STATE OF DELAWARE
DELAWARE GEOLOGICAL SURVEY

BULLETIN No. 5

SEDIMENTARY PETROLOGY OF THE CRETACEOUS SEDIMENTS OF NORTHERN DELAWARE IN RELATION TO PALEOGEOGRAPHIC PROBLEMS

by
JOHAN J. GROOT
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FOREWORD

The writer is greatly indebted to Jan P. Bakker, Professor at the University of Amsterdam, for his constructive criticism and valuable suggestions regarding the interpretation of the mechanical and mineral analyses. Thanks are due to Lincoln and Clarissa Dryden of Bryn Mawr College who, because of their great knowledge of Coastal Plain sediments, were able to give sound advice concerning the main problems discussed in this report. D. J. Doeglas, Professor at the Landbouwhogeschool, Wageningen, the Netherlands, critically read Chapters IV and V, and H. J. MacGillavry of the University of Amsterdam read Chapters I, II and III.

Donna M. Organist, Geologist, Delaware Geological Survey, participated in the field work and the study of the mineral slides. Her help in preparing the report has been invaluable.

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SEDIMENTARY PETROLOGY OF THE CRETACEOUS SEDIMENTS OF NORTHERN DELAWARE IN RELATION TO PALEOGEOGRAPHIC PROBLEMS

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ABSTRACT

THE NON-MARINE Cretaceous sediments of northern Delaware older than the Magothy formation cannot be divided accurately into formations or mappable geologic units because their lithologic characteristics are very similar. However, two heavy mineral zones can be distinguished in these deposits: a lower staurolite-kyanite-tourmaline-zircon zone, and an upper tourmaline-zircon-rutile zone with abundant alterites. They have been named the Patuxent zone and the Patapsco-Raritan zone respectively.

The Magothy formation is characterized by abundant staurolite and also contains significant amounts of tourmaline.

The marine Upper Cretaceous deposits have a greater variety of heavy minerals than the underlying non-marine sediments. They contain abundant epidote; chloritoid, first appearing at the base of the Merchantville formation, is persistently present. Garnet is found in the Merchantville and the Mount Laurel-Navesink formations. The heavy mineral composition of the Cretaceous sediments is shown in table IV.

The non-marine Cretaceous sediments were all derived from essentially the same source area, namely, the nearby Piedmont Province, and to an increasing degree in the younger of these deposits, from the adjacent Folded Appalachian Mountains. Thus, although they are composed of detrital grains from a great variety of parent materials, such as metamorphic, igneous, and sedimentary rocks, they form a complex of sediments which, by their geographical distribution, age, and origin form a natural unit. Therefore they can be said to belong to *one sedimentary petrological province*.

The marine Cretaceous formations of northern Delaware consist of a mixture of detrital materials from two sources. One source is located to the south providing an epidote-rich suite, the second source is located to the northwest, and is the same which supplied detrital material to the non-marine Cretaceous sediments. Thus, the marine Cretaceous formations of northern Delaware belong to another sedimentary petrological province which differs from the first in being composed of *mixed sediments*.

A study of the environment of deposition was made primarily on the basis of the mechanical composition of the sediments. Arithmetic probability paper was used for plotting the size frequency distributions, with the grain size intervals in phi units on the arithmetic scale and the cumulative weight percentages on the probability scale. Statistical parameters computed are the median grain size, and the coefficients of sorting, skewness and kurtosis. Their interrelationship is discussed.

When a cumulative curve of a size frequency distribution plotted on arithmetic probability paper is a straight line, the distribution is log normal (because the phi scale is logarithmic). Log normal distributions of sediments occur apparently when a sediment is transported for a sufficient time in a certain way, for instance by traction, or in suspension. Thus, a purely tractional deposit as well as a pure suspension deposit tend to have log normal distributions. When, however, deposition of tractional as well as suspension material takes place, the deviation from the log normal distribution becomes considerable, and therefore, the coefficient of skewness becomes great.

Because the threshold velocity for fine sand is smaller than that for either finer or coarser material (Inman, 1949), and because the settling velocity of very fine sand, silt, and clay is smaller than their threshold velocities, these fine-grained materials tend to move in suspension, whereas the coarser materials tend to move by traction, unless friction velocities exceed their settling velocities. If a cumulative curve consists of two parts, each approaching a straight line, it represents a deposit of coarse, tractional material having a log normal distribution, and fine, suspension material having a log normal distribution.

If currents have a great range in velocity, some material can be removed from a deposit, fine sand being removed first. The effects of changes in current velocities are shown in figures 45 and 46.

After some deductions were made from the cumulative curves with regard to current velocities, the environments of deposition of the Cretaceous formations are discussed. The sediments of the Patuxent and Patapsco-Raritan zones are considered to consist mainly of fluviatile and estuarine deposits. The environment of deposition of the Magothy formation is transitional between that of the Patapsco-Raritan and that of the marine Upper Cretaceous formations, and consists of swamp and lagoon deposits on a low lying coast. The marine sediments were deposited in a very shallow sea subject to tidal currents.

It has been generally recognized that earth movements which have taken place in mountains are reflected in the sedimentary record of adjacent basins of deposition. Thus, the study of the Cretaceous sediments of the Coastal Plain affords an opportunity to examine what clues can be derived from the sedimentary record with regard to the diastrophic and erosional history of the Appalachian region which furnished much of the material of the Coastal Plain.

The controversial problems of the reversal of Appalachian drainage, and peneplanation of the Appalachian region are discussed. There are strong indications that the reversal of Appalachian drainage did not take place on a cover of marine sedimentary rocks which, according to Johnson (1931), once must have overlain the whole region, but by the slow process of headward erosion, as indicated by the increase in the percentage of oval- and circular-shaped, well-rounded, second or more sedimentary cycle tourmaline grains in the nonmarine Cretaceous sediments which were derived from the sedimentary rocks of the Folded Appalachian Mountains. Moreover, it could be shown that abundant material was derived from the metamorphic rocks from the Piedmont Province, which would have been impossible if this area had been completely overlain by a cover of sediments.

Patapsco-Raritan time was a period of intensive chemical weathering as indicated by the presence of the very stable minerals tourmaline, rutile and zircon, the abundance of alterites, and the near absence of any other minerals in the Patapsco-Raritan zone.

In view of the fact that a warm and humid climate prevailed in the area during the Cretaceous Period some caution was exercised in the interpretation of the correlative strata. The impoverished mineral suite of the Patapsco-Raritan zone, as well as the predominantly fine-grained character of the sediments do not necessarily indicate that the source area was a region of very low relief, because it has been found that in the humid tropics very thorough decomposition and disintegration of source rocks occur even in regions with fairly steep slopes (Bakker, 1955). However, the mineralogical and mechanical composition of the Patapsco-Raritan sediments does indicate a reduction of relief in the source area (the Piedmont and the Appalachian region) *relative* to that existing during Patuxent and Magothy time.

In summary, up to the close of the Cretaceous Period development of at most two peneplanes or pediments can have taken place, one of Jurassic age, on which the Patuxent sediments were laid down, and one of Patapsco-Raritan or middle Cretaceous age. However, it is possible that during the last mentioned period the peneplane or pediment had only a limited extent, and that farther from the basin of deposition a region of considerable relief persisted.

CHAPTER I

INTRODUCTION

Purpose and Scope

THE SEDIMENTS OF the Costal Plain of Delaware have never been studied in great detail. Until a few years ago interest in this subject was dormant. However, the rapid industrial expansion now taking place in the State necessitates the accelerated development of ground water and other mineral resources, and it is well known that such development can not be accomplished in an intelligent manner without a thorough understanding of the character, the properties, and the origin of the rocks which contain these natural resources.

If the need for detailed geologic study is recognized in view of its practical applications, scientific interest also demands consideration. The knowledge of the sediments of the Coastal Plain of New Jersey and Maryland is considerable because they have been studied for many years, and although most geologic formations in these states are similar to the ones in Delaware, there are some very significant differences also. Due to its location, Delaware can be considered the "missing link" between them, and a contribution to its geology should also aid the understanding of the morphological and geological development of the Atlantic Coastal Plain in general.

The study of the sediments of the Delaware Coastal Plain presents several difficulties. Firstly, most of the non-marine sediments in northern New Castle County are devoid of identifiable fossils, while others, for instance the Pleistocene and the Wenonah formations, yield only very few. Secondly, the lithology of the Patuxent, Patapsco, and Raritan formations is very similar, so much so, that they cannot be separated from each other with accuracy on the basis of mass properties, such as color and structure. To a smaller degree this is true for the Pleistocene sediments, some of which closely resemble some Patuxent or other Cretaceous sands. This feature is responsible for considerable confusion, and has resulted in faulty mapping of some areas, as pointed out by Groot and Rasmussen (1953).* Thirdly, there is a lack of deep road cuts or other exposures, apart from the good outcrops in the banks of the Chesapeake and Delaware Canal.

In view of this situation it appeared necessary to study the sediments of the Coastal Plain in more detail than could be done in the field or by megascopic inspection alone. It was decided to employ modern methods of mechanical and heavy mineral analyses, thus adding precise quantitative analysis in the laboratory to the usual field investigations.

The purpose of the sedimentary analysis was to throw light on the following fundamental questions:

*See references at end of text.

1. Do some or all of the Cretaceous formations of the Coastal Plain of Delaware have distinct mineral associations, each different enough from the other, and similar enough within one formation, to permit their use for the identification of the various formations, thus offering a possibility for clarifying stratigraphic problems?
2. What are the possible sources of origin of these sediments, or what is their provenance?
3. What were the agents of transportation of these sediments, and what was the direction of transportation? Are the sediments of marine, fluviatile, eolian, or other facies?
4. And finally, what conclusions can be deduced from the results of the sedimentary analysis and the field investigations regarding geomorphological and paleogeographic problems, in particular problems relative to the climatic and physiographic conditions prevailing during Cretaceous time in the Coastal Plain and the adjacent Appalachian region? This question is most important because it refers to the ultimate goal of geologic and physiographic research, that is, to give an accurate account of the history of an area on the basis of the record of its rocks and its landforms. This question is mentioned last only because the first three need to be answered before an attempt can be made to deal with the fourth one, and consequently, paleogeographic problems are primarily discussed in the final chapter of this report.

Previous Investigations

There are no published accounts of any previous investigations concerning the sedimentary petrography of the Delaware Coastal Plain employing up-to-date methods of mechanical and heavy mineral analysis, with the exception of some analyses of a very small number of samples from the Upper Cretaceous formations in the Chesapeake and Delaware Canal (Clark, *et al.*, 1916). So far, all reports concerning the geology of the State are based on field investigations of the sediments, and on the paleontology of the formations.

In view of this situation, and also because an exhaustive review of the literature concerning the marine Upper Cretaceous formations has been presented by Groot, Organist and Richards (1954), the present discussion of previous investigations can be brief.

One of the first publications dealing with the geology of Delaware is the Memoir of the Geological Survey of the State of Delaware (Booth, 1841). Some geological aspects of the State as applied to agriculture were described. A few references were made to outcrops in the Chesapeake and Delaware Canal.

Chester (1884) studied the Plastic Clays of Lower Cretaceous age and various Upper Cretaceous marls; he described each formation in some detail, and presented a geologic map of northern Delaware.

Clark, Bagg and Shattuck (1897) published an article concerning the Upper Cretaceous formations of New Jersey, Delaware and Maryland in which they distinguished the Matawan and Monmouth formations, and the Rancocas formation, which is now considered to be of Tertiary age. The character of the materials was described in detail, and their areal distribution shown on a geologic map.

Upper Cretaceous stratigraphic problems were discussed by Clark (1904). He was the first to suggest that the black, micaceous, sandy clays found near Summit Bridge were equivalent to the Crosswicks Clay of New Jersey.

The Lower Cretaceous deposits of Maryland were described by Clark, Bibbins and Berry (1911). The greater part of this publication is devoted to the paleontology of the Patuxent, Arundel, and Patapsco formations, although also fairly detailed descriptions of their lithology and structure are given. With regard to their structure, the authors stated that (p. 63)

> a warping of the beds occurs whether with or without dislocation of the strata. The main body of the deposits may well have been subjected to deformation in the many differential movements which are known to have taken place in the Coastal Plain in post-Patuxent time. Furthermore, some of the marked changes in dip in the later formations, as notably in the Magothy formation along the line of the Chesapeake and Delaware Canal, suggest the possibility of actual folding of the underlying formations.

The writer of this report has noticed such changes in dip also, not only in the Magothy, but in the Raritan and Merchantville formations as well. This phenomenon will be further discussed in Chapter VII.

Attention was also given to the origin of the Lower Cretaceous sediments; for instance, the high feldspar content of the Patuxent formation was ascribed to rapid and short transportation from the source area, which was believed to be the nearby Piedmont Upland. The sediments of the Patapsco formation were doubtless derived to a considerable extent from those of the Patuxent terrane (Clark, *et al.*, 1911, p. 84). This statement concerning the provenance of the Patapsco sediments was, however, not explained.

Of special interest is Goldman's (Clark, *et al.*, 1916) investigation of the sediments of the Upper Cretaceous formations of Maryland, not only because he extended his studies to portions of the Chesapeake and Delaware Canal, but also because he applied for the first time some laboratory techniques determining the mechanical and mineral composition of these formations for the purpose of interpreting the environment of deposition of the Upper Cretaceous formations. He did not, however, enter into a discussion of their possible source areas.

The mechanical analysis of each sample rendered five sand fractions ranging from coarse to "extra fine" sand and clay, or six fractions in total (Clark, *et al.*, 1916, p. 120). The boundaries between them do not coincide with those

now commonly used in the United States in sedimentary investigations. Also, the heavy mineral analysis was not carried out in the same detail as the one discussed in this report, as the heavy mineral associations were not quantitatively determined by Goldman. Furthermore, only thirteen samples were subjected to his laboratory investigations. For these reasons, a direct comparison between the results obtained by Goldman and those presented in this report is not possible.

The formations of the Coastal Plain of Delaware were mapped by Miller (Miller, 1906, and Bascom and Miller, 1920), who extended the work done previously in Maryland under the direction of Wm. Bullock Clark. Miller's observations as to the lithology and origin of these formations concurred with those of the Maryland Geological Survey.

In connection with one of the fieldtrips arranged by the 16th International Geological Congress a guidebook was prepared for the Chesapeake Bay Region (Stephenson, *et al.*, 1932). Several outcrops in the banks of the Chesapeake and Delaware Canal were briefly described and characteristic fossils listed.

