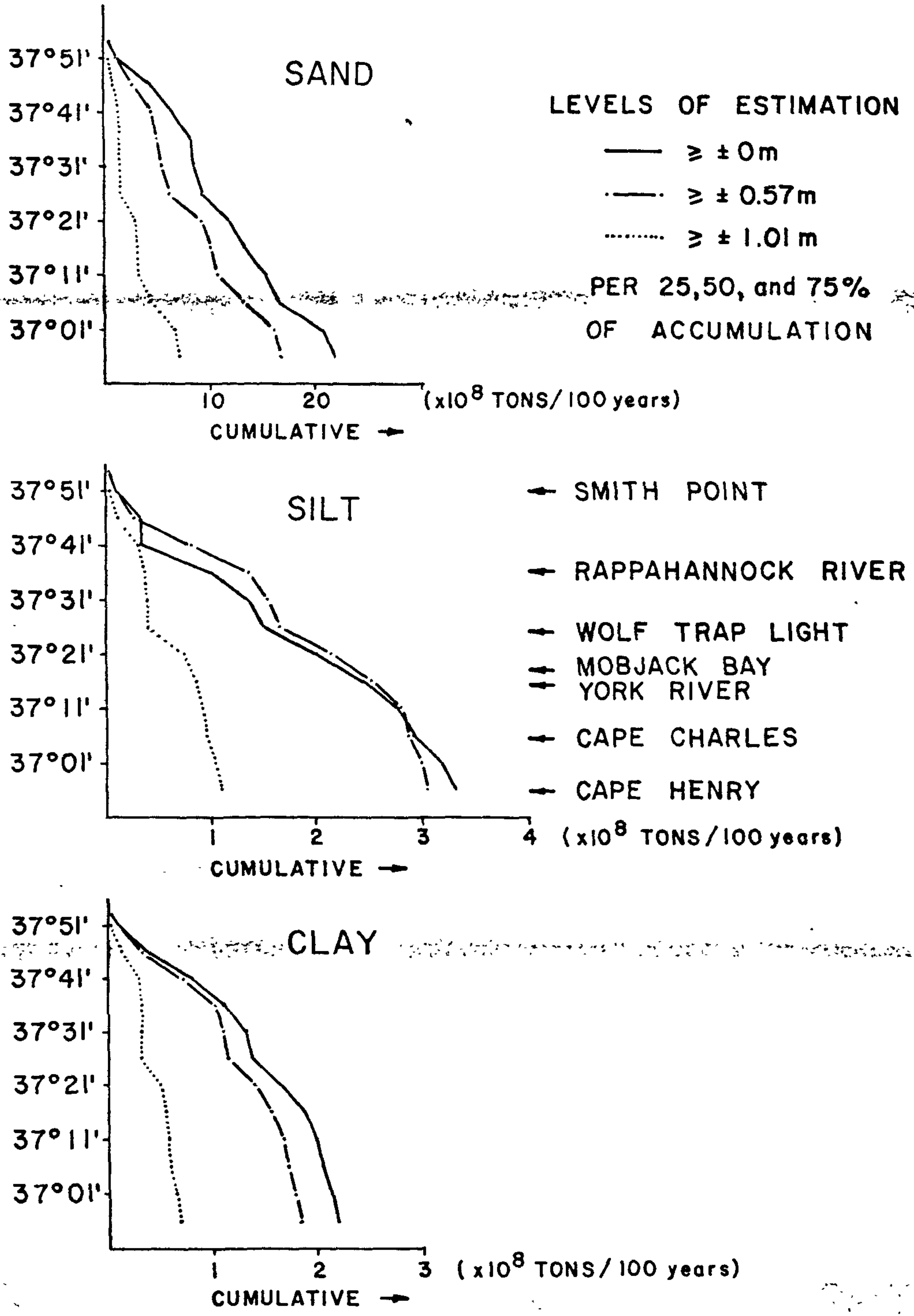


Figure 51. Cumulative mass accumulation as a function of latitude.

Table 16a

Sand Accumulation as a Function of Latitude Zone

Zone	Western Shore			West Tangier & Eastern Shore			Combined		
	±	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m
					(X 10^8 m-tons/100 years)				
7	0.04086	.03127	.0125	0.26824	0.2548	.0326	0.30910	0.2861	0.0451
10	0.21101	.12399	.0414	1.06852	0.9522	.1820	1.27953	1.0762	0.7234
15	0.78713	.43896	.0870	3.61521	2.5123	.7749	4.40234	2.9513	0.8619
20	1.23478	.67525	.2004	5.31464	3.8564	1.1095	6.54942	4.5316	1.3099
25	1.68965	.42500	.2070	6.32143	4.5315	1.1892	8.01108	4.9565	1.3962
30	2.06133	.53728	.2329	6.52804	4.5758	1.2067	8.58937	5.1131	1.4396
35	2.52701	1.26580	.2514	6.80355	4.8558	1.2820	9.33056	6.1216	1.5334
40	4.42937	3.5093	1.4512	7.36998	5.5598	1.4870	11.79935	9.0691	2.9382
45	5.68464	4.5474	1.8264	7.66694	5.5109	1.6507	13.35158	10.0583	3.4771
50	7.34806	4.7725	1.9762	8.14356	5.8522	1.7624	15.49162	10.6247	3.7386
55	8.18757	6.3413	2.0697	8.43523	6.6749	2.5174	16.62280	13.0162	4.5871
60	10.60754	8.2921	3.4289	10.32394	7.7872	3.2858	20.93148	16.0793	6.7147
65	11.72405	9.1028	3.9432	10.37972	7.8046	3.2253	22.10377	16.9074	7.1685

