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Stratigraphy and heavy mineral analysis in the lower Chesapeake Bay, Virginia

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STRATIGRAPHY AND HEAVY MINERAL ANALYSIS IN THE LOWER CHESAPEAKE BAY, VIRGINIA

A DISSERTATION

PRESENTED TO

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

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By

Carl Richard Berquist, Jr.

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APPROVAL SHEET

This dissertation is submitted in partial fulfillment of

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ABSTRACT

Spatially continuous patterns of heavy mineral distributions in three dimensions characterized the sandy Holocene sediments of the lower Chesapeake Bay. A pilot study using Q-mode factor analysis on data from an earlier study determined mineral assemblages and mineral composition gradients; the gradients suggested that surficial sediments entered the Bay from offshore and from older deposits to the west. Principal components analysis of the same data indicated that the abundances of only 5 out of 21 minerals were adequate to explain most of the mineral variance.

The mineralogy of 87 samples from cores defining two geologic cross-sections was added to the pilot study data and formed a new data set of 173 samples and 5 minerals. Q-mode factor analysis gave similar end-member compositions and mineral gradients as compared to the pilot study. Mineral gradients in the cross-sections show offshore sediment rich in amphibole, garnet, and pyroxene has entered the Bay mouth and presently overlies landward-derived sediment rich in zircon and epidote. The gradients depict tube- and tongue-shaped pathways located above paleodrainages. Surficial gradients support the notion of mutually evasive ebb and flood channels in the Bay entrance. Most of the Holocene sediment in the lower Bay appears to have originated from outside the Bay mouth, to include littoral drift from the north. The techniques used in this study may be useful in an attempt to subdivide a massive sandy lithosome by recognizing distinct stratigraphic units of different age or origin. A magnetohydrostatic mineral separator was constructed and tested.

INTRODUCTION

Setting

Southeastern Virginia, including the Chesapeake Bay and the Eastern Shore, has been the site of considerable geologic research over the past several years. This dissertation takes advantage of data generated from some of these earlier studies and examines minerals in post-Wisconsinan sediments of the lower Chesapeake Bay (Figure 1); also, it is concerned with the stratigraphy, composition and origin of these sediments through an analysis of mineral assemblage composition and variability.

Rational for this Study

Recent mapping in the Virginia Coastal Plain (Berquist, Mixon, and Newell, in preparation; Richmond and others, in press) shows that relationships among late Pliocene and younger formations are complex. Similar processes are responsible for the deposition of sediments of many of these formations. For example, the Windsor, Charles City, Shirley, and Tabb formations (Johnson and Berquist, in preparation) are all composed of sediments that accumulated in fluvial, estuarine, bay, and marine environments. Areas underlain by these units are composed of juxtaposed, massively bedded sands which commonly are devoid of fossil or distinctive sedimentary structures, and are of different ages but similar origin (depositional environment). Without some contrasting characteristics it is difficult

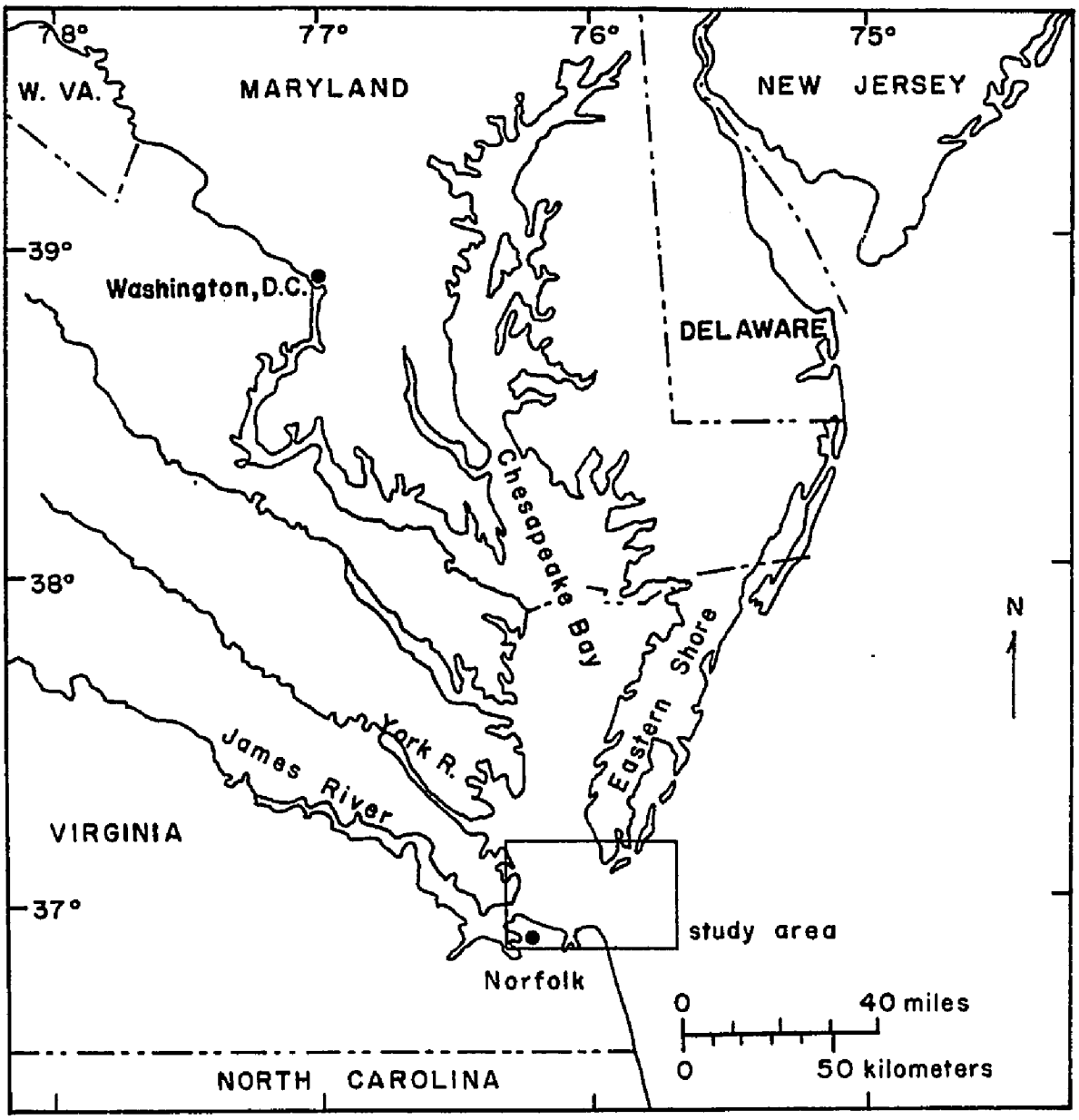


Figure 1. Location of study area in southeastern Virginia.

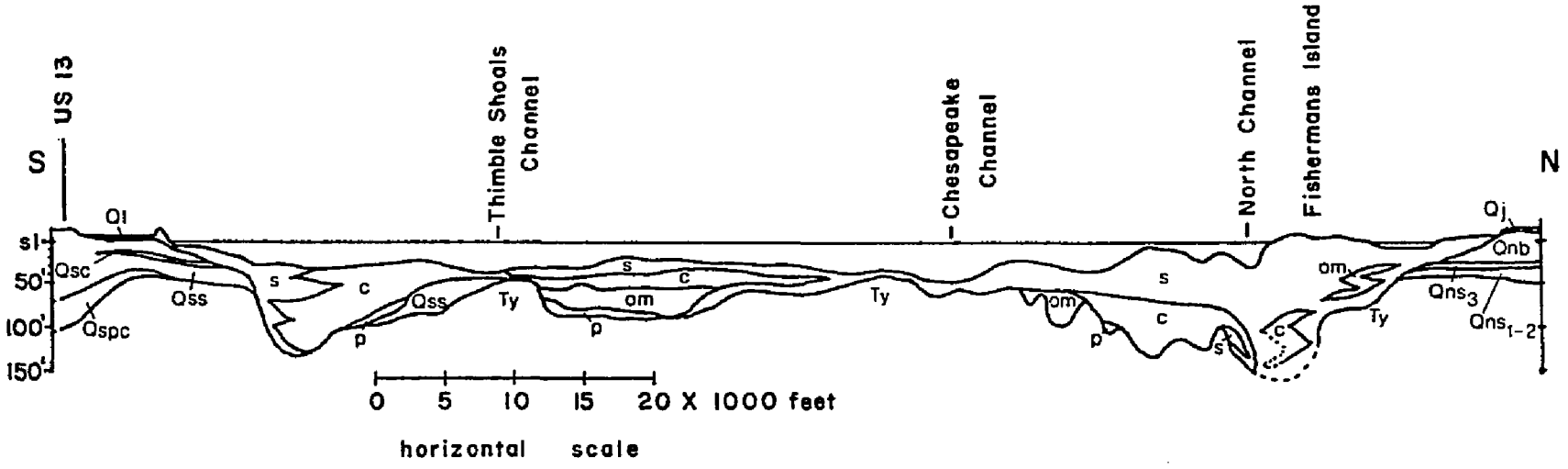
to discriminate between these similar lithosomes and therefore to map the deposits.

There are several solutions to this problem. Morphologic relationships have some usefulness in delineating units in the coastal plain. (Coch, 1965; Oaks and Coch, 1973; Peebles, 1984). Absolute soil ages based on ^{10}Be disequilibrium (Pavich and others, 1982) and relative soil ages based on weathering characteristics (Mausbach and others, 1982; Owens and others, 1982; and Markewich and others, 1983) are limited to surficial units that have developed soil profiles. Other age-dating methods may be useful, but only if appropriate carbonate or organic matter is available. Flora or fauna can be used in correlation, but commonly these materials are either leached from the unconsolidated coastal plain sediments, or there is not enough variability of the biota to discern between the different formations. Relative placement in a stratigraphic framework is possible but only if the entire sequence of a unit or a mappable unconformity is preserved (Johnson and others, 1982; Peebles, 1984). The distribution of heavy minerals (those with a specific gravity greater than 2.8) has also been used to characterize sediments.

V.C. Illing was the first to use heavy minerals for stratigraphic correlation in 1916; this method culminated with little advancement in the late 1930's (Luepke, 1985). Mineralogic correlations fell into disuse because heavy mineral suites were found to be time-transgressive and other methods of correlation (palynology, micropaleontology, electric well-logs) were found to be more sensitive and convenient (Van Andel, 1959). Geologists in countries other than the U.S. continued to use heavy minerals with success (Feo-Codecido, 1956; Luepke, 1985). Van Andel (1959) explained that this method of research was not worthless and that a great deal of information could be brought out in projects involving location and characterization of source regions and sediment distribution patterns.

Some stratigraphic problems in the Virginia Coastal Plain appear resolvable by means of a systematic study of heavy minerals. Although contrasting mineral suites have been generally helpful in the past, identifying patterns of heavy mineral distributions may significantly improve the characterization of massive sands in particular. Distribution patterns or gradients of mineral compositions may be unique to different environments, so contrasting patterns in older sediments could be another means of discerning between otherwise similar lithosomes. Specifically, Q-mode factor analysis of textural and mineralogic data has been used successfully to identify unique heavy mineral assemblages and their mixing gradients (distribution patterns) in modern sediments (Imbrie and Van Andel, 1964; Klovan, 1966; Flores and Shideler, 1978; Rosato and Kulm, 1981; Scheidegger and Krissek, 1982). Before this method can be used to differentiate between lithosomes, diagnostic mineral distribution patterns should first be established within modern analogs.

The Chesapeake Bay, as well as other estuaries, has only recently been recognized as a center of exceptional sedimentation. The tributary estuaries, eroding shorelines, and mainly offshore bottom sediments are probable sources for the present filling of the Bay (Hobbs and others, 1986); however, the identification of all the sources and the quantification of sediment from these sources is unknown. Only one other sediment study in the lower Bay begins to address this question; Fourier grain-shape analysis shows that there is a southerly littoral drift of sand along the Eastern Shore which enters the Bay mouth at Cape Charles (Boon and Frisch, 1983). Figure 2 is a stratigraphic cross-section across the Chesapeake Bay mouth. It is similar to one by Meisburger (1972) but is based on more information than that available to him. It basically shows that sediments in the lower



EXPLANATION

c	Holocene clays
s	Holocene sands
om	Holocene organic mud
p	Holocene peat
Ql	Lynnhaven Formation: sandy mud
Qs	Sedgefield Formation: Qsc- silty clay; Qss- sand; Qspc- peat and organic clay
Qj	Joynes Neck Formation: sand and mud
Qnb	Nassawadox Fm., Butler's Bluff Mbr.: sands
Qns	Nassawadox Formation, Stumptown Member: Qns_1- coarse sand; Qns_2- peat and sand; Qns_3- clayey silt
Ty	Yorktown Formation: shelly muddy fine sand; may include Chowan River and Eastover formations

Figure 2. Cross-section along the Chesapeake Bay Bridge Tunnel

Chesapeake Bay are composed mainly of massive post-Wisconsinan sands overlying Tertiary strata and that much of the Pleistocene sediment has been eroded during preceeding lowstands of sea level.

Quaternary sediments in the Virginia Coastal Plain were deposited primarily during marine transgressions (Johnson and others, 1982) and are therefore similar to the post-Wisconsinan Chesapeake Bay sediments in terms of a depositional model. If Q-mode factor analysis is applied to the heavy mineral data in the post-Wisconsinan sand lithosome of the lower Bay, these patterns resulting from contoured plots of sample composition loadings on end-members theoretically should reflect transgressive (marine) sedimentation and the influx of sand into the Bay from offshore and other "sources"; although absolute sources of sediment would not be known, transport directions may be implied by mixing gradients. Some mineral distribution patterns might then be established for the mouth of a modern estuary .

Hypotheses

Two hypotheses guided this research. The first is that heavy minerals exist in the post-Wisconsinan Bay sands, and that these minerals and their distributions can be used to characterize patterns and features otherwise impossible to distinguish within this massive sand lithosome. The second hypothesis is that patterns or gradients of mineral compositions defined by Q-mode factor analysis should reflect the advection of sand into the Chesapeake Bay mouth from offshore and from other sources during the post-Wisconsinan transgression. Therefore, in the Bay entrance area, fluvial deposits that originated landward should generally be

found below sands that originated on the shelf if the post-Wisconsinan sediments were deposited during a marine transgression.

Objectives

The purpose of this research is to characterize post-Wisconsinan sands of the lower Chesapeake Bay based on heavy mineral compositions by establishing mineral patterns or composition gradients in three dimensions. These patterns should reflect real processes and indicate sediment transport directions. This information should substiantiate some prior notions of the origin of sediments deposited in an estuarine environment and hopefully provide a basis for future comparison of massively-bedded sands.

Procedures

In order to accomplish these goals, the stratigraphy of the lower Bay (in three cross-sections) and the surrounding land area was established using published and unpublished or new core and seismic data. Fifteen cores were selected and defined two cross-sections oriented approximately east-west and out of the Bay mouth (Figure 3). At least six samples were taken from each core; textural analysis was achieved by sieving. Heavy minerals were separated from the 3 to 4 Phi size range by means of a heavy liquid (tetrabromoethane). Samples were subdivided into six groups using the Frantz Isodynamic separator and mineral compositions were determined under a binocular microscope. Q-mode factor analysis was used to establish unique heavy mineral suites and distribution gradients for the post-

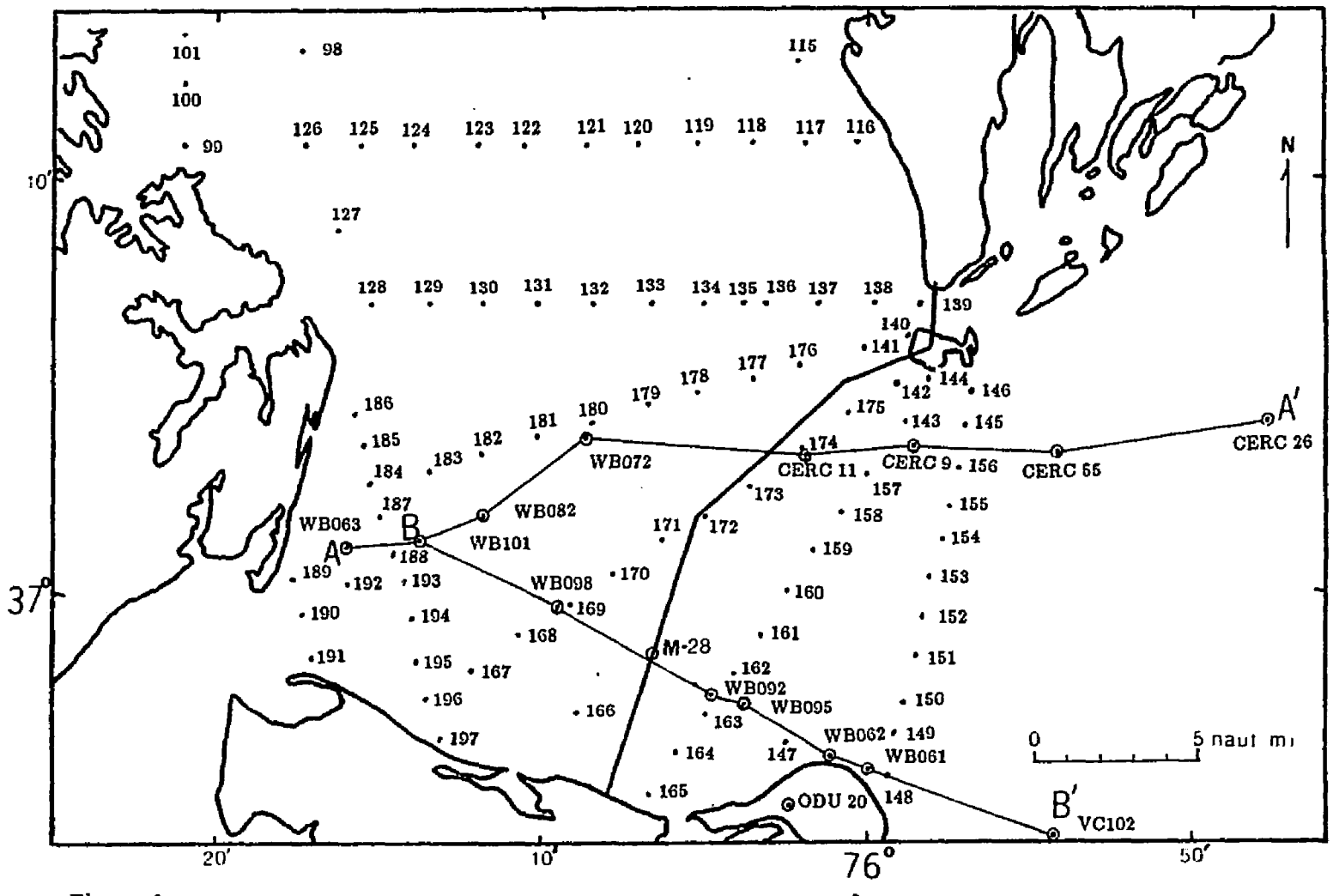


Figure 3.
Location of cross-sections, cores used in this study, and Firck's grab samples in the lower Chesapeake Bay.

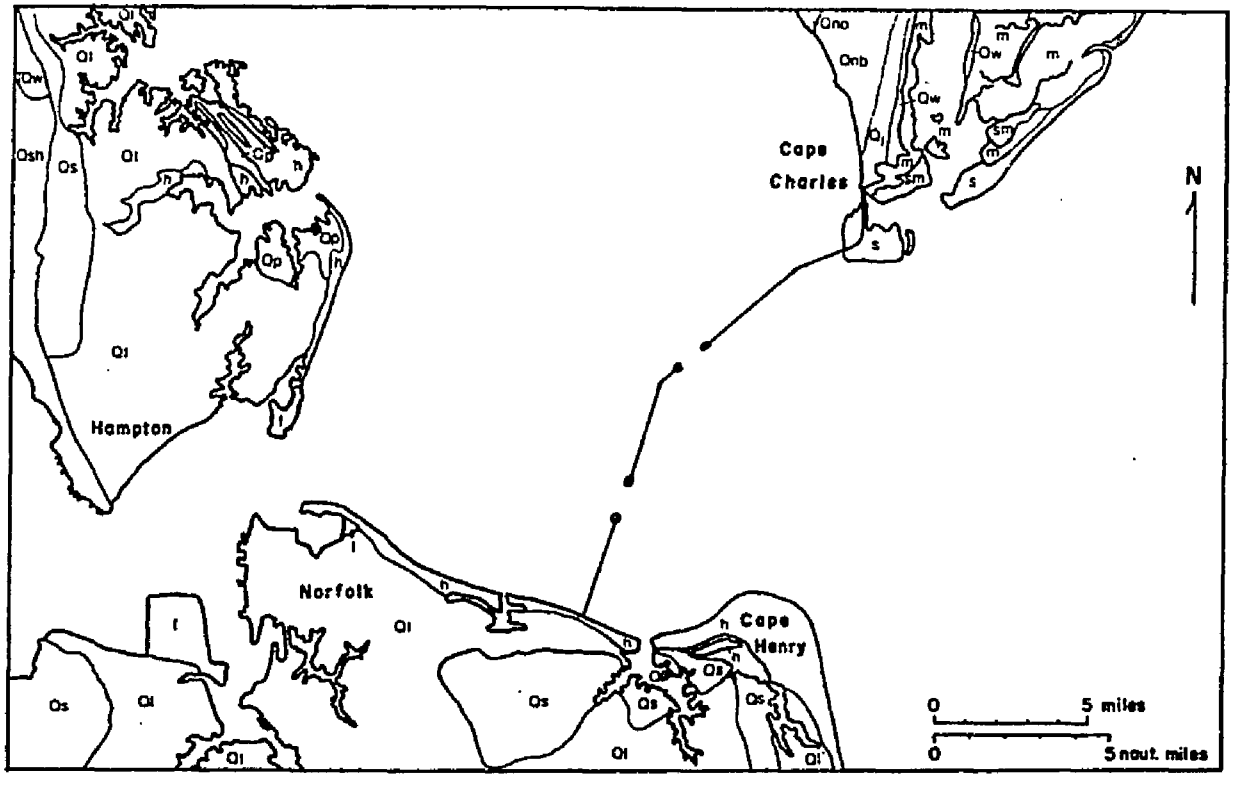
Wisconsinan sediments in each cross-section. The procedure for acquiring mineral compositions was compatable with the work of Firek (1975) so that both her data and the data from this study could be combined. In this dissertation, the following chapters contain more detailed procedures used to obtain data.

STRATIGRAPHY

Land

Many individuals studied the geology in the lower Bay area beginning with W.B. Rodgers in 1835. Subsequent work was summarized by Oaks and Dubar (1974) and Peebles (1984). Much of the present geologic knowledge of southeastern Virginia evolved from Oaks and Coch (1973); however, their stratigraphic framework was amended by more recent detailed and regional mapping. In the Hampton-Newport News area, Johnson (1976) recognized regional unconformities in previously mapped facies of the Norfolk Formation. He clarified stratigraphic relationships on the York-James Peninsula and named the Tabb Formation with three members, Sedgefield, Lynnhaven, and Poquoson. These units did not correlate clearly with the stratigraphy defined by Oaks and Coch (1973) south of the James River. Additional work by Peebles (1984) and Peebles and others (1984) simplified the regional stratigraphy and resolved correlation problems across the James River.

Richmond and others (1986) mapped the Quaternary deposits of this area without using formal stratigraphic names. This dissertation relied upon a similar project of compilation and mapping by Berquist, Mixon and Newell (in preparation); their report used formalized geologic names (Figure 4) and the members of the Tabb Formation were elevated in rank to formations. Both of these regional maps showed comparable distributions of Quaternary sediments, but differed in detail because of the published scale and mapping units.