Carter (1937) investigated the Upper Cretaceous formations exposed in the Chesapeake and Delaware Canal. He was able to divide the Matawan into three formations: the Crosswicks clay, the Englishtown sand and the Marshalltown formation. In doing so, Carter raised the Matawan to the rank of group. The Monmouth, which, according to Carter, is only represented by the Mount Laurel sand in the Chesapeake and Delaware Canal, was also raised to group rank.

The subsurface stratigraphy of the Atlantic Coastal Plain was discussed by Richards (1945) mainly on the basis of paleontological data and well records. Evidence of the presence of Lower Cretaceous sediments in a deep well at Salem (southern New Jersey) was found in the occurrence of heavy minerals which were considered similar to the ones found in the Lower Cretaceous of Maryland (p. 895).

Anderson (1948) described the subsurface geology of three deep test wells on the Eastern Shore of Maryland. Much detailed work was done, particularly on the samples of the Ohio Oil Company's Larry G. Hammond Well No. 1 near Salisbury, Maryland. This well was cored from 1000 feet down to the bottom at 5568 feet; thus, reliable samples were obtained for study of the sedimentary petrography of the Cretaceous and a part of the Tertiary formations. Heavy mineral studies were conducted, resulting in a description of the heavy mineral associations of the various formations, and in the recognition of several mineral zones in the well. The mineral associations of the Cretaceous formations show some similarity to, and also some marked differences from the ones found in northern Delaware(see Chapters IV and V).

The geology of Charles County, Maryland, was described by Dryden and Overbeck (1948). Although this area is located at a considerable distance from northern Delaware (over 100 miles), it is of interest because Dryden investigated the heavy minerals of the Cretaceous and some of the Tertiary formations. Unfortunately, Dryden did not present frequency percentages of the various heavy minerals, but only described the general character of the mineral suites of the formations.

Dryden did not use his heavy mineral work in Charles County for a study of the provenance of the sediments.

Spangler and Peterson (1950) discussed the geology of the Coastal Plain from New Jersey to Virginia, and stirred up controversies about two important stratigraphic problems. The first concerns Spangler and Peterson's belief that the Raritan of New Jersey is equivalent to the formations of the Potomac group (Patuxent, Arundel, Patapsco) and the Raritan formation in Maryland and Delaware. They stated (p. 16):

> In recent years no Lower Cretaceous has been thought to occur either in the outcrop or the subsurface of New Jersey. The writers found in examining the Cretaceous outcrops from New Jersey through Delaware and Maryland that the sediments of the Raritan formation of New Jersey were so similar to the combined sediments of the Raritan formation and Potomac group of Maryland-Delaware that they were led to believe the two were correlative.

Dorf (1952) challenged this correlation on floral and faunal evidence and stated that none of the Potomac group formations can be correlated with any part of the Raritan formation of New Jersey. This does not mean that in New Jersey, at least in the subsurface, no Lower Cretaceous is present. Richards (1945) and later Johnson and Richards (1952) indicated that they believe Lower Cretaceous sediments to be present in a deep well at Salem, New Jersey, at a depth of 1376 feet. Their conclusion was partially based on the heavy minerals from that depth which they reported to be similar to those of the Lower Cretaceous in outcrop in Maryland.

The second controversy concerns the stratigraphy of the marine Upper Cretaceous formations in Delaware, particularly the presence or absence of the Englishtown sand described by Carter (1937). Spangler and Peterson (1950) stated (p. 29):

> The writers examined the sections in the Chesapeake and Delaware Canal and believe that Carter's interpretation of the stratigraphy of the Canal is in error. There is no Englishtown present in the Canal and beds referred to the Englishtown are in reality the Wenonah.

In addition to the Wenonah, Spangler and Peterson recognized the Navesink marl and the Vincentown (Eocene) formation.

In preparation of the study of the sedimentary petrography of the Cretaceous formations in northern Delaware, the Delaware Geological Survey investigated the stratigraphy of the marine Upper Cretaceous deposits exposed in the Chesapeake and Delaware Canal (Groot, *et al.*, 1954). The conclusions are discussed in Chapter III of this report.

CHAPTER II

METHODS OF INVESTIGATION

Methods of mechanical and heavy mineral analyses, presentation of data, and their statistical treatment have been developed relatively recently, and no uniformity in methods has been reached as yet. This is unfortunate, because differences in methods often make it difficult, if not impossible, to compare successfully the results obtained by different workers in the field of sedimentary petrography. It is desirable, therefore, to acquaint the reader with the methods of analysis employed by each individual investigator.

Sampling Techniques

Most of the samples described in this report were obtained from outcrops. Outcrop samples have several advantages over those obtained from drill holes. Firstly, contamination with foreign matter can be easily avoided. Secondly, the sample can be studied in its environment and the occurrence of structural features can be observed. Moreover, chances to collect identifiable fossils are considerably better from outcrops than from drill holes, and correlation between the age and the sedimentary characteristics of a formation is possible. For these reasons all good outcrops in the Coastal Plain of northern Delaware were studied and sampled.

Krumbein and Pettijohn (1938, pp. 14-15) recommended that samples be taken according to a simple rectangular grid, or a logarithmic grid, in order to have an even geographic distribution of sampling sites. Although the desirability of such a systematic pattern is recognized, the distribution of outcrops of the Cretaceous sediments did not permit adherence to any grid system.

Before a sample was taken, the outcrop was thoroughly cleaned of any alien material in order to avoid contamination and erroneous results in the sedimentary analyses. Care was exercised to obtain a sample representative of the formation, or sedimentation unit, so that the mechanical analysis would give accurate information relative to the mode of sedimentation. Thus, samples were always taken from layers which, upon examination with the hand lens, appeared to be homogeneous in mechanical composition.

In cross-bedded sands, samples were usually taken from horizontal beds intercalated with inclined beds, because the former seem to give mineral residues characteristic of the deposit as a whole (Milner, 1952, p. 468).

Exploratory drilling for a water supply in the New Castle area afforded an opportunity to secure a great number of drill samples from depths up to 148 feet below surface. The method of drilling was such that uncontaminated core samples could be obtained. In addition, the Delaware Geological Survey took some samples with a "Shelby tube", consisting of a hollow cylinder 2 feet long and 3 inches in diameter. Suitable samples could be obtained only at shallow depth, generally above the water table, because below this level the drill hole usually caved in, causing contamination to an undetermined degree. The procedure was as follows: a 3½ inch diameter hole was drilled by a rotating auger to the desired depth; the augers were taken out of the hole, the Shelby tube was inserted, and forced into the ground by hydraulic pressure. By noting the exact depth to which the hole was augered, and by observing the depth at which the Shelby tube first hit the bottom of the hole, the amount of cave-in, if any, was determined. In order to avoid contamination the first Shelby tube sample was generally discarded, and the final sample taken at one half or one foot below the depth reached by the auger.

Sample Numbering System

During the preliminary stages of the work, a number of Recent samples were studied in order to obtain an insight into the heavy mineral composition and size frequency distribution of some beach sands, dune sands and floodplain deposits. The beach sands were given numbers in the 0-100 series, the dune sands in the 100 series (101, 102, etc.) and floodplain deposits in the 200 series (201, 202, etc.). Outcrop samples of Cretaceous and Pleistocene sediments were numbered in the 1000 series (1000, 1001, 1002, etc.), and drill samples in the 2000 series (2000, 2001, 2002, etc.). Thus, each number indicates the type of sample investigated.

The localities at which the samples were obtained are shown on plates I and II.

Methods of Mechanical Analysis and Presentation of Data

The mechanical and heavy mineral analyses were carried out by the Bedrijfslaboratorium van het Physisch-geografisch Laboratorium van de Gemeentelijke Universiteit van Amsterdam en het Bodemkundig Laboratorium van het Koninklijk Instituut voor de Tropen, Amsterdam, the Netherlands.

Disaggregation and dispersion of the sample into its constituent particles were the first steps taken in order to obtain reliable data on the mechanical composition of the sediments. Although all samples were taken from unconsolidated materials, some particles were lightly cemented by iron hydroxide or clay, and some silt and clay particles adhered to the larger sand grains. Disaggregation was accomplished by gently crushing the samples by mortar and rubber pestle; the sample was treated with hydrogen peroxide and dilute hydrochloric acid, then washed by decantation and the fine particles brought into suspension by boiling with a solution containing sodium pyrophosphate and sodium carbonate.

The method of sieving was used for mechanical analysis of the coarse portion of the sediment (particles of 62 microns and larger). A Ro-Tap automatic shaking machine was used with U. S. Standard sieves, separating the various

sand fractions. The fine portion of the sediments was analyzed by the pipette method.

The samples were split into fractions according to the National Research Council grade scale (1947). The limits of the various grades, expressed in millimeters, are all powers of 2. Since detail in the mechanical analyses was required, the usual grade limits of 2, 1, ½, ¼ mm, etc. were considered to give class intervals which were too large. Rather than use the ratio 2, the ratio $\sqrt{2}$ was employed. Thus, grade limits were 2, $2^{1/2}$, 2^0, $2^{-1/2}$, etc., or 2, 1.41, 1, 0.71 mm., etc. For ease in plotting the results of the size analysis, the phi (ϕ) scale or negative logarithm to the base 2 of the National Research Council scale was used to prepare cumulative frequency curves and to compute statistical values. Table I describes the grade limits and their phi (ϕ) equivalents as used in this report.

TABLE I

Classification of Texture of Clastic Sediments

Classification	Millimeters	Millimeters (in powers of 2)	Phi (ϕ) Grades
Gravel	greater than 2	greater than 2^1	less than −1
Very coarse sand	2 to 1.41	2^1 to $2^{1/2}$	−1 to −½
Very coarse sand	1.41 to 1	$2^{1/2}$ to 2^0	−½ to 0
Coarse sand	1 to 0.71	2^0 to $2^{-1/2}$	0 to ½
Coarse sand	0.71 to 0.5	$2^{-1/2}$ to 2^{-1}	½ to 1
Medium sand	0.5 to 0.35	2^{-1} to $2^{-3/2}$	1 to 1½
Medium sand	0.35 to 0.25	$2^{-3/2}$ to 2^{-2}	1½ to 2
Fine sand	0.25 to 0.177	2^{-2} to $2^{-5/2}$	2 to 2½
Fine sand	0.177 to 0.125	$2^{-5/2}$ to 2^{-3}	2½ to 3
Very fine sand	0.125 to 0.088	2^{-3} to $2^{-7/2}$	3 to 3½
Very fine sand	0.088 to 0.0625	$2^{-7/2}$ to 2^{-4}	3½ to 4
Very coarse silt	0.0625 to 0.03125	2^{-4} to 2^{-5}	4 to 5
Coarse silt	0.03125 to 0.016	2^{-5} to 2^{-6}	5 to 6
Medium silt	0.016 to 0.008	2^{-6} to 2^{-7}	6 to 7
Fine silt	0.008 to 0.004	2^{-7} to 2^{-8}	7 to 8
Clay	0.004 to 0.002	2^{-8} to 2^{-9}	8 to 9
Clay	smaller than 0.002	smaller than 2^{-9}	Larger than 9

The advantage of the phi scale is not only its convenience in plotting cumulative curves, but also because it provides a logarithmic scale. It has been found that many sands have a symmetrical distribution, or approach one, if the logarithm of grain size or diameter is plotted, rather than the diameter itself.

Cumulative frequence curves representing the mechanical composition of the sediments were plotted on linear probability paper.

The parameters used to describe the sediments are those proposed by Inman (1952). In the United States, the quartile system is often used, in which the basic parameters are the first quartile ($Q_{1\phi}$) or 25th percentile, the median (Md_ϕ) or 50th percentile, and the third quartile ($Q_{3\phi}$) or 75th percentile.

Inman pointed out that (p. 126):

> quartile measures are limited in value since they are based on the central 50 percent of the sediment distribution. Significant differences in the upper or lower 25 percent of a sample are not shown by quartile measurements.

The feature of describing only the central 50 percent of a sediment has also been attacked by Doeglas (1946). Inman (1952) stated that there is (p. 126):

> no particular significance in the geometry of the normal curve, whereas the standard deviation, which is the measure of dispersion or sorting most commonly used in statistics, gives the inflection points in a normal distribution.

Inman prefers to use the 16th and 84th percentile, because they represent diameters one standard deviation either side of the mean in case of a normal cumulative frequency curve, and the 2½ and 97½ percentiles represent diameters two standard deviations either side of the mean. The use of the 2½ and 97½ percentile would have the serious disadvantage, however, of introducing possible inaccuracies, as was shown by Inman (1952). He stated (p. 129):

> Inspection of these figures (cumulative curve of repeated analyses of each of several sediments) indicates that percentiles one standard deviation either side of the median (ϕ_{16} and ϕ_{84}) can be determined with almost the same accuracy as the median, and that there is appreciably greater inaccuracy in percentile measurements two standard deviations either side of the median ($\phi_{2½}$ and $\phi_{97½}$). However, the errors in measuring the 5th and 95th percentile are appreciably less than those for the 2½ and 97½ percentiles. Further, it would be extremely difficult to obtain the 97½ percentile in the analysis of many fine-grained sediments. For these reasons, the 5th and 95th percentile diameters, obtained from the cumulative frequency curve, are used in this study as a working approximation to two standard deviations from the mean.

Inman's statement that the 97½ percentile would be difficult to obtain in fine-grained sediments also applies, to a smaller degree, to the 95th percentile. In some cases, it was not possible to obtain values for ϕ_{95} from the cumulative frequency curve, except by extending the curve beyond the point of the smallest diameter determined (2 microns); in the case of a few clayey fine silts analyzed, even ϕ_{84} could not be directly determined from the curve. In order to find the values for ϕ_{84} and ϕ_{95} for these samples, the curve was extended as a straight line in the general direction of the last portion of the curve. No accuracy can be claimed for this procedure, but it seems the only possible one. However, since the number of very fine-grained samples analyzed was relatively small, this difficulty did not arise often.