Table 16b

Silt Accumulation as a Function of Latitude Zone

	Western Shore			West Tangier & Eastern Shore			Combined		
Zone	±	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m
					(X 10^8 m-tons/100 years)				
7	.0111	.0111	.0028	.0090	.0086	.0008	.0201	.0197	.0036
10	.0708	.0686	.0242	.0343	.0324	.0027	.1051	.1010	.0269
15	.1824	.1572	.0792	.1565	.1553	.0458	.3389	.3125	.1250
20	.4441	.4117	.2054	-.1197	.3988	.1066	.3244	.8105	.3120
25	.8208	.7268	.2705	.1582	.6168	.1070	.9790	1.3536	.3775
30	1.1939	.9220	.2756	.1713	.6170	.1072	1.3652	1.5390	.3828
35	1.3554	1.0131	.2756	.1511	.6220	.1083	1.5065	1.6351	.3839
40	1.8493	1.5025	.6055	.1901	.6534	.1254	2.0394	2.1559	.7309
45	2.2500	1.8370	.7162	.2165	.6749	.1475	2.4665	2.5119	.8637
50	2.5489	2.0926	.7514	.2528	.7024	.1740	2.8017	2.7950	.9254
55	2.6191	2.1380	.7588	.2946	.7268	.1961	2.9137	2.8648	.9549
60	2.7305	2.2410	.8310	.4500	.7429	.2061	3.1805	2.9839	1.0371
64	2.8402	2.3153	.9010	.4556	.7441	.2007	3.2958	3.0594	1.1017

Table 16c

Clay Accumulation as a Function of Latitude Zone

	Western Shore			West Tangier & Eastern Shore			Combined		
Zone	±	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m	± 0	± 0.57 m	± 1.10 m
					(X 10^8 m-tons/100 years)				
7	.0139	.0123	.0028	.0113	.0110	.0012	.0252	.0233	.0040
10	.0689	.0669	.0247	.0467	.0419	.0050	.1156	.1088	.0297
15	.1895	.1695	.0876	.1785	.1760	.0502	.3680	.3455	.1378
20	.4147	.3806	.1914	.3949	.3534	.0996	.8096	.7340	.2910
25	.6233	.5632	.2227	.5274	.4559	.1006	1.1507	1.0191	.3233
30	.7640	.6331	.2294	.5356	.4568	.1009	1.2996	1.0899	.3303
35	.8356	.6805	.2297	.5295	.4637	.1026	1.3651	1.1442	.3323
40	1.0920	.9165	.3885	.5532	.4827	.1128	1.6452	1.3992	.5013
45	1.3129	1.0713	.4353	.5657	.4943	.1190	1.8786	1.5656	.5543
50	1.4071	1.1786	.4485	.5804	.5054	.1294	1.9875	1.6840	.5779
55	1.4523	1.1996	.4522	.5996	.5205	.1455	2.0519	1.7201	.5977
60	1.5298	1.2628	.5004	.6140	.5349	.1549	2.1438	1.7977	.6553
64	1.5896	1.3061	.5300	.6155	.5348	.1521	2.2051	1.8409	.6821