EXPLANATION

WESTERN SHORE		EASTERN SHORE (Mixon,1985)	
f	Fill or man-made deposits	s	Sand, quartz and shell
h	Swamp, marsh, beach and fluvial deposits, undifferentiated	m	Mud and peat
		sm	Sandy mud and muddy fine sand with some shell
Qp	Poquoson Formation		
Ql	Lynnhaven Formation	Qk	Kent Island Formation
Qs	Sedgefield Formation	Qw	Wachapreague Formation
Qsh	Shirley Formation	Qj	Joynes Neck Formation
TQw	Windsor Formation	Qnb	Nassawadox Formation, Butlers Bluff and
		Qno	Occohannock Members

Figure 4. Geologic map of southeastern Virginia

Mixon (1985) published a geologic map of the Eastern Shore and summarized absolute ages for the coastal plain area (Mixon and others, 1982). The stratigraphic nomenclature in Delaware and Maryland (Owens and Denny, 1979) was continued with some modifications into the Virginia Eastern Shore; for this reason, the nomenclature on the Eastern Shore is different from the rest of Virginia. Table 1 summarizes the present knowledge of stratigraphic relationships within the boundaries of this dissertation. Some correlation problems between the Delmarva Peninsula and the rest of Virginia remain to be solved.

TABLE 1

Correlation chart of pre-Holocene stratigraphic units on the Eastern Shore and southeastern Virginia.

In this study area only	Eastern Shore (Mixon, 1985)
Sedgefield Formation	Stumptown and Butler's Bluff Members, Nassawadox Formation
Lynnhaven Formation	Joynes Neck Sand and part of Occohannock Member, Nassawadox Formation
Poquoson Formation	Wachapreague Formation

These formations (Table 1) are composed of sediments deposited during the Sangamon Interglaciation. The older units (Lynnhaven and Sedgefield and their equivalents) were formed during marine transgressions. Uranium-series dates from correlative deposits ranged from 51,000 to 101,000 years; correlation with these

dates was determined by attributing Mixon's samples (Mixon and others, 1982) not to the formations he used but to units (Sedgefield, Lynnhaven, and Poquoson formations) from unpublished mapping by Johnson and Berquist. The Poquoson - Wachapreague deposits were formed during a marine regression prior to the Wisconsinan (Johnson, 1976; Leonard, 1986). Estimates of absolute ages for the Wachapreague Formation range from 128,000 to 82,000 years B.P. (Mixon, 1985).

Sediments composing these late Pleistocene formations are variable in composition because many depositional environments are represented in each unit. In actuality, the Pleistocene units are alloformations because they are usually bounded by unconformities (North American Stratigraphic Code, 1983); however, this report will continue to use "formation" in terminology.

Stratigraphic mapping and correlation done for the Virginia Division of Mineral Resources is based predominantly upon lithologic criteria. However, formation boundaries are not placed, for example, between any sand and clay lithosome. A logical and very workable subdivision of coastal plain sediments is one based on an expected succession of environments (deposits) which occur during a major marine transgression or regression and is discussed by Peebles (1984). In addition, there is a consistent relationship of the surficial sediments to morphology (topographic expression) of the stratigraphic units throughout the region. For example, sandy barrier deposits of the Sedgefield Formation are at the same elevation as sandy barrier sediments of the Butlers Bluff Member of the Nassawadox Formation; muddy estuarine and back-barrier deposits of these two units are also at the same position relative to sea-level. Furthermore, the stratigraphic position of these units is comparable: they are both inset against older stratigraphic units;

the older units share the same sediment-morphologic relationships (but at a higher elevation) as the Sedgefield-Butlers Bluff deposits. Thus, regional stratigraphic correlation of coastal plain stratigraphic units is dependent upon the determination of several criteria.

Marine

Figure 2 is a cross-section which is similar to that of Meisburger (1972) and Moran and others (1960); there are two reasons for differences between Figure 2 and the earlier sections. First, the stratigraphy on land is now more thoroughly known, and second, I have re-interpreted lateral continuity of sediments between borings based on an expected succession of environments during a marine transgression.

Figure 2 shows that the muddy sediments of the Lynnhaven Formation are less than 5 feet thick and contrast to the coarse sands of the underlying Sedgefield Formation. Similar relationships are found on the southern tip of the Eastern Shore where thin and muddy Joynes Neck deposits overlie the sandy Occohannock sediments. Correlation is guided by superposition of sequences of material (determined by hand augering) and by the subtle but very consistent morphology around the shores of the Bay.

Figures 5 and 6 are two geologic cross-sections joining the cores used in this study. The indicated post-Wisconsinan-Tertiary contact between cores is based on seismic data and/or additional cores from Meisburger (1972), Byrne and others (1982), and Carron (1979). Descriptions of the core sediments are in Appendix A.

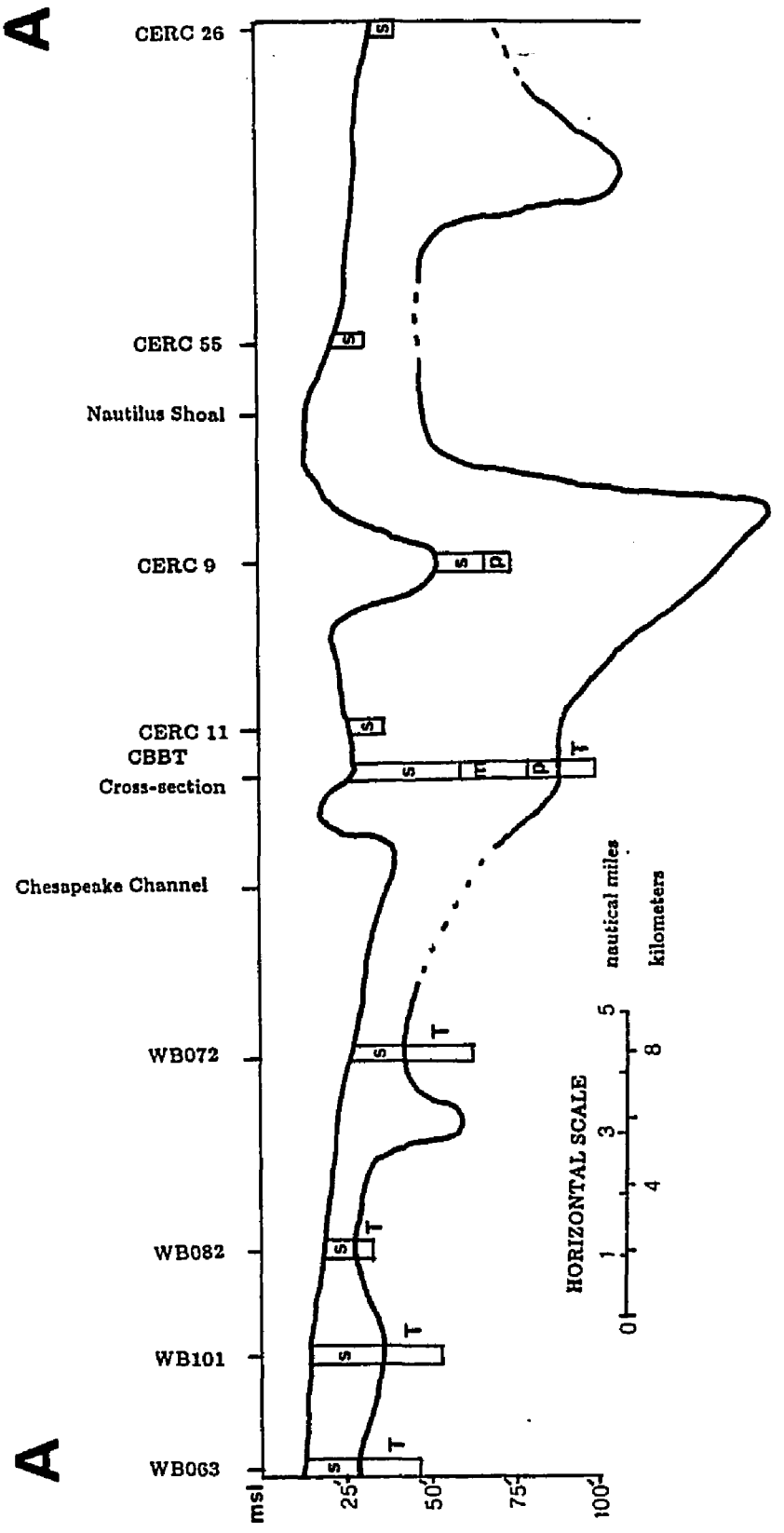


Figure 5.
Northern geologic cross-section A - A' drawn from borings and seismic profiles. S = sand, M = mud, P = peat, T = Tertiary sediments.

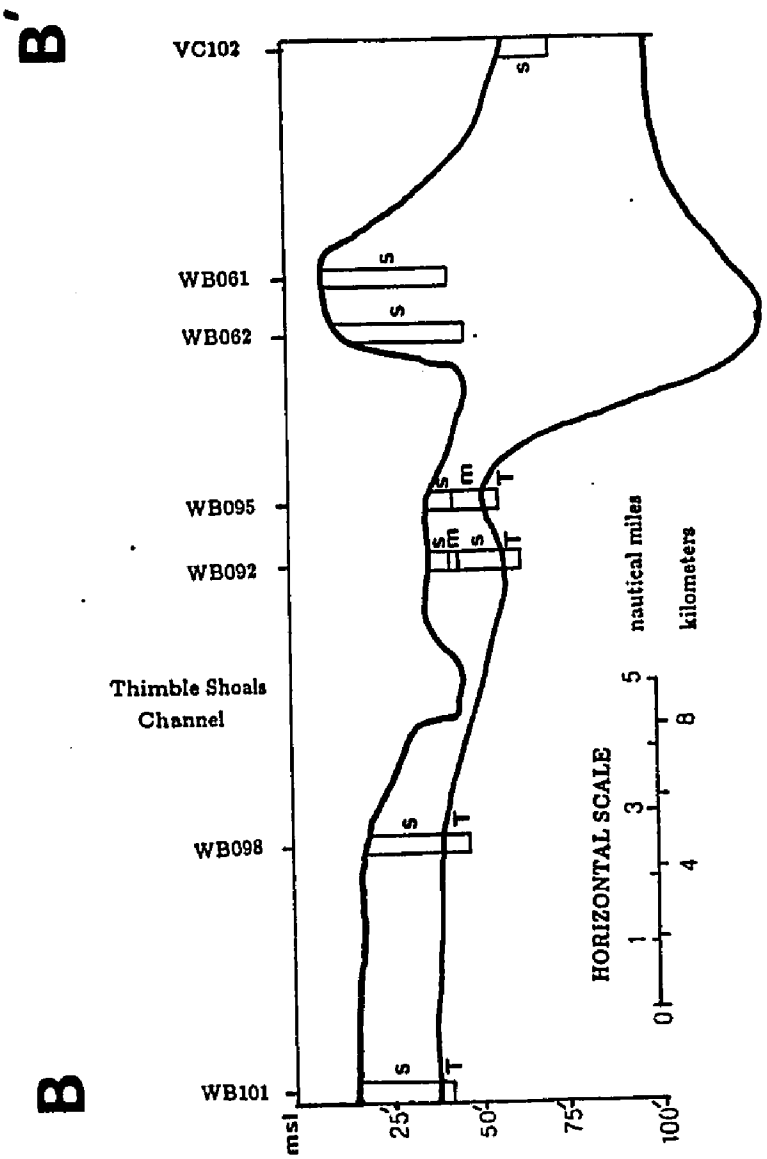


Figure 6.
Southern geologic cross-section B - B' drawn from borings and seismic profiles. S = sand, M = mud, P = peat, T = Tertiary sediments.

The coordinates and water depths of the cores are given in Appendix B.

The post-Wisconsinan age of the sediments overlying the Tertiary deposits as shown in cross-sections of Figures 2, 5, and 6 can be demonstrated by relying upon absolute ages and by tracing repetitive sequences of sediments laterally from borings. Carbon-14 dates on peat in boring M-28 define ages of 10,340 $-^{+}130$ and 15,280 $-^{+}200$ years B.P. at respective depths of 82 and 89 feet below mean low water; other younger dates are also reported (Harrison and others, 1965). Consequently, the overlying sands are of post-Wisconsinan age. In areas where no ages have been determined and lateral continuity of organic deposits cannot be shown, a definite age is less certain; however, correlation can be based on a similar vertical arrangement of sediments. Nearly all paleochannels in the lower Bay contain sediments that show a marine transgressive sequence; this is from bottom to top, a lag gravel (fluvial), organics (fluvial to estuarine), muds (estuarine), and sand (bay-mouth to marine). For example, the sediments in the buried channel under Fishermans Island are not dated, but are probably post-Wisconsinan based on continuity of the upper sand and a similar sequence to the region of boring M-28. Other areas in the Bay may show a different vertical sequence because the succession of environments at those locations during the transgression is variable, as supported by Kraft (1971).

Several criteria allow for recognition of the Pliocene Yorktown Formation. McLean (1966) shows a Tertiary-Quaternary contact based on lithologic and faunal changes in the Chesapeake Bay Bridge-Tunnel cores. The same contact is evident in seismic reflection and core data from Meisburger (1972) and Byrne and others (1982). Engineering data from Moran and others (1960) is also helpful as

Yorktown sediments are commonly over-consolidated (very high penetration blow-counts). Sediments of the Pliocene Chowan River Formation are identified below Cape Henry (Oyler, 1984). These deposits overlying the Yorktown occur sporadically in the Virginia Beach area and are not delineated in this study.

Having defined the stratigraphy in the study area, the location of the post-Wisconsinan deposits relative to older stratigraphic units is established. This is important for two reasons. First, possible sources of sediment to the Bay from land are indicated. Second, the origin of samples taken for mineral analysis should not be questionable. If samples were unknowingly selected from Pleistocene or Tertiary deposits, the interpretation of mineral gradients from the post-Wisconsinan deposits could be erroneous.

FACTOR ANALYSIS

Introduction

Although originally applied in psychological studies, factor analysis has recently been used for gaining greater insight into solutions of geologic problems. When the number of variables and/or samples becomes large, interpretation of data by inspection is difficult or impossible. Factor analysis provides an objective solution to the problem of simplifying and explaining large amounts of multivariate data. In this research, the variables are the weight percent of up to 18 minerals observed on 277 samples in the lower Chesapeake Bay.

The methods described later in this chapter may be introduced with a geometric presentation. A "variable space" may be created where each coordinate axis represents the abundance of a particular mineral. Samples plotted in this space may be compared with each other in terms of their similarity or dissimilarity. Conversely, each observation can be used to define a "sample space" in which one variable is compared to one another. A close grouping in space signifies a close or common relationship. The goal of these multivariate procedures is to arrive with fewer but more meaningful variables which are combinations of the original ones.

R-mode factor analysis is concerned with the groupings and relationships of variables. Firek (1975) and Firek and others (1977) used one-way analysis of

variance between pairs of arbitrarily defined provinces and R-mode factor analysis on a data base of heavy mineral compositions obtained from bottom grab samples in the lower Chesapeake Bay. Firek determined five mineral suites for each of her five provinces. Two factors were used in her analysis and corresponded to two mineral suites; she believed that sediment maturity was responsible for the grouping of minerals in one suite while provenance accounted for the association of minerals in the other suite. Based on the way minerals compared between the provinces in the Bay and the combination of minerals composing each factor, she believed that her study supported the notion of sediment transport into the bay from offshore as well as from erosion of surrounding land.

Q-mode factor analysis establishes the relationships between samples. Previous studies involving compositional data from spatially distributed samples have benefitted in particular from Q-mode factor analysis. The first geological application of this method was made by Imbrie and Purdy (1962) where they defined five sample groups (oolite, oolitic, grapestone, coralgal, and lime mud) as a basis for classification of carbonate sediments. Imbrie and Van Andel (1964) compared conventional comparison methods with Q-mode factor analysis (vector) techniques in heavy-mineral province studies. In the Gulf of California they found that characteristic mineral assemblages were clearly defined by inspection of the data and that mixing during sediment transport was minimal; there was also a clear relationship between sources of mineral suites and the calculated end-members or factors. However, on the Orinoco-Guayana Shelf off the north coast of South America, mixing of sediment was common and sources and mineral assemblages

were complex. They found that vector patterns were much more meaningful than conventional inspection of the data; the interpretation of factor plots suggested that submerged Pleistocene shorelines and ancient littoral drift could have been responsible for the distribution of observed heavy minerals.

Klovan (1966) attributed the grain size distribution of sediments to a hydraulic energy regime. His study showed that sediments from Barataria Bay on the southeast coast of Louisiana could be subdivided into three groups (factors) through vector analysis; plotting the samples (as vectors in factor space) on a map indicated that three regimes characterized by their relative energies (surf, current or gravitational settling) were responsible for trends in the grain size distributions.

Constant row-sums of compositional data pose no problem in Q-mode analysis. Miesch (1976) took advantage of this fact and modified the Klovan and Imbrie (1971) routine to reproduce approximations of the observed data in similar units (weight percent or parts per million, etc.). The earlier method reproduced the original data in a normalized form, so the later improvement gave the user an additional means of critizing factor analysis results for geologic reality. Miesch (1976) also demonstrated the usefulness of this modification in geochemical and petrologic mixing problems.

Flores and Shideler (1978) used Q-mode factor analysis to define three suites of heavy minerals in the Texas Gulf of Mexico which were: opaque-pyroxene-garnet from the ancestral Rio Grande delta; tourmaline-green hornblende from the ancestral Brazos-Colorado delta; and a mixed suite from both regions. Variation of the minerals within each factor-defined province was thought to be

caused by hydraulic fractionation and selective chemical decomposition.

Perhaps the most powerful attribute of the Q-mode method is its ability to simplify real but complex compositional data. Q-mode factor analysis has been used to describe a collection of samples not in terms of many original variables but as a mixture of a few theoretical or real "end-member" samples. The samples usually represent compositional extremes for the data set. The routine indicates how much of each end-member is present in all samples. Because the dimensionality of the original data is reduced, composition gradients of a suite of minerals (based on the amount of an end-member in each sample) can be shown on a map; these patterns can suggest a direction of sediment transport similar to the results of using tracer sediments (Imbrie and Van Andel, 1964; Flores and Shideler, 1978).

In summary, the use of factor analysis results in objectively defined groups of samples which may not be apparent from conventional inspection of the data, as shown by the Orinoco-Guayana Shelf study (Imbrie and Van Andel, 1964). New or different associations of data may result from a factor analysis model and therefore may require a reasonable geologic explanation. This added insight gained from the analysis provides increased clarification of otherwise enigmatically related data.

Pilot study

In order to establish the validity of the proposed approach, Q-mode factor

analysis programs developed by Klovan and Imbrie (1971), Klovan and Miesch (1975) and Full and others (1981), were applied to Firek's original data. The location and tabulation of all her data may be found in her thesis (Firek, 1975); Figure 3 and Appendix E only gives the data that I used in my final analysis. Firek identified 21 minerals (plus "other") but olivene, topaz, and zoisite were reported as absent or as non-numeric (trace) amounts; these minerals were therefore excluded from all of my work. I then incorporated her data into several factor analysis models. First, all data were used (190 samples and 19 variables, or 18 minerals plus "unidentified") in three, four, five and six factor models. The three factor solution provided the most geologically reasonable model because end-members uniquely coincided with three of Firek's provinces. Solutions using additional factors partially duplicated the end-member suite of minerals and their locations in the provinces of the three factor solution. Plots of the composition loadings of samples on end-members showed geologically reasonable patterns: the gradient of garnet-hornblende composition decreased in the up-Bay direction and was consistent with sand advection into the Bay mouth from offshore; the gradient of clinopyroxene-hornblende opposed the first plot and probably represented the contribution of sediment from rivers or shoreline erosion; the third plot showed mixing of both factors. Unfortunately, the end-members were characterized by large negative mineral percentages, so a more realistic solution was sought.

Next, I introduced Firek's data to a principal component analysis using the programs from Davis (1973); it was determined that seven minerals (hornblende, zircon, garnet, clinopyroxene, sphene, epidote, and staurolite) out of the original

18 accounted for 96% of the variance in the entire data set. Then, using only eight variables (seven minerals and one "other", recalculated to constant row-sums of 100%) and 190 samples, several factor solutions were attempted with similar results which were duplication of provinces and negative end-member compositions. Because the sampled area was so large, there could have been more than six extreme samples (or end-members); the spread or diversity of the data might have required greater than six factors for a reasonable solution. Another analytical approach gave more understandable results. The geographic size of the study area was reduced and only 87 samples (location shown in Figure 3) from the lower Bay area were used; also, the samples (each composed of seven minerals) were row-normalized. A three factor solution gave large negative values of end-member compositions, but accounted for 97% of the total variance; a four factor solution gave more reasonable results because end-member compositions were essentially positive. Two of the four factor plots were not easily explainable; one suggested a western source of material to the Bay that was rich in staurolite, while the other plot showed high concentrations of amphibole-rich material around the margins of the lower Bay. The other plots of sample composition loadings were similar to two of those from the 3 factor solution. These results reflected the complex currents and zig-zag shoals shown by Ludwick's (1970) studies, and the diverse sediment sources in the lower Bay area.

Figure 7 showing the distribution of Factor 2 very clearly depicts the influx of sediment into the Bay mouth from offshore. The end-member is located off Cape Charles and is composed of 27% amphibole and 72% garnet; this composi-

tion is similar to mineral compositions on North Carolina beaches and dunes (Giles and Pilkey, 1965). The offshore source is also predicted by littoral drift convergence at the Bay mouth (Swift and others, 1972; Firek and others, 1977; Harrison and others, 1967).

The existance of a zircon-rich region through the center of the lower Bay (Figure 8) warrants further study partly because heavy mineral data from the surrounding land and tributary estuaries is lacking. The high zircon composition with associated sphene, epidote, and staurolite suggests that a combination of moderately young material and much older sediments are being reworked by modern processes. Zircon is a more stable mineral and is more commonly found in older sediments while the other minerals are less stable and are commonly found in younger sediments (Pettijohn, 1957). Because of duplicated patterns in a three and four factor solution with different data sets, it is strongly believed that these gradients of mineral compositions suggest the pathways of sediment transport in the lower Bay area.

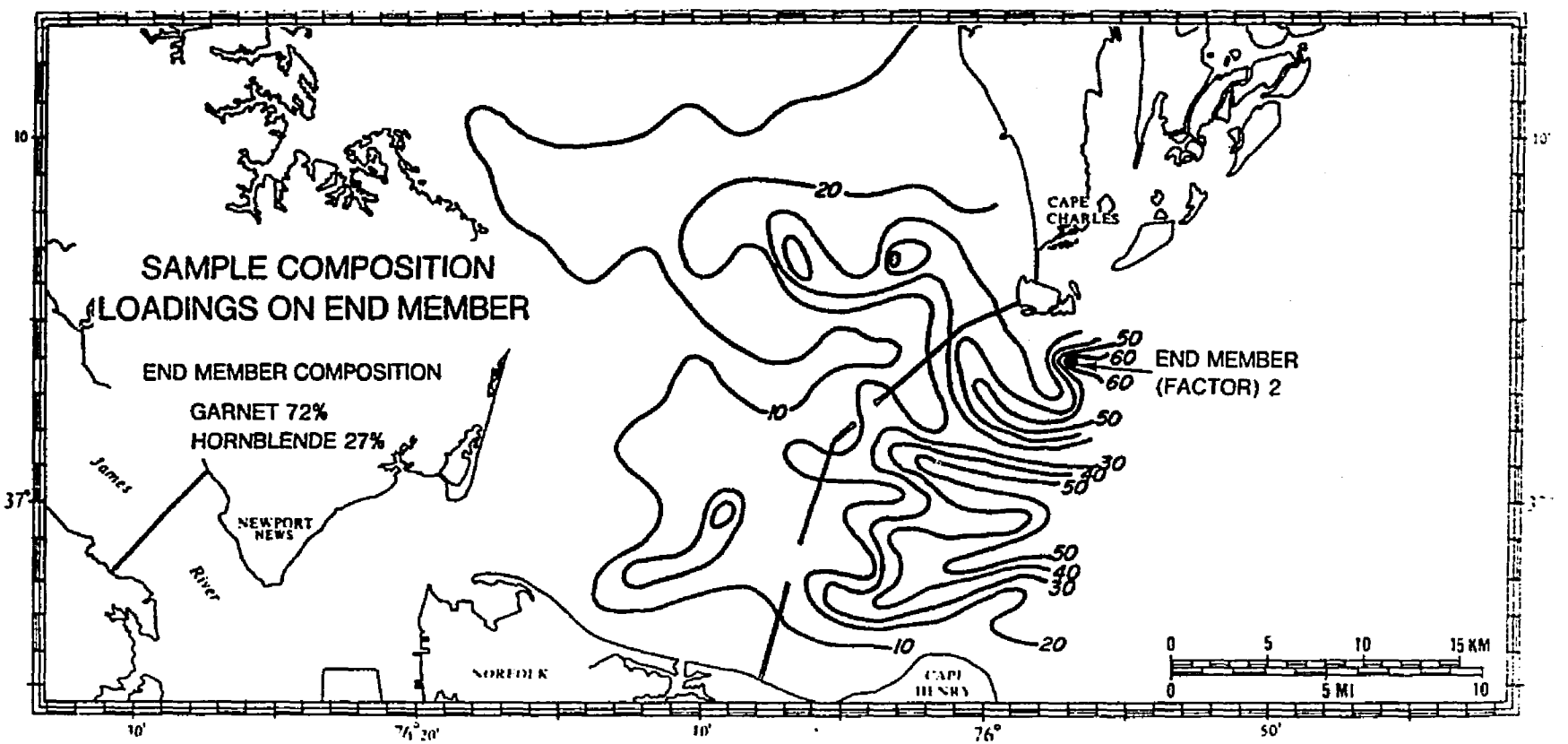


Figure 7.
Contour map of sample composition loadings on a factor composed of 72% garnet and 27% amphibole; sample marked "Factor 2" was chosed by the Q-MODEL program as an end-member from Firek's data only.