The folowing measures were derived from the cumulative frequency curves: ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84} and ϕ_{95} (the 5th, 16th, 50th, 84th and 95th percentiles). ϕ_{50} is a measure of the central tendency of the grain size distribution and is called the median diameter, Md_ϕ. It represents the midpoint of the distribution, and 50 per cent of the sediment is coarser and 50 per cent finer than Md_ϕ. Another measure of the central tendency of the distribution is the mean diameter,

$$M_\phi = \tfrac{1}{2} (\phi_{16} + \phi_{84})$$

Phi deviation is a measure of dispersion or sorting of the sediment, and indicates the degree of "spread" of the curve. The steeper the cumulative frequency curve, the better is the sorting of the sediment. The measures of the average size of the distribution, Md_ϕ and M_ϕ, and of sorting, σ_ϕ, are of particular importance for the practical application of mechanical analyses to ground water problems. Following Inman (1952), the sorting measure is defined as

$$\sigma_\phi = \tfrac{1}{2} (\phi_{84} - \phi_{16})$$

Often the cumulative frequency curves indicate that the grain size distribution is not normal, and not symmetrical. The degree of asymmetry of a distribution is called skewness. Two measures of skewness were proposed by Inman (1952), but only one of them was used in this report. It is defined as

$$\alpha_\phi = \frac{M_\phi - Md_\phi}{\sigma_\phi}$$

Finally a measure of kurtosis was computed, indicating the degree of peakedness of the frequency curve of a distribution. It is defined as

$$\beta_\phi = \frac{\tfrac{1}{2} (\phi_{95} - \phi_5) - \sigma_\phi}{\sigma_\phi}$$

The values of the measures described above are found in Appendix C.

Methods of Heavy Mineral Analysis and Presentation of Data

The fraction of the sample used for heavy mineral analysis falls between 500 and 40 microns; thus, it comprises medium sand, fine sand and some very coarse silt (see table I). This fraction was boiled for a short time in a 10 percent solution of hydrochloric acid and nitric acid in order to clear mineral grains of iron oxide or other coatings. Although there seems to be no unanimity of opinion as to the effects of this treatment on some mineral grains, Reed (1924) stated that (p. 324):

> boiling in 50 percent HCl solution for as long as an hour did not have a visible influence on minerals like apatite, hypersthene and others of a similar degree of stability.

Krumbein and Pettijohn (1938) are of the opinion that with hydrochloric acid treatment (p. 314)

> certain detrital minerals are likely to be partly or wholly dissolved, and a microscopic check is necessary to determine whether or not this has been the case.

The same writers mentioned only one mineral, apatite, which will be completely dissolved by boiling in concentrated HCl; hornblende may be bleached somewhat, and magnetite may show traces of rounding. It must be stated here that no apatite was found in the heavy mineral residues, and this may be due to the acid treatment. The hornblendes did not suffer any significant changes; since only the non-opaque minerals were studied, no observations were made concerning magnetite. Hypersthene, also considered to be subject to complete or partial solution, was present in small percentages in a few samples.

The heavy minerals were separated from the light fraction of the sample by using bromoform ($CHBr_3$) having a specific gravity of 2.87 at 20°C. Frequent checks of the specific gravity were made, and care was taken to prevent convection currents in the bromoform. After separation, the minerals were mounted in Canada balsam on rectangular glass slides. If the amount of heavies warranted it, several slides were made of each sample. The minerals were determined with a polarizing microscope equipped with a mechanical stage. The procedure followed for counting the heavy minerals is the same as the one described by Edelman. Briefly, it consists of determining one hundred non-opaque minerals successively coming under the cross-hairs of the microscope by moving the slide with the mechanical stage (the line counting method). The opaque minerals are counted, but they are not determined. The frequencies with which various non-opaques occur on a slide, are expressed in percentages. In addition, the percentages of opaques are given.

The writer is aware of the fact that some workers in the field of sedimentary petrology consider a count of one hundred non-opaque grains insufficient for obtaining accurate mineral percentages. However, Doeglas (1940) pointed out that a count of one hundred non-opaques of a great number of samples within a certain area or stratigraphic interval is to be preferred over an investigation of a small number of samples with a count greater than one hundred, provided the purpose of the investigation is to establish petrological provinces or heavy mineral suites of formations for correlation and provenance study, rather than exact sediment-petrographic work *per se.* Moreover, the study of a great number of samples has the advantage of gaining a knowledge of the areal and vertical variations of the mineral content of a deposit which could not be obtained by a grain count greater than one hundred for the same expenditure of time and funds.

CHAPTER III

THE CRETACEOUS FORMATIONS OF NORTHERN DELAWARE

A DETAILED ACCOUNT of the mineral and mechanical composition of the Cretaceous sedimentary rocks of northern Delaware will be given in the following chapters, but a discussion of their stratigraphy and lithologic characteristics is considered necessary here, not only to acquaint the reader with the general geologic setting, but also to describe features which can be observed in the field and which have a bearing on problems of provenance, mode of deposition and paleogeography.

In the eastern United States there are two great geologic units: the Appalachian Mountain system and the Atlantic Plain. The Appalachian region is divided into two major parts: an area of sedimentary rocks of Cambrian to Permian age in the west, and an area of tightly folded crystalline rocks in the east. The exact age of some of these crystalline rocks is still a matter of discussion, but they are generally considered to be pre-Cambrian and early Paleozoic in age, and consequently, most of them are older than the sedimentary rocks to the west. Therefore, the Appalachian region is said to consist of the Newer Appalachians in the west, and the Older Appalachians in the east.

The Older Appalachians include the Piedmont Province and the Blue Ridge, and the Newer Appalachians comprise the Valley and Ridge Province and the Appalachian Plateau (see fig. 1). The Piedmont Province consists of an upland underlain by pre-Cambrian and lower Paleozoic crystalline rocks of sedimentary, intrusive, and extrusive origin, and a lowland consisting of down-faulted blocks filled with Triassic sandstones and shales.

In Delaware and adjacent Pennsylvania and Maryland, the Piedmont Province consists of tightly folded pre-Cambrian and lower Paleozoic metamorphic rocks and intrusive igneous rocks. The metamorphic rocks are represented by the Baltimore gneiss, the Wissahickon mica gneiss which is schistose in places, and the Cockeysville marble. Igneous and meta-igneous rocks found in Delaware are various gabbros—quartz gabbro, hypersthene gabbro, hornblende gabbro and olivine gabbro—in large intrusive bodies and dikes, granodiorite, some serpentine and numerous pegmatite dikes.

The Blue Ridge forms a long mountain ridge consisting of pre-Cambrian crystalline rocks, and Lower Cambrian conglomerates, slates and quartzites.

The Valley and Ridge Province of the Newer Appalachians is underlain by Cambrian and Ordovician limestones and shales, forming a relatively low and flat valley, and Silurian, Devonian and Mississippian sandstones, shales and limestones which, owing to differential erosion, form a series of ridges and valleys. Finally, the Appalachian Plateau is underlain by slightly deformed shales and sandstones of the Carboniferous coal measures, and Permian barren measures.

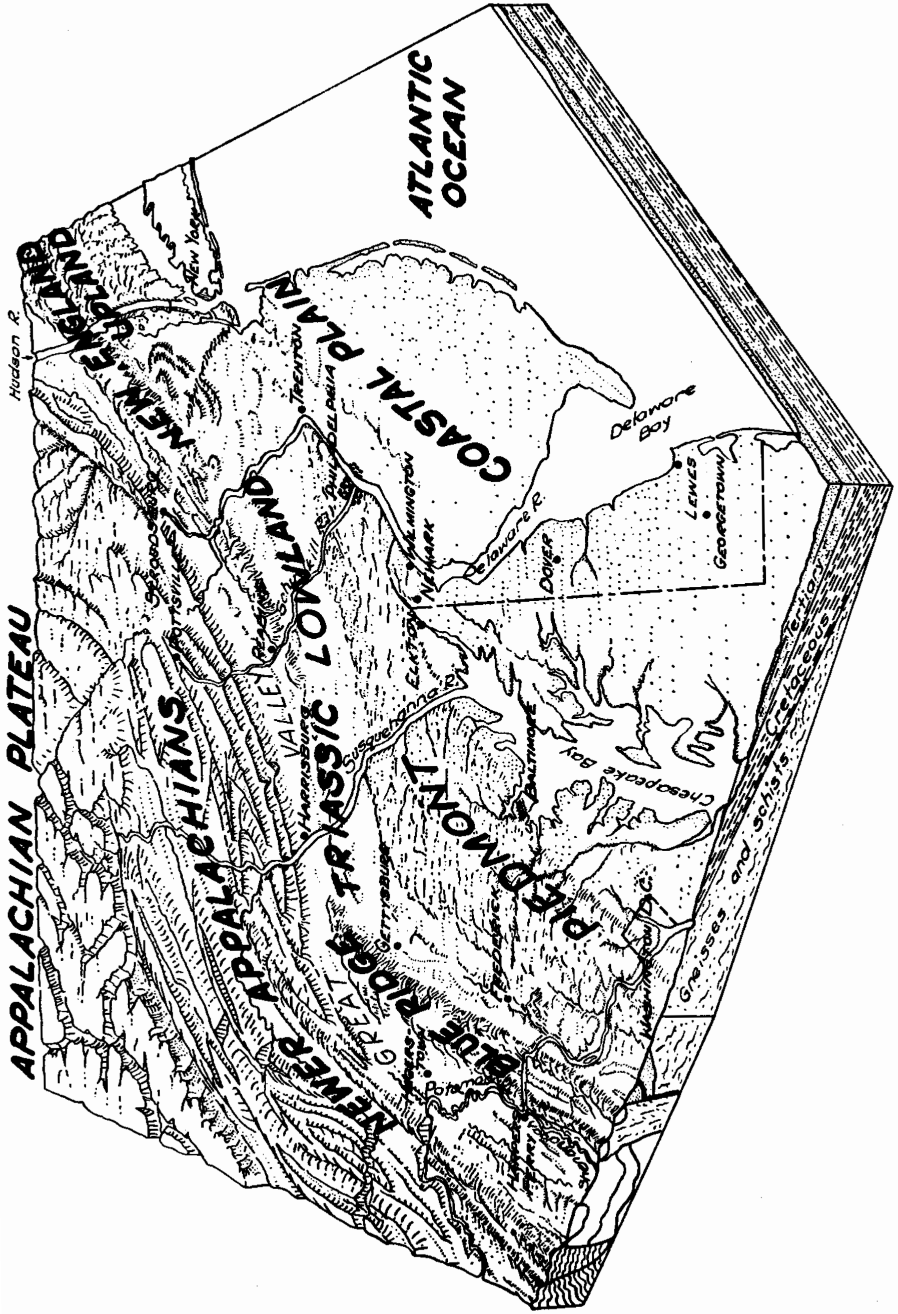


Figure 1. Block diagram showing the physiographic provinces of the Appalachian region and the Coastal Plain. Modified from an original by Erwin Raisz (Stephenson, *et al.*, 1932).

The Atlantic Plain, the subaerial portion of which is called the Coastal Plain, is separated from the Piedmont Province by the Fall Zone. This appropriate name has been given to a narrow zone in which the streams descend in rapids or falls from the Piedmont Province to the Coastal Plain, which, because it is underlain by unconsolidated sedimentary rocks, is subject to more rapid erosion than the resistant crystalline rocks of the Piedmont.

The formations of the Coastal Plain consist of a wedge-like series of generally unconsolidated sands, gravels, and clays, gradually thickening toward the southeast. These rocks are of Cretaceous age and younger, and were deposited on the subsiding eastern margin of the Older Appalachians. The strike of the sediments is approximately northeast, and they dip to the southeast.

The sedimentary formations in northern Delaware described by Miller (Bascom and Miller, 1920) are: the Patuxent and Patapsco formations of Early Cretaceous age, the Raritan, Magothy, Matawan, and Monmouth formations of Late Cretaceous age, and the Pleistocene. The Patapsco is now considered to be of Late Cretaceous age. The Cretaceous formations mentioned here have also been described in Maryland (Clark, *et al.*, 1911, 1916).

The mapping of the Cretaceous formations present in northern Delaware has created many difficulties in the past. This is particularly true for the non-marine Patuxent, Patapsco and Raritan formations which were mapped by Miller (Bascom and Miller, 1920). These formations are so similar in lithology and so devoid of recognizable fossils in this area, that it is not clear on what basis Miller differentiated them. In fact, the question arises whether or not they deserve to be called formations at all. If the definition of the term "formation" involves a mappable geologic unit with definite contacts (i.e. the top and bottom of a sedimentary formation), recognizable and capable of being traced in the field, then the Patuxent, Patapsco and Raritan can hardly be called formations. If, however, the word "formation" is used to designate a deposit of a certain age, as opposed to deposits similar or dissimilar in lithology of different *age*, then the term may be applied to the Patuxent, Patapsco and Raritan, because some workers have found that these sediments can be differentiated on the basis of their fossil flora, at least in parts of Maryland and Virginia (Clark, *et al.*, 1911). In Delaware, neither lithologic nor fossil criteria permit this differentiation with any degree of certainty. However, the deposits can be divided into two zones on the basis of their heavy mineral content. The lower, or older, of these zones contains a mineral suite similar to that of the Patuxent formation in the Baltimore area, Maryland (Bennett and Meyer, 1952), whereas the upper, or younger zone is mineralogically similar to the Patapsco. Those sediments which were mapped by Miller (Bascom and Miller, 1920) as Raritan, contain the same mineral suite as the Patapsco of Maryland. As long as there is no conclusive evidence that the mineral zones in Delaware coincide precisely with lithologic or mappable geologic units, as the definition of the term "formation" requires, nor any demonstrable correlation with fossil horizons, it is considered advisable not to apply the term "formation", but to discuss the sediments involved in terms of mineral zones, keeping in mind their correlation with the formations in Maryland. This correlation is further discussed in Chapter IV.

In view of the above discussion the mineral zone correlated with the Patuxent formation is called the Patuxent zone; the same procedure is followed in naming the Patapsco-Raritan zone.

The Magothy formation is found in New Jersey, Delaware and Maryland; it is well exposed in the Chesapeake and Delaware Canal. It is overlain by a series of marine Upper Cretaceous formations, described by Groot, Organist and Richards (1954). The oldest formation of marine origin is the Merchantville, which is overlain by the Wenonah. These two formations belong to the Matawan group, which is conformably overlain by the Monmouth group consisting of the Mount Laurel-Navesink and Red Bank formations.

The Cretaceous stratigraphy of the Coastal Plain of northern Delaware is summarized in table II.