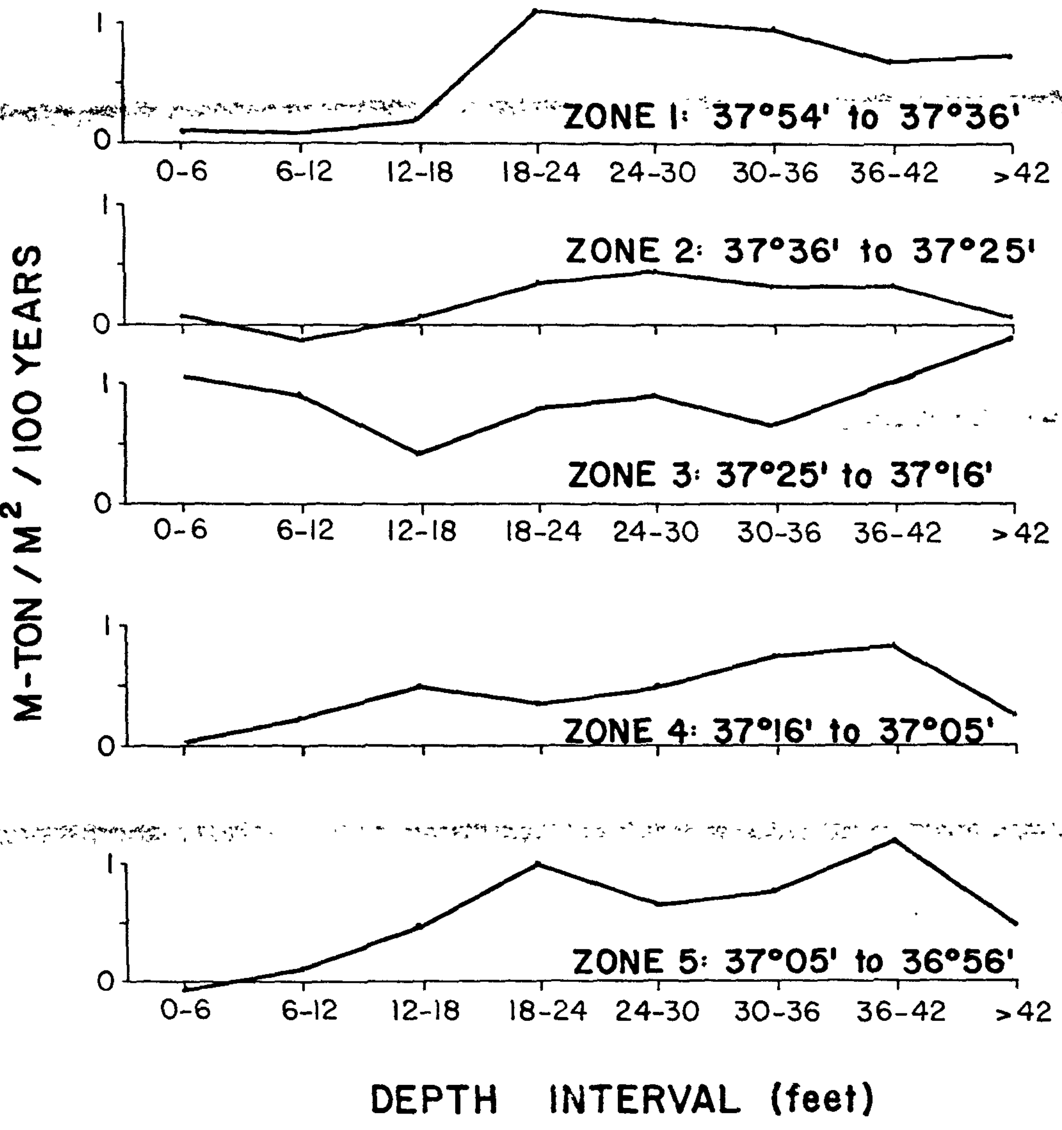


Figure 52. Total sediment mass accumulation per unit area per century

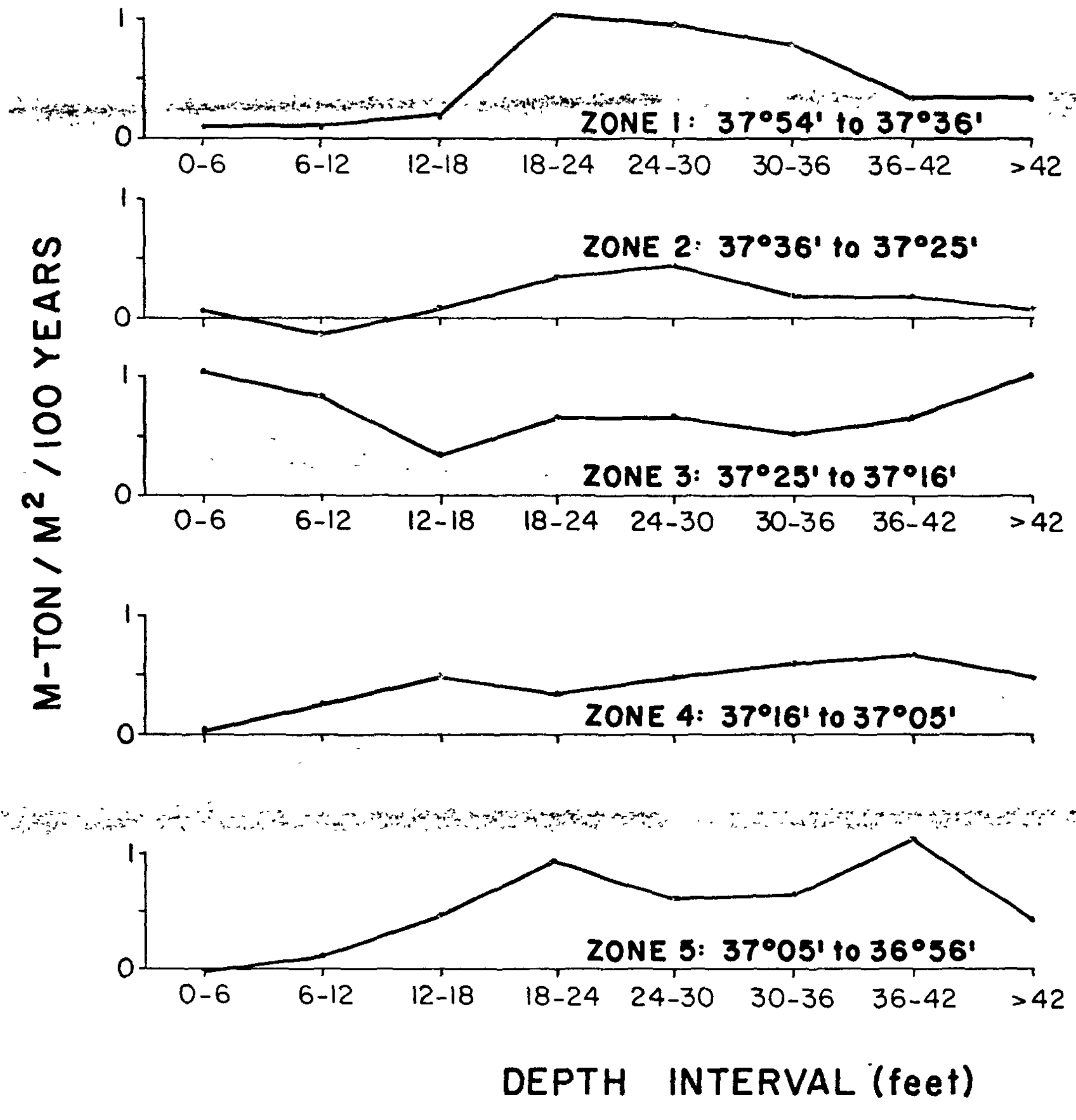


Figure 53a. Sand; mass accumulation per unit area per century as a function of depth interval.