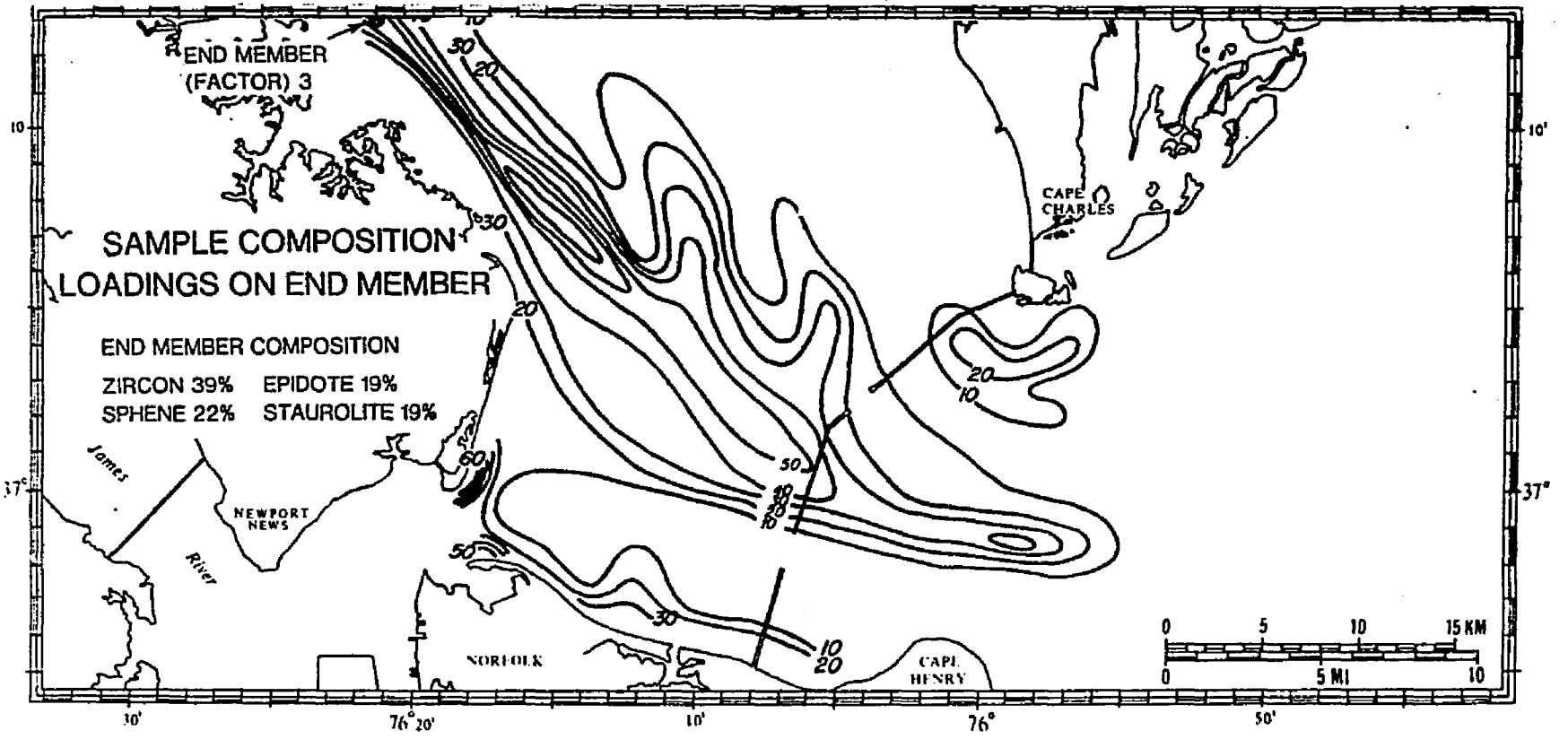


Figure 8.
Contour map of sample composition loadings on a factor composed of zircon, sphene, epidote, and staurolite; the sample marked "Factor 3" was chosen by the Q-MODEL program as an end-member from Firek's data only.

Explanation of Q-mode Factor Analysis

Two kinds of factor analysis routines have been used in geologic work, R- and Q-mode. R-mode factor analysis creates a lesser number of new variables which are linear combinations of a larger number of original variables. The new variables also account for a larger share of the data variance than any other combination of the same number of any other original variables. In Q-mode factor analysis the role of samples and variables is reversed, and a relationship between samples is established; the purpose of this method in geological applications is to describe each sample not in terms of a combination of many original variables, but as a mixture of a few theoretical or real end-member samples. An idealized geologic example, modified from Joreskog and others (1976, p.87), is shown in Figure 9.

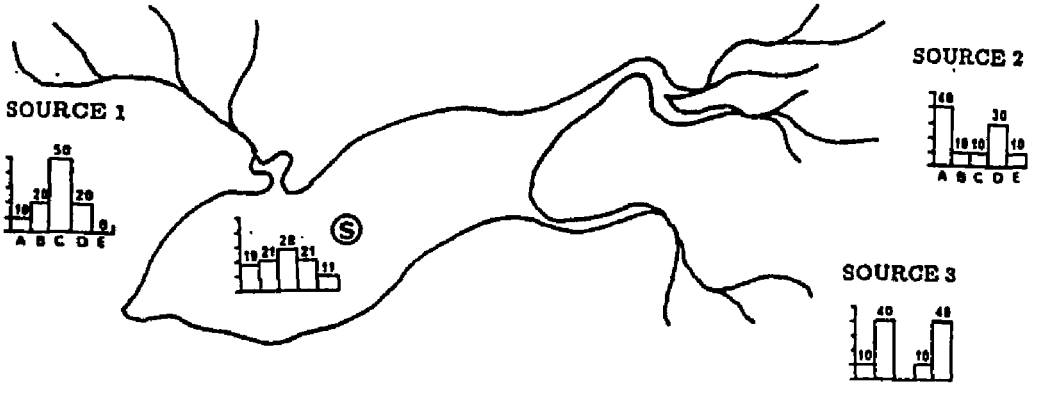


Figure 9. A schematic diagram of a depositional basin being supplied with minerals from three different sources. Each source is composed of five mineral species, A,B,C,D,E in different proportions. The sample S may be characterized by concentrations of minerals A-E or as a mixture of the three "end-member" sources in the proportions 0.5(1) + 0.3(2) + 0.2(3). For example, for mineral species A we have 0.5(10) + 0.3(40) + 0.2(10) = 19.

As minerals arrive in the basin (Figure 9) from each of the source rivers, they are mixed into new proportions. If this were an ancient system and we were relying on core data, and our objective was to find the sources of the minerals, we would not know how many sources there were and it would be very difficult to solve this problem by mere inspection of the mineral compositions. Q-mode factor analysis has the potential of finding the end-members and their compositions and "un-mixing" all the samples in terms of the end-members.

Although Davis (1973, 1986) and Joreskog and others (1976) present a detailed explanation of the method, an abbreviated description of this process will be explained here. We should first arrange our data into a matrix format where each row represents a different sample and each column is a different variable (Figure 10).

sample	garnet	hornblende	zircon	...k
s1	15%	25%	60%	
s2	8%	11%	21%	
.				
.				
r				

Figure 10. Data matrix C, with r rows of samples and k columns of variables.

This data matrix C can be approximated or factored into two other matrices of lesser rank where "the rank of a matrix is the smallest common order among all pairs of matrices whose product is the matrix" (Joreskog and others, 1976, p. 36).

Matrix C can actually be decomposed into an infinite number of product matrices A and B (Joreskog and others, 1976, p. 35); combinations involving matrices of three different ranks are shown in Figure 11. Matrix multiplication requires that the number of columns (m) in the pre-factor (A) must equal the number of rows (m) in the post-factor (B).

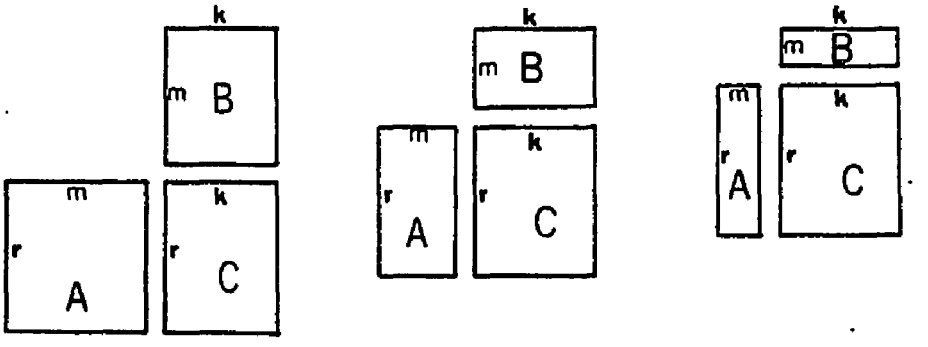


Figure 11. The number of rows (r) and columns (k) of the matrices are drawn to scale. The rank of C is m in each example; m is also the number of factors that could be chosen for any particular solution.

Having an infinite number of choices of product matrices does not provide any help in simplifying the data matrix. We can limit our choices by asking that the new matrices will fulfill certain additional requirements. At this point in the discussion, eigenvectors, eigenvalues and the Eckart-Young theorem will be introduced.

It is difficult to define eigenvalues and eigenvectors without a lengthy dis-

cussion (see Davis, 1973 and Joreskog and others, 1976 for more detail). For this discussion I will use a few simple examples. A matrix can be geometrically represented as vectors in multidimensional space. Each vector is defined by a row in the matrix where row values are the coordinates of the vector end-point. For example, sample S1 of Figure 10 is plotted in Figure 12 A. The values of a symmetric matrix (2 x 2) may be shown to plot on an ellipse (in 2 dimensional space). The eigenvectors of this matrix are the major and minor axes of the ellipse; the eigenvalues are the lengths of each axis. The eigenvectors are perpendicular (orthogonal) to each other and each one has an associated eigenvalue. Being orthogonal means that the vectors are independent of one another. A symmetric matrix will always have real as opposed to imaginary eigenvalues; this fact is important because the original data matrix is converted to a symmetric matrix in R- and Q-mode factor anlysis routines. The rank of a matrix is also equivalent to the number of its non-zero eigenvalues.

The Eckart-Young theorem states (after rearranging the matrices) that any real matrix [C] equals [V][N][U]' where [V] and [U] are orthogonal matrices and [N] is a diagonal matrix containing the eigenvalues of [R] or [Q] described below. (U' means the transpose of U). The minor product matrix [R] = [C][C]' and the columns of [U] contain the eigenvectors of [R]. Likewise, the major product matrix [Q] equals [C]'[C] and the columns of [V] contain the eigenvectors of [Q] (Davis, 1986, p. 517 - 519). Without going into more detail, it may be shown that [V][N] becomes the factor loadings matrix (matrix A in Figure 11) and [U] becomes the factor scores matrix (matrix B in Figure 11).

In Q-mode factor analysis, the data matrix is factored into A, the factor loadings matrix (which gives the composition of each sample in terms of the factors) and B, the factor scores matrix (which describes the composition of each factor in terms of the original variables and may be used to convert new data into "factor space". The investigator may choose the number of factors (which will often be less than the rank of the transformed data matrix) based on criteria explained later.

Finding the eigenvalues and eigenvectors of a variance-covariance matrix or similarity matrix (derived from the original data matrix) has special significance to understanding the structure of the original data. The total variance of the data is equal to the sum of the eigenvalues of the variance-covariance or similarity matrix. Thus the choice in the number of factors is directly related to the amount of variance in the data to be retained and explained.

It would be helpful to the understanding of this type of analysis if we can visualize each sample as a vector which is plotted in variable space, that is, within a coordinate system where each axis is a variable. For more than three variables it is difficult to see how this can be done, so a simple example is shown in Figure 12.

Through Q-mode factor analysis, we may find that the contribution of garnet (Figure 12) to the total variance in this geologic data is very small (for most samples, garnet composition may remain nearly the same or vary only slightly) and we could simplify the relationship of samples to one another by reducing the dimensions of the data. In Figure 12 a three-variable data matrix is reduced to a two-factor matrix. Through the analysis, garnet composition is combined with

another variable in defining a factor; alternately garnet composition could be eliminated, particularly if its abundance varies only slightly. The composition of the sample is changed relative to the new factor coordinates. Each new axis or factor has a composition in terms of original variables and can be an actual sample from the data matrix. The value of this approach can be appreciated when the analysis reduces a ten-variable system to a three or four factor model.

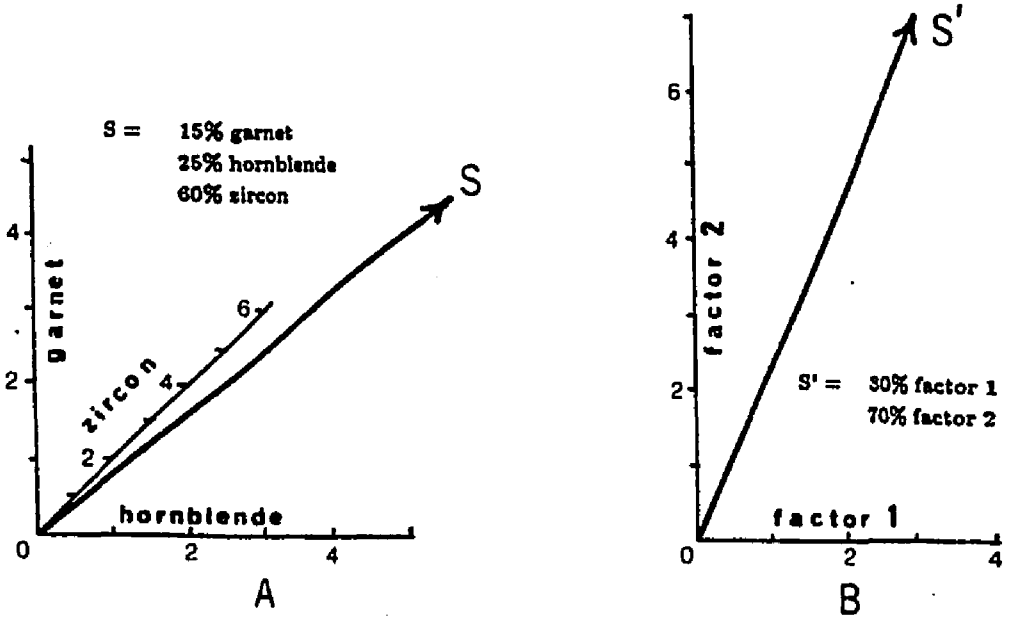


Figure 12. Sample S plotted in variable space (A) and factor space (B). Factor 1 may be composed predominantly of hornblende or a combination of hornblende and garnet. Factor 2 may be composed mainly of zircon.

Q-mode Procedure as Used in Computer Programs

Mineral composition data was used in three computer programs, CABFAC (Klovan and Imbrie, 1971), QMODEL (Klovan and Miesch, 1975), and EXQMODEL (Full and others, 1981). The Q-mode factor analysis method is explained as the programs derive a final result.

CABFAC Program

Depending on the type of data, some transformation may be needed (Davis, 1973; Miesch, 1976). Several options are available in the program to scale columns of variables. The reason for scaling is to give all variables an equal weight in the factor analysis.

All factor routines begin with the calculation of a square "similarity" matrix which may be the correlation coefficients or some other measure of similarity that does not exceed the range of $-^{+}1.0$. The correlation coefficient, (r, and thus R-mode) is not used as a measure of similarity between samples (in Q-mode) because it requires the calculation of variance across variables; averaging the amount of each variable in a sample is an obscure procedure (Davis, 1973, p. 526). Imbrie and Purdy (1962) defined an "index of proportional similarity" or cosine Theta which is the cosine of the angle between two row vectors plotted in

variable space. If two samples are plotted orthogonal to each other, Theta = 90° and cosine Theta = 0 so it can be said that the two samples have no similarity. If two samples are co-linear, Theta = 0° and cosine Theta = 1 and it is obvious that the samples are identical. This concept is difficult to visualize beyond three dimensional (variable) space, but the mathematical calculations of cosine Theta in hyperspace is not affected by our lack of perception. CABFAC computes a cosine Theta matrix from the data which will be symmetric in all cases.

The next step requires calculation of the principal components or eigenvectors and eigenvalues of the cosine Theta matrix. Davis (1973) explains the utility of eigenvectors and how they are calculated, so only a few important facts are summarized here. The similarity matrix is symmetric so the eigenvalues will be real, and the eigenvectors will be at right angles to each other, or orthogonal. For example, the values of a 2 X 2 symmetric matrix can be shown to represent coordinates of points in two dimensional space. The points lie on the boundary of an ellipse whose center is the origin of the coordinate system. The eigenvalues are the lengths of the major and minor axes of the ellipse; each eigenvalue has an associated eigenvector that is the slope of each ellipse axis. In addition, the sum of the eigenvalues equals the sum of the diagonal elements or trace of the similarity matrix. These facts are important when applied to the similarity matrix because they describe some major characteristics of the original data. The trace of the similarity matrix also represents the variance in the original data matrix; so each eigenvalue then represents a portion of the total variance. CABFAC converts a normalized eigenvector to a factor by multiplying every element of the eigenvector

by the square root of the corresponding eigenvalue. In other words, the orientation of the factors are the same as the eigenvectors. The "factors" in factor analysis are then eigenvectors that are weighted proportionally to the amount of total variance which it represents. These weightings of the eigenvector are called factor loadings. CABFAC calculates and lists the eigenvalues and their cumulative variance so one has the means of choosing how much variance he would like to explain and therefore how many factors will be needed; a three factor solution would more simply explain the data but with some loss of resolution or variance compared to a solution with a greater number of factors. The loss of a small amount of variance may be worth the gain of additional insight from simplified data. Factors may also be regarded as a new set of axes to which the data may be related (Figure 12b); choosing fewer axes reduces the dimensionality of (or simplifies) interpretation of the original data.

A matrix of factor loadings is constructed where columns are factors and rows are samples. Summing the squared elements of each row gives the amount of variance the factors contribute to each sample; this value (sum) is called a communality. If we choose less than m factors from an m X m similarity matrix, the communalities will be less that 1.0 and will quantify how well the reduced number of factors approaches explaining the original variance.

CABFAC requires that the user specify how much variance is to be accounted for in the analysis. This is usually 95% to 99%. Eigenvalues contributing more than this limit are discarded along with their eigenvectors, and the dimensionality of the analysis is reduced. This means that communalities will assuredly

be less that 1.0.

The goodness of fit statistics is helpful in choosing the final number of factors to be used (a modification from Klovan and Miesch, 1975). Post-multiplying the factor loadings matrix by the the factor scores matrix approximates the original data matrix. The differences between the original and approximated data are called residuals. The coefficient of determination is an index to how well the factor solution reconstruction approaches the original data and ranges from 0 (poor reconstruction) to 1.0 (perfect reconstruction). If, for example, five eigenvalues account for the specified amount of variance (say 95%) the means and standard deviation of the residuals and a coefficient of determination is calculated for each variable in a two, three, four, and five factor solution. Inspection of this information also helps decide how many factors should be needed.

After the factors, or new orthogonal axes, are defined, it is possible to futher simplify the relationship of the sample data to these new axes (factors). This can be achieved by rigid rotation of the factor axes to new positions so that most of the data may be confined inside the space defined by the axes. After one specifies the desired number of factors, CABFAC discards the extra axes and rotates the specified number of reference axes to coincide as closely as possible to the sample vectors lying at the extremes of the vector configuration. This rotation changes the factor loadings and therefore the communalities. The new communalities are printed to indicate how well the rotated axes have accounted for the sample variance.

In summary, CABFAC does the following:

1. optionally transform the original data matrix
2. compute a cosine Theta (similarity) matrix
3. compute (normalized) principal factor axes (principal factor scores matrix)
4. compute rotated (normalized) factor axes (varimax factor scores matrix)
5. compute varimax loadings matrix (with communalities)
6. compute composition loadings and scores matrices (Klovan and Miesch, 1975)

QMODEL Program

The program QMODEL (Klovan and Miesch, 1975) was written to extend the capability of the CABFAC program. First, CABFAC was modified to transfer data for input to QMODEL, and to calculate composition scores, composition loadings, and goodness of fit statistics. Because most geologic data has constant row-sums, Miesch (1976) was able to determine the composition of the factors (factor composition scores matrix) in the original units of measurement of the variables and compute composition loadings expressed as true proportions rather than normalized factor loadings. These improvements enable the user to easily interprete the factor analysis model and to attain a plausible simplification of the data.

QMODEL also provides several choices of end-members to be used. The reference axes may be: the principal or the varimax factor axes; samples of extreme normalized composition (oblique projection); samples of extreme raw composition; other arbitrary, real, or hypothetical samples. These options are most valuable if the data set does not include samples close to known or suspected end-

members. Specifying different reference axes is a helpful tactic used to eliminate negative compositions.

When samples are chosen for reference axes it is almost certain that the axes will not be orthogonal; only the principal or varimax axes are orthogonal because they evolved from eigen-analysis of a symmetric matrix. Orthogonality of axes means that they are perpendicular to one another in space and therefore unrelated or uncorrelated to one another. Sample axes are then said to be oblique, and are therefore somewhat related; for most geologic applications this mathematical "defect" is of no great concern. In this study, oblique axes are used, based on samples of extreme normalized composition.

QMODEL takes the output from CABFAC and provides a composition loadings matrix (the amount of each factor in every sample), the factor scores matrix (composition of the reference axes), an estimated raw data matrix (by multiplying the previous two matrices), and goodness of fit statistics.

EXQMODEL Program

A realistic solution to most geologic mixing problems requires positive compositions of samples and end-members. This constraint is not often met even with oblique solutions; if a "true" end-member does not exist in the data, then determining a hypothetical sample composition that will extend factor space to include all data (and therefore insure positive values) is a real problem for large data sets with four or more end-members.