TABLE II

Cretaceous Stratigraphy of the Coastal Plain of Northern Delaware

		Formation or Zone	*Brief description*
Upper Cretaceous	Monmouth group	Red Bank	Reddish-yellow to reddish-brown with some rust-brown spots, fine to medium, well-sorted, subrounded, slightly "dirty", quartz sand with some glauconite.
		Navesink-Mount Laurel	Dark greenish-brown with numerous rust-brown spots, very fine to fine, poorly-sorted, subangular, glauconitic, quartz sand with some silt and clay, grading into dark green to black, coarse silt with abundant glauconite.
	Matawan group	Wenonah	Rust-brown and gray, well-stratified, fine, subangular, well-sorted, micaceous, quartz sand with some glauconite.
		Merchantville	Dark greenish-brown, very fine, subangular, poorly- to well-sorted, micaceous, glauconitic, quartz sand with considerable silt and clay, grading into a very coarse to coarse, poorly-sorted, micaceous, glauconitic silt.
		unconformity	
		Magothy	White, lignitic sands and black clays with abundant carbonaceous matter.
		unconformity	
		Raritan-Patapsco zone	Predominantly red, white, and gray, sandy clays, and white, brown, and red sands with thin gravel layers.
		unconformity	
Lower Cretaceous		Patuxent zone	Predominantly white and gray, feldspathic sands with thin gravel beds, and red, white, and yellow silts and clays.

The Patuxent zone sediments consist of predominantly white, gray, buff, and light-brown, fine to coarse, usually angular, well-sorted to poorly-sorted

sands, often displaying small-scale cross bedding. The sands contain intraformational conglomerates, and in nearby Maryland coarse basal gravels have been reported (Clark, *et al.*, 1911, p. 59). The sands contain varying amounts of feldspar, although, in Delaware, never enough to warrant the term arkose.

The silts and clays are often sandy and gritty, plastic or hard, and display a variety of colors. Most are variegated silts with red, white, and gray the predominant colors. Some clays are black due to finely disseminated carbonaceous material.

The sands of the Patuxent zone grade laterally into sandy silts and clays in short distances, and the sands are usually channel sands rather than sheet sands. In the vicinity of New Castle (for location see map, pl. I) such a subsurface channel sand was discovered and its extent outlined with the aid of numerous test borings.

The Patapsco-Raritan zone immediately overlies the Patuxent zone. It consists largely of variegated sandy silts and clays, predominantly red in color, but white, yellow, and drab clays have also been observed. Intraformational conglomerates have been found, although they are of limited extent. A little kaolinized feldspar is present, but less than in the Patuxent zone.

The upper portion of this zone is generally more sandy than the lower portion, as evidenced by logs of wells drilled in the Delaware City area. The sands are usually white or gray, although brown and red sands occur also. In Maryland, the Raritan formation is described as more sandy than the underlying Patapsco. Therefore, this sandy upper part of the Patapsco-Raritan zone may be correlated with the Raritan formation of Maryland, although it is impossible to establish an accurate boundary between these two parts in Delaware.

In nearby Maryland, plant fossils indicate an earlier age for the sediments of the Patapsco-Raritan than those of the Patuxent zone.

In Maryland, the Patapsco formation is underlain by the Arundel clay, which is apparently absent in Delaware. This Arundel clay (Clark, *et al.*, 1911, p. 66) overlies the Patuxent formation unconformably, occupying what appears to be old drainage lines therein. In Delaware there is evidence that before the deposition of the Patapsco-Raritan sediments took place, the Patuxent zone was also eroded, and therefore, the Patuxent and Patapsco-Raritan zones are separated by an unconformity. This evidence is discussed in Chapter V.

The Magothy formation—in contrast to the sediments described above—is very well exposed, particularly in the south bank of the Chesapeake and Delaware Canal where it can be seen for a distance of several miles. It consists mainly of white, "sugary", subangular, well-sorted sands with lignitized branches and tree trunks, and lenses of black, carbonaceous clays. In several localities marcasite and pyritized or marcasitized lignite were found. The formation cannot be subdivided into distinct beds of clay and sand occurring over great distances. In some places, black clay beds occur at the base of the formation, on top of the variegated clays of the Patapsco-Raritan zone; in other localities the carbonaceous clay is found at the top of the Magothy formation.

The marine Upper Cretaceous formations were investigated by Groot, Organist and Richards (1954) and the following descriptions were taken from their report.

The Merchantville formation, which is well exposed in the Chesapeake and Delaware Canal

> grades from a dark-blue to black, very coarse to coarse, poorly-sorted, micaceous, glauconitic silt, to a dark greenish-brown, very fine, subangular, poorly- to well-sorted, micaceous, glauconitic, quartz sand with considerable silt and clay (p. 23).

The lithology of the Merchantville in Delaware is similar to that of the same formation in New Jersey.

The Wenonah formation was described as follows (p. 25):

> The Wenonah is composed of rust-brown and gray, well-stratified, fine, subangular, well-sorted, micaceous, quartz sand, with some glauconite and numerous cylindrical tubes which have been called *Halymenites major* Lesquereux.

These tubes also occur in the Wenonah of New Jersey which is lithologically similar to the formation exposed in the banks of the Chesapeake and Delaware Canal.

The two marine formations described above form the Matawan group, which is overlain by the Mount Laurel-Navesink and Red Bank formations of the Monmouth group.

> There is a gradual change downward within the Mount Laurel-Navesink formation from a dark greenish-brown with numerous rust-brown spots, very fine to fine, poorly-sorted, subangular, glauconitic, quartz sand with some silt and clay and little mica, to a dark green to black coarse silt with abundant glauconite (p. 26).

The Mount Laurel-Navesink grades upward into the Red Bank formation which was described as follows (p. 28):

> The Red Bank is a reddish-yellow to reddish-brown fine to medium, well-sorted, subrounded, slightly "dirty", quartz sand with some glauconite and black minerals, and a little mica and feldspar. Most of the quartz grains are stained with iron hydroxide.

The Cretaceous formations of northern Delaware are unconformably overlain by Pleistocene deposits.

CHAPTER IV

THE HEAVY MINERAL CONTENT OF THE CRETACEOUS FORMATIONS OF NORTHERN DELAWARE

General Considerations

IT HAS BEEN observed that the heavy mineral content of a formation can change in the direction of strike or dip, and that mineral assemblages do not necessarily coincide with formations. Cogen (1940) stated (p. 2071):

> Mineral-zone boundaries need not of necessity coincide with formation boundaries based on paleontology or lithology, but may occur within formations and may transect formation boundaries and faunal horizons.

In northern Delaware, however, it was found that, in general, the outcropping formations have characteristic mineral suites, and thus that formations do coincide with mineral zones. In some instances, it could be proven that the mineral suite of a certain formation outcropping in northern Delaware has the same, or very similar, heavy mineral content as its equivalent in Maryland or New Jersey. This is particularly true for the marine Upper Cretaceous formations, indicating that at least along the strike there is little variation in their mineral suites. In the directions of dip, however, some marked changes occur. The similarities and differences in the mineral content of the formations of the Coastal Plain are further discussed in the following pages, and are interpreted in Chapter V.

Doeglas (1940) pointed out that it is necessary in studies of regional sedimentary petrology to collect samples from a large area or from a large stratigraphic interval. He stated (p. 104):

> By "large" we mean here that it should include many petrological changes. This again depends on the object to be studied and the best manner is to start with the examination of a few samples distributed uniformly over a large stratigraphical interval or area and then to continue the investigation with as many samples as necessary for the interpretation of the mineral data.

In this study it was possible to obtain samples from a large stratigraphic interval, but it was not feasible to collect samples from a large area; therefore, it was necessary to rely on the data which already existed, with the obvious disadvantage that the results obtained by other workers were not always easy to compare with the data collected by the present writer owing to differences in the techniques used. For instance, in other studies (Anderson, 1948; Bennett and Meyer, 1952) alterites were apparently never counted, at least these altered minerals are not mentioned. Moreover, other investigators have sometimes used a different sand fraction, or failed to state the exact methods used in separating the heavy minerals from the sands.

In spite of the difficulties arising from the lack of uniformity in techniques, comparison of mineral suites has been attempted between the formations in northern Delaware and the same formations found in some deep wells in Maryland. In addition, some samples of the marine Upper Cretaceous formations in New Jersey were studied in order to obtain data outside the relatively small area of northern Delaware.

The mineral suites found in the Cretaceous formations of northern Delaware are shown in table III.

TABLE III

Heavy Mineral Suites of the Cretaceous Formations of Northern Delaware

Characteristic Mineral Suite	Formation or Zone
Epidote—staurolite—chloritoid	Red Bank formation
Epidote—chloritoid—garnet	Mt. Laurel-Navesink formation
Epidote—chloritoid	Wenonah formation
Epidote—chloritoid—garnet	Merchantville formation
Staurolite—tourmaline with varying amounts of alterites	Magothy formation
Zircon—rutile with varying amounts of tourmaline and abundant alterites	Patapsco-Raritan zone
Staurolite—zircon—tourmaline—kyanite with varying amounts of alterites	Patuxent zone

The minerals called characteristic for each formation are not necessarily the most abundant ones. For instance, chloritoid seldom occurs in percentages greater than 10 but it is nevertheless a very persistent and characteristic mineral in the marine Upper Cretaceous formations. Again, garnet is never prominent or persistent in any formation except the Merchantville and the Mount Laurel-Navesink, although even in these formations it does not occur in really large percentages.

The average, maximum and minimum frequency percentages of the common heavy minerals of the various zones and formations are summarized in table IV.

Presentation of the results of heavy mineral analyses, and particularly, attempts to correlate on the basis of heavy minerals, must take into consideration the errors of analysis, and the probable errors of sampling and correlation. Dryden (1931) was one of the first to propound this problem. The errors in heavy mineral analysis of beach sand were the subject of a rather exhaustive determination by Rasmussen (1939). He found that the average sampling error was about 10 per cent, but that there was a particular sampling error associated with each mineral in the suite. The laboratory error, of splitting, mounting and counting, is of approximately the same magnitude as the sampling error.

In spite of these manifest errors, the heavy mineral correlation on the basis of frequency percentages is easily apparent for the sediments sampled in this study. This is the more remarkable when it is considered that a relatively random sample taken in outcrop represents a large sedimentation unit in area and in space.

In order to express the error factor, the probable error from the mean is a useful statistical device. It denotes the amount that must be added to, or subtracted from, the mean to obtain the two extreme figures within which there is an even chance that the true value lies. There is an even chance also that it lies outside these limits (Post, 1924).

The probable error, PE, is roughly ⅔ of the standard deviation σ, or

$$PE = 0.6745\ \sigma$$

and

$$\sigma = \sqrt{\frac{\Sigma d^2}{n}}$$

where d is the deviation of a mineral percentage from the mean, and n is the number of samples.

The same probable error in a mineral which comprises a large percentage of the suite is relatively a smaller error than in a mineral comprising only a small percentage. Therefore the relative error, RE, is defined as the percent ratio of the probable error to the mean, that is,

$$RE = \frac{PE}{\%\ Ma}$$

where % Ma is the arithmetic mean percentage.

The % Ma, σ, PE, and RE were determined for each mineral of the Red Bank formation; this formation was chosen for these statistical computations because only 8 samples were available, and the chances of introducing significant errors were greater, therefore, than in any other formation discussed. After the relative error, RE, was determined, the maximum percentage, P_{max}, and minimum percentage, P_{min}, were computed. The results are shown in the upper column of table IV. Percentages less than 0.5 are totaled as T, for trace.

Although the relative errors are considerable, their significance from a geologic point of view is small. Much more significant than absolute percentages is the proportion of components within a suite, one to the other. These proportions in the sediments of Delaware are sufficiently distinctive so that the samples of each formation are readily identifiable.

Although it is realized that average percentages of heavy minerals conceal variations in frequency percentages within one formation—variations which in themselves are of significance— table IV has been included because it indi-

TABLE IV

Heavy Mineral Frequency Percentages of Cretaceous Sediments in Northern Delaware
(for explanation see text)

Formation or Mineral Zone		Opaque	Tourmaline	Zircon	Garnet	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Sillimanite	Fibrolite	Chloritoid	Epidote	Alterites	Hornblende	Actinolite	Tremolite	Remarks
	Pmax.	52	12	6	3	12				30	11	6		5	22	13	2			
Red Bank	%Ma	47	10	5	2	8	T	0	T	26	7	5	T	4	19	10	1	T	T	Based on 8 samples.
	Pmin.	43	7	3	1	3				23	3	4		3	15	8	0			
	Min. %	37	6	1	0	5	0	0	0	20	3	2	0	2	11	5	0	0	0	
Red Bank	Max. %	56	16	7	3	12	2	0	1	34	10	9	1	7	25	16	2	1	1	Based on 8 samples.
	Av. %	47	10	5	2	8	1	0	1	26	7	5	0	4	19	10	1	0	0	
Mt. Laurel-	Min. %	25	4	3	0	4	0	0	0	2	0	1	0	1	12	3	0	0	0	
Navesink	Max. %	66	14	22	20	18	4	1	1	28	7	5	1	12	26	15	3	1	0	Based on 22 samples.
	Av. %	46	9	12	12	10	2	0	1	13	3	3	0	6	19	8	1	0	0	
	Min. %	17	5	2	0	6	0	0	0	4	1	0	0	7	15	6	0	0	0	
Wenonah	Max. %	64	16	16	9	16	5	0	2	14	5	7	0	15	38	23	1	1	0	Based on 16 samples.
	Av. %	42	10	10	3	11	2	0	1	11	3	3	0	10	24	12	0	0	0	
	Min. %	4	3	2	0	4	0	0	0	6	0	0	0	4	10	5	0	0	0	
Merchantville	Max. %	60	12	19	17	13	3	0	2	20	7	5	1	15	28	13	1	0	0	Based on 16 samples.
	Av. %	40	8	10	14	10	1	0	1	9	2	2	0	10	22	9	0	0	0	
	Min. %	4	3	1	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	
Magothy	Max. %	54	27	24	1	14	6	0	1	84	7	1	4	1	1	44	1	1	1	Based on 26 samples.
	Av. %	22	12	9	0	3	1	0	0	59	3	0	1	0	0	12	0	0	0	
Patapsco-	Min. %	2	2	15	0	4	0	0	0	0	0	0	0	0	0	9	0	0	0	
Raritan	Max. %	54	25	56	2	33	13	3	3	14	2	3	0	2	4	62	3	0	0	Based on 54 samples.
	Av. %	20	11	33	0	15	4	0	0	2	0	0	0	0	0	34	0	0	0	
	Min. %	3	3	2	0	0	0	0	0	19	0	0	0	0	0	1	0	0	0	
Patuxent	Max. %	63	28	27	1	18	6	1	2	80	17	1	1	1	2	29	2	0	0	Based on 29 samples.
	Av. %	33	13	12	0	5	2	0	0	50	5	0	0	0	0	11	0	0	0	

cates, in a quantitative way, the composition of the mineral zones in the Cretaceous of Northern Delaware, and therefore is useful for the purpose of stratigraphic correlation.