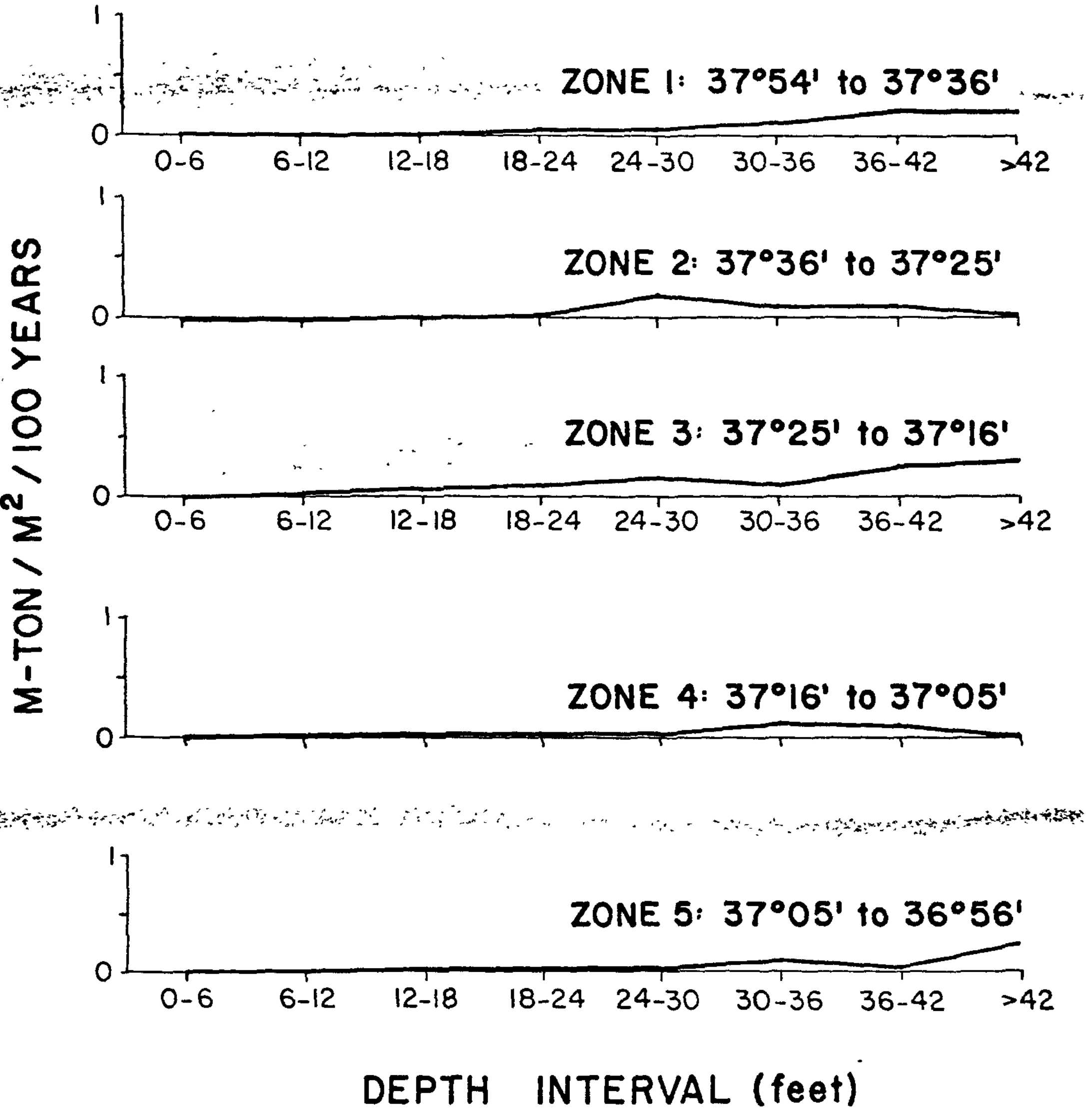


Figure 53b. Silt; mass accumulation per unit area per century as a function of depth interval.