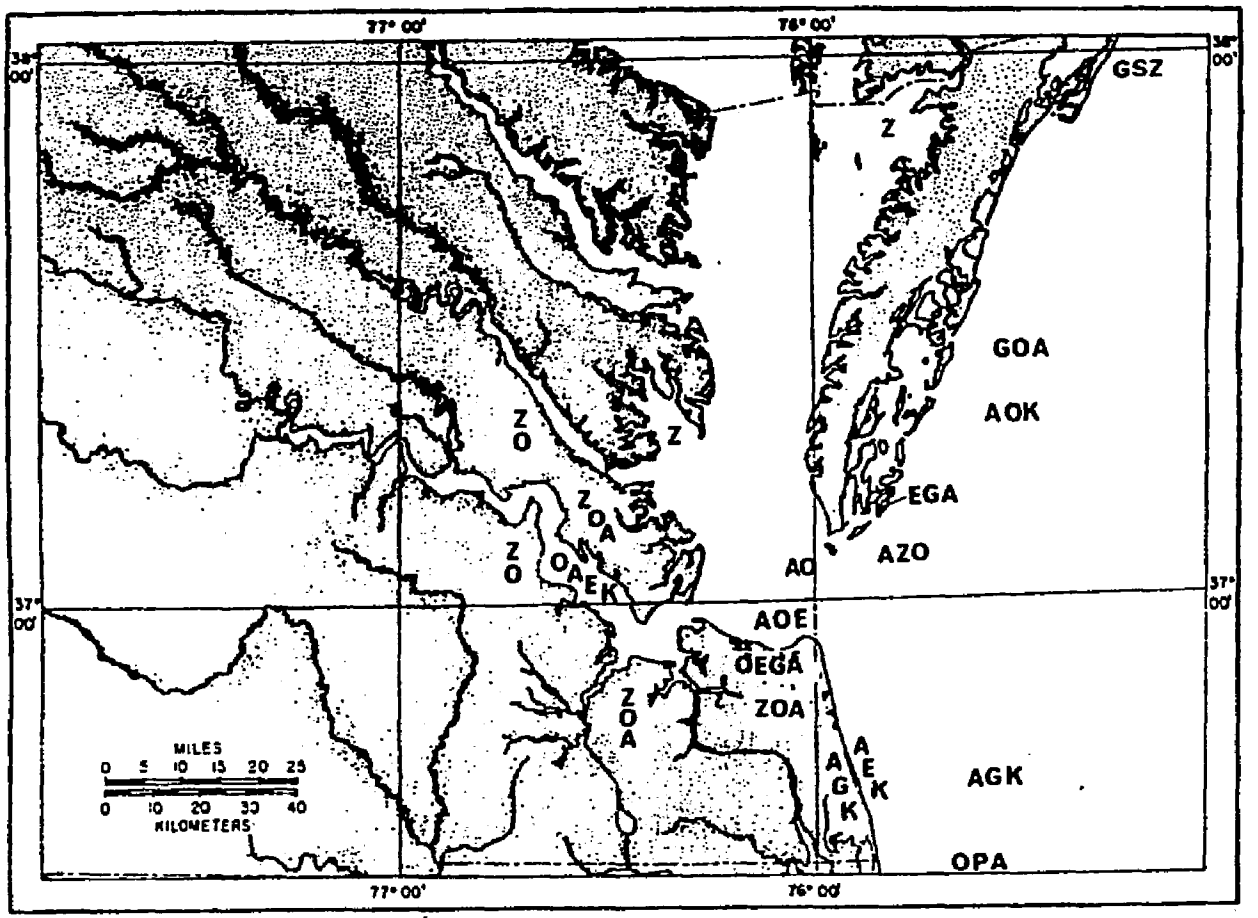
Full and others (1981) revised the QMODEL program to eliminate negative compositions. The resultant program was called EXTENDED QMODEL or EX-QMODEL. Through an iterative process, the outer surfaces of the factor space are moved outward to capture and enclose all data. In the end, some new end-member compositions will be specified because the apices of the factor space will also be moved; however, at least one data point will fall on the new surface. The iteration continues for a chosen (10 is default) number of times or until composition loadings are more positive that another specified value (-0.05 is default). Small negative values can be regarded as zero in the final solution. Non-convergence in the iteration could indicate a wrong choice in the number of end-members (Full and others, 1981).

HEAVY MINERALS

Setting

Heavy minerals are so defined because their specific gravities are greater than those of other more common constituent minerals (quartz, calcite, feldspar). Establishment of mineral distributions is valuable not only for gaining insight into stratigraphic problems but also for understanding their potential as an economic resource. A summary of mineral occurrence in the Chesapeake Bay area of Virginia is given in order to review previous work, describe local mineral distribution, and suggest possible source (or sink) mineral compositions. Figure 13 is a geographic depiction of the mineral summary; minerals may or may not be listed in their order of abundance because their representative studies did not make such a distinction.

Because of hydraulic sorting, different concentrations of minerals commonly exist in each size fraction of the same sample. This relationship prohibits making a totally valid comparison of mineral data within a region unless all studies in that area have analyzed minerals from the same grain size interval; unfortunately, a standard size fraction is neither utilized nor established. For example Hubbard's (1977) data clearly displays such complex relationships; garnet and staurolite are more abundant in coarse fractions while zircon is more abundant in the fine fraction. This shortfall must be kept in mind while making conclusions from the mineral summary (Figure 13 and following discussion).



A = amphibole
E = epidote
G = garnet
K = kyanite
O = opaque
P = pyroxene
S = staurolite
Z = zircon

Figure 13.
Summary of abundant minerals from previous studies in southeastern Virginia. No order of abundance is implied.

Pliocene and Pleistocene Sediments

There are few detailed heavy mineral studies of ancient sediments in the Virginial Coastal Plain. Coch (1965) determined the abundance of several minerals in six different coastal plain formations. These data are compiled by Goodwin (1967). Because of stratigraphic correlation differences between Coch's (1965) units and those presently used, (Peebles and others, 1984; Berquist and others, in preparation; Richmond and others, in press) the stratigraphic origin of Coch's samples is uncertain; therefore, his original values have been averaged across all units. Table 2 shows the results.

TABLE 2

Average composition of heavy minerals in Pliocene- Pleistocene Sediments, Southeastern Virginia, adapted from Goodwin (1967) (values assumed to be weight percent).

	lowest value	highest value	average
zircon	5.9	17.2	11.0
staurolite	0.25	6.0	3.4
hornblende	0.0	16.0	4.3
kyanite	1.3	3.7	2.4
rutile	0.25	3.0	1.3
epidote	0.25	4.0	1.4

This table shows that zircon is the most abundant mineral (of those listed) in ancient sediments in a part of the Tidewater area. This is consistent with the

notion that weathering has removed the less resistant minerals. (There are many different lists of heavy mineral stability. Zircon, tourmaline and rutile are commonly regarded as the most resistant to weathering while hornblende, garnet and augite are usually found to be least resistant.) Rutile is probably supplied in low concentrations although it is one of the most stable minerals (Giles and Pilkey, 1965; Morton, 1982). No size range is specified for Coch's (1965) study.

A regional study by Force and Geraci (1975) shows fairly high concentrations of ilmenite in southeastern Virginia. Their analysis was done without sieving and methylene iodide (s.g. = 3.3) was used to make initial mineral separations. The non-economic middle-density minerals were eliminated because this work was concerned only with the more valuable minerals. A detailed analysis of heavy minerals in each coastal plain formation is needed to adequately characterize ancient sediments by mineral data; some of this existing information is proprietory.

James River Sediments

Goodwin (1967) showed considerable variation of mineral composition both along and across the bottom of the James River from Richmond to north of Willoughby Spit. Because of landward bottom currents and other complex estuarine circulation within the James, the trends of abundances of several minerals on the shallow flats are opposite to trends in the channel, so regional variations are not clear; however, hornblende concentration decreased slightly downriver.

Table 3 summarizes the overall mineralogy within the James. This study compliments and surpasses in detail the mineral data of Stow (1939). Nichols

(1972) also refers to Goodwin's work and concluded that staurolite concentration increased seaward while kyanite and sillimanite decreased seaward.

TABLE 3

Average Composition of Heavy Minerals in the James River Estuary, Adapted from Goodwin (1967).

	lowest value	highest value	average
zircon	tr	9.0	4.6
staurolite	0.0	6.0	2.7
hornblende	tr	32.0	16.0
kyanite	tr	11.0	5.4
rutile	tr	4.0	2.0
epidote	1.0	13.0	5.6
sillimanite	tr	6.0	3.0
opaque	21.0	64.0	47.4

Atlantic Shelf and Beach

Hubbard (1977) examined the heavy minerals in a washover fan from northern Assateague Island, Virginia. These data showed abundances of selected minerals from 1.5 to 3.0 Phi in 1/4 Phi intervals. Concentration of garnet and staurolite decreased as grain size decreased; zircon concentration increased with diminishing grain size. The most abundant minerals in this report area were garnet, staurolite, and zircon with lesser amounts of rutile, tourmaline and hornblende (no order implied).

Johnston (1985) examined the vertical variability of minerals from two cores on Smith Island of the Eastern Shore, Virginia. He showed that the changing

depositional environment shown in the cores correlated with the vertical change in mineral compositions. The sediments were characterized by an epidote-garnet-hornblende suite from the 2 to 3 Phi fraction. Swift and others (1971) showed three well-defined provinces of minerals paralleling the Atlantic coast from Cape Henry toward Cape Hatteras from the 2 1/2 to 3 1/2 Phi fraction. An amphibole-garnet-kyanite suite characterized the beach and offshore while amphibole-epidote-kyanite defined the nearshore zone. Towards the south, garnet and opaque mineral concentrations increased while amphibole abundance decreased.

Giles and Pilkey (1965) studied the mineral composition and texture of beaches and dunes from North Carolina to Florida. For North Carolina, the most abundant minerals (from the 2 to 3 Phi fraction) in both environments were hornblende, garnet, sillimanite, epidote and staurolite.

Pilkey (1963) showed high concentrations of garnet, kyanite and rutile (less that the 2 Phi fraction) on the shelf of North Carolina. However, average mineral composition on the shelf in decreasing abundance was opaques, pyroxenes and amphiboles, epidote, staurolite, and garnet.

Flores and Shideler (1978) attempted but failed to differentiate between beach and dune sediments along the Outer Banks of North Carolina by using discriminant analysis on the 3 to 4 Phi fraction of heavy minerals. In decreasing abundance, an overall average concentration was opaques, garnet, amphibole, sillimanite, zircon and epidote.

Goodwin and Thomas (1973) found dominant concentrations of garnet, magnetite-ilmenite, hornblende, and epidote on the shelf between Assateague Island and the Chesapeake Bay mouth. It is important to note that the data from

this study was the basis for the current interest in offshore heavy minerals. Grosz and Escowitz (1983) found amphibole, ilmenite, sillimanite/kyanite, and staurolite in decreasing abundance from approximately the same area. Hornblende, zircon, and ilmenite in decreasing order of abundance were found on the shelf about 5 nautical miles east of Smith Island and within a few nautical miles of Wachapreague and Quinby Inlets (Berquist and Hobbs, 1986). In these reports the heavy minerals were examined from the entire size range of the sample.

Lower Chesapeake Bay

Meisburger interpreted the tabulated heavy mineral data from Ryan (1953). He observed that hornblende, chlorite and black opaque concentrations (2 to 3 Phi fraction) were higher in the Bay entrance area compared to the rest of the Bay. He thought this distribution was evidence of a seaward origin for at least some material in the lower Bay.

Delong (1985) compared heavy minerals in the 2 to 3 Phi fraction with the 3 to 4 Phi fraction along a traverse normal to the shoreline at Seashore State Park. Mineral abundance changed with environment (station) along the traverse as well as between fractions at the same station. Overall, the four most abundant minerals were opaques, epidote, garnet, and hornblende.

Firek's (1975) detailed work provides a key step in understanding the distribution of heavy minerals in the lower Bay. Although her arbitrarily defined provinces are not "natural" or real, some of her mineral associations are meaningful and are replicated, in part, by this study. The factor plots shown earlier in this

study (Figures 7 and 8) mimic her isopleth maps of zircon, hornblende, and garnet concentrations; access to her data enabled the author to define more "natural" provinces via Q-mode factor analysis.

Mobjack Bay and Pocomoke Sound were characterized by high zircon concentrations (40% to 50% of the heavy mineral fraction) with lesser amounts of tourmaline, staurolite, epidote, and hornblende (Mittwede, 1981). The Mobjack Bay samples showed some agreement with the western shore province (zircon-epidote-staurolite...) of Firek (1975). He analyzed the 3 to 4 Phi fraction.

Myers (1984) studied the vertical variation of heavy minerals (2 to 3 Phi fraction) in two cores from the lower Chesapeake Bay. His eastern core was located in an area of net landward non-tidal flow (Ludwick, 1970) and his western core was in an area of net seaward non-tidal flow. Hornblende, opaques and epidote were generally the most abundant minerals throughout both cores. Considerable mineral variability prohibited interpretation of trends; chlorite concentration, however, increased toward the top of both cores. The mineralogy from both cores did not correspond to Firek's provinces, but placed well inside a hornblende-epidote province defined by Q-mode factor analysis (pilot study) of this dissertation.

The abundance of unstable minerals (amphibole, epidote, kyanite, staurolite) is a characteristic of the shelf, beach, and Bay entrance areas (Figure 13); their lack of abundance is noted in pre-Holocene sediments (Table 2). This suggests that weathering (intrastratal solution) may be responsible for such variation between Pleistocene and Holocene sediments, similar to the findings by Carver and Scott (1978) in the Georgia Coastal Plain. North Carolina beach and dune

mineralogy closly resemble piedmont rivers (Giles and Pilkey, 1965). Futhermore, several studies demonstrate little loss of heavy minerals by abrasion during transport (Morton, 1982).

Methods

Sample collection

Samples for this study were taken from cores provided by VIMS (Byrne and others, 1983) and the U.S. Army Corps of Engineers, Norfolk District (1986). Meisburger provided samples (Meisburger, 1972) as the original cores used in his study were not available at the time needed. Appendices A and B contain the description and locations of cores; Appendix C shows where samples were taken from within each core.

Several criteria determined the choice of cores used in this study. First, those cores which contained sandy Holocene sediments were identified. Any cores which contained excessive muddy intervals or which were suspected of being located in dredge spoil areas were eliminated. Second, the locations of cores were required to define two cross-sections oriented roughly east-west from the Hampton area to outside the Chesapeake Bay mouth (Figures 3, 5, and 6). Third, preference was given to cores which included a basal contact with Tertiary sediments.

Each core was described (Appendix A) and samples were carefully taken only from fine sand intervals. A minimum of six samples from each core were

selected where possible to provide even distribution over the thickness of Holocene sediments and to enable the detection of vertical changes in mineral composition. Grain size data was obtained by seiving at 1/2 Phi intervals; the 3 to 4 Phi fraction was washed and dried; heavy mineral concentrates were acquired by the filter-funnel method using tetrabromoethane (s.g.= 2.96). Use of a Magnetohydrodynamic mineral separator was deferred because of time constraints. Sample compositions and statistics are tabulated in Appendix D.

Reduction of Unwanted Mineral Variation

Mineral availability and "progressive sorting" are two major processes controlling heavy mineral populations in sediments (Rubey, 1933; Rittenhouse, 1943; Lowright and others, 1972; Luepke, 1984). Composition of source rocks, weathering, intrastratal solution, and abrasion affect mineral availability; physical differences between grains such as density, size, and shape enable selective transportational and depositional mechanisms to progressively sort mineral populations. Clearly, the total heavy mineral composition of a sample is the result of many processes. It is yet an impossible task to attribute any part of the abundance of a mineral to any of the above processes.

One way to mitigate the contribution of unwanted variance in provenance studies is by sampling only a narrow size range from cores or outcrop and then by analyzing a narrow size range of the sample for mineralogy (Carver, 1971; Rubey, 1933; Morton, 1982). This suggestion was incorporated into my sampling procedure

as previously described. After mineral abundance and the overall size distribution of the original sample was determined, correlation of mean grain size with the abundance of each mineral indicated the extent to which size-sorting affected a mineral's variability. Correlation can be done arithmetically and/or with scatter plots as shown by Firek (1975), Flores and Shideler (1978), and Swift and others (1971).

In this research I have attempted to reduce the mineral variability due to weathering or intrastratal solution by examining only the Holocene sands because these deposits contain high concentrations of unstable minerals (Figure 1). Firek (1975) has shown that there was little correlation of garnet, zircon, pyroxene, and hornblende with grain size in the lower Bay. Because size-sorting was minimized by sampling techniques, then only the mixing of material from various sources caused most of the mineral variability in the study area. The authenticity of the factor plots (Figures 7 and 8) offers further encouragement that undesirable variance was reduced. Table 4 shows there is little correlation (Pearson) of mean grain size to mineral abundance for samples analyzed in this study. Computer programs from Davis (1985) were used for obtaining the values in Table 4.

TABLE 4

Correlation of mean grain size with mineral abundance for 85 samples used in this study.

mineral	r^2
zircon	-0.36
hornblende	0.40
epidote	-0.26
pyroxene	0.21
garnet	0.26

Determination of Mineral Abundance

Firek identified and determined the abundance (number frequency) of minerals in the 3 to 4 Phi size range by using grain mounts and the line method of point-counting. The number frequency cannot be used statistically because the line method preferentially excludes counting smaller grains in the sample. Number percentage can be used statistically because all grains are counted within a defined area regardless of grain size and comparison among samples is theoretically valid. The discrepancy between data obtained by the two methods can be reduced by restricting samples to a narrow size range (Galehouse, 1969). Firek used this relationship to her advantage.

A procedure which was suggested by Andrew Grosz and Eric Force of the U.S. Geological Survey was slightly modified for use in this research. The heavy mineral sample was weighed and magnetite and magnetic ilmenite was removed with a hand magnet. Five additional splits of the sample were made by successive passes through a Frantz Isodynamic separator (with forward slope at 30 degrees and side slope at 20 degrees, 0.4, 0.8, and 1.2 amperes current; forward slope at 30 degrees and side slope at 5 degrees, 1.2 amperes current). Each of the six splits was weighed; minerals were identified and their abundances were estimated under a binocular microscope. Final composition in weight percent was calculated as shown in Figure 14. It was shown that visual estimation of percentages is unbiased under varied conditions and can be used to estimate true abundance (Dennison and Shea, 1966); error is less than 10 percent (A. Grosz, personal communication). My

method differed from that used by the U.S.G.S. in that I restricted the analysis to the 3 to 4 Phi size fraction (0.125 to 0.0625 mm) for reasons mentioned above.

An example of the calculation of mineral abundance for sample 61-9 is shown in Figure 14. Weights are recorded at the top of the columns for each Frantz split. Each of these splits is examined and the proportion of selected minerals is estimated. In the 0.4 ampere fraction, 60% of the minerals are ilmenite and 30% are garnet; unidentified or non-essential minerals make up the remainder of the fraction. The weight of garnet in this fraction is then 30% of 0.0462 grams, or 0.0139 grams. Because the Frantz separator isolates some but not all minerals with one current setting, minerals appearing in subsequent fractions can be totaled by their weight. The 0.8 ampere split contained 20% garnet, or 0.0602 grams. The total weight of garnet in the sample is found by summing along the garnet row and is shown to be 0.0761 grams. This weight divided by the total weight of required minerals gives the weight percent of garnet in this sample (0.0761 / 0.3411 = 22.3%) relative to the abundance of the required minerals.

SAMPLE 61-9

hand magnet fraction, weight 0.0235

	0.4a	0.8a	1.2a	1.2a5	nonmag	wt.SUM
fract wt	0.0462	0.3012	0.0157	0.0196	0.0315	
mineral						
il %	60					
wt	.0277					
gar %	30	20		10		
wt	.0139	.0602		.0020		.0761
hbld%		40				
wt		.1205				.1205
cpx %			60			
wt			.0094			.0094
star %		5	10			
wt		.0151	.0016			.0167
ep %		30				
wt		.0904				.0904
sphn%				20	5	
wt				.0039	0016	.0055
zr %				10	65	
wt				.0020	.0205	.0225
						.3411

Figure 14. Example of mineral data sheet and calculation of mineral abundance.

MHS Construction and Separation Principles

While the author was collecting core data from the U. S. Geological Survey, Andrew Grosz (USGS) demonstrated a new instrument for separating heavy minerals. This device, a magnetohydrostatic (MHS) separator, was developed by the USGS (Alminas and Marceau, 1982, Alminas and others, 1984) following experimental work by Andres (1976).

Andres (1976) coined the term MHS and MHD (magnetohydrodynamic). MHD separation involves the use of magnetic and electric fields and a conducting fluid. MHS separation requires a magnetic field and a paramagnetic fluid (a fluid which responds to a magnetic field).

The MHS separator designed by Alminas provides the equivalent of an instantly variable (non-toxic) heavy liquid, which ranges in density from 1.4 to about 9.0. This is achieved because when a paramagnetic fluid is placed in an inhomogenous magnetic field its apparent specific gravity will be proportional to the strength of the surrounding field. The magnetic poles of the MHS separator are wedge-shaped, so there is a gradient of magnetic field strength which decreases away from the area of maximum constriction. The fluid exhibits a corresponding specific gravity that is greatest where the pole separation is the narrowest and decreases upward as shown in Figure 15. The liquid is a saturated solution of manganese chloride ($MnCl_2$).

The response of a mineral in this environment depends on its magnetic susceptability (X) and density. Non-magnetic minerals are affected only by the

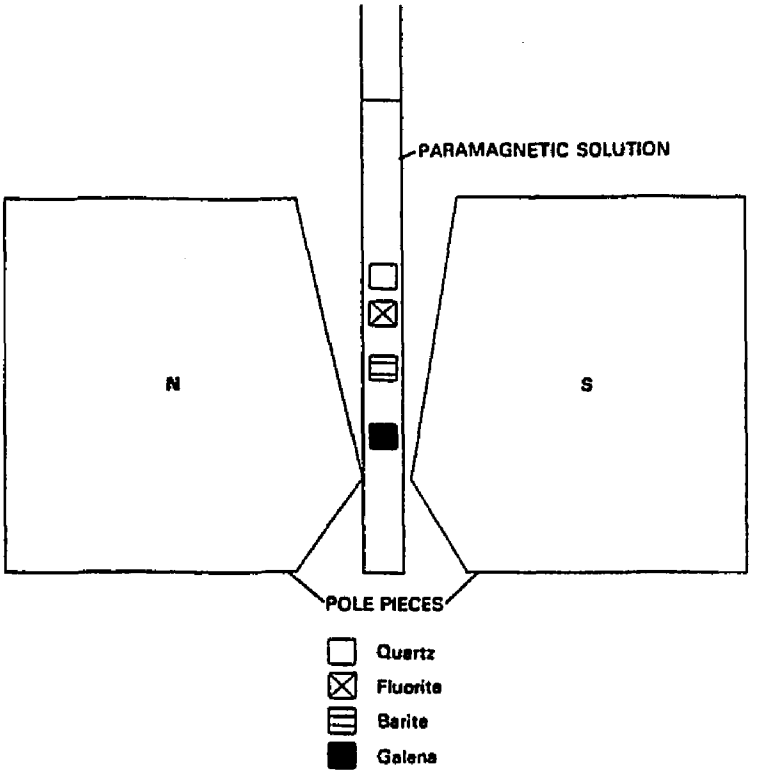


Figure 15. Relative height of suspension of grains of quartz, fluorite, barite, and galena in a paramagnetic solution within a magnetic field gradient (from Alminas and others, 1984).

"effective" specific gravity of the solution, thus they will float at different levels within the magnetic field, the less dense minerals floating higher than the more dense minerals. Paramagnetic or "somewhat magnetic" minerals respond to both the changing "effective" density of the liquid and the magnetic field strength. Minerals with a high X are pulled lower in the liquid or further into the field than minerals with a lesser X. Magnetic minerals are simply pulled out of solution by the electromagnet. This combination of gravitational and magnetic forces offers a new means of mineral separation.

Figure 16 is a diagram showing the flow of minerals through the MHS separator as designed by Alminas. Particles can fall through the system by gravity

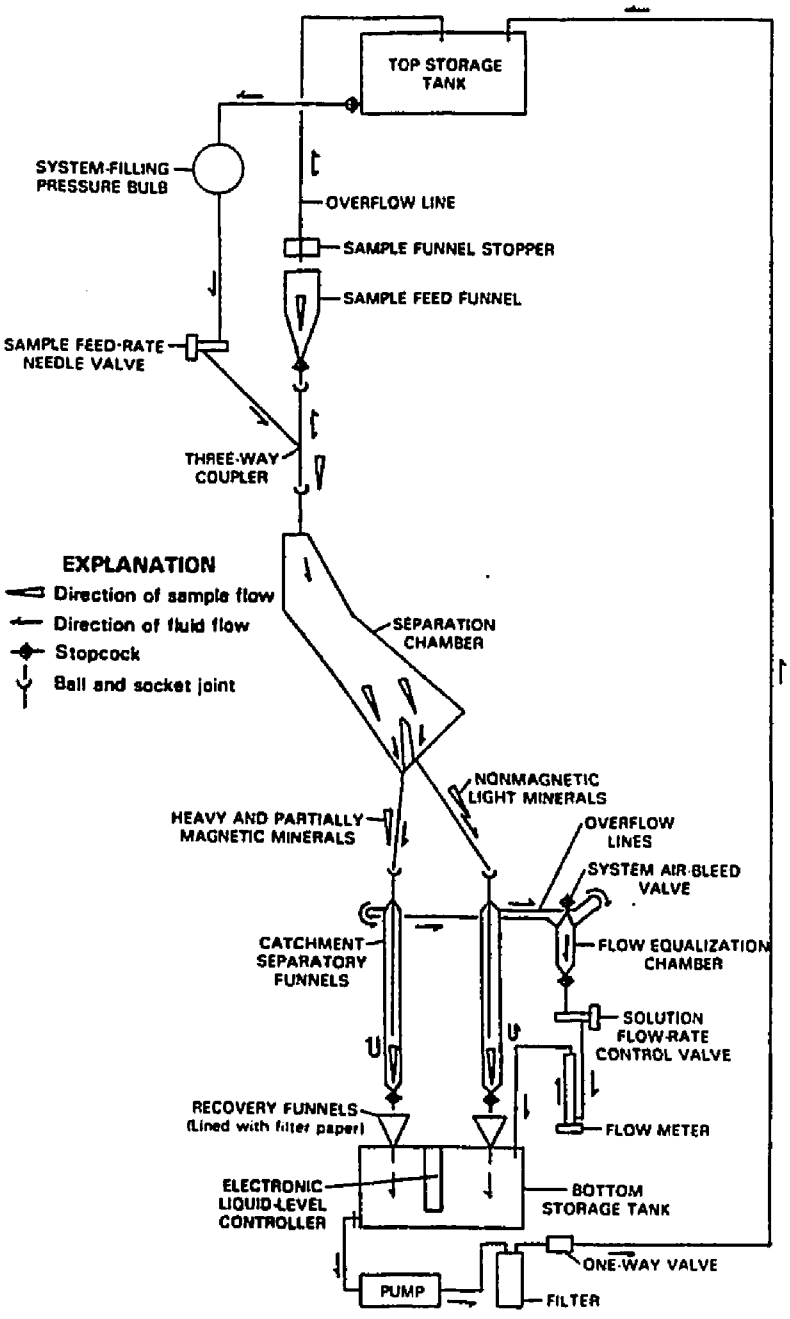


Figure 16. Schematic diagram of the MHS separator (from Alminas and others, 1984).

alone, or the speed of the process can be increased (with some loss in separation precision) by allowing the fluid and minerals to flow through the system.