Appendix A lists heavy mineral analyses of Cretaceous, Pleistocene, and

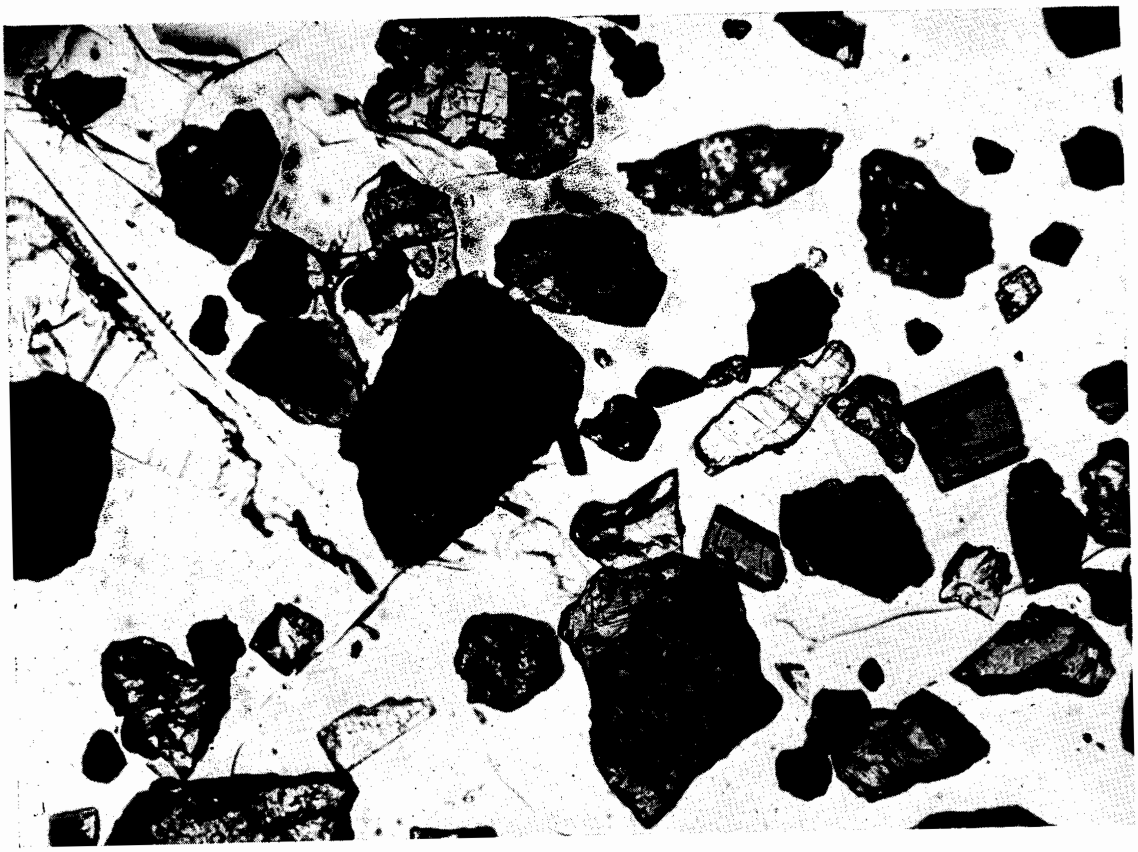


Figure 2a.

Photomicrographs of representative mineral slides of the Cretaceous formations.

Patuxent zone. Magnification 55x.

Large staurolite grains, some kyanite and tourmaline grains.

Figure 2b.

Photomicrographs of representative mineral slides of the Cretaceous formations.

Patapsco-Raritan zone. Magnification 55x.

The large transparent grain is tourmaline; many small zircons.

Recent samples. Some heavy mineral frequencies of the Cretaceous formations of New Jersey are presented in Appendix B.

Photomicrographs of representative slides are shown in figure 2.

Patuxent Zone

The mineral suite of the sediments correlated with the Patuxent formation is a staurolite-zircon-tourmaline-kyanite suite.

Staurolite is by far the most abundant mineral of this zone. In 29 samples,

Figure 2c.

Photomicrographs of representative mineral slides of the Cretaceous formations.

Magothy formation. Magnification 55x.

Very large kyanite and tourmaline grains; smaller staurolite and zircon grains.

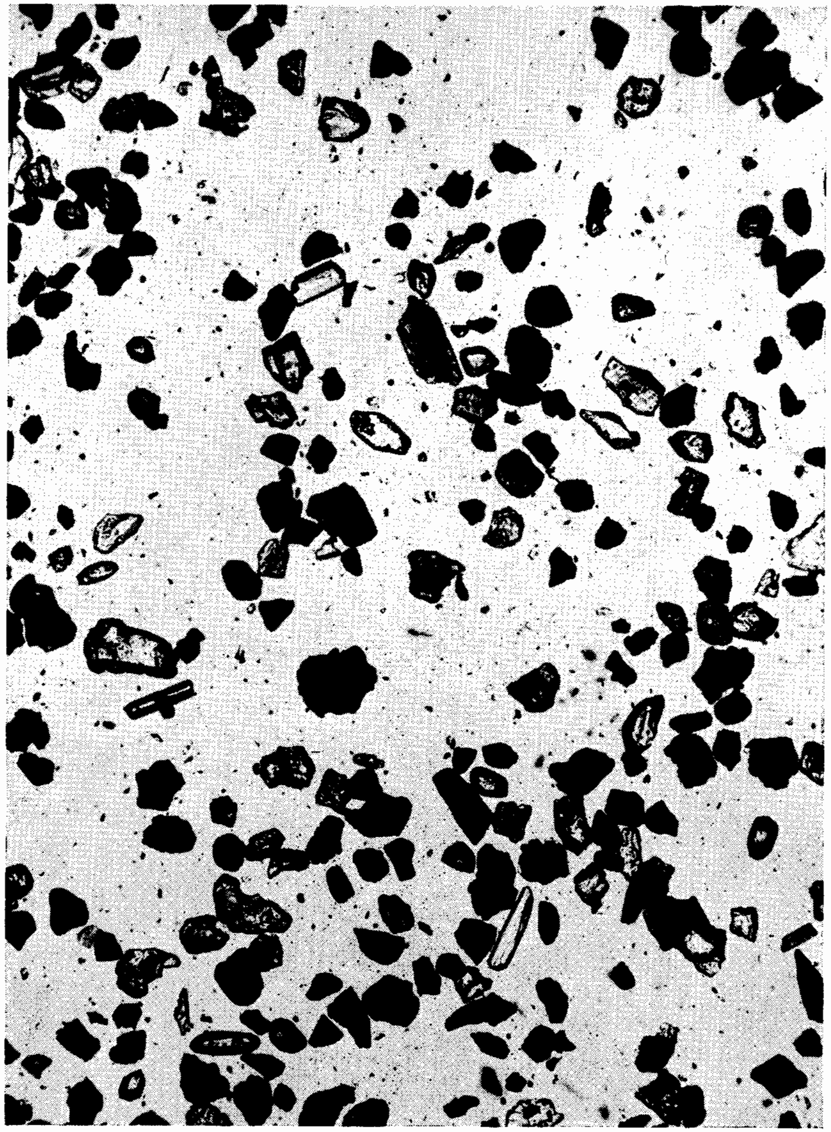


Figure 2d.

Photomicrographs of representative mineral slides of the Cretaceous formations.
Marine Upper Cretaceous, Merchantville formation.
Magnification 55x. Many epidote grains.

the average percentage of staurolite is 50, but percentages as high as 80 were found in a few samples. Zircon averages about 13%, tourmaline 12%, and kyanite and rutile each approximately 5%. The percentage of alterites varies a great deal, and averages about 11%. Anatase, sillimanite and epidote are very rare.

Some typical examples of this heavy mineral suite are shown in figure 3. Analyses of Patuxent, Patapsco-Raritan and Pleistocene deposits are graphically presented in figure 4.

The most outstanding mineral in this suite is staurolite. It is usually straw-yellow or brownish-yellow; the grains are large compared to other mineral grains of the suite; most are subangular, and have a fresh appearance; they often have numerous inclusions. On all slides some staurolite grains were found showing good cleavage resulting in saw-tooth termination of the grains (see fig. 5). Anderson (1948, p. 21, and fig. 10) observed the same phenomenon in a part of the Patuxent and Arundel-Patapsco formations in the deep test hole in Salisbury, Maryland.

The zircon grains are usually colorless and often without inclusions; many grains are nearly euhedral, although the edges are rounded. In general, the grains appear quite fresh.

The tourmaline grains are usually brown, angular to subangular, and fresh.

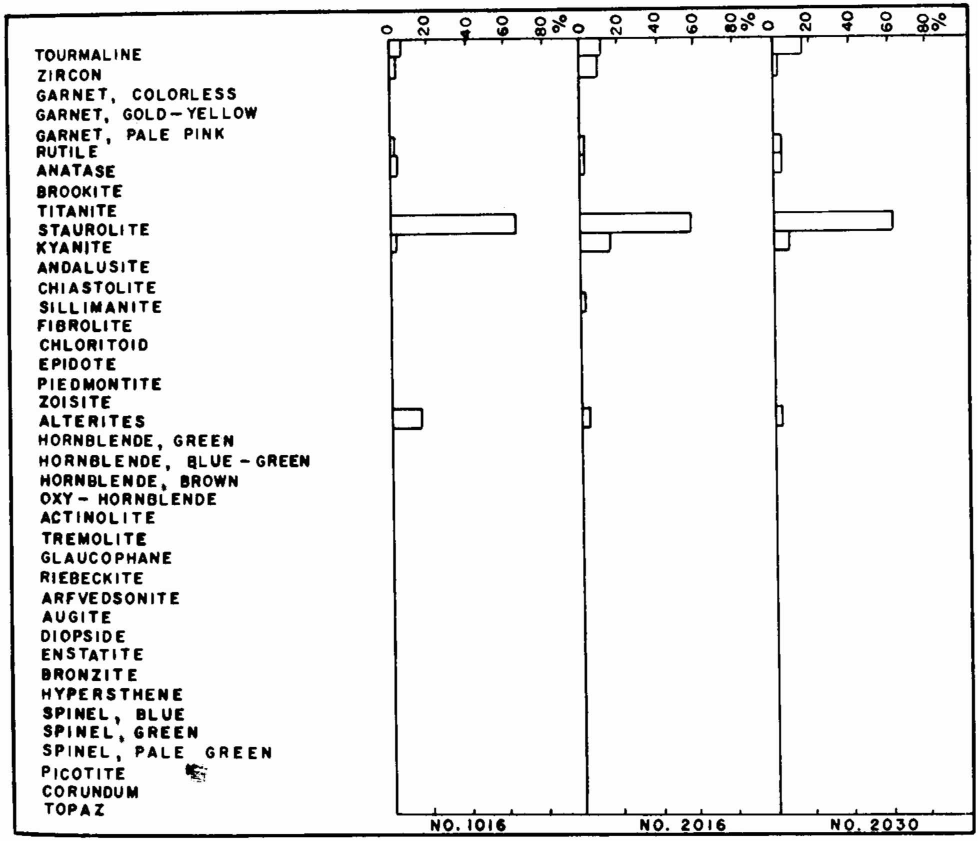


Figure 3. Examples of the heavy mineral suite of the Patuxent zone.

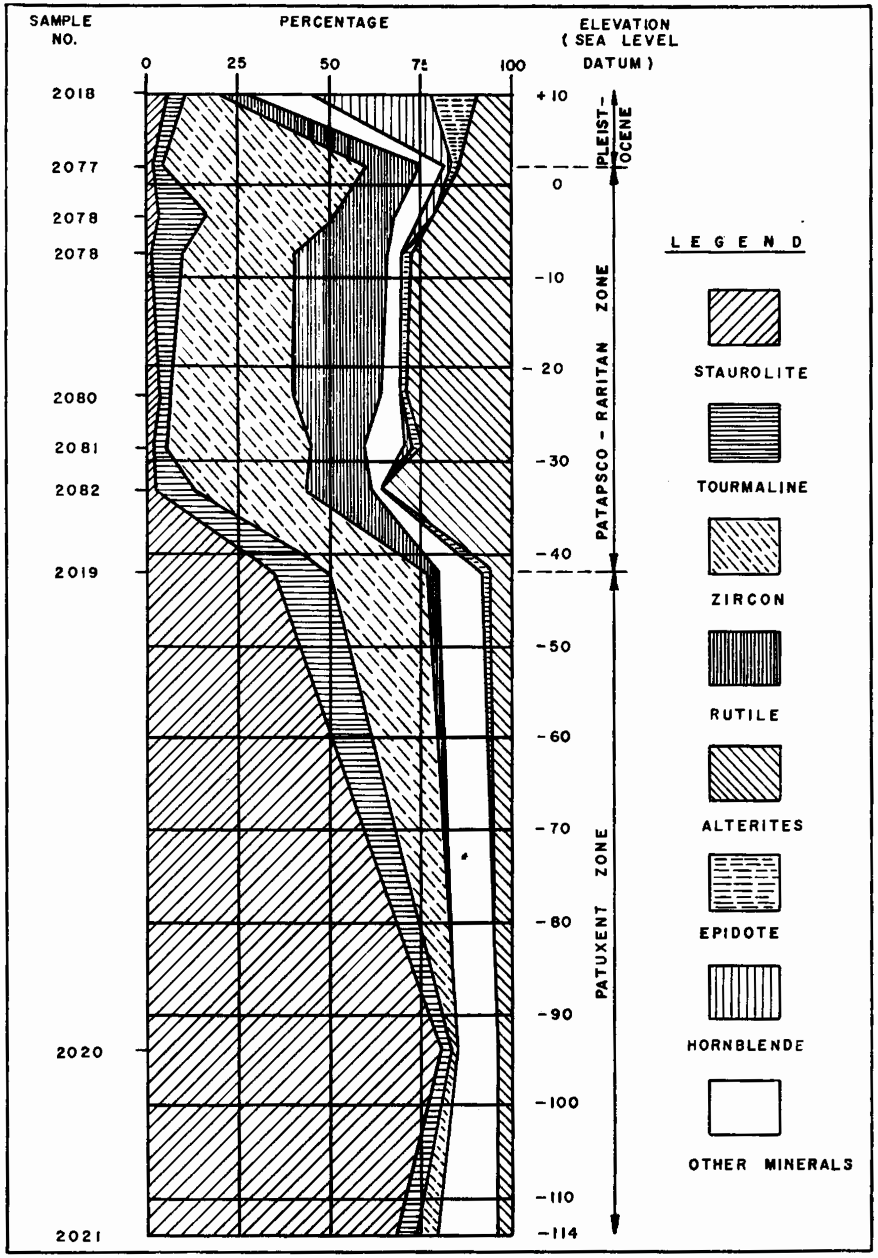


Figure 4. Heavy mineral suites of the Patuxent, Patapsco-Raritan, and Pleistocene of test hole 25, New Castle, Delaware.