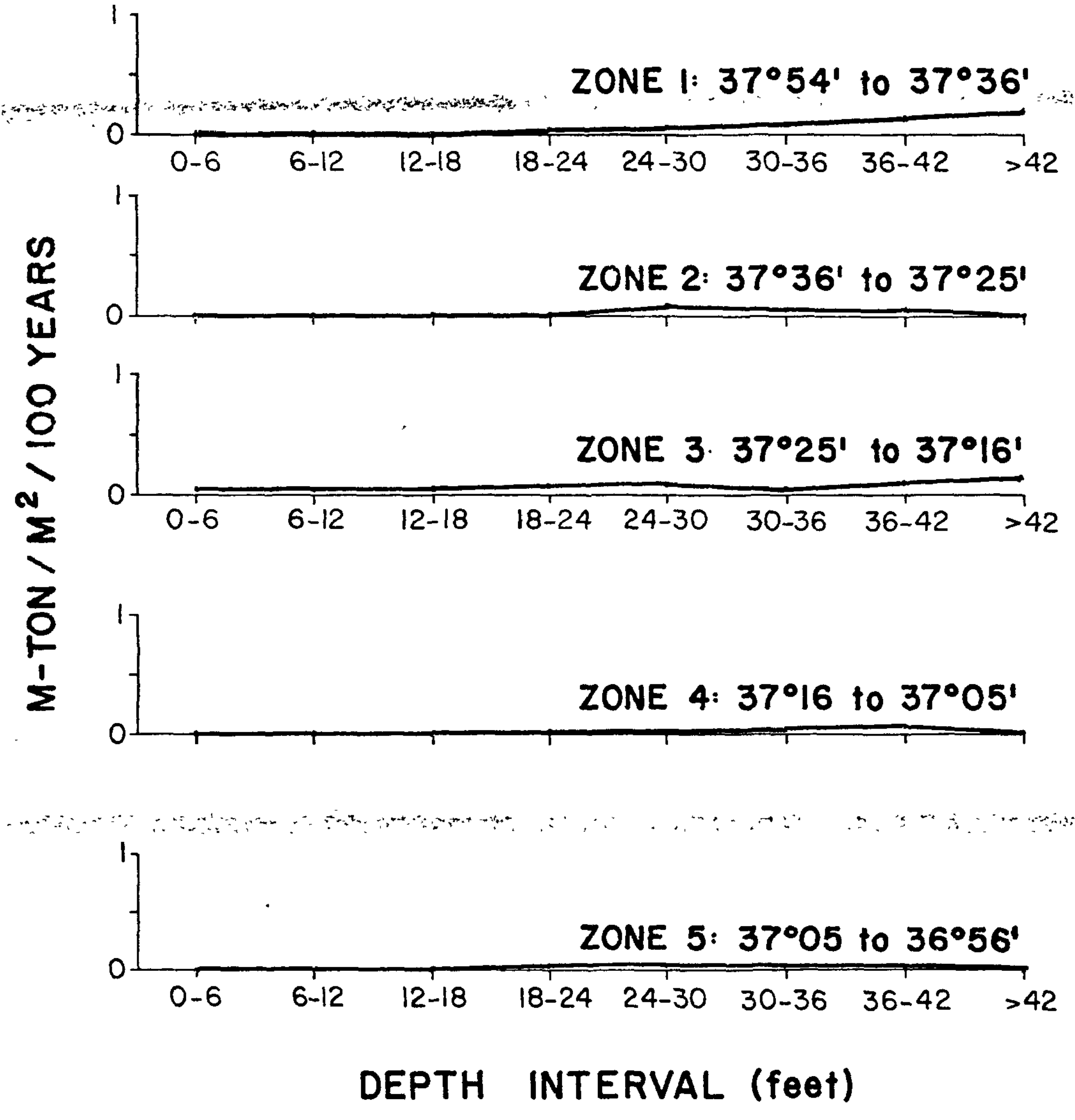


Figure 53c. Clay; mass accumulation per unit area per century as a function of depth interval.

Table 17. Sediment Mass Accumulation Rate as a Function of Zone and Depth Interval for ± 0.57 m Level of Estimation

(m-tons/100 yrs. X 10^8)

Depth Interval (ft.)

Zone 1	0/6	6/12	12/18	18/24	24/30	30/36	36/42	> 42	Combined
37°54' to 37°36'									
SAND	0.051	0.064	0.186	0.992	1.498	1.429	0.636	0.750	5.605
SILT	0.003	0.004	0.007	0.038	0.078	0.174	0.432	0.503	1.238
CLAY	0.002	0.003	0.007	0.040	0.081	0.152	0.264	0.416	0.966
TOTAL	0.066	0.071	0.200	1.070	1.658	1.755	1.332	1.669	7.819
AREA (m^2 X 10^8)	0.638	0.876	1.106	0.984	1.595	1.874	1.984	2.342	11.400
Zone 2									
37°36' to 37°25'									
SAND	0.027	-0.051	0.024	0.156	0.343	0.161	0.265	0.035	0.959
SILT	-0.001	-0.002	0.001	0.005	0.149	0.083	0.157	0.012	0.404
CLAY	-0.001	-0.003	-0.003	0.005	0.066	0.036	0.073	0.005	0.177
TOTAL	0.025	-0.057	0.022	0.165	0.557	0.280	0.494	0.052	1.540
AREA	0.354	0.381	0.456	0.477	0.810	0.933	1.593	1.151	6.156
Zone 3									
37°25' to 37°16'									
SAND	0.345	0.256	0.132	0.312	0.389	0.247	0.755	0.987	3.424
SILT	0.000	0.013	0.022	0.044	0.090	0.050	0.296	0.313	0.829
CLAY	0.011	0.013	0.017	0.036	0.046	0.024	0.119	0.142	0.409
TOTAL	0.357	0.282	0.172	0.392	0.526	0.322	1.170	1.442	4.662
AREA	0.335	0.312	0.410	0.496	0.594	0.491	1.160	1.017	4.817
Zone 4									
37°16' to 37°05'									
SAND	0.019	0.131	0.265	0.425	0.642	1.012	0.393	0.127	3.014
SILT	0.000	0.001	0.004	0.017	0.037	0.219	0.066	0.017	0.362
CLAY	0.000	0.002	0.004	0.005	0.019	0.095	0.032	0.007	0.164
TOTAL	0.019	0.133	0.274	0.447	0.698	1.327	0.491	0.151	3.540
AREA	0.664	0.534	0.568	1.235	1.431	1.737	0.595	0.602	7.366
Zone 5									
37°05' to 36°56'									
SAND	-0.009	0.033	0.265	1.390	0.946	0.500	0.447	0.317	3.898
SILT	-0.000	0.000	0.007	0.051	0.049	0.086	0.022	0.020	0.234
CLAY	-0.000	0.000	0.008	0.038	0.034	0.022	0.013	0.012	0.128
TOTAL	-0.009	0.034	0.280	[illegible]	1.029	0.609	0.482	0.349	[illegible]
AREA	0.363	0.312	0.572	[illegible]	1.573	0.782	0.398	0.734	[illegible]

Table 18. Sediment Mass Accumulation Rate per Unit Area as a Function of Zone and Depth Interval for > ± 0.57 m Level of Estimation

(m-tons/m^2/100 yrs.)