In 1984 the author and Dr. John Boon were awarded an NSF grant and a similar instrument was built. The MHS separator was constructed by the author, except for the glassware and separation chamber which was built by contracted services. A Frantz Isodynamic separator belonging to the Geology Department of the College of William and Mary was modified to provide the magnetic field. Andrew Grosz (USGS) loaned spare parts which were used during initial tests of this instrument. Several improvements were incorporated into the final design. Preliminary results are shown in Table 5. For separating into light and heavy mineral fractions, splits of the same sample were used by both MHS and tetrabromoethane methods; the results did not compare well because turbulent flow in the MHS instrument caused quartz contamination of the MHS heavy mineral fraction. However, the MHS instrument did separate glauconite, wheras the tetrabromoethane method left glauconite in the light mineral fraction; The specific gravity of glauconite ranges between 2.4 and 2.8 but it is also somewhat magnetic.

At the time of writing, a decision was made to use tetrabromoethane for separating light and heavy minerals for this study. A substantial amount of time was spent on construction, testing and improving the design of the MHS separator. The instrument made pure separations when the operator was attentive to maintaining low turbulance. The additional time and patience required of the user reduced the time-efficiency of this method. The author is encouraged by the present results and is optimistic that the few remaining engineering problems will be solved. Because continued work with this instrument goes beyond the scope of this research, present efforts with this instrument will be temporarily suspended.

TABLE 5

Response of selected minerals to MHS separation: threshold current is noted when some grains became suspended in the upper chamber; minimum current is specified when most all grains are suspended in the upper chamber; these two values are different because some monomineralic samples are of variable composition or contain impurities. NR means no response of the mineral to the magnetic field was noted; the mineral flowed into the lower chamber.

mineral	PHI size	threshold current (amps)	minimum current (amps)
apatite	2-3	0.6	0.92
augite	2-3	NR	NR
calcite	3-4	0.5	0.75
cassiterite	2-3	NR	NR
chloritoid	3-4	NR	NR
corundum	2-3	NR	NR
diopside	2-3	1.0	1.6
enstatite, Fe	3-4	0.8	1.6
enstatite, Mg	2-3	NR	NR
epidote	2-3	NR	NR
garnet, almd.	2-3	NR	NR
garnet, and.	3-4	NR	NR
hornblende	2-3	NR	NR
hypersthene	3-4	1.1	1.3
ilmenite	2-4	NR	NR
kyanite	2-3	0.7	1.25
lepidolite	2-3	0.7	0.95
leucoxene	2-3	NR	NR
microcline	3-4	0.5	0.75
monazite	2-3	NR	NR
rutile	2-3	0.8	1.25
sillimanite	3-4	0.65	0.9
sphene	2-3	0.8	1.2
spinel	3-4	NR	NR
staurolite	2-3	0.9	1.6
tourmaline	2-3	NR	NR
zircon	2-4	0.9	1.07

RESULTS AND DISCUSSION

Factor Analysis

Procedure

Mineral data from 86 samples from cores used in this study were combined with Firek's data in the lower Chesapeake Bay to form a data matrix of seven variables (minerals) and 173 observations (samples). Results of the pilot study indicated that seven minerals would adequately explain most of the variance in the initial 18-variable data matrix. Figure 3 shows the location of the combined data used in this analysis.

Factor solutions with two, three and four end-members resulted in high negative factor compositions. A second data matrix was constructed by eliminating sphene and staurolite as compositional components. The rational for excluding these minerals was based on two facts: the coefficients of determination of these minerals in the QMODEL program were extremely low and they accounted for only 2.9% additional variance according to principal components analysis (from the pilot study).

Factor analysis specifying two, three and four end-members was run using the five variable matrix. The two-factor solution was rejected because only 76% of the variance was explained, and the coefficents of determination were low for epidote, pyroxene and garnet. In addition, the sample compositions (factor loadings) were interdependent; as loadings on one factor increased, the loadings on the other factor necessarily decreased. It was thought that this dependency would

hide any significant composition gradients in the Bay sediments. A four-factor solution was rejected because it gave high negative factor scores, and plots of composition gradients showed no meaningful patterns.

A three-factor solution using both data matrices (five and seven variables) accounted for about 91% of the variance. Coefficents of determination markedly improved over the two-factor solution. The EXQMODEL program selected the same samples for end-members from both data sets, and the composition of the end-members were comparable. A final solution using the five-variable array was selected because the solution gave the least negative compositions (only one factor had one negative variable). The average mineral abundance for all samples (in weight percent) was: 40% amphibole, 18% zircon, 16% garnet, 13% epidote and 13% pyroxene. Table 6 gives the end-members and their compositions from the final solution.

TABLE 6

Compositions of end-members from the three-factor solution on combined data.

FACTOR 1	FACTOR 2	FACTOR 3
sample 124	sample 63-7	sample 61-5
64% amphibole	64% zircon	68% garnet
28% pyroxene	21% epidote	23% amphibole
7% epidote	7% amphibole	19% epidote
	7% pyroxene	-11% pyroxene

Althought different samples were selected as end-members, these compositions were similar to the results of the pilot study. Some actual end-members which contributed to the composition of the samples were probably not represented in the data set; some real sources were probably outside the study area. It is expected that slightly different end-members would be found with the additions of data and so the single negative pyroxene composition was not a significant problem.

Composition Plots

Figures 17, 18, and 19 are contoured plots of composition loadings on each factor from the final solution (combined data, five variables, three-factor solution). Factor 1 is composed mainly of amphibole and pyroxene. Alone, the surficial gradients of composition loadings on this factor (Figure 17) are difficult to explain in terms of real sediment transport. Without the high concentrations in the central Bay, it may appear that the shoreline areas are contributing material to the Bay. Factor 1 may contain much of the "residual" or unexplained variance in this particular solution, and so the plot may not represent any specific geologic process. Often the first factor does not reveal much about the structure of the data and is ignored (Davis, 1986). Alternatively, amphibole and pyroxene may be very common to all samples because of sediment mixing throughout the lower Bay; in this case a particularly strong gradient may be absent as the minerals would exist nearly everywhere in equal abundance. Although there may be some real significance to the gradients of this factor, it is likely imbedded in or confused by

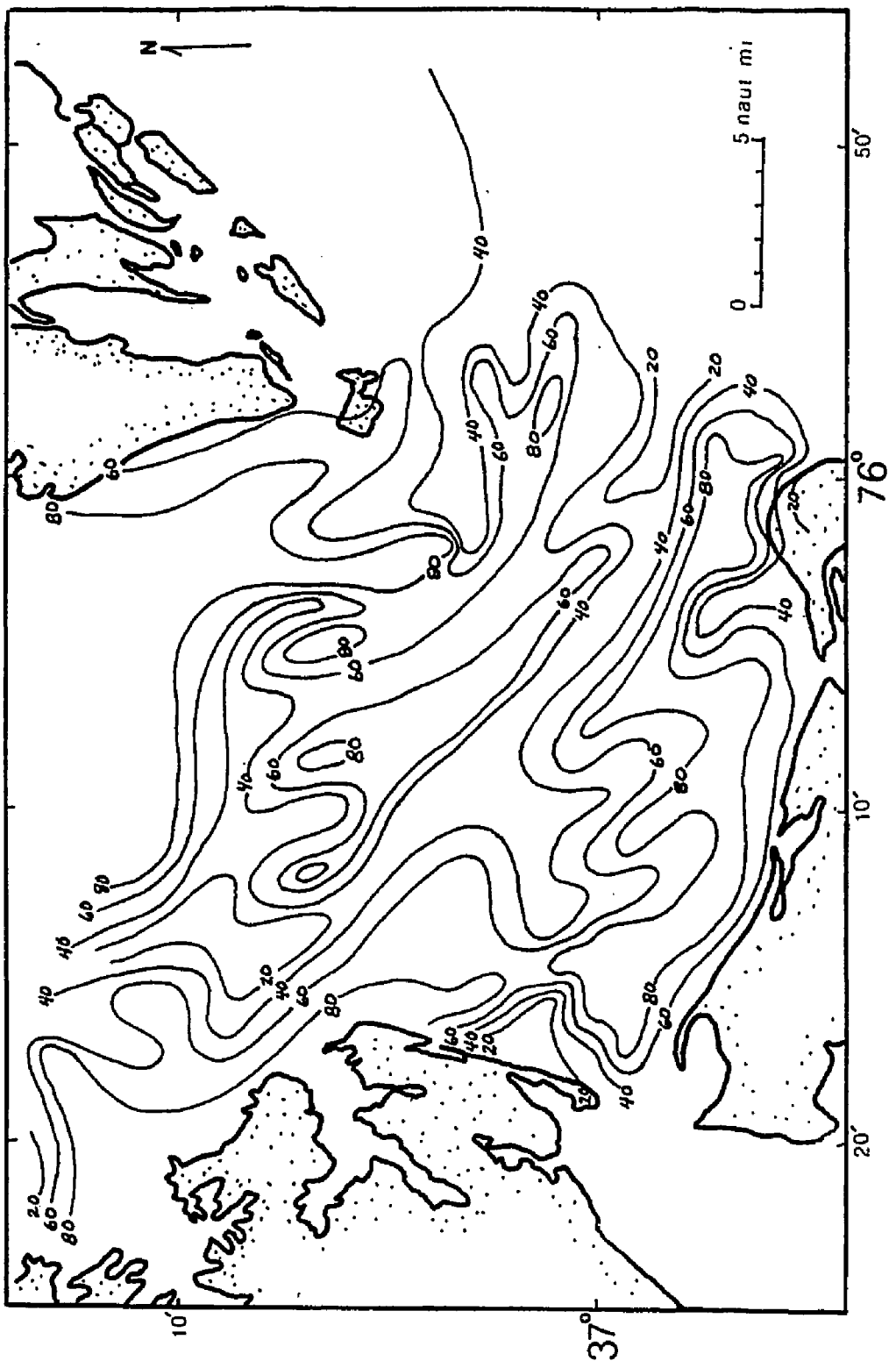


Figure 17. Contour map of sample composition loadings on Factor 1 (final solution).

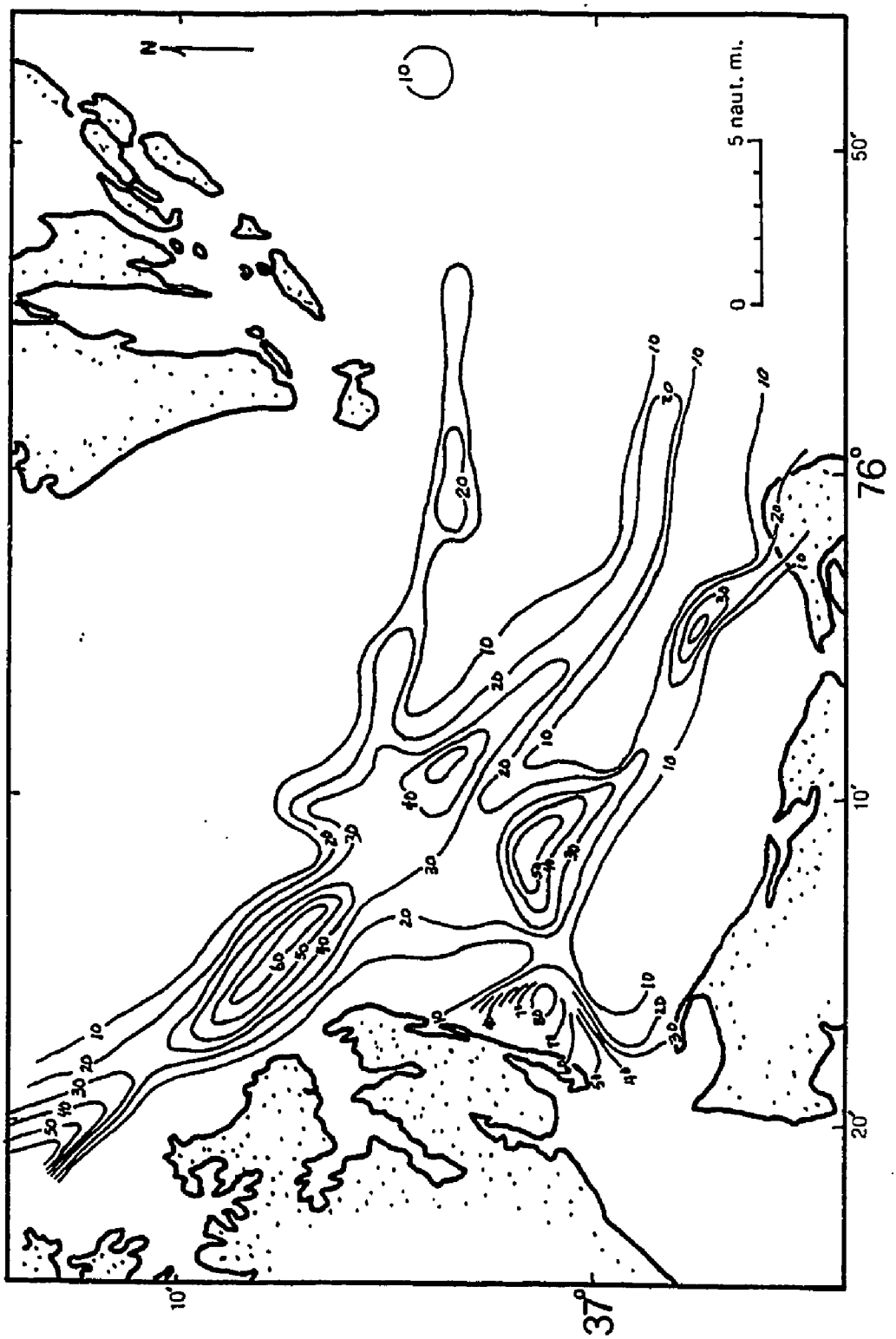


Figure 18. Contour map of sample composition loadings on Factor 2 (final solution).

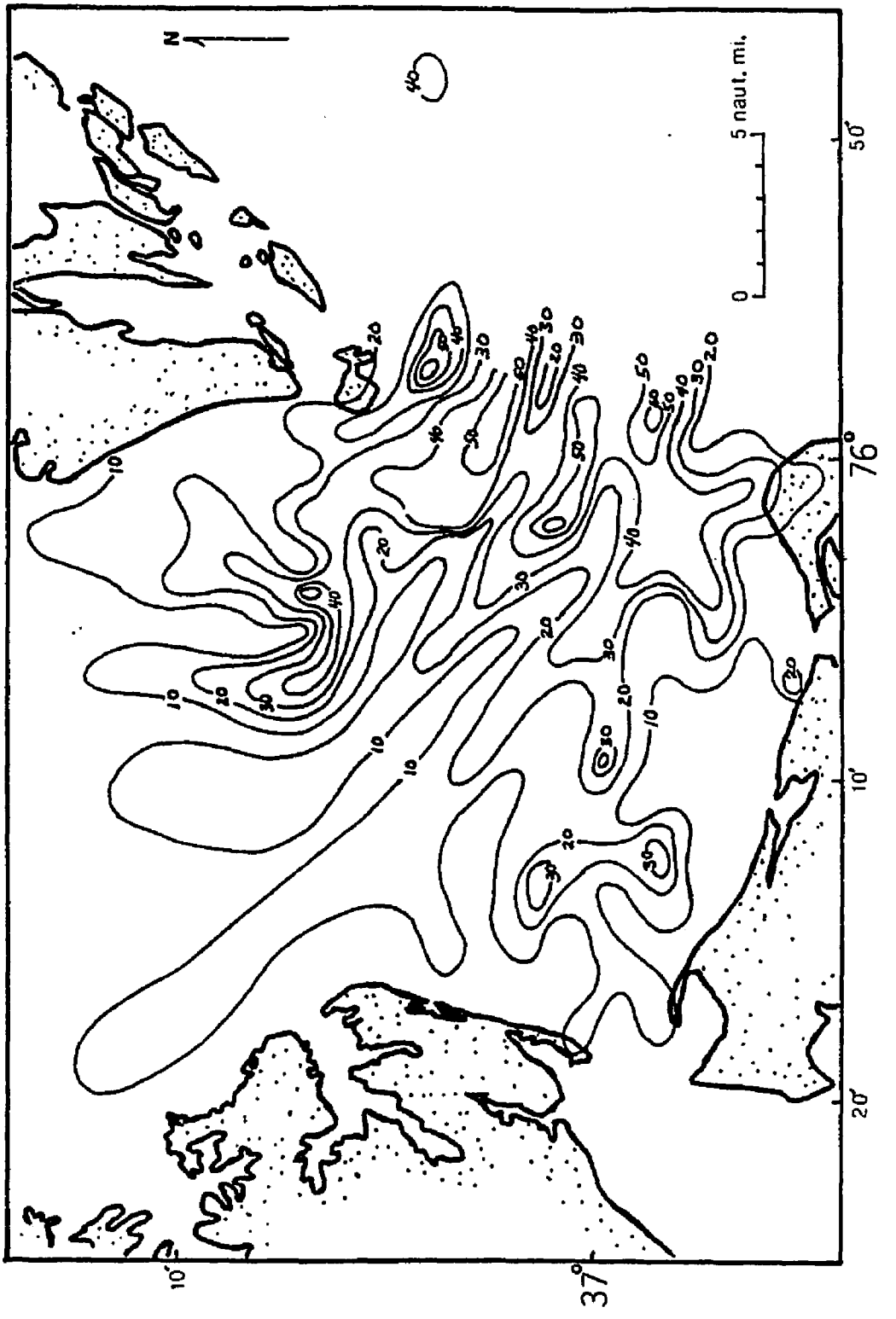


Figure 19. Contour map of sample composition loadings on Factor 3 (final solution).

residual variance. The patterns of Figure 17 are similar to those of an additional factor of comparable composition (not shown) from the pilot study.

Factor 2 (Figure 18) is composed primarily of zircon and epidote. The composition and gradient pattern is similar to factor 3 of the pilot study. The interpretation is also the same; sediment from land or an older source which was enriched in resistant minerals by weathering is being diluted seaward. Although mean bottom currents are not known for most of the lower Bay, the gradient suggests seaward movement of material in discrete pathways. There does not appear to be any correlation between the pathways and bathymetry (or channels).

Factor 3 is composed mostly of garnet, amphibole, and epidote, and is similar in mineralogy and distribution to factor 2 of the pilot study. Figure 19 (and Figure 7) shows that sediment having a seaward source enters the Bay mouth and is diluted landward. Amphibole and garnet are major constituents of shelf sediments (Figure 13); their mutual concentration with respect to Factor 3 decreases into the Bay.

Figure 20 is a plot of composition loadings along the northern transect, cross-section A - A'; Figure 21 shows contoured loadings along the southern transect, cross-section B - B'. These diagrams showing the vertical change of mineral compositions suggest three characteristics of sediment transport in the lower Bay. First, sediment with high concentrations of end-member composition is restricted to tube- and tongue-shaped pathways upon entering or leaving the Bay. This suggests that mean bottom currents responsible for transporting the offshore and western Bay sediments are centralized. Second, because of the tube-shaped pathways, a "wedge" of offshore sediment is not always depicted because the cross-

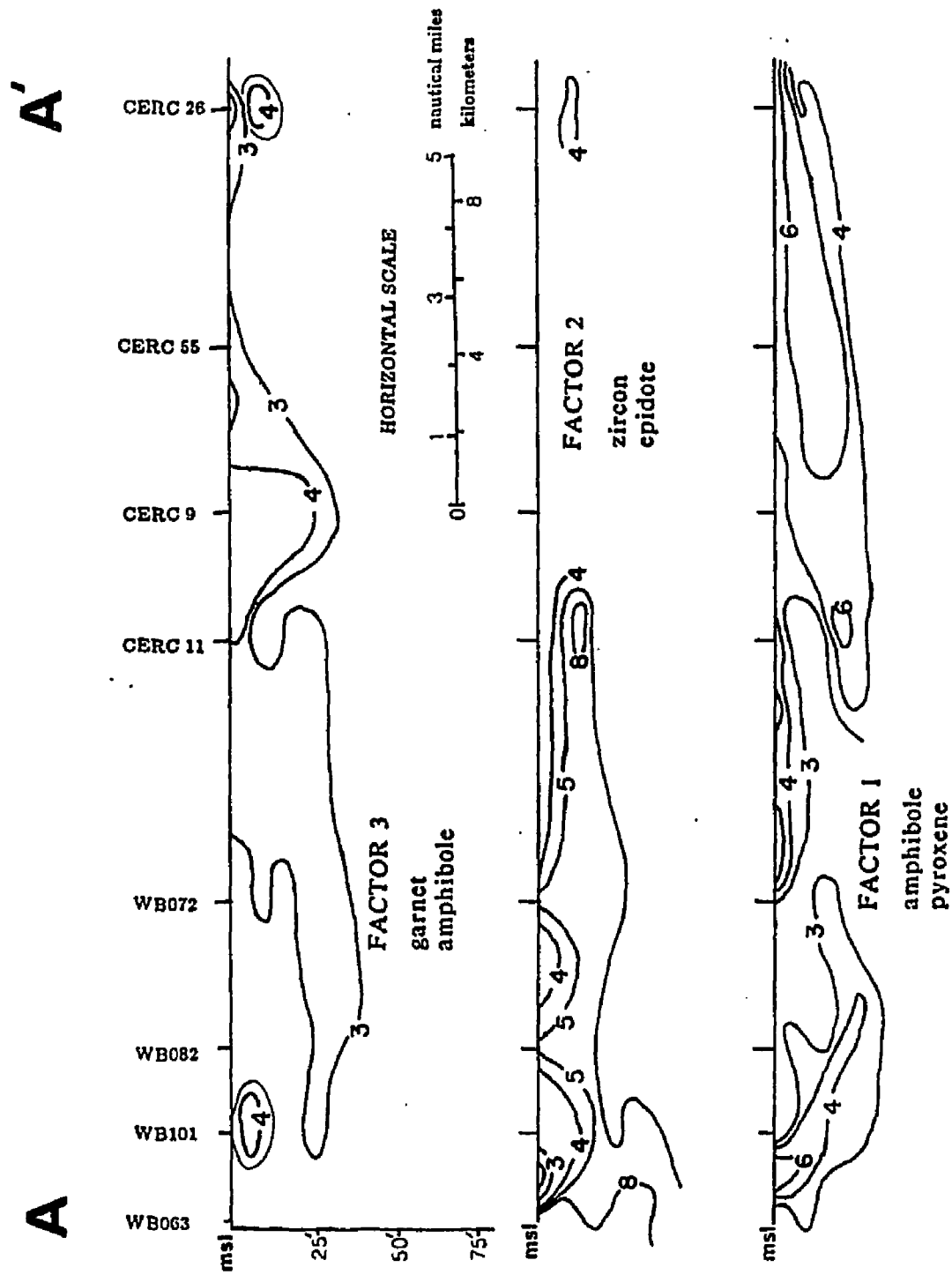


Figure 20. Isopleth of sample composition loadings for cross-section A - A'.