Kyanite is colorless and often occurs in large slender prisms having a "bladed" appearance. Some kyanite grains have mineral and liquid inclusions, but most are remarkably free of them. The grains are usually subangular.

The mineral suite described above is similar to the one described by Bennett and Meyer (1952). They stated (p. 37):

> The heavy mineral suite of the Patuxent formation is composed predominantly of zircon, tourmaline and staurolite, with minor amounts of rutile, sillimanite and kyanite. The most significant feature of the Patuxent formation is the relatively high content of staurolite.

Anderson (1948) described the heavy mineral content of the Patuxent formation in the deep test hole in Salisbury, Maryland as follows:

> The Patuxent formation may be classified as a garnet-staurolite-zircon zone. Garnet is abundant and is represented by colorless, pink and deep-brown species . . . staurolite is of the deep-orange type and commonly has saw-tooth edges. It is more abundant in the upper 250 feet of the formation. Zircon, although present throughout the entire well section, is more abundant in certain parts than in others and is on the whole more abundant in the Patuxent than in the overlying Arundel-Patapsco section. The grains are predominantly colorless, slightly rounded, and contain numerous inclusions.

The main difference between the mineral suite described by Anderson for the upper 250 feet of the Patuxent and the suite correlated with the Patuxent in northern Delaware is in the garnet content of this formation. In the Salisbury test hole garnet percentages are high, whereas in Delaware garnet is very rare in the Lower Cretaceous.

The presence of abundant staurolite in the upper portion of the Patuxent formation in the deep test hole at Salisbury, as well as in the Baltimore area,

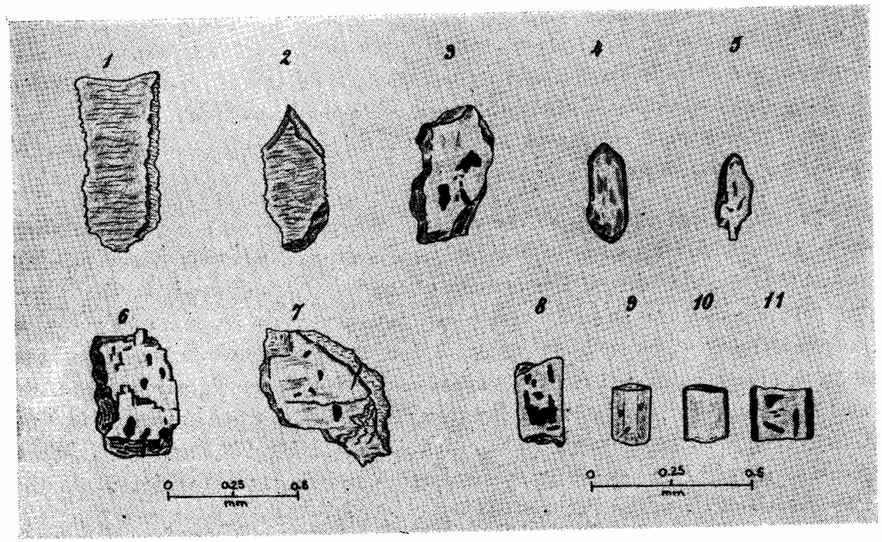


Figure 5. Specimens of mineral grains of the Patuxent zone

1 - 3	**Staurolite**	**6 - 7**	**Kyanite**
4 - 5	**Zircon**	**8 - 11**	**Tourmaline**

and in addition, the decrease in staurolite percentage in the overlying Arundel and Patapsco, indicate that the staurolite-tourmaline-zircon zone in northern Delaware can be correlated with the Patuxent formation in the Baltimore area, and possibly with the upper portion of the Patuxent in the Salisbury well.

Dryden (Dryden and Overbeck, 1948) investigated the heavy minerals of the Cretaceous and Tertiary formations in Charles County, Maryland. On the basis of analysis of twenty-five samples of the Patuxent, Arundel and Patapsco formations, he stated that they contain (p. 33)

> abundant staurolite, common kyanite, tourmaline and zircon, rare sillimanite and epidote.

Furthermore, Dryden observed that the grains

> are large, fresh and angular, and garnet and chloritoid are conspicuous by their absence.

Unfortunately Dryden did not differentiate between the suites of the Patuxent, Arundel and Patapsco, and this lack of detail makes it impossible to compare his analyses with the ones of the same formations in northern Delaware. His description compares very well, however, with that of the Patuxent zone of northern Delaware.

Patapsco-Raritan Zone

This zone contains relatively high percentages of zircon and rutile and varying amounts of tourmaline and alterites. Zircon is the most abundant mineral of this zone, averaging, in 54 samples, about 33%. It is followed by rutile with an average of about 15%. Tourmaline is consistently present, but varies considerably in amount. Alterites are usually abundant. Small amounts of anatase, brookite and titanite are generally present. Epidote and sillimanite are found in very small quantities in a few samples. Typical examples of the mineral content of this zone are shown in figure 6a-d, and drawings of specimens of mineral grains are presented in figure 7.

The mechanical analyses of the samples of this suite show a great variation in texture, which apparently has no great influence on their heavy mineral content. Thus, the mineral frequencies of sands, silts, and sandy or silty clays are very similar and can be readily distinguished from the mineral suites of the underlying and overlying zones. A few samples, however, seem to have some characteristics of both the zone correlated with the Patuxent formation and the zone correlated with the Patapsco formation. In test hole #27 in New Castle (for location see plate I) samples #2083, 2084, 2085 and 2086 show a gradual increase in staurolite percentage indicating a transition from the Patapsco-Raritan to the Patuxent suites.

The suite discussed here differs from others not only in its mineral content, but also in the degree of weathering and abrasion of the mineral grains. Zircon is often pitted and worn, always small and rounded, and far from the euhedral

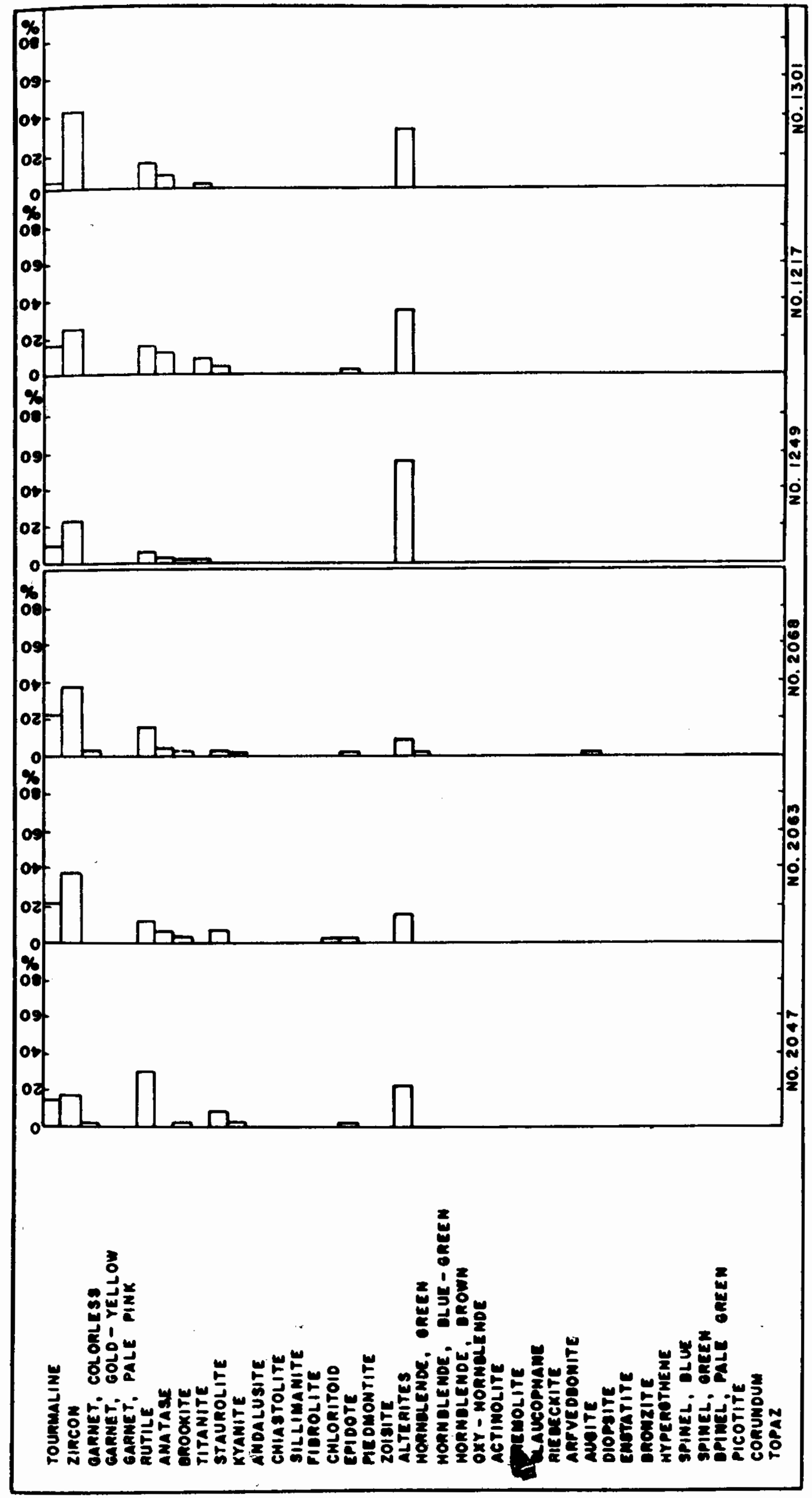


Figure 6. Examples of the heavy mineral suite of the Patapsco-Raritan zone.
a. Sediments mapped as Patapsco by Miller (Bascom & Miller, 1920). b. Sediments mapped as Raritan by Miller (Bascom & Miller, 1920).

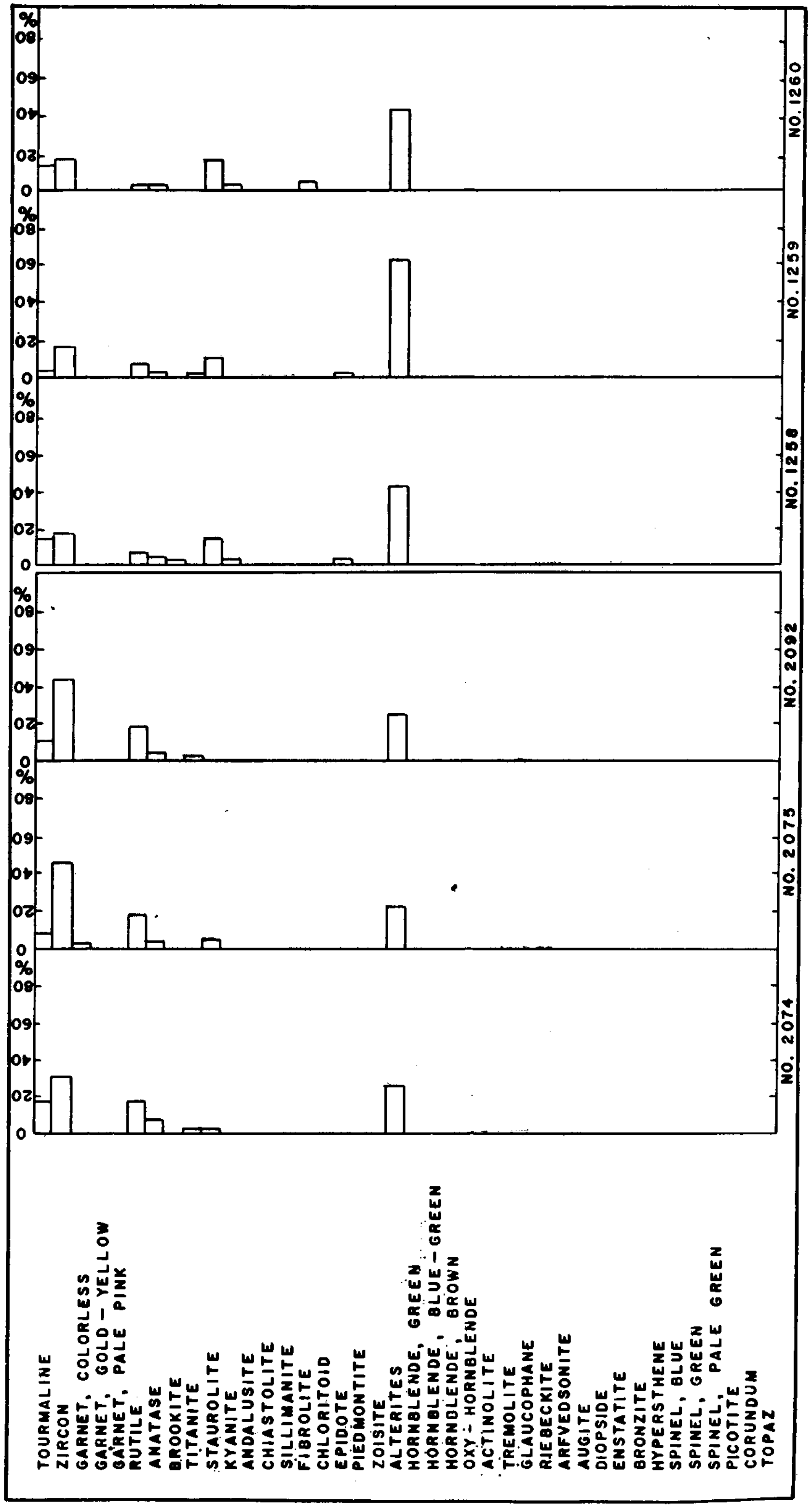
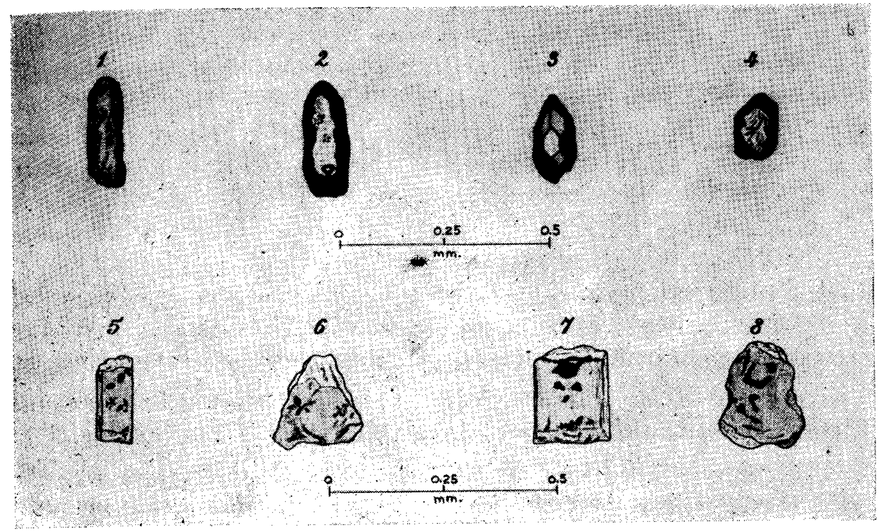


Figure 6 (cont.).