	Depth Interval (ft.)								
	0/6	6/12	12/18	18/24	24/30	30/36	36/42	> 42	Combined
Zone 1									
37°54' to 37°36'									
SAND	0.080	0.072	0.168	1.007	0.939	0.762	0.320	0.320	0.492
SILT	0.004	0.004	0.007	0.038	0.049	0.093	0.218	0.215	0.109
CLAY	0.003	0.003	0.006	0.041	0.051	0.081	0.133	0.178	0.085
TOTAL	0.103	0.080	0.181	1.086	1.050	0.936	0.672	0.713	0.686
Zone 2									
37°36' to 37°25'									
SAND	0.077	-0.135	0.054	0.327	0.424	0.172	0.166	0.030	0.156
SILT	-0.002	-0.005	0.002	0.010	0.184	0.089	0.098	0.011	0.066
CLAY	-0.003	-0.008	-0.006	0.010	0.081	0.038	0.046	0.004	0.029
TOTAL	0.072	-0.149	0.049	0.346	0.688	0.300	0.310	0.045	0.250
Zone 3									
37°25' to 37°16'									
SAND	1.031	0.821	0.323	0.630	0.655	0.503	0.651	0.970	0.711
SILT	0.000	0.042	0.054	0.089	0.152	0.102	0.255	0.308	0.172
CLAY	0.034	0.041	0.042	0.072	0.078	0.050	0.102	0.140	0.085
TOTAL	1.066	0.904	0.419	0.793	0.885	0.654	1.008	1.418	0.968
Zone 4									
37°16' to 37°05'									
SAND	0.028	0.245	0.467	0.344	0.449	0.583	0.660	0.212	0.409
SILT	0.000	0.002	0.008	0.013	0.026	0.126	0.112	0.028	0.049
CLAY	0.000	0.003	0.008	0.004	0.013	0.055	0.054	0.011	0.022
TOTAL	0.028	0.250	0.482	0.362	0.488	0.764	0.826	0.251	0.481
Zone 5									
37°05' to 36°56'									
SAND	-0.025	0.107	0.464	0.948	0.602	0.640	1.125	0.432	0.629
SILT	-0.000	0.001	0.012	0.035	0.031	0.110	0.055	0.266	0.038
CLAY	-0.001	0.001	0.001	0.026	0.022	0.028	0.032	0.017	0.021
TOTAL	-0.026	0.109	0.490	1.008	0.654	0.779	1.212	0.476	0.686

relative to the earlier discussion of the mapable patterns. Zones 1 and 3 contain substantial accumulations of sand; the accumulation in Zone 1 is attributed to southerly advection of sediment from the Tangier-Smith sand-shield, and the accumulation in Zone 3 is attributed to sources to the south (including the Bay mouth), and to additional contributing from the shallows to the north on the western side of the Bay. This interpretation thus views Zone 2 as a relatively inactive area of sand accumulation between opposing sources. The contribution from silt to the total mass accumulation parallels that of sand: the strongest contribution is in Zone 3 followed by Zone 1 with a relatively weak accumulation in Zone 2. This may argue for a mixture of sources, particularly since the absolute rate of mass-accumulation and mass-accumulation rate per unit area follow the same patterns (Tables 17 and 18) for sand and silt. As there is little basis for arguing that the Maryland portion of the Bay's stem is a principal source of silt relative to clay, the Bay mouth may serve with the "Maryland" Bay-stem, the Potomac, and the Virginia tributaries as secondary sources along with shore erosion. Such interpretation is, of course, conjectural and is based upon the intuitive notion that clay would be expected as the principal component contributed by the tributaries and by the "Maryland" Bay-stem whereas the nearshore wave energy could maintain silt from the Eastern Shore oceanic shoreline and lagoonal system in suspension for advection into the Bay where tidal resuspension could foster net up-Bay drift. This argument is tantamount to the claim that silt-sized particles are carried from the Bay mouth to points throughout the Virginia portion of the Bay.

The zonal distribution of the accumulation of clay-sized particles indicates the strongest depositional center occurs in Zone 1 followed by Zone 3, and a relatively weak contribution in Zone 2 (Table 16). The relatively low accumulation of clay (viewed either as mass or mass per area) raises some interesting questions. What is the principal source of the clay deposited in Zone 3? What is the fate of the suspended sediment which escapes the Rappahannock River? Does the sediment exiting in surface waters become, after settling, entrained in up-estuary bottom-flows by steps in tidal resuspension with ultimate deposition in Zone 1 where tidal energy is relatively small? Or does the material follow the net down-Bay drift along the western side of the Bay? Resolution of these questions await further research.

The patterns of deposition and magnitude of the accumulations suggest the following summary interpretation:

1.) Appreciable influx of fine sand occurs at the Bay mouth (on the order of 10^9 m-tons/100 years). The influx apparently results from tidal transport coupled with a net up-estuary bottom-flow associated with estuarine circulation. The advection zone of the sands extends at least as far up estuary as 37°25' and perhaps as far as 37°41'.

    In addition to the sand accumulating at the mouth of the Bay, there is significant quantity of sand moving from the north along the fringes of the relict Tangier-Smith Islands sand-shield. In this case, the transport processes are probably dominated traction and suspension driven by wind-waves generated during north to westerly wind events coupled with "surface" wind-driven and net down-Bay estuarine circulation.

By comparison to these sources, the sands derived by shore erosion are a minor constituent. Previous work (Schubel and Carter, 1976) has assumed shore erosion would be the principal source of sand.

2.) Silt-sized particles also are an important component of the influx of sediment through the Bay mouth. Principal centers of deposition of silt occur in the central Bay between 37°15' and 37°45'. The degrees of partitioning of the total accumulation between the oceanic and estuarine sources is not clear, but as about fifty percent of the total accumulation occurs south of 37°25', the Bay mouth likely is a strong source.

3.) Fifty percent of the total accumulation of clay occurs north of Rappahannock River mouth (37°35') which suggests that the principal source of clay is the water to the north. However, as the area between 37°40' and 37°55' is a region of relatively low tidal-energy relative to the influence of estuarine circulation, the region may also represent a trap for sources to the south.