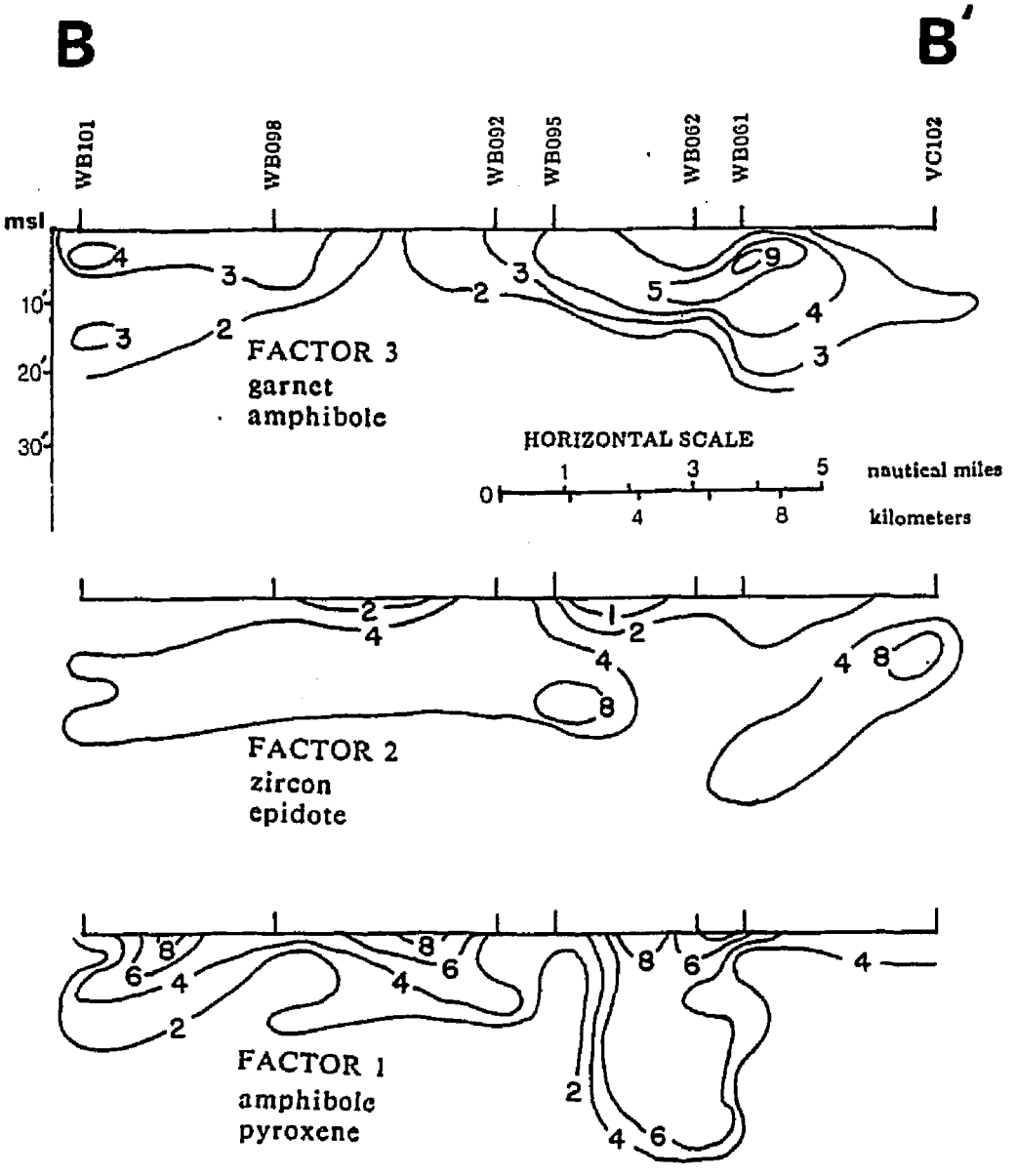


Figure 21. Isopleth of sample composition loadings for cross-section B - B'.

section is not aligned along the "tube". However, high concentrations of landward material (Factor 2 in Figure 20) are shown to exist in a pattern as hypothesized; high zircon concentration is found at depth and decreases upward and seaward in a wedge- or tongue-shaped body. Conversly, the composition of sediment rich in offshore material (garnet, amphibole) decreases downward. Third, the surficial gradients of composition of Factor 1 material (in map view, Figure 17) are problematic, but cross-section plots show that sediment containing high concentrations of amphibole-pyroxene are also in tube- and tongue-shaped bodies. Pyroxene is reported to be a common mineral in shelf sands off North Carolina (Figure 13; Pilkey, 1963). Figure 20 suggests an offshore source, in part, for this material. Without information in the third dimension, any contribution of information from Factor 1 may have been entirely disregarded. It now appears that the shelf could also be a partial source of Factor 1 material.

Data from one land boring (ODU-20) was used in the study because of a lack of deep cores for sampling in the study area. Factor loadings of samples from this core showed little vertical change in value and did not change the cross-section patterns. It was therefore excluded from the cross-section B - B'.

Bottom circulation in the lower Bay is poorly known. Boicourt (1981) shows that the mean flow of bottom currents at the Bay entrance is landward-directed and confined to channels. Ludwick (1970) has a more detailed presentation, but his results may be problematic (Boicourt, personal communication). In any case, surficial composition plots from my study were compared with a map of "an hydraulic and geomorphic interpretation of the net nontidal (residual) flow pattern at the bottom in the entrance to Chesapeake Bay" (Ludwick, 1970, p. 183). It

was presumed that in the Bay entrance, high concentrations of offshore sediment defined by factor analysis would be located in areas of flood-dominant channels, and landward sediment would be confined to ebb-dominant channels. The results of the comparison showed these relationships in several areas, but not in other areas. Some shoals contained samples with high factor loadings; this would not be predicted because the shallow areas were thought to be the result of mixed sediment from ebb and flood currents (Ludwick, 1974). The high values may be anomolous because of some localized processes causing enrichment of heavy minerals.

Conclusions are difficult to draw from this comparison to Ludwick's work for several reasons. First, hand-contoured data is subject to a certain amount of individual bias; more densly-spaced data can reduce this contribution (Berquist, 1970) as well as add sharper detail to the gradients. Contour plots of more closely-spaced mineral and current data are probably necessary to make a valid comparison. Second, my study does not include as many sample sites from offshore as it does from inside the Bay. Were this imbalance corrected, more zircon-rich material may be found offshore. Zircon concentrations are high in some places offshore (Berquist and Hobbs, 1986) and there is no reason to believe that some zircon-rich sediment is not entering the Bay mouth. Third, it is not known if either the sediment samples or data collected for Ludwick's map (mentioned above) were all taken after or during average or less common bottom current conditions in the Bay. The plots (Figures 17 - 21) oversimplify a complicated depositional environment but substantiate prior notions of sediment transport at the Bay entrance.

There are very few guidelines to determine a "correct" or plausable factor

analysis solution to any data set. The gradient patterns in cross-sections and on the Bay bottom are spatially continuous in the final solution; they depict the transport of sediment through the Bay entrance. Furthermore, these patterns are replicated by factor solutions requiring three and four end-members as well as by solutions using different data sets. Other attempted factor solutions are rejected because of mathematical constraints and because the resultant patterns show a random distribution of high and low values; these patterns could not be related to a defensible process of sediment transport.

Plotting the concentrations of an individual mineral may or may not provide the same conclusions as derived from plotting factor loadings. Zircon concentration in the lower Bay is similar to the distribution of the factor 2 assemblage of zircon, epidote, amphibole, and pyroxene. Gradients of garnet concentration are somewhat similar to factor 3 patterns. Plots of other individual mineral compositions do not compare to the factor plots. The determination of significant and natural mineral associations by Q-mode factor analysis displays part of the power of the routine.

Several points need to be discussed regarding the relationship between gradients and sediment transport. The first is the notion that "sources" are represented by areas of high mineral concentrations. Absolute sources would not be known without expanding the study area boundaries and sampling from surrounding older deposits. Similar to diffusion phenomena, minerals are dispersed by currents and moved from a region of high concentration to an area of low concentration (over a broad area); however, localized enrichment of heavy minerals because of currents and bottom morphology may also be possible (Berquist and Hobbs,

1986).

The second point deals with the shape of gradient patterns. Pathways of sediment transport are determined by prevailing currents; both pathways and currents are spatially continuous natural features as opposed to being "piecewise discontinuous". This expectation suggested the rejection of solutions giving patterns of randomly located high and low concentrations (detached patterns) as opposed to solutions showing a regional gradient. The final solution shows agreement not only in the concept of transported material in and out of the Bay but also in an anticipated continuous shape of the gradient patterns. Detached patterns might be expected in a different stratigraphic setting, for example, if older sediments (with a contrasting mineral assemblage) protrude through a thin veneer of Holocene sediments.

The third point deals with the location of shoals and crossed transport pathways. When factor 2 and factor 3 patterns (Figures 18 and 19) are overlain, there are places where high concentrations or pathways tend to cross each other. These convergence areas are located in channels and on shoals (Figure 22). Although it seems rational to expect convergence over shoals, it is not clear how high concentrations of minerals would continuously enter and a leave a shoal via the plotted surficial pathways. Possibly, there are buried high-concentration pathways which have been exposed at the convergence areas; dispersion by daily tidal currents may cause the surrounding low concentrations. If this situation is true, then the high-concentration pathways may have originated during a less common event,

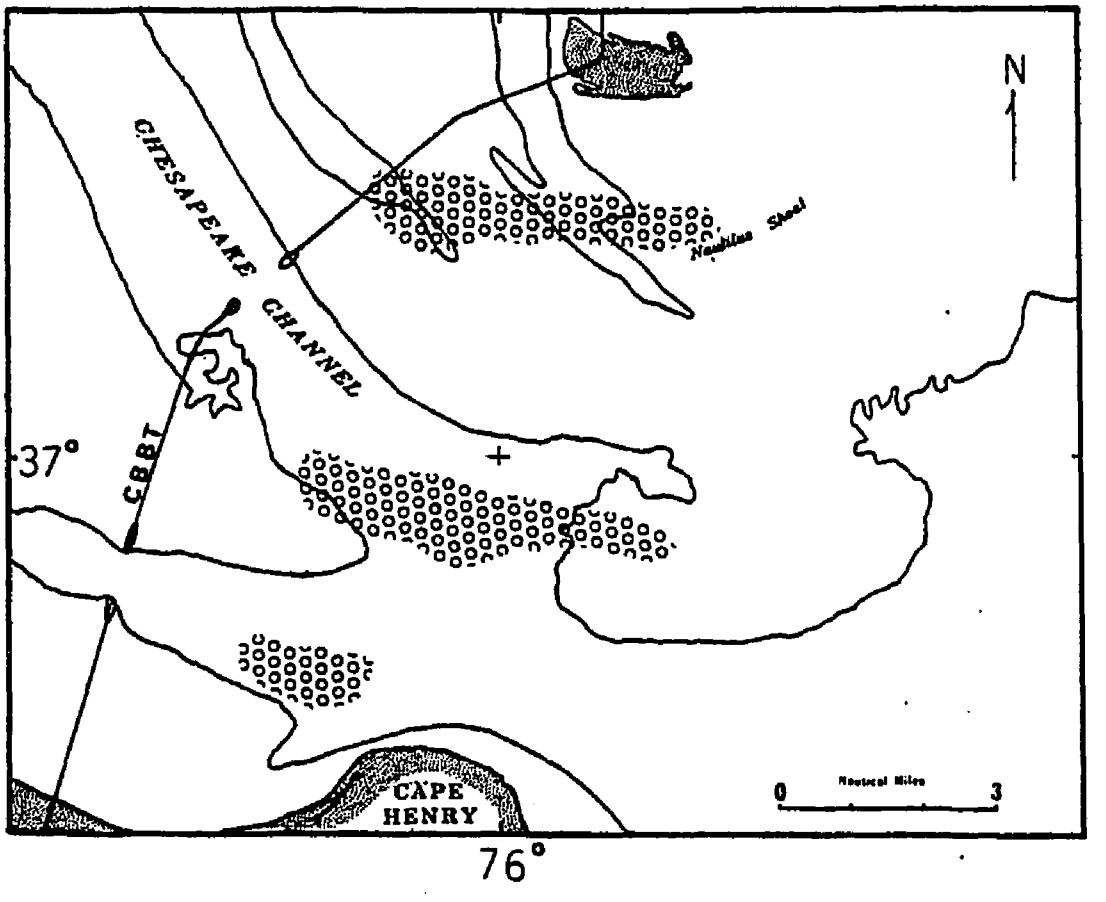


Figure 22. Convergence of F2 and F3 high concentrations is marked by circles. The contour line is the 30-foot isobath.

like a storm. It would be necessary to expand the study area and increase the number of core and surface samples before this question could be substantiated or addressed.

The fourth point involves the unproven correlation of bottom currents to mineral gradients. Because there is some agreement of data from Boicourt and Ludwick with the Factor 3 gradients of this study, it might be assumed that all

gradients locate mean bottom currents transporting sediment. However, a decreasing mineral concentration may also be caused by dilution from the introduction of foreign material where the average currents could be from any direction.

Other Observations

The most abundant mineral in most samples examined for this study was ilmenite. Leucoxene and ilmenite with leucoxene rinds were also common. These minerals were not used by Firek and consequently were excluded from this study. Unless the concentrations of these minerals were variable, it would not be very useful to include them in a study that relied on gradients because even if they were abundant their contribution to the total variance in the data might be small. Trace elements within ilmenite were used to characterize different sediment sources (Darby, 1984); such a varietal study is currently in progrss in the Chesapeake Bay (Chip Council, personal communication).

Chlorite and magnetite (or magnetic ilmenite) seemed to be more abundant in seaward cores. Concentrations of these minerals were not quantified because they were not included in Firek's work. These minerals along with hornblende, garnet and epidote might be used to characterize offshore sediment in future studies.

Glauconite is absent in heavy mineral separates because the range of its specific gravity is less than the specific gravity of tetrabromoethane (2.96); however, it was found in the heavy mineral fraction during tests of the MHS separator. The relative proportions of primary and secondary (reworked)

glauconite may also be important in future studies.

SUMMARY AND CONCLUSIONS

The post-Wisconsinan sands in the lower Cheaspeake Bay can be characterized by three suites of heavy minerals (factors) and associated concentration gradients. The gradients are based on the percentage of an identified compositional end-member present the samples. The suites and gradients are derived from Q-mode factor analysis on data from Firek (1975) (pilot study) and on a combination of her data with new mineral abundances from cores. Each mineral suite is defined by the composition of a factor (or end-member) in terms of its mineral constituents. In this scheme, the relative amount of each mineral in the sample is treated as a variable; thus, if a sample consists of seven minerals (variables), it can be located in a variable space of dimension seven. Through factor analysis, the dimensionality is effectively reduced from seven to three. Mineral composition gradients in three dimensions are defined for each suite by contouring sample composition loadings on each factor.

Because an estuary is a complex dynamic environment, simplification of the sediment composition relationships was achieved by restricting the analysis to post-Wisconsinan sediments. In order to insure that only post-Wisconsinan sediments were sampled, the geology of the study area was described by geologic mapping, and compilation and correlation of previous mapping by Oaks and Coch (1973),

Johnson (1976), Peebles (1984), and Mixon (1985). Three cross-sections were drawn to show the vertical distribution of post-Wisconsinan sediments in the lower Bay. The stratigraphy of the Eastern Shore and the Virginia Beach-Norfolk area was connected along the Chesapeake Bay Bridge-Tunnel route. The cross-sections showed that the Bay bottom is composed mainly of post-Wisconsinan sediments overlying Tertiary deposits. Nearly all Pleistocene material in the present Bay entrance had been eroded prior to the post-Wisconsinan transgression.

A pilot study was designed to test the Q-mode procedure and to try to simplify the task of adding subsurface data for a three-dimensional analysis. Principle components analysis on Firek's original data of 18 minerals and 190 samples showed that the abundances of five minerals accounted for about 96% of the variance in the entire data set. Mineral distribution patterns from a four-factor solution on a reduced number of samples (87) and variables (seven) showed sediment transport from offshore into the Bay as predicted by earlier studies; landward-derived material rich in zircon was also shown to contribute to the Bay sediments. The results of the pilot study were promising because they indicated that there was a need to determine the abundance of only five to seven minerals and because the mineral patterns supported prior notions of sediment transport.

The abundances of zircon, amphibole, pyroxene, epidote, and garnet from 86 samples out of 15 cores (which defined two cross-sections, Figures 5 and 6) were added to Firek's reduced data set. A three-factor solution showed the same surficial mineral patterns and nearly the same end-member compositions as derived from the pilot study. Plots of sample composition loadings in the cross-sections (Figures 20 and 21) indicates that offshore sediment entered the Bay mouth and

now overlies landward-derived sediment rich in zircon and epidote.

Two factors (end-member samples) define the offshore sediments; one factor is composed mainly of amphibole and pyroxene, the other is composed of garnet, amphibole, and epidote. Mineral gradients in the cross-sections and on the sediment-water interface show that high concentrations of minerals have entered the Bay in tube- and tongue-shaped avenues overlying paleochannels; although the locations of these avenues do not exactly coincide with ebb and flood channels shown by Ludwick (1970), the notion that sediment enters and leaves the bay in discreet or mutually evasive channels is substantiated. Quantities of transported sediment are not specified by this study. A characteristic of the post-Wisconsinan sands of the lower Bay is that they are derived from both land and shelf sources.

This research began from an attempt to use mineral gradient patterns to characterize estuarine sands and to indicate sediment transport directions at the mouth of Chesapeake Bay. It has been shown that an otherwise massively-bedded sand can be subdivided in three dimensions based on its contained heavy minerals; this characteristic has potential value for stratigraphic as well as economic investigations.

The results of this work are important to future exploration of economic placer deposits. Higher grade zircon-rich sediment is located on the western Bay bottom and continues in the subsurface with decreasing concentration seaward. Early identification of possible economic deposits and their distribution is necessary not only for recovery schemes but also for intelligent management of the resources of the Chesapeake Bay. Other economic placer minerals are excluded from this study as previously explained, so their distribution is unknown. If fu-

ture analysis shows an association of additional minerals with those of the end-members defined in this study, the present patterns would be useful to predict the occurrence of the new minerals.

This work has shown that heavy minerals can be used to characterize and further subdivide a massive sand lithosome. It is potentially possible to discern between any two lithologically similar (sandy) geologic units where one overlies the other. Based on the results of this research, some suggestions can be made to help investigate future situations. If only one unit is present, one could expect a gradual vertical change of minerals, with coherent diagnostic patterns as shown in Figures 18-22. If there are two units present, one could expect an abrupt vertical change of minerals across the contact between the units because of different sources or depositional environments; if the age difference is great enough this change may have resulted from weathering. In addition, one could expect repeated diagnostic patterns in a vertical profile. Portions of the lower (older) patterns may be incomplete because of erosion prior to deposition of the overlying (younger) sediments.

These suggestions are based solely on the study of one environment. In the future it may be shown that other depositional environments may be characterized by vertically repetitive patterns, in contradiction to the suggestions offered here. Such patterns may exist in subsiding basins receiving sediment in pulses over time (the Mesozoic basins in Virginia are an example). It is important that some information on the stratigraphy and depositional environment of an area be known before using the results from this kind of mineral analysis.

Several facts brought out by this research have important implications to the

broader understanding of the origin of coastal plain and shelf sediments. First, the geologic cross-sections show that most all of the post-Teriary sediment in the Bay is post-Wisconsinan. Erosion of pre-existing deposits is a major process which occurred following the last marine regression, at least in the low-relief coastal environment as the Bay area; for the same region, deposition occurred during the present marine transgression. This further supports the observation that most of the mapped coastal plain deposits ranging in age from the present to at least the late Pliocene (Bacons Castle Formation) were also formed during marine transgressions.

Second, the mineral gradients and mean bottom current velocities in the Chesapeake Bay entrance together strongly indicate a shelf origin for presumably much of the sands in the lower Bay. However, erosion of older deposits provided material to the western part of the lower Bay, based on zircon concentrations (Figure 18). This is in agreement with recent work by Hobbs and others (1986) and Boon and Frisch (1983). A corollary to this statement is that the shelf supplies most of the sediment to the coast (Giles and Pilkey, 1965; Pilkey and Field 1972). There really is no other major source of material to the Bay and coast in Virginia because eventual conversion of Wisconsinan fluvial systems to estuaries in the lower Chesapeake Bay area over the past 10,000 years (Harrison and others, 1965; Meisburger, 1972) prohibited sub-aqueous transport of sediments to the east and the tributary estuaries to the Chesapeake Bay are sediment traps (Schubel and Carter, 1976).

These facts lead to asking about the source of the shelf sediments. Amphibole is one of the least stable heavy minerals and would be expected to be

found in abundance in the youngest sediments; it is one of the most abundant minerals on the shelf (Carver and Kaplan, 1976), but zircon is also abundant (Berquist and Hobbs, 1986). If there was as much erosion on the shelf as there had been in the Bay area during the previous low stand of sea level, it could be that most of the shelf sediment is also post-Wisconsinan. Post-Wisconsinan (and Pleistocene) shelf stratigraphy, however, is not as well established as the stratigraphy on land and it really is not known how much erosion took place on the shelf during the Wisconsinan low stand of sea level. However, when sea level was at its lowest point, material transported across the present shelf via fluvial systems was forever lost to the continental slope and rise. As sea level rose, young material rich in unstable minerals and older material were probably trapped on the newly-formed shelf. Narrow, ephemeral estuaries at the transgressive western edge of the Atlantic would have accelerated the filling of drainages. In order to account for the high amphibole concentrations in shelf sediments, at least some material transported to the east while sea level was rising could have been brought back to the west. Longshore drift to the south may have transferred sediment from the ancestral Delaware Bay into the Chesapeake Bay, and material from the ancestral Chesapeake Bay toward North Carolina (A. Grosz, personal communication). In actuality, Pleistocene sediments were probably not entirely removed from the present shelf area during lowered sea level, and it is likely that they have been reworked during the present transgression and blended with some Wisconsinan-age sediment which had been carried further east. These ideas are only speculations because this dissertation has little data outside the Bay mouth and comprehensive mineral studies are lacking on shore deposits.

The problem with this sequence of events is that the relative contribution of young material versus old in shelf sediments is partially dependent upon knowing the origin of the unstable minerals. The amount of the young material freshly supplied from the piedmont would be greatly reduced if, for example, Wachapreague and Poquoson deposits (or even Sedgefield-Butlers Bluff) were shown to have high amphibole content because then these older units could also have contributed their sediments (rich in unstable minerals) to transport and deposition by the present transgression. In that case, a large proportion of the post-Wisconsinan shelf and Bay deposits would be relict or palimpsest.

The distribution of minerals shown on Figure 13 and the gradient patterns (Figures 18 - 21) are supporting evidence that the Atlantic Continental Shelf is now (and has been for about the past 10,000 years) a sediment source for the lower Bay (Ryan, 1953; Meisburger, 1972; Ludwick, 1974; Granat, 1976; Byrne and others, 1982) and beaches (Giles and Pilkey, 1965; Pilkey and Field, 1972). The "shelf" source includes longshore drift east of Virginia Beach and the Eastern Shore; adding mineral data from these areas and from further east on the shelf to the data of this dissertation should show what parts of the shelf are more actively involved in transport of sediment into the Bay.

Detailed circulation in the lower Bay is not established, so it is not known how well mineral gradients correlate with bottom currents. This relationship might be trivial in an environment of unidirectional flow, but remains somewhat questionable in a complex estuary. It would be useful if the mineral gradients predicted a long-term pathway for bottom sediment movement.

The surficial distribution patterns were judged to be an accurate repre-

sentation of mineral distributions because they have been replicated by factor solutions requiring three and four end-members as well as by solutions using different data sets. These patterns may or may not be unique to this or other estuaries. In order to show that these or any patterns would be diagnostic of estuaries, a similar study should be done in another modern area, perhaps Delaware Bay, and in the mapped sediments of an ancient system. Although mineral compositions would be different because of source or weathering, patterns or gradients might be similar. Comparison of such results to studies in different environments such as rivers, sounds, and lagoons may provide additional means to discriminate between massive sand lithosomes of different or juxtaposed similar origin.