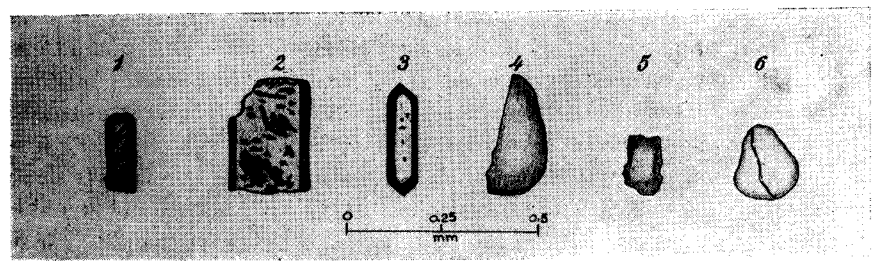
c. Sediments from test holes in the New Castle area.

d. New Jersey Raritan-Magothy, undifferentiated.

Figure 7. Specimens of mineral grains of the Patapsco-Raritan zone



a. 1 Rutile
2 - 4 Zircon
5 - 8 Tourmaline



b. 1 Brookite
2 Tourmaline
3 Zircon
4 - 5 Rutile
6 Tourmaline

form. The high percentage of alterites also indicates the unusual degree of weathering to which the minerals must have been subjected. Although it is not possible to determine with the petrographic microscope the origin of the alterites, it is believed that the small variety in the mineral content of this suite as shown in figure 6 a-d is due to alteration of a range of minerals, and not to the "poverty" of the source area, because very small percentages of several mineral species occur in most samples.

The heavy mineral content of the Patapsco-Raritan zone is very small as compared with that of other Cretaceous formations, as is shown by table V.

TABLE V

Percentage of Heavy Minerals in the Cretaceous Formations of Northern Delaware (500-40 micron, after treatment with acid)

Formation or Zone	Maximum Percentage	Minimum Percentage	Average Percentage
Red Bank	2.08	0.71	1.21
Mount Laurel-Navesink	4.75	0.11	1.69
Wenonah	1.52	0.17	0.69
Merchantville	3.25	0.28	1.32
Magothy	13.27	0.68	2.05
Patapsco-Raritan	2.60	0.06	0.38
Patuxent	3.01	0.27	1.94

Thus, the impoverishment of the Patapsco-Raritan zone is not only expressed by the small variety of heavy minerals it contains, but also by the very low average and minimum percentages of heavy minerals present in the sediments.

Bennett and Meyer (1952) investigated the heavy mineral content of the Patapsco formation in the Baltimore area, Maryland. They stated (p. 60):

> The heavy mineral suite of the Patapsco formation contrasts with the Pleistocene by its large amount of zircon and tourmaline, and by the small amount of garnet and hornblende. It contrasts with the mineral suite of the Patuxent formation by its low content of staurolite.

Most of the Patapsco samples investigated by Bennett were obtained from drill cuttings and may have been slightly contaminated. However, in 8 outcrop samples of the formation, zircon is the most abundant mineral, as is the case in the mineral zone correlated with the Patapsco-Raritan in northern Delaware. The zircon content varies between 45% and 66% in Bennett's samples. In the Delaware samples, it varies between 15% and 56%. Tourmaline, consistently abundant in Bennett's samples (ranging between 15% and 40%), is abundant in some Delaware samples, but it often occurs only in relatively small percentages (2% to 25%). The titanium minerals, rutile, anatase and brookite, are persistently present both in the Baltimore and Delaware samples, but in slightly higher percentages in the latter area.

Anderson (1948) described the heavy minerals of the Arundel-Patapsco formations (undifferentiated) as follows (p. 22):

> One of the outstanding mineral characteristics of this portion of the section is the abrupt appearance of an abundance of epidote minerals in the basal part . . . They continue in abundance to the top of the Magothy formation of the Upper Cretaceous. Staurolite shows a marked decrease in passing from the Patuxent formation into the Arundel-Patapsco sections and continues to be very scarce to very common to the top of the interval . . . colorless and pale-brown titanite grains . . . occur in all sands but seldom reached 11% or 13% . . .

The section correlated with the Patapsco-Raritan in Delaware also contains titaniferous minerals, but they are primarily rutile and anatase rather than titanite. The decrease in staurolite content found by Anderson is similar to that occurring in Delaware and the Baltimore area. However, epidote, abundant in the Salisbury test well in the Arundel-Patapsco and Magothy formations, is practically absent in the Baltimore area and northern Delaware, and becomes abundant only at the base of the marine Upper Cretaceous.

Anderson's description of the Arundel-Patapsco, and for that matter, of the Raritan formation, fails to mention any deviations from the prevailing epidote suite. However, a study of the heavy mineral content of these formations in the deep Salisbury well (Anderson, 1948, fig. 2) reveals that they also contain relatively thin beds characterized by a zircon suite with minor amounts of staurolite, tourmaline and rutile. The significance of these deviations is discussed in Chapter V.

Because high percentages of alterites are found in the Patapsco-Raritan zone of northern Delaware, altered minerals would be expected also in the equivalent sediments of the deep well near Salisbury, Maryland. Although Anderson did not count alterites, a check of several slides indicated that they are present in abundance.

Dryden (Dryden and Overbeck, 1948) reported that in Charles County the Raritan and Magothy formations contain mineral suites much smaller than those of the underlying sediments, and that the grains are small and worn. The same observation can be made concerning the Patapsco-Raritan suite of northern Delaware, but it does not pertain to the suite of the Magothy formation.

Magothy Formation

The Magothy formation may be classified as a staurolite-tourmaline zone with varying, but usually small amounts of alterites. Its mineral suite is somewhat similar to that of the zone correlated with the Patuxent formation, but it has an even higher staurolite content than the Patuxent. The average percentage of staurolite is about 59. Tourmaline is second in abundance, averaging about 12%. Zircon is consistently present in relatively small percentages, and rutile, anatase, kyanite, and epidote are sometimes minor accessory minerals. Some typical examples of the mineral content of the Magothy formation are shown in figure 8. Specimens of heavy minerals are presented in figure 9.

The staurolite grains are brown and straw-yellow, usually subangular, although some are rounded; they often are worn and pitted, have numerous inclusions and are usually larger than the other minerals of this suite. Often they are less fresh and have more inclusions than the staurolite grains of the Patuxent zone. The tourmaline grains are brown and pink, fresh, often prismatic, and sometimes nearly euhedral. The zircon grains are colorless and usually small. Some of these zircon grains are close to the euhedral form, but many are more rounded than those of the Patuxent zone, and most grains have lost their euhedral form entirely.

The kyanite grains are colorless, large prisms with rounded edges. In general, they are somewhat pitted.

Anderson's description (Anderson, 1948) of the minerals of the Magothy formation in the Salisbury well reveals an entirely different suite from the one

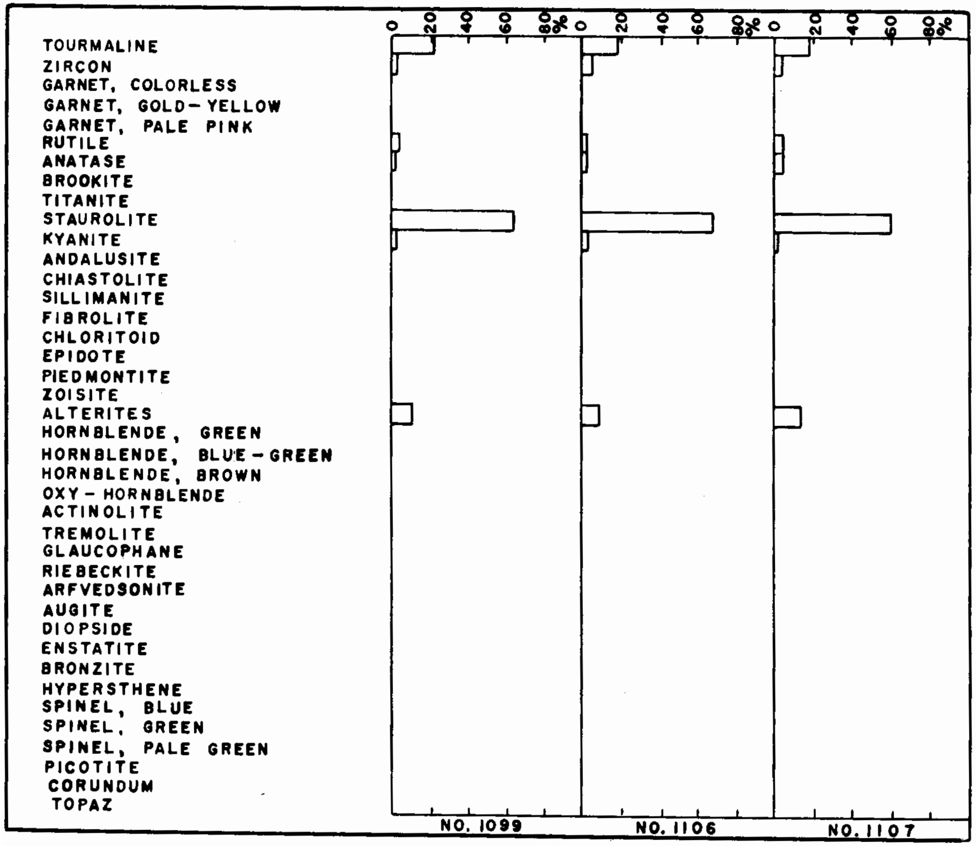


Figure 8. Examples of the heavy mineral suite of the Magothy formation.

found in northern Delaware. In the Salisbury deep well, it is primarily an epidote-clinozoisite-zircon zone with minor amounts of staurolite and rutile.

Marine Upper Cretaceous Formations

The heavy mineral suites of the four marine Upper Cretaceous formations are so similar that they are discussed together. They can all be characterized as epidote-chloritoid suites. High percentages of epidote appear for the first time in the Merchantville formation and persist throughout the Cretaceous formations above it. Chloritoid, although never present in a percentage higher than 15, is also persistent, and is practically absent in the non-marine Cretaceous. A great variety of other minerals occurs, particularly rutile, staurolite, zircon, and tourmaline. Small percentages of anatase, sillimanite, and kyanite are also found, and some other minerals, such as andalusite, hornblende, and zoisite are sporadically present.

In spite of the similarity of the heavy mineral content of these formations, there are minor differences which prove to be of value in differentiating them.

Thus, the Merchantville always contains garnet, usually of the colorless variety; the Mount Laurel-Navesink closely resembles the Merchantville in its heavy mineral content, but, apart from colorless garnet, small amounts of pale pink garnet are generally present. The Red Bank formation, the youngest Cretaceous formation found in outcrop, contrasts with the underlying Mount Laurel-Navesink by its higher staurolite and kyanite content, and its lower zircon, epidote, and garnet content.

Typical mineral analyses of the marine Cretaceous formations discussed above are presented in figures 10-13, inclusive. Specimens of the heavy minerals are shown in figure 14.

Epidote, the most abundant heavy mineral, is usually rather small and weathered. Yellow, yellow-green, green and colorless grains occur. The epidote grains are irregularly shaped and usually subangular to subrounded, but some well-rounded, smooth grains are also present. No evidence of authigenic epidote was found.

Zircon is colorless, rounded, worn, small, and usually pitted. Very few grains are close to the euhedral form. Some grains are long, very narrow prisms, needle-like, a shape not found in the older sediments. Tourmaline is brown, green, or colorless, usually prismatic, and angular to subangular, although some well-rounded grains were also observed. Most tourmaline grains have inclusions, both mineral and liquid or gaseous. Staurolite is usually small and subangular, some grains are fresh, but others are somewhat altered. Blue and blue-green chloritoid, characteristic for the marine Upper Cretaceous formations, is generally fresh, irregularly shaped and subangular. Most garnet grains are colorless and fresh.