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APPENDIX 1

LORAN C

BIAS CORRECTION DATA

LORAN-C BIAS CORRECTION DATA

Location	Latitude	Longitude
Gwynn Island	37°29.31'	76°18.14'
Windmill Pt. Light	37°35.79'	76°14.17'
Smith Pt. Light	37°52.88'	76°11.04'
Tangier Is. Channel	37°49.78'	75°59.66'
Saxis Boat Ramp	37°59.18'	75°43.89'
Onancock Ck. Ent. #1	37°43.47'	75°51.07'
Onancock Ck. Town Wharf	37°42.74'	75°45.37'
Occohannock Ck. Ent. #1	37°22.55'	75°57.86'
Wolf Trap Light	37°23.41'	76°11.38'
Hungars Ck. Ent., Mkr. 1PA	37°23.40'	75°59.72'
Swash Channel, York Spit, Mkr. 3	37°15.73'	76°19.97'
Cape Charles Harbor, 3 M "5" 5A	37°15.32'	76°01.95'
Tue Marshes Light	37°14.13'	76°23.17'
York Spit Light	37°12.57'	76°15.27'
Wise Pt. Channel Mkr. "269"	37°06.92'	75°58.87'
Back River Ent., Mkr. "4"	37°06.07'	76°15.77'
Thimble Shoal Light	37°00.87'	76°14.42'
Fort Wool Pier	36°59.15'	76°18.08'
James River Bridge	36°58.68'	76°28.78'
Chesapeake Bay Ent. 2T Bell	36°58.45'	76°02.28'
Fish Pier, C.B. Bridge Tunnel	36°58.05'	76°06.87'
Little Ck., BW "LG"	36°56.95'	76°10.75'
Middle Ground Light	36°56.70'	76°23.55'
Lynnhaven In. Marina	36°54.28'	76°05.08'
Lafayette River Ent.	36°53.57'	76°19.47'

TO CORRECT FROM THEORETICAL TO REAL

9930-Y	9930-Z	9960-X	9960-Y
- 2.09	+ 1.31	- 2.68	- 0.47
- 1.27	+ 1.31	- 2.32	- 0.35
- 1.52	+ 1.32	- 2.08	- 0.16
- 1.47	+ 1.42	- 2.40	- 0.62
- 1.31	+ 1.30	- 2.79	- 1.28
- 1.45	+ 1.60	- 2.59	- 0.80
- 1.75	+ 1.22	- 2.55	- 0.62
- 1.48	+ 1.39	- 2.42	- 0.60
- 1.38	+ 1.33	- 2.29	- 0.55
- 1.20	+ 1.56	- 2.63	- 1.05
- 1.55	+ 1.33	-	-
- 2.06	+ 0.53	- 2.22	- 0.20
- 1.66	+ 1.21	- 2.97	- 1.06
- 1.64	+ 1.22	- 2.59	- 0.55
- 1.71	+ 1.27	-	- 0.77
- 2.16	+ 1.05	- 2.71	- 0.17
- 1.75	+ 1.28	- 2.74	- 0.67
- 1.77	+ 0.94	- 2.71	- 0.52
- 1.61	+ 1.22	- 3.15	- 1.09
- 1.98	+ 1.06	- 2.44	- 0.15
- 1.81	+ 1.10	- 2.46	- 0.25
- 2.17	+ 1.06	- 2.72	- 0.29
- 2.15	+ 1.26	- 3.23	- 0.67
- 2.02	+ 1.11	- 2.57	- 0.31
- 2.07	+ 1.08	- 2.92	- 0.35

APPENDIX 2

THE MASS OF SEDIMENT ERODED FROM THE SHORELINE

MASS OF SEDIMENT ERODED OR ACCRETED
ALONG THE SHORELINE BY MINUTE OF LONGITUDE
FOR THE SOUTHERN SHORE OF THE LOWER CHESAPEAKE BAY

Minute of Longitude	Metric Tons				
	Gravel	Sand	Silt	Clay	Total
76° 01'	1,073	2,143,675	0	0	2,144,748
02'	(1,779)	157,719	0	0	155,940
03'	(20,590)	(315,568)	0	0	(336,158)
04'	(21,525)	(329,912)	0	0	(351,437)
05'	(12,167)	(186,472)	0	0	(198,639)
06'	14,195	364,329	0	0	378,524
07'	14,195	364,329	0	0	378,524
08'	ND	ND	ND	ND	ND
09'	429	8,075	0	0	8,504
10'	4,929	92,864	0	0	97,793
11'	4,983	93,873	0	0	98,856
12'	375	150,334	0	0	150,709
13'	0	157,133	0	0	157,133
14'	0	251,551	0	0	251,551
15'	346	172,464	0	0	172,810
16'	252	125,782	0	0	126,034
17'	182	90,770	0	0	90,952
	(15,102)	3,340,946	0	0	3,325,844
Percent	(0.5)	100.5			

NOTES: ND = No data.

() = Accretion.

MASS OF SEDIMENT ERODED OR ACCRETED ALONG THE SHORELINE BY MINUTE OF LATITUDE FOR THE EASTERN SHORE OF THE LOWER CHESAPEAKE BAY

Minute of Latitude			Metric Tons		
	Gravel	Sand	Silt	Clay	Total
37° 07'	(1,298)	(20,844)	(6)	ND	(22,148)
08'	(1,298)	(20,844)	(6)	ND	(22,148)
09'	5,390	392,413	28,564	18,708	445,075
10'	4,684	341,069	24,436	16,260	386,449
11'	7,840	707,924	36,561	23,908	776,233
12'	9,904	894,219	46,182	30,199	980,504
13'	7,482	680,966	37,268	24,225	749,941
14'	(1,568)	(167,725)	18,224	11,334	(139,735)
15'	(5,153)	(536,944)	0	0	(542,097)
16'	ND	ND	ND	ND	ND
17'	(1,344)	(204,702)	(724)	0	(206,770)
18'	(832)	153,316	(236)	0	152,248
19'	8,043	998,288	1,148	0	1,007,479
20'	20,685	1,697,597	180,230	82,009	1,980,521
21'	ND	ND	ND	ND	ND
22'	ND	ND	ND	ND	ND
23'	ND	ND	ND	ND	ND
24'	0	138,356	85,826	20,292	244,474
25'	0	159,109	98,700	23,336	281,145
26'	(4,328)	87,059	72,942	17,248	172,921
27'	5,413	308,422	167	0	314,002
28'	23,368	996,104	10,807	43,403	1,073,682
29'	35,009	1,643,257	21,435	86,807	1,786,508
30'	100,006	1,133,770	132,469	108,639	1,474,884
31'	7,886	(23,568)	(126,758)	11,416	(131,024)
32'	0	50,059	4,789	0	54,848
33'	43	(68,008)	0	0	(67,965)
34'	811	810,499	0	0	811,310
35'	55	20,949	49	0	21,053
36'	1,040	398,025	932	0	399,997
37'	469	179,560	421	0	180,450
38'	ND	ND	ND	ND	ND
39'	ND	ND	ND	ND	ND
40'	ND	ND	ND	ND	ND

EASTERN SHORE (cont'd.)