APPENDIX A

The following is a description of the vibracores used by the author. Location coordinates and water depths are listed in Appendix B.

WB061

top	to 1'6"	light gray (5Y 7/1) dry fine sand with light gray clayey silt flasers, micaceous
1'6"	to 7'	light gray (5Y 7/1) fine sand micaceous, shell fragments, Ensis, granules at bottom
7'	to 7'3"	light gray silty clay
7'3"	to 12'4"	light gray (5Y 7/1) fine sand with scattered shell fragments and granules, more granules toward base, massive, yellow (2.5Y 8/6) mottles
12'4"	to 16'	light gray fine sand with clayey silt flasers
16'	to 23'6"	wavey bedded light gray fine sand, shell fragments
23'6"	to 29'6"	lenticular bedded light gray clayey silt and white fine sand, some shell fragments
29'6"	to 32'	light gray fine to coarse sand with granules, shell fragments and a few silty clay flasers, Astarte, crab claw
32'	to 33'	no sample, liner empty

WB062

top	to 10"	light gray (5Y 7/1) fine sand with granules, pebbles at base
10"	to 3'9"	laminated to interbedded (up to 2" thick) granules and fine to coarse sand, white and yellow (2.5Y 8/8) mottles, shell fragments
3'9"	to 8'6"	white (2.5Y 8/2) fine sand, disturbed planar crossbeds of micaceous clayey silt; massive, micaceous; gray clayey silt flasers at base
8'6"	to 10'8"	light gray (2.5Y 7/2) massive fine sand; two light gray clayey silt flasers
10'8"	to 18'	white fine sand, planar bedding defined by medium sand, few gray flasers, micaceous, few granules, mottled colors of yellow, gray
18'	to 23'	missing
23'	to 29'6"	white fine sand with light gray flasers, some shell fragments, few granules
29'6"	to 32'6"	wavy grading down to lenticular bedded white fine sand
32'6"	to 33'	light gray (5Y 7/1) fine sand, micaceous

WB063

top	to 4'8"	moist, light gray, fine to medium sand with shell fragments, some clay flasers at 3 1/2'
4'8"	to 5'8"	dark grayish brown (2.5Y 4/2) mud flasers and bioturbated with light gray (2.5Y 7/2) fine to coarse sand
5'8"	to 7'6"	light gray (2.5Y 7/2) fine sand, some clay chips; micaceous
7'6"	to 9'	dark grayish brown (2.5Y 4/2) mud and light gray (2.5Y 7/2) fine sand, bioturbated
9'	to 12'6"	white (2.5Y 8/2) dry micaceous fine sand, shell fragments
12'6"	to 14'	white (2.5Y 8/2) dry slightly muddy fine sand grading to grayish brown (2.5Y 5/2) fine sandy silt
14'	to 19'	missing
19'	to 34'	Yorktown Formation (top at 16'): gray (5Y 6/1) dry mud clayey silt, massive

WB072

1'	to 3'	missing
3'	to 6'	very dark grayish brown slightly moist mud and fine to medium sand, bioturbated, shell fragments
6'	to 8'	white (2.5Y 7/2) grading to yellow (2.5Y 7/8) dry fine to coarse sand, some granules
8'	to 9'	yellow (2.5Y 7/8) dry fine to coarse sand with granules
9'	to 14'6"	light gray (2.5Y 7/2) fine to coarse granule sand (core damaged, no structures) coarsens downward to pebbly coarse sand
14'6"	to 34'	Yorktown Formation: grayish brown (2.5Y 5/2) fine sandy mud, mottled

WB082

top	to 6"	dry, light brownish gray (10YR 6/2) fine sand with Turritella, Mercenaria fragments, Ensis
6"	to 4'6"	dry light gray (10YR 6/1) fine sand and shell fragments; thin laminae of white fine sand; more granules and coarse sand in lower 6" with a few silty fine sand laminae and flasers
4'6"	to 8'4"	dry pale yellow (2.5Y 7/4) and white fine to coarse sand with gray (N 5/0) muddy sand laminae and blebs; heavy mineral laminations, crude planar bedding
8'4"	to 9'3"	light gray (N 6/0) indurated muddy medium to coarse granule sand; rock fragments (phyllite) and pebbles at base
9'3"	to 12'	Yorktown Formation: shell and shell fragments with 6"thick weak red (2.5YR 4/2) clay and shell fragments at base
12'	to 14'7"	light brownish gray (10YR 6/2) biofragmental fine sand

WB092

top	to 7'6"	dark olive gray (5Y 3/2) moist silty fine to medium sand; shell fragments, massive; gray (5Y 6/1) fine to coarse sandy mud ball at base.
7'6"	to 9'10"	gray (5Y 6/1) moist fine to coarse sandy mud; sand filled vertical burrow, 4mm in diameter; few pebbles; massive
9'10"	to 12'3"	mottled yellowish-red (5YR 5/8) olive yellow (2.5Y 6/8) moist fine to medium sand, some granules with dark gray (N 4/0) mud or sandy mud flasers and blebs, massive
12'3"	to 15'5"	olive yellow (2.5Y 6/8) to brownish yellow (10YR 6/8) stained dry fine to coarse sand, some granules, yellowish brown (10YR 5/8) mud lens at base
15'5"	to 19'	pale yellow (2.5Y 7/4) fine to medium sand, few granules; heavy mineral laminae
19'	to 21'8"	white, moist medium sand, massive; opaque heavy minerals; 3" granule bed at 21' to 21'3"
21'8"	to 22'6"	light gray (2.5Y 7/2) pebbly fine to coarse sand
22'6"	to 22'8"	light brownish gray (2.5Y 6/2) fine sand, heavy mineral laminations
22'8"	to 23'6"	grayish brown (2.5Y 5/2) coarse sand and shell hash; clay pebbles
23'6"	to 27'6"	Yorktown Formation: very dark grayish brown (2.5Y 3/2) interior and dark yellowish brown (10YR 3/4) weathered exterior; moist micaceous very fine sandy mud

WB095

top	to 6"	grayish-brown (10YR 5/2) medium to fine sand, loose
6"	to 2'	very dark grayish brown (10YR 3/2) moist muddy sand, Ilyanassa, shell fragments
2'	to 6'6"	exterior, slightly dried dark brown (10YR 3/3), interior moist, dark gray (10YR 4/1 and N 4/0) clayey sand, some very fine sand with organics and root matter, few shell fragments; gypsum needles common, massively bedded
6'6"	to 9'9"	dry light gray (10YR 6/1) claycy silt with gypsum needles; cracked surfaces have pale yellow (5Y 7/3) sulfur stains, wood fragments, massively bedded
9'9"	to 11'	light gray (10YR 6/1) to very dark gray (10YR 3/1) dry very fine sandy mud, planar bedded with organic fragments
11'	to 16'	very dark gray organic rich silty clay and very fine sandy mud; some lenticular beds of pale brown (10YR 6/3) fine sand; lower 6" is pebbley coarse sand with a 3" diameter cobble with sulfur stains
16'	to 16'2"	Yorktown Formation: dark gray (10YR 4/1) fine sandy mud and light gray (10YR 6/1) very fine sand
16'2"	to 21'3"	mottled brown (10YR 4/3) and yellowish-red (5YR 5/8) and dark gray (N 4/0) slightly moist micaceous muddy very fine sand to very fine mud, massively bedded, bioturbated

WB095 (continued)

21'3"	to 26'4"	mottled dry pinkish gray (7.5YR 6/2) and reddish-yellow (7.5YR 7/8) micaceous very fine sand and silt to muddy very fine sand; weathered shell fragments, massive
26'4"	to 36'6"	mottled brown (7.5YR 4/4) and dark brown (7.5YR 3/2) slightly moist micaceous muddy very fine sand with weathered shell fragments, massive, (Mercenaria?)

WB098

top	to 3'	light gray (5Y 6/1) dry micaceous silty fine sand and shell fragments, massive
3'	to 5'4"	as above, coarsening downward to dry medium to coarse sand
5'4"	to 7'10"	dry, white fine sand, heavy mineral laminations
7'10"	to 8"2"	light gray (5Y 6/1) dry fine to coarse sand, massive
8'2"	to 11'7"	as above, with more granules, pebbles in lower 2'; massive, with two light gray clay (5Y 7/1) beds 1" thick at 9'
11'7"	to 12'	light gray (5Y 7/1) dry silty fine sand, some heavy mineral laminations
12'	to 13'	white, medium to coarse granule sand, massive
13'	to 15'7"	white, dry fine to medium sand; pebbles at top with heavy mineral laminations
15'7"	to 18'2"	white, fine to coarse pebbley sand
18'2"	to 21'1"	white, dry granule coarse sand, planar bedded
21'1"	to 21'7"	white, dry fine to medium sand, coarse sand and pebbles at base
21'7"	to 23'2"	Yorktown Formation: light olive gray, moist micaceous (5Y 6/2) silty very fine sand with sulfur stains
23'2"	to 28'3"	as above with lower 2' mottled olive gray (5Y 4/2) and olive brown (2.5Y 4/4) moist silty very fine sand; few clay flasers, burrows, bioturbation

WB101

top	to 1'	light brownish gray (2.5Y 6/2) slightly moist fine sand and shell fragments, massive
1'	to 4'	as above, grading to olive gray (5Y 5/2) slightly moist silty fine sand, micaceous, shell fragments and small shell ghosts
4'	to 4'6"	as above, mixed with slight brownish gray (2.5Y 6/2) medium sand
4'6"	to 6'	dry light brownish gray (2.5Y 6/2) fine to coarse sand, micaceous
6'	to 6'2"	brownish yellow (10YR 6/6) silty very fine sand
6'2"	to 9'4"	white fine sand, heavy mineral laminae with olive gray (5Y 5/2) and olive yellow (2.5Y 6/8) several muddy sand flasers micaceous, bioturbated

WB101 (continued)

9'4"	to 9'7"	olive gray (5Y 5/2) mud and sandy mud layer
9'7"	to 9'9"	white fine sand
9'9"	to 10'	dry olive gray (5Y 5/2) muddy fine sand
10'	to 11'11"	white fine to coarse sand with two olive gray mud and muddy sand layers and flasers up to 1/2" thick
11'11"	to 15'	white fine to coarse granule sand, clay pebbles, feldspar
15'	to 20'2"	wet light yellowish brown (2.5Y 6/4) fine to coarse granule sand, several pebble layers, heavy mineral laminations
20'2"	to 21'	brownish yellow (10YR 6/8) fine to coarse granule sand, massive
21'	to 21'11"	reddish yellow (7.5YR 6/8) fine to coarse granule sand, massive
21'11'	to 22'1"	dark reddish brown (2.5YR 3.4) sandy mud and pebbles
22'1"	to 23'	Yorktown Formation: reddish yellow (7.5YR 6/8) weathered shell hash
23'	to 25'6"	dark gray (N 4/1) fine sandy mud and shell fragments

VC102

top	to 1'	fine to medium sand, massive coarse sand and granule layer with clay pebbles at 8"
1'	to 2'	missing
2'	to 4'6"	fine to coarse sand with clay pebbles and pebbles at base
4'6"	to 5'9"	fine to medium sand, massive
5'9"	to 8'	missing
8'	to 11'9"	fine to medium sand, several clay flasers and clay chips, massive
11'9"	to 15'7"	fine to medium sand, as above

CERC 11 (Meisburger, 1972)

top	to 12.3'	gray (10YR 6/1) fine well sorted quartz sand

CERC 26 (Meisburger, 1972)

top	to 6'	light brownish gray (10 YR 6/2) fine well sorted quartz sand
6'	to 6.5'	light yellowish brown (10YR 6/4) sandy silty plastic clay
6.5'	to 7.5'	brown (10YR 5/3) fine silty clayey sand becoming more clayey and plastic at bottom

CERC 55 (Meisburger 1972)

top	to 9.5'	light gray (10YR 7/2) fine quartz sand

ODU 20

top	to 15'	light brown to orange fine sand
15'	to 32.5'	light gray fine to coarse sand, some pebbles
32.5'	to 42.5'	light gray fine sand
42.5'	to 47.5'	no sample
47.5'	to 57.5'	light gray silty fine sand
57.5'	to 62.5'	dark gray clay
62.5'	to 77.5'	light gray fine to coarse sand, some pebbles, cobbles? at base
77.5'	to 87.5'	dark gray sandy clay (Tertiary)

APPENDIX B

Coordinates of these cores are in degrees, minutes, and tenths of minutes. Samples from VC 102 were obtained from the Norfolk District, U.S. Army Corps of Engineers. Mr. Ed Meisburger of the U.S. Army Coastal Engineering Research Center provided samples from the CERC cores. Dr. Rich Whitticar of Old Dominion University provided samples from core ODU 20 (Oyler, 1984); this core was taken on land at Cape Henry. The remainder of the cores were obtained from the VIMS sand inventory study (Byrne and others, 1982). Depths are relative to mean sea-level.

Station	Latitude(N)	Longitude(W)	water depth
WB 061	36 55.75	76 00.10	10'
WB 062	36 56.05	76 01.25	15'
WB 063	37 01.10	76 16.02	12'
WB 072	37 03.69	76 08.70	28'
WB 082	37 01.83	76 11.85	18.5'
WB 092	36 57.58	76 04.92	37'
WB 095	36 57.35	76 03.87	37'
WB 098	36 59.65	76 09.55	18'
WB 101	37 01.25	76 13.75	15.5'
VC 102	36 54.11	75 54.37	59'
CERC 9	37 03.42	75 58.69	56'
CERC 11	37 03.24	76 02.00	33'
CERC 26	37 04.00	75 47.91	36'
CERC 55	37 03.26	75 54.25	23'
ODU 20	36 54.92	76 02.50	+10'

APPENDIX C

Location of samples relative to the top of each core.

SAMPLE	DEPTH
61-1	top
61-1	7' 6"
61-7	12'10"
61-9	17' 6"
61-11	27'
61-12	29'10"
62-1	top
62-3	5'
62-5	9'
62-7	15'
62-10	27' 6"
62-12	29'10"
63-1	top
63-3	4'
63-4	6' 6"
63-5	9'
63-6	10'
63-7	12'
72-1	3'
72-3	6' 6"
72-4	7'
72-6	10'
72-7	10' 6"
72-8	12'
82-1	top
82-3	3'
82-4	3'
82-6	6'10"
82-7	7' 6"
82-8	8' 9"
92-1	top
92-2	5'
92-5	11' 6"
92-8	16' 6"
92-10	19' 4"
92-12	22' 7"

SAMPLE	DEPTH
98-1	top
98-3	7'
98-6	10'
98-8	13' 3"
98-11	15' 3"
98-13	21' 4"
101-1	6"
101-4	7'
101-7	11' 9"
101-8	15'
101-10	18'
101-11	20'
102-1B	6"
102-3	4'10"
102-4	5' 6"
102-6	8'
102-8	11' 9"
102-11	15' 7"
9-1	top
9-2	3'
9-3	6'
9-6	10' 5"
9-7	13' 3"
11-1	top
11-3	7"
11-4	3'
11-5	6' 3"
11-6	9' 2"
11-8	12' 3"
26-1	top
26-2	3'
26-3	4' 3"
26-4	5'
26-7	6' 6"

APPENDIX C (continued)

SAMPLE	DEPTH
95-1	top
95-2	1' 6"
95-5	14'
95-6	15' 2"
95-7	16' 2"
95-TY	20'-34'

SAMPLE	DEPTH
20-1	10'
20-2	19' 6"
20-3	22' 6"
20-4	32' 6"
20-6	50'
20-8	75'
55-1	top
55-2	9"
55-3	9' 9"

APPENDIX D

Sample composition and statistics. Mean and standard deviation (SD) are in PHI units (Phi= $-\log_2$ diameter in mm). Weight percent of heavy minerals (%HM) is based only on the 3 to 4 PHI sieve fraction from each sample. Compositions are in units of 10^{-4} grams; for example, 380 is 0.0380 grams. ZR=zircon; SPH=sphene; AB=amphibole; EP=epidote; STR=staurolite; PX=pyroxene; GAR=garnet.

SAMPLE	PHI MEAN	SD	%HM 3-4 PHI	COMPOSITION ZR	SPH	AB	EP	STR	PX	GAR
61-1	2.84	.74	4.6	413	27	1433	1075	216	148	892
61-5	2.49	.80	6.6	9	6	75	51	23	72	430
61-7	2.38	.64	7.6	495	175	1516	1535	292	671	1101
61-9	2.67	.81	9.5	225	55	1205	904	167	94	761
61-11	2.3	.58	2.4	118	2	89	74	18	3	79
61-12	1.74	1.14	2.3	264	3	174	70	20	22	112
62-1	2.55	0.72	6.6	271	47	1293	575	145	155	649
62-3	2.62	.43	5.6	202	48	1016	407	118	268	257
62-5	2.51	.48	3.6	139	79	260	110	30	235	420
62-7	2.16	.54	N.A	99	73	243	241	65	207	130
62-10	2.16	.50	5.6	73	10	160	113	41	172	98
62-12	2.82	.44	2.1	70	0	622	155	31	126	102
95-1	1.91	1.10	3.3	258	44	558	399	805	73	514
95-2	1.58	1.24	2.4	108	10	130	111	22	7	124
95-5	2.06	0.75	6.7	154	15	76	76	2	16	139
95-6	1.97	0.83	7.3	189	16	52	63	14	27	96
95-7	3.2	1.93	0.4	41	4	11	0	3	11	89
95-TY	0.0	0.0	0.5	26	5	5	5	0	1	6
102-1B	1.46	0.7	11.4	189	5	279	124	1	41	93
102-3	1.51	0.49	7.5	13	0	20	13	3	3	8
102-4	1.53	0.51	5.7	49	0	24	9	1	2	5
102-6	1.18	0.80	4.9	64	0	5	24	0	16	2
102-8	1.67	0.73	11.3	214	0	14	47	13	33	119
102-11	1.01	0.58	4.3	108	0	72	87	1	33	3
101-1	2.79	0.47	6.0	591	8	772	662	266	247	533
101-4	2.52	0.52	25.7	1102	18	1191	1389	242	102	1098
101-7	1.72	0.76	11.1	307	24	458	458	57	56	114
101-8	1.54	0.91	4.7	118	7	113	162	0	6	31
101-10	1.29	0.68	9.4	70	10	86	76	11	4	43
101-11	1.12	0.95	11.3	91	0	50	38	10	1	32

APPENDIX D, continued

SAMPLE	PHI MEAN	SD	%HM 3-4 PHI	COMPOSITION ZR	SPH	AB	EP	STR	PX	GAR
98-1	2.97	0.83	1.5	151	38	304	228	39	60	152
98-3	2.38	0.65	14.8	538	28	367	489	97	26	287
98-6	1.82	0.81	16.2	282	13	288	334	49	17	175
98-8	1.53	0.51	1.8	64	8	37	28	0	13	20
98-11	1.47	0.70	6.2	107	14	80	63	16	10	23
98-13	1.52	0.65	5.8	81	5	32	18	2	11	19
92-1	2.18	1.15	0.8	65	1	42	28	8	21	47
92-2	1.72	0.9.	6.6	120	5	60	61	10	13	57
92-5	1.1	0.92	86.4	89	7	71	71	13	21	35
92-8	1.27	0.69	10.9	90	1	45	34	5	94	28
92-10	1.29	0.58	7.4	56	4	26	15	2	2	9
92-12	2.69	0.49	14.8	1287	62	1269	922	88	324	1207
55-1	3.25	0.51	2.8	148	22	520	104	68	152	264
55-2	3.28	0.54	7.3	584	47	1846	154	120	502	534
55-3	3.27	0.75	1.4	133	7	243	19	13	46	67
9-1	3.24	0.58	2.8	123	11	412	353	28	74	379
9-2	3.13	0.48	5.1	196	24	649	324	5	188	553
9-3	3.24	0.74	2.4	120	12	567	252	43	90	401
9-4	3.20	0.66	2.7	128	17	637	191	43	26	394
9-6	2.14	1.20	6.8	380	80	1387	514	44	426	1056
9-7	3.06	1.10	1.1	63	13	236	177	0	42	202
11-1	3.18	0.57	1.5	62	2	147	73	11	30	112
11-3	3.17	0.54	0.6	22	1	40	23	2	15	38
11-4	3.24	0.59	2.7	311	7	135	27	11	49	58
11-5	3.13	0.79	11.1	1922	13	270	116	51	139	178
11-6	3.38	0.66	1.4	108	7	270	66	18	84	112
11-8	3.18	0.51	1.7	120	10	368	179	19	121	217
26-1	3.10	0.53	8.8	374	24	1174	440	118	386	1014
26-2	3.25	0.60	3.2	202	21	739	123	44	200	239
26-3	3.31	0.69	1.6	132	10	410	136	49	134	163
26-4	3.09	1.26	0.7	71	2	14	7	13	44	28
26-7	3.12	0.64	9.4	269	35	994	373	140	222	858
20-1	1.81	0.57	4.3	182	4	148	74	26	61	116
20-2	1.78	0.94	1.0	37	0	33	14	1	5	30
20-3	1.73	0.55	9.4	246	15	140	112	29	34	209
20-4	2.42	1.05	1.6	102	3	242	152	19	73	95
20-6	2.24	0.98	1.5	48	0	130	81	16	37	50
20-8	2.22	0.94	1.9	121	6	110	55	15	42	66
82-1	2.37	0.50	7.4	264	0	152	76	19	48	76
82-3	2.91	0.60	0.9	82	12	62	31	9	24	31
82-4	2.66	0.88	1.1	86	3	69	49	6	49	36
82-6	1.38	0.77	5.8	176	0	76	76	10	20	59
82-7	1.69	0.88	1.7	65	0	36	42	0	10	9
82-8	2.02	0.94	8.3	41	7	97	242	16	119	54

APPENDIX D, continued

SAMPLE	PHI MEAN	SD	%HM 3-4 PHI	ZR	SPH	COMPOSITION AB	EP	STR	PX	GAR
72-1	2.02	0.96	1.8	66	2	42	26	10	15	21
72-3	1.77	0.74	6.3	154	2	91	34	20	30	50
72-4	1.91	0.68	7.4	157	11	15	30	40	34	91
72-6	1.80	0.76	12.2	364	4	334	167	50	16	167
72-7	1.81	0.7.	7.6	187	0	95	63	32	9	116
72-8	1.63	0.83	6.6	250	0	112	45	16	9	171
63-1	1.66	0.6.	21.9	518	5	101	121	18	25	60
63-3	1.83	0.52	1.7	.71	3	22	16	2	6	3
63-4	2.32	0.56	7.3	341	2	263	350	53	77	88
63-5	2.44	0.75	4.4	263	4	217	434	49	43	95
63-6	2.87	0.58	6.4	1951	7	357	408	59	84	102
63-7	3.20	0.74	3.6	1487	17	209	314	44	70	35

APPENDIX E

Location and normalized composition (weight percent) of data used from Firek (1975). Coordinates are in degrees, minutes and tenths of minutes. ZR=zircon; AB=amphibole; EP=epidote; PX=pyroxene; GAR=garnet.