Minute of Latitude	Metric Tons Gravel	Sand	Silt	Clay	Total
41'	ND	ND	ND	ND	ND
42'	ND	ND	ND	ND	ND
43'	3,949	341,841	416	0	346,206
44'	11,846	1,025,522	1,247	0	1,038,615
45'	5,430	175,373	0	0	180,803
46'	3,620	116,915	0	0	120,535
47'	5,093	162,419	0	0	167,512
48'	4,658	146,903	0	0	151,561
49'	3,025	94,471	0	0	97,496
50'	ND	ND	ND	ND	ND
51'	ND	ND	ND	ND	ND
52'	ND	ND	ND	ND	ND
53'	11,364	56,057	224	272	67,917
54'	106,059	523,200	2,093	2,537	633,889
55'	82,824	505,822	3,381	815	592,842
56'	2,565	17,771	143	0	20,479
	462,740	13,914,620	680,924	521,408	15,579,692
Percent	3	89	4	3	

NOTES: ND = No Data.

() = Accretion.

MASS OF SEDIMENT ERODED OR ACCRETED

ALONG THE SHORELINE BY MINUTE OF LATITUDE

FOR THE WESTERN SHORE OF THE LOWER CHESAPEAKE BAY

Minute of Latitude	Metric Tons				
	Gravel	Sand	Silt	Clay	Total
37° 01'	2,428	123,767	0	0	126,195
02'	4,654	237,220	0	0	241,874
03'	19,410	627,943	33,240	56,084	736,677
04'	54,736	799,222	33,240	56,084	943,282
05'	167,155	1,025,104	0	0	1,192,259
06'	232,563	1,426,232	0	0	1,658,795
07'	ND	ND	ND	ND	ND
08'	ND	ND	ND	ND	ND
09'	9,359	602,365	2,009	5,754	619,487
10'	15,816	215,154	5,735	9,584	246,289
11'	66,518	173,436	2,314	2,993	245,261
12'	79,307	194,079	2,514	3,351	279,251
13'	ND	ND	ND	ND	ND
14'	ND	ND	ND	ND	ND
15'	ND	ND	ND	ND	ND
16'	ND	ND	ND	ND	ND
17'	627	41,807	3,802	2,963	49,199
18'	2,099	371,528	6,929	8,343	388,899
19'	(4)	8,386	30	0	8,412
20'	(14)	(47,910)	0	0	(47,924)
21'	(1,517)	(94,028)	(224)	(59)	(95,828)
22'	(3,466)	(30,542)	(329)	(249)	(34,586)
23'	382	36,748	(340)	9	36,799
24'	24,045	400,228	555	1,623	426,451
25'	22,769	379,219	525	1,536	404,049
26'	49,608	587,676	1,537	1,690	640,511
27'	55,269	562,543	1,862	1,242	620,916
28'	22,469	586,336	3,694	3,078	615,577
29'	52,427	1,368,116	8,618	7,182	1,436,343
30'	37,448	977,226	6,156	5,130	1,025,960
31'	168	50,663	41	0	50,872
32'	2,878	307,445	301	0	310,624
33'	12,326	879,936	982	0	893,244
34'	ND	ND	ND	ND	ND
35'	ND	ND	ND	ND	ND

WESTERN SHORE (cont'd.)

Minute of Latitude	Metric Tons Gravel	Sand	Silt	Clay	Total
36'	3,383	110,620	9,766	3,395	127,164
37'	52,430	1,714,612	151,376	52,627	1,971,045
38'	63,890	1,887,668	174,567	71,166	2,197,291
39'	17,876	160,385	33,485	21,782	233,528
40'	ND	ND	ND	ND	ND
41'	11,576	169,686	145	0	181,407
42'	34,728	509,058	436	0	544,222
43'	14,691	220,521	161	0	235,373
44'	21,803	355,842	114	0	377,759
45'	ND	ND	ND	ND	ND
46'	ND	ND	ND	ND	ND
47'	ND	ND	ND	ND	ND
48'	2,146	244,848	51,162	37,081	335,237
49'	32,872	954,752	104,972	69,551	1,162,147
50'	43,843	942,271	61,008	34,832	1,081,954
51'	47,265	1,024,207	66,313	37,860	1,175,645
52'	30,250	655,493	42,440	24,230	752,413
	1,306,213	20,759,862	809,136	518,862	23,394,073
Percent	6	89	3	2	

NOTES: ND = No Data.

() = Accretion.

MASS OF SEDIMENT ERODED OR ACCRETED
ALONG THE SHORELINE BY MINUTE OF LATITUDE/LONGITUDE
FOR THE EASTERN, WESTERN, AND SOUTHERN SHORES
OF THE LOWER CHESAPEAKE BAY

			Metric Tons		
	Gravel	Sand	Silt	Clay	Total
Southern Shore	(15,102)	3,340,946	0	0	3,325,844
Eastern Shore	462,740	13,914,620	680,924	521,408	15,579,692
Western Shore	1,306,213	20,759,862	809,136	518,862	23,394,073
Percent	Southern Shore - 8 Eastern Shore - 37 Western Shore - 55				
Total	1,753,851	38,015,428	1,490,060	1,040,270	42,299,609
Percent	4	90	4	2	