sample	latitude	longitude	ZR	AB	EP	PX	GAR
98	37.13.0	76.17.4	2.60	60.39	5.19	29.87	1.95
99	37.10.8	76.21.0	1.36	65.99	7.48	20.41	4.76
100	37.12.2	76.21.0	2.63	67.11	7.24	19.74	3.29
101	37.13.4	76.21.0	49.04	25.96	13.46	10.58	0.96
115	37.12.7	76.02.2	0.00	64.54	2.84	21.99	10.64
116	37.10.8	76.00.4	7.24	57.89	4.61	15.13	15.13
117	37.10.8	76.02.0	0.00	60.81	10.14	18.92	10.14
118	37.10.8	76.03.6	0.00	68.42	5.26	13.16	13.16
119	37.10.8	76.05.3	0.62	62.35	6.79	19.75	10.49
120	37.10.8	76.07.1	0.00	67.92	3.14	20.75	8.18
121	37.10.8	76.08.7	0.00	71.83	4.23	17.61	6.34
122	37.10.8	76.10.6	0.00	68.42	2.63	18.42	10.53
123	37.10.8	76.12.0	3.10	70.54	8.53	17.83	0.00
124	37.10.8	76.14.0	0.00	59.87	4.46	32.48	3.18
125	37.10.8	76.15.6	3.60	56.12	12.95	25.18	2.16
126	37.10.8	76.17.3	14.29	41.27	8.73	19.05	16.67
127	37.08.7	76.16.3	42.74	23.93	9.40	9.40	14.53
128	37.06.8	76.15.3	19.83	33.62	10.34	28.45	7.76
129	37.06.8	76.13.5	47.33	16.03	16.03	3.05	17.56
130	37.06.8	76.11.9	6.49	61.04	4.55	21.43	6.49
131	37.06.8	76.10.2	20.00	33.33	16.67	4.17	25.83
132	37.06.8	76.08.5	0.63	58.49	5.03	29.56	6.29
133	37.06.8	76.06.7	3.08	43.08	13.85	6.92	33.08
134	37.06.8	76.05.1	0.65	54.55	2.60	31.17	11.04
135	37.06.8	76.03.9	3.33	34.67	14.67	6.00	41.33
136	37.06.8	76.03.2	0.60	57.49	7.19	24.55	10.18
137	37.06.8	76.01.6	1.36	44.90	8.16	17.69	27.89
138	37.06.8	75.59.9	0.00	47.65	4.03	32.21	16.11
139	37.06.8	75.58.5	0.00	61.94	7.46	14.18	16.42
140	37.06.0	75.58.8	4.55	52.60	6.49	13.64	22.73
141	37.05.7	76.00.2	3.36	48.32	4.70	14.77	28.86
142	37.04.9	75.59.2	0.63	59.49	6.33	11.39	22.15
143	37.04.0	75.58.9	0.00	49.66	4.08	17.69	28.57
144	37.05.0	75.58.2	1.84	59.51	5.52	14.72	18.40
145	37.03.9	75.57.1	8.27	28.57	5.26	6.77	51.13
146	37.04.7	75.56.9	1.21	59.39	4.85	14.55	20.00
147	36.56.4	76.02.6	1.44	63.31	6.47	16.55	12.23
148	36.55.6	75.59.5	0.60	59.52	4.76	23.81	11.31
149	36.56.6	75.59.3	3.82	63.36	6.11	8.40	18.32
150	36.57.4	75.59.0	2.65	60.93	2.65	21.19	12.58
151	36.58.5	75.58.6	18.71	22.30	6.47	1.44	51.08

APPENDIX E, continued

sample	latitude	longitude	ZR	AB	EP	PX	GAR
152	36.59.4	75.58.4	7.19	39.52	2.40	18.56	32.34
153	37.00.3	75.58.2	1.53	46.56	5.34	6.87	39.69
154	37.01.2	75.57.8	0.62	57.76	4.35	23.60	13.66
155	37.02.0	75.57.6	4.58	41.22	3.82	8.40	41.98
156	37.02.9	75.57.3	2.45	53.99	4.91	15.34	23.31
157	37.02.8	76.00.1	5.52	39.31	6.90	6.90	41.38
158	37.01.9	76.00.9	2.42	57.58	5.45	15.76	18.79
159	37.01.0	76.01.8	3.90	39.61	7.14	4.55	44.81
160	37.00.0	76.02.6	5.84	53.90	7.79	16.23	16.23
161	36.59.0	76.03.4	12.93	35.37	13.61	6.80	31.29
162	36.58.1	76.04.2	0.60	61.31	8.93	19.05	10.12
163	36.57.1	76.05.1	1.44	55.40	7.19	7.91	28.06
164	36.56.2	76.06.0	1.25	51.25	5.00	33.13	9.38
165	36.55.2	76.06.8	13.39	48.82	9.45	7.09	21.26
166	36.57.2	76.09.0	1.82	60.61	6.06	25.45	6.06
167	36.58.2	76.12.2	1.60	53.60	16.80	8.00	20.00
168	36.59.0	76.10.8	0.00	59.48	5.88	27.45	7.19
169	36.59.7	76.09.2	2.74	52.05	9.59	6.16	29.45
170	37.00.4	76.07.9	1.85	54.32	6.17	25.93	11.73
171	37.01.2	76.06.4	24.59	33.61	12.30	7.38	22.13
172	37.01.8	76.05.1	9.15	41.18	9.15	29.41	11.11
173	37.02.5	76.03.7	2.92	51.82	14.60	10.22	20.44
174	37.03.4	76.02.1	0.58	64.91	2.34	21.64	10.53
175	37.04.2	76.00.7	6.57	40.88	10.95	8.76	32.85
176	37.05.3	76.02.2	3.92	56.21	3.92	22.22	13.73
177	37.05.0	76.03.6	0.69	63.89	7.64	14.58	13.19
178	37.04.7	76.05.3	15.49	33.80	9.86	33.10	7.75
179	37.04.4	76.06.8	7.03	54.69	7.81	16.41	14.06
180	37.04.0	76.08.5	17.78	42.96	8.89	24.44	5.93
181	37.03.7	76.10.2	21.49	25.62	23.97	16.53	12.40
182	37.03.3	76.11.9	11.48	36.07	13.93	36.89	1.64
183	37.02.9	76.13.5	9.73	37.17	23.89	25.66	3.54
184	37.02.6	76.15.3	0.67	54.36	5.37	32.89	6.71
185	37.03.5	76.15.5	4.69	56.25	12.50	19.53	7.03
186	37.04.2	76.15.8	2.68	48.32	9.40	35.57	4.03
187	37.01.8	76.15.0	2.21	53.68	19.12	19.12	5.88
188	37.00.9	76.14.6	5.16	41.29	11.61	40.00	1.94
189	37.00.3	76.17.7	33.64	30.00	25.45	5.45	5.45
190	36.59.5	76.17.4	12.00	48.67	6.00	30.67	2.67
191	36.58.5	76.17.1	16.95	50.00	27.12	2.54	3.39
192	37.00.2	76.16.0	0.62	60.62	8.12	26.25	4.37
193	37.00.2	76.14.3	1.35	66.22	12.16	15.54	4.73
194	36.59.4	76.14.0	0.61	51.83	12.80	31.10	3.66
195	36.58.4	76.13.9	1.42	69.50	11.35	12.77	4.96
196	36.57.5	76.13.6	1.22	51.22	4.88	34.76	7.93
197	36.56.5	76.13.2	20.90	41.79	13.43	18.66	5.22

BIBLIOGRAPHY

Alminas, H.V., and Marceau, T.L., 1982, Construction plans and operating instructions for a laboratory-scale Magnetohydrostatic (MHS) mineral separator. USGS open-file report 82-895, two sheets.

Alminas, H.V., Marceau, T.L., Hoffman, J.D., and Bigelow, R.C., 1984, A Laboratory-Scale Magnetohydrostatic Separator and its Application to Mineralogic Problems. U.S. Geological Survey Bulletin 1541, 21 pp.

Andres, U., 1976, Magnetohydrodynamic and Magnetohydrostatic Methods of Mineral Separation. John Wiley & Sons, N.Y., Israel University Press, Jerusalem.

Berquist, C.R., Jr., 1970, Analysis of Structure Contour Mapping of the Bellwood Quadrangle, Tennessee. Unpublished M.S. Thesis, Vanderbilt University, Nashville, Tennessee, 79 pp.

Berquist, C.R., Jr., and Hobbs, C.H., III, 1986, Assessment of Economic Heavy Minerals of the Virginia Inner Continental Shelf. Virginia Division of Mineral Resoures Open-File Report 86-1, 16 p.

Berquist, C.R., Jr., Mixon, R.B., and Newell, W.L., Geologic Map of the Coastal Plain, Virginia, in preparation.

Boicourt, W.C., 1981, Circulation in the Chesapeake Bay entrance region: Estuary-Shelf Interaction. in Cheaspeake Bay Plume Study, Superflux 1980, NASA Conference publication 2188, p. 61 - 78.

Boon, J.D, III, and Frisch, A.A., 1983, Sand transport pathways in the entrance to Chesapeake Bay: Evidence from fourier grain-shape analysis (abs). Seventh Biannial International Estuarine Research Conference sponsored by the Estuarine Research Federation, October 23-26, Virginia Beach, Virginia.

Byrne, R.J., Hobbs, C.H., and Carron, M.J., 1982, Final Report, Baseline Sediment Studies to Determine Distribution, Physical Properties, Sedimentation Budgets and Rates in the Virginia Portion of the Chesapeake Bay. Virginia Institute of Marine Science, 154 pp.

Carron, M., 1979, The Virginia Chesapeake Bay: Paleodrainage and Recent sedimentation. Unpublished Doctoral Dissertation, Virginia Institute of Marine Science, College of William and Mary, Williamsburg, Virginia, 86 pp.

Carver, R.E., 1971, Procedures in Sedimentary Petrology. John Wiley and Sons, New York, 653 pp.

Carver, R.E., and Kaplan, D.M., 1976, Distribution of hornblende on the Atlantic Continental Shelf off Georgia, United States. Marine Geology, Vol. 20, p. 335, - 343.

Carver, R.E., and Scott, R.M., 1978, Stratigraphic significance of heavy minerals in Atlantic Coastal Plain sediments of Georgia. in Short Contributions to the Geology of Georgia, Georgia Department of Natural Resources Bulletin, p. 11 - 14.

Coch, N.K., 1965, Post-Miocene Stratigraphy and Morphology, Inner Coastal Plain, Southeastern Virginia. U.S. Office of Naval Research, Technical Report Number 6, 97 pp.

Darby, D.A., 1984, Trace elements in ilmenite: A way to discriminate provenance or age in coastal sands. Geological Society of America Bulletin, vol. 95, p. 1208-1218.

Davis, J.C., 1973, Statistics and Data Analysis in Gelogy. John Wiley & Sons, N.Y., 550 pp.

Davis, J.C., 1986, Statistics and Data Analysis in Geology, second edition. John Wiley & Sons, N.Y., 646 pp.

Delong, K., 1985, Heavy minerals at Seashore State Park, Virginia. Unpublished Senior Thesis, Department of Geology, College of William and Mary, 25 pp.

Dennison, J.M., and Shea, J.H., 1966, Reliability of visual estimates of grain abundance. Journal of Sedimentary Petrology, vol. 36, p. 81-89.

Feo-Codecido,, G., 1956, Heavy mineral techniques and their applications to Venezuelan stratigraphy. American Association of Petroleum Geologists Bulletin vol. 40, p. 984-1000.

Firek, F., 1975, Heavy Mineral Distribution in the Lower Chesapeake Bay, Virginia. Unpublished Master's Thesis, Old Dominion University, Norfolk, Virginia, 147 pp.

Firek, F., Shideler, G.L., and Fleischer, P., 1977, Heavy mineral variability in bottom sediments of the lower Chesapeake Bay, Virginia. Marine Geology, vol 23, p. 217-235.

Flores, R.M., and Shideler, G.L., 1978, Factors controlling heavy-mineral variations on the South Texas Outer Continmental Shelf, Gulf of Mexico. Journal of Sedimentary Petrology, vol. 48, no. 1, p. 269-280.

Force, E.R., and Geraci, P.J., 1975, Map showing heavy minerals in Pleistocene shoreline sand bodies of southeastern Virginia. U.S. Geological Survey Miscellaneous Field Studies Map No. MF-718.

Full, W.E., Ehrlich, R., and Klovan, J.E., 1981, EXTENDED QMODEL- Objective definition of external end-members in the analysis of mixtures. Journal of Mathematical Geology, vol. 13, no. 4, p. 331-344.

Galehouse, J.S., 1969, Counting grain mounts: number percentage vs. number frequency. Journal of Sedimentary Petrology, vol. 39, p. 812-815.

Giles, R.T., and Pilkey, O.H., 1965, Atlantic beach and dune sediments of the southern U.S.. Journal of Sedimentary Petrology, vol. 35, p. 900-910.

Goodwin, B.K., 1967, Heavy minerals of James River sands. Unpublished report.

Goodwin, B.K., and Thomas, J.B., 1973, Inner Shelf Sediments off Chesapeake Bay, III. Virginia Institute of Marine Science Special Scientific Report No. 68.

Granat, M.A.,1976, Dynamics and Sedimentology of Inner Middle Ground - Nine Foot Shoal, Chesapeake Bay, Virginia. Unpublished M.S. Thesis, Old Dominion University, Norfolk, Virginia, 150 pp.

Grosz, A.E., and Escowitz, E.C., 1983, Placer heavy minerals of the United States Atlantic Continental Shelf, in Tanner, W.F. (ed), Proceedings of the Sixth Symposium on Coastal Sedimentology, Florida State University, Tallahassee, Florida, p. 231-242.

Harrison, W., Malloy, R.J., Rusnak, G.A., and Terasmae, J., 1965, Possible late Pleistocene uplift Chesapeake Bay entrance. Journal of Geology, vol. 73, no. 2, p. 201-229.

Harrison, W.R., Norcross, J.J., Pore, N.A., and Stanley, E.M., 1967, Circulation of shelf waters of the Chesapeake Bight, surface and bottom drift of continental shelf waters between Cape Henlopen, Delaware and Cape Hatteras, North Carolina, June, 1963 - December, 1964. ESSA Professional Paper 3, 82 pp.

Hobbs, C.H., III, Colman, S.M., and Berquist, C.R., Jr., 1986, Sandy estuarine fill transported into the mouth of Chesapeake Bay (abs). Abstracts with Programs, Southeastern Section Meeting, Geological Society of America, vol. 18, no. 3, p.227.

Hubbard, D.A., Jr., 1977, The mineralogical composition and variation of heavy mineral sands of a washover fan at Assateague Island, Maryland. Unpublished M. S. Thesis, University of Virginia, 41 pp.

Imbrie, J., and Purdy, E. G., 1962, Classification of modern Bahamian carbonate sediments, p. 253-272: in Ham, W.E. (ed.), American Association of Petroleum Geologists Memoir 1, 279 pp.

Imbrie, J., and Van Andel, T.H., 1964, Vector analysis of heavy-mineral data. Geological Society of America Bulletin, vol. 75, p. 1131-1156.

Johnson, G.H., 1976, Geology of the Mulberry Island, Newport News North and Hampton Quadrangles, Virginia. Report of Investigations 41, Virginia Division of Mineral Resources, 57 pp.

Johnson, G. H., Peebles, P. C., and Berquist, C. R., 1982, Pleistocene depositional patterns of the Southeastern Virginia and Northeastern North Carolina Coastal Plain (abs). Virginia Academy of Science.

Johnson, G.H., and Berquist, C.R. Jr., Geology of the Norge and Brandon Quadrangles, Virginia. Virginia Division of Mineral Resources, in preparation.

Johnston, M.L., Jr., 1985, The vertical distribution of heavy minerals on Smith Island, Eastern Shore, Virginia. Unpublished Senior Thesis, Department of Geology, College of William and Mary, 26 pp.

Joreskog, K.G., Klovan, J.E., Reyment, R.A., 1976, Geological Factor Analysis. Elsevier Scientific Publishing Company, New York, 178 pp.

Klovan, J. E., 1966, The use of factor analysis in determining depositional environments from grain size distributions. Journal of Sedimentary Petrology, vol. 36, p. 115-125.

Klovan, J.E., and Imbrie, J., 1971, An algorithm and Fortran-IV program for large-scale Q-mode factor analysis and calculation of factor scores. Journal of the International Association for Mathematical Geology, vol. 3, no. 1, p. 61-77.

Klovan, J.E., and Miesch, A.T., 1975, Extended CABFAC and QMODEL computer programs for Q-mode factor analysis of compositional data. Computers and Geosciences, vol. 1, no. 3 (1976).

Kraft J.C., 1971, Sedimentary facies patterns and geologic history of a Holocene marine transgression. Geological Society of America Bulletin, vol. 82, p. 2131-2158.

Leonard, L.A., 1986, The stratigraphy, origin and development of the Goodwin Islands near Seaford, Virginia. Unpublished Senior Thesis, Department of Geology, College of William and Mary, Williamsburg, Virginia, 59 pp.

Lowright, R., Williams, E.G., and Dachille, F., 1972, An analysis of factors controlling deviation in hydraulic equivalence in some modern sands, Journal of Sedimentary Petrology, vol. 42, p. 635-645.

Ludwick, J. C., 1970, Sand waves and tidal channels in the entrance to Chesapeake Bay. Virginia Journal of Science, vol. 21, p. 178-184.

Ludwick, J.C., 1974, Tidal currents and zig-zag shoals in a wide estuary entrance. Geological Society of America Bulletin, vol. 85., p. 717-726.

Luepke, G., (ed), 1984, Stability of Heavy Minerals in Sediments. Van Nostrand Reinhold Company, New York, 306 pp.

Luepke, G., (ed), 1985, Economic Analysis of Heavy Minerals in Sediments. Van Nostrand Reinhold Company, New York, 321 pp.

Markewich, H. W., Pavich, M. J., and Gonzalez, V. M., 1983, Soil chronosequences from the Virginia to South Carolina Quaternary Coastal Plain deposits (abs). Abstracts with Programs, Southeastern Section Meeting, Geological Society of America, vol. 15, no. 2, p. 56.

Mausbach, M. J., Pavich, M. J., and Markewich, H. W., 1982, Properties of some Atlantic Coastal Plain soils related to ages of sedimentary formations (abs). Abstracts with Programs, Combined Southeastern and Northeastern Sections Meeting, Geological Society of America, vol. 14, no. 1 & 2, p. 39.

McLean, J.D., Jr., 1966, Miocene and Pleistocene Foraminifera and Ostracoda of Southeastern Virginia. Report of Investigations 9, Virginia Division of Mineral Resources, 123 pp.

Meisburger, E.P., 1972, Geomorphology and Sediments of the Chesapeake Bay Entrance. Technical Memorandum No. 38, U.S. Army Corps of Engineers Coastal Engineering Research Center, 61 pp.

Miesch, A.T., 1976, Q-Mode Factor Analysis of Geochemical and Petrologic Data Matrices with Constant Row-Sums. U. S. Geological Survey Professional Paper 574-G, 47 pp.

Mixon, R.B., 1985, Stratigraphic and Geomorphic Framework of Uppermost Cenozoic Deposits in the Southern Delmarva Peninsula, Virginia and Maryland. U.S. Geological Survey Professional Paper 1067-G, 53 pp.

Mixon, R.B., Szabo, B.J., and Owens, J.P., 1982, Uranium-series dating of mollusks and corals, and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland. U.S. Geological Survey Professional Paper 1067-E, 18 pp.

Mittwede, S.K., 1981, The distribution and variability of heavy minerals in Mobjack Bay and the Virginia portion of Pocomoke Sound, lower Chesapeake Bay, Virginia. Unpublished class report, Virginia Institute of Marine Science, 26 pp.

Moran, Proctor, Mueser, and Rutledge, 1960, Engineering logs of borings, Chesapeake Bay-Bridge Tunnel, file no. 1970.

Morton, A.C., 1982, Lower Tertiary sand development in Viking Graben, North Sea. American Association of Petroleum Geologists Bulletin, vol. 66, p. 1542-1559.

Myers, C.R., 1984, A study of the vertical distribution of heavy minerals in the lower Chesapeake Bay sediments. Unpublished Senior Thesis, Department of Geology, College of William and Mary, 47 pp.

Nichols, M.M., 1972, Sediments of the James River estuary, Virginia, in Environmental framework of coastal plain estuaries. Geological Society of America Memoir 133, p. 169-212.

North American Stratigraphic Code, 1983, American Association of Petroleum Geologists Bulletin, vol. 67, no. 5, p. 841-875.

Oaks, R.Q., and Coch, N.K., 1973, Post-Miocene Stratigraphy and Morphology, Southeastern Virginia. Virginia Division of Mineral Resources Bulletin 82, 135 pp.

Oaks, R.Q., Jr., and DuBar, J.R., (eds.), 1974, Post-Miocene stratigraphy, Central and Southern Atlantic Coastal Plain. Utah State University Press, Logan, Utah, 275 pp.

Owens J.P., and Denny, C.S., 1979, Upper Cenozic deposits of the central Delmarva Peninsula, Maryland and Delaware. U.S. Geological Survey Professional Paper 1067-A, 28 pp.

Owens, J. P., McCartan, L., and Lemon, E.M., 1982, Mineral phases produced by weathering on surfaces of different ages from New Jersey to South Carolina: A comparison of rate and duration of weathering (abs). Abstracts with Programs, Combined Southeastern and Northeastern Sections Meeting, Geological Society of America, vol. 14, no. 1 & 2, p. 72.

Oyler, D. L., 1984, Stratigraphy and Textural Analysis of a Beach Ridge Complex, Cape Henry, Virginia. Unpublished Masters Thesis, Old Dominion University, Norfolk, Virginia, 107 pp.

Pavich, M. J., Brown, L., Tera, F., Middleton, R., and Klein, J., 1982, Evaluation of ^{10}Be as a method of dating late Cenozoic soils (abs). Abstracts with Programs, Combined Southeastern and Northeastern Sections Meeting, Geological Society of America, vol. 14, no. 1 & 2, p. 71.

Peebles, P.C., 1984, Late Cenozoic Landforms, Stratigraphy and History of Sea Level Oscillations of Southeastern Virginia and Northeastern North Carolina. Unpublished Doctoral Dissertation, College of William and Mary, Williamsburg, Virginia, 227 pp.

Peebles, P.C., Johnson, G.H., and Berquist, C.R., Jr., 1984, The middle and late Pleistocene stratigraphy of the outer coastal plain, southeastern Virginia. Virginia Minerals, vol. 30, no. 2, p. 13 - 22.

Pettijohn, F.J., 1957, Sedimentary Rocks, second edition. Harper and Row, New York, 718 pp.

Pilkey, O.H., 1963, Heavy minerals of the U.S. South Atlantic Continental Shelf and Slope, Geological Society of America Bulletin, vol. 74, p. 641-648.

Pilkey, O.H., and Field, M.E., 1972, Onshore transportation of continental shelf sediment: Atlantic Southeastern United States. in D.J.P. Swift, D.B. Duane, and O.H. Pilkey, (eds), Shelf Sediment Transport: Process and Pattern, Dowden, Hutchinson and Ross, Inc. Stroudsburg, Pa., p. 429-446.

Richmond, G.M., and others, 1986, Quaternary Deposits of the Chesapeake Sheet, in press.

Rittenhouse, G., 1943, The transportation and deposition of heavy minerals. Geological Society of America Bulletin, vol. 54, p. 1725-1780.

Rosato, V. J., and Kulm, L. D. 1981, Clay mineralogy of the Peru continental margin and adjacent Nazca plate: Implications for provenance, sea level changes and continental accretion, in Kulm, L. D. and others (eds.), Nazca Plate: Crustal Formation and Andean Convergence. Geological Society of America Memoir 154, p.545-568.

Rubey, W.W., 1933, The size distribution of heavy minerals within a water-laid sandstone. Journal of Sedimentary Petrology, vol. 3. p. 3-29.

Ryan, J.D., 1953, The Sediments of the Chesapeake Bay. Maryland Department of Geology, Mines, and Water Resources Bulletin 12, 120 pp.

Scheidegger, K. F., and Krissek, L. A., 1982, Dispersal and deposition of eolian and fluvial sediments off Peru and Northern Chile. Geological Society of America Bulletin, vol. 93. p. 150-162.

Schubel, J.R., and Carter, H.H., 1976, Suspended sediment budget for Chesapeake Bay. in M. Wiley, (ed), Estuarine Perspectives, vol. II, Academic Pdress, New York, p. 48-62.

Stow, M.H., 1939, Reflection of provenance in heavy minerals of James River, Virginia. Journal of Sedimentary Petrology, vol. 9, p. 86-91.

Swift, D.J.P., Dill, C.E., Jr., and McHone, J., 1971, Hydraulic fractionation of heavy mineral suites on an unconsolidated retreating coast. Journal of Sedimentary Petrology, vol. 41, p. 683-690.

Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P., and Sears, P., 1972, Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America, in D. Swift and O.H. Pilkey (eds), Shelf Sediment Transport: Process and Pattern. Dowden, Hutchenson, and Ross, Stroudsburg, Pa., p. 449-574.

U.S. Army Corps of Engineers, Norfolk District, 1986, Draft, General Design Memorandum 1, Hampton Roads Deepening, Geology and Soils Atlantic Ocean Channel, Appendix C, Volume 4.

Van Andel, T. J. H., 1959, Reflections on the interpretation of heavy mineral analyses. Journal of Sedimentary Petrology, vol. 29, p. 153-163.

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