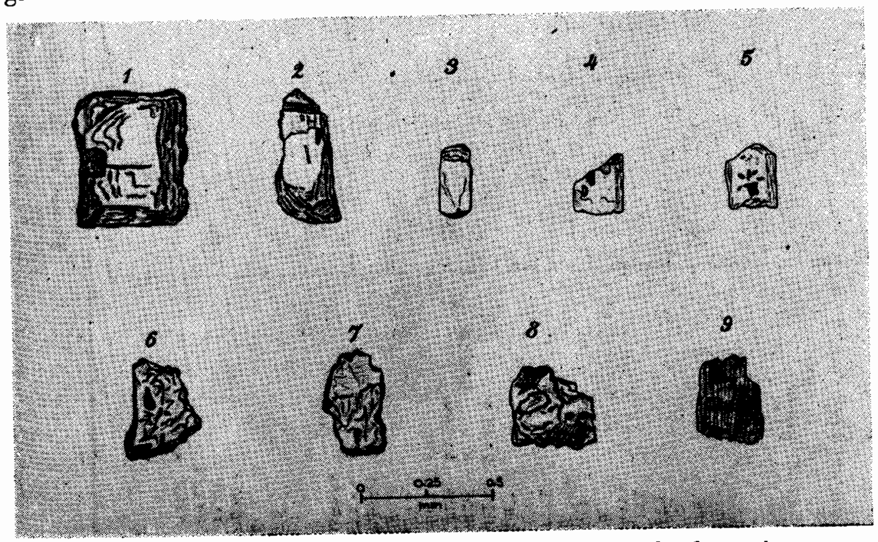


Figure 9. Specimens of mineral grains of the Magothy formation
1 - 2 Kyanite 6 - 9 Staurolite
3 - 5 Tourmaline

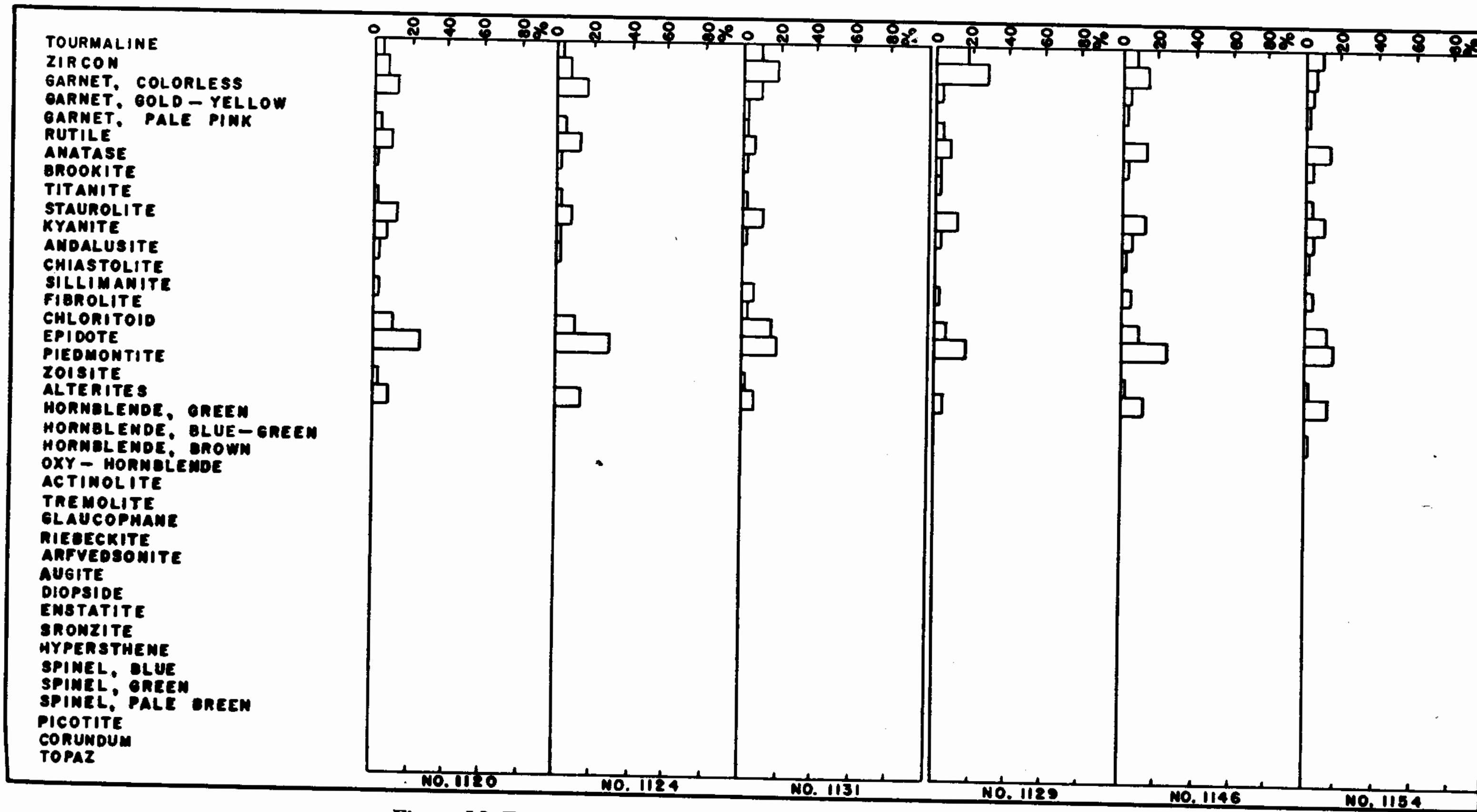


Figure 10. Examples of the heavy mineral suite of the Merchantville formation.

Figure 11. Examples of the heavy mineral suite of the Wenonah formation.

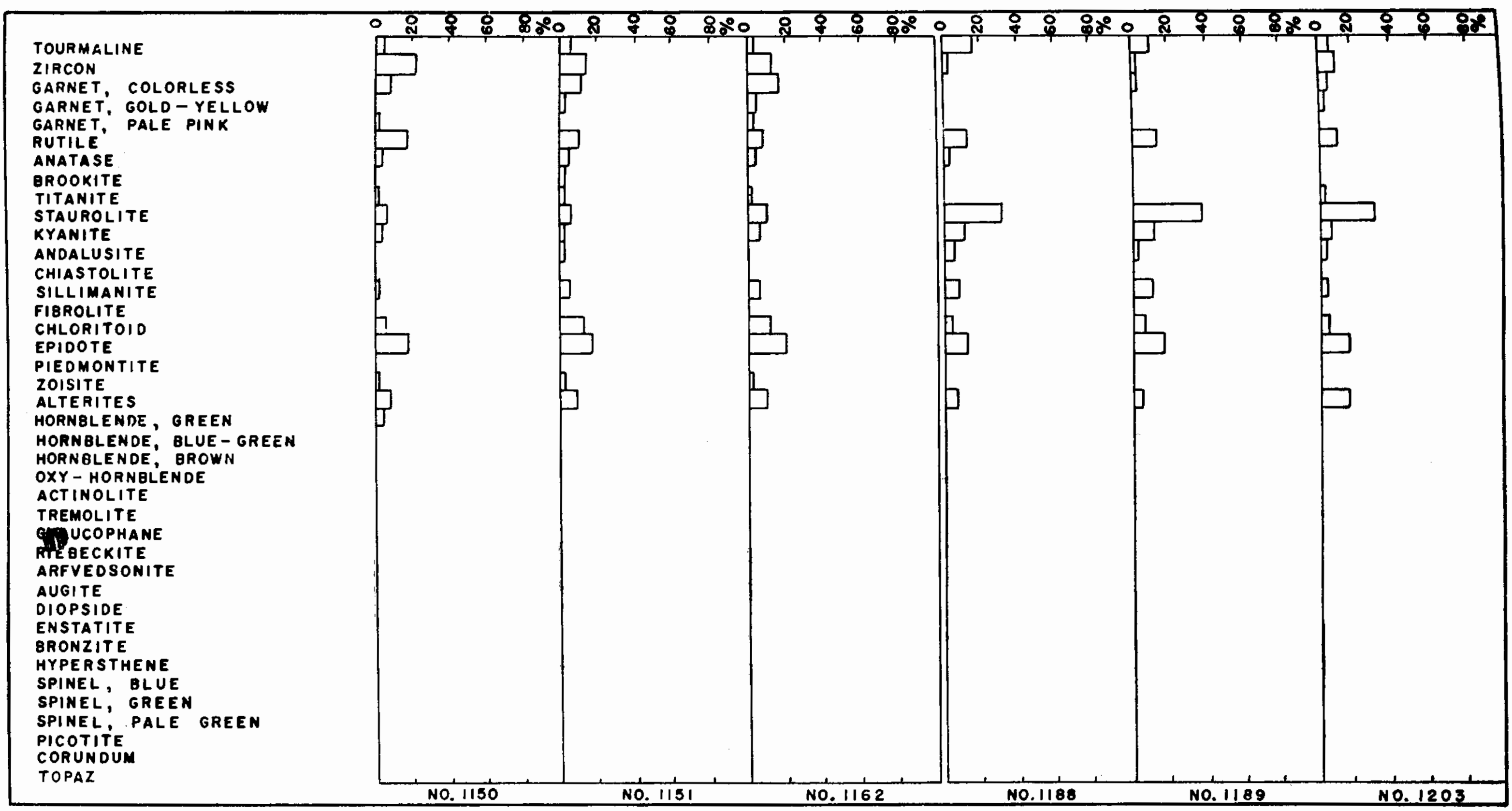
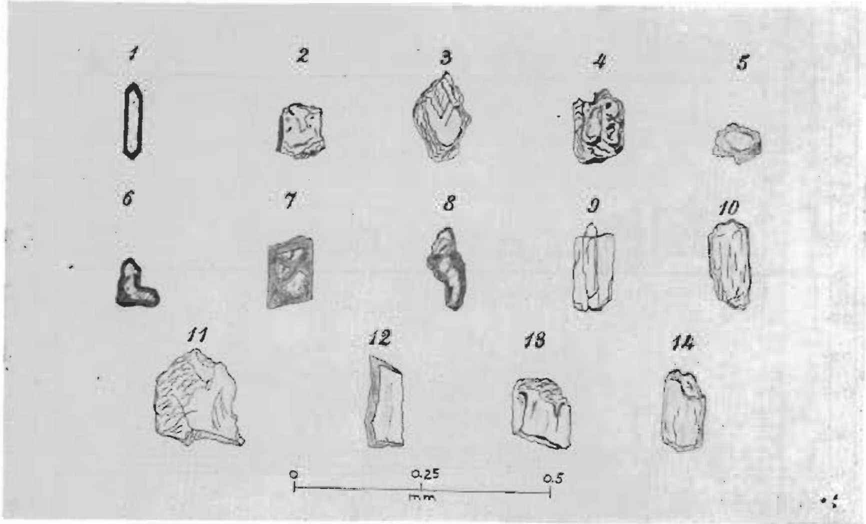


Figure 12. Examples of the heavy mineral suite of the Mount Laurel-Navesink formation.

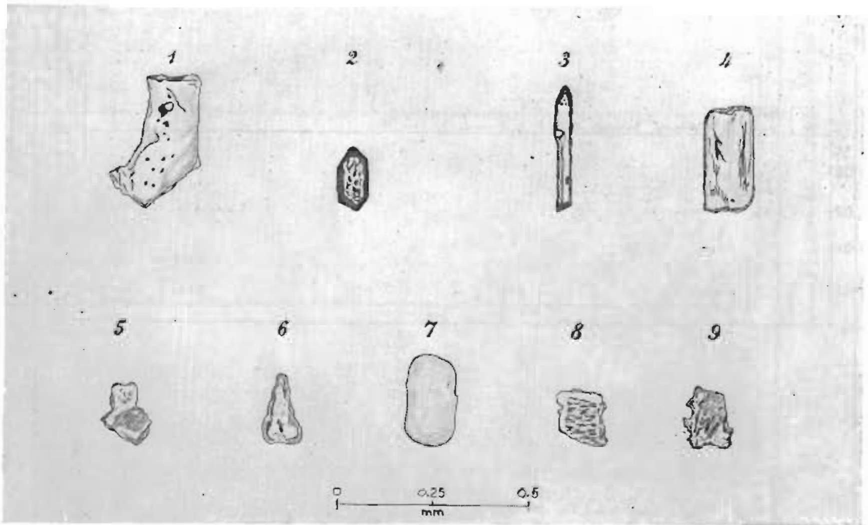
Figure 13. Examples of the heavy mineral suite of the Red Bank formation.

Figure 14. Specimens of mineral grains of the marine Upper Cretaceous formations



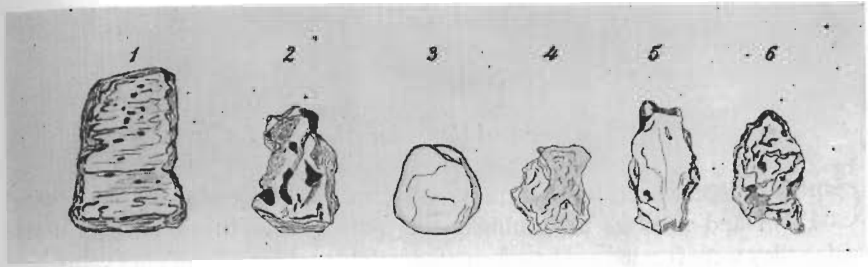
a. Merchantville formation

1	Zircon	9 - 10	Sillimanite
2 - 3	Chloritoid	11 - 13	Garnet
4 - 5	Epidote	14	Tourmaline
6 - 8	Rutile		



b. Wenonah and Mount Laurel-Navesink formations

1	Staurolite	4	Tourmaline
2 - 3	Zircon	5 - 9	Epidote



c. Red Bank formation

1	Sillimanite	4 - 5	Chloritoid
2	Staurolite	6	Epidote
3	Tourmaline		

CHAPTER V

THE PROVENANCE OF THE SEDIMENTS

General Considerations

CONCLUSIONS concerning the provenance of the sediments of the Coastal Plain and remarks pertaining to the paleogeographic conditions under which they were formed are based on all available evidence, and not exclusively on the sedimentary analyses described in the previous chapter. The presence or absence of feldspar, the color, the stratification, and the fossil content of the sediments are as important to the interpretation of the environmental conditions of the areas of provenance and deposition as the heavy mineral and mechanical analyses. In arriving at any conclusions, therefore, the field observations described in Chapter III have been taken into account.

This chapter will deal primarily with the provenance of the sediments and the conditions under which the sediments were *produced;* Chapter VI will be concerned with the conditions under which the sediments were *deposited,* and Chapter VII with the erosional history of the Appalachian region during the Cretaceous as reflected in the sedimentary record.

The provenance of the sediments, as discussed here, is not only concerned with the types of rocks from which they were derived, but also encompasses an appreciation of the physiographic conditions prevailing during the time the sediments were formed. These physiographic conditions involve climate, duration or distance of transportation, and, ultimately, diastrophism.

The differences among the mineral suites previously described are due not only to differences in the source rocks, but also reflect climatic conditions. Even when no change in source rocks occurs, the sediments may show different heavy mineral frequencies because the less stable minerals have been decomposed owing to prolonged intensive weathering. Thus, the relative stability of the minerals or their resistance toward decomposition should be considered in the interpretation of the provenance of the sediments.

Smithson (1950) reviewed some investigations concerning the stability of heavy minerals. His study shows that there is still a great deal to be learned about this subject. In the first place, there is no complete agreement on the relative stability of the minerals; and secondly, the number of minerals studied was limited. Yet, there is agreement on some major points, particularly regarding the very stable and the very unstable minerals. Thus, when a list of heavy minerals in decreasing order of stability is made, zircon, tourmaline, and rutile are always found at the top, and hornblende and augite at the bottom of the list.

In view of the importance of the stability of the heavy minerals relative to the interpretation of provenance and paleogeographic problems, it is consid-

THE STABILITY OF HEAVY MINERALS[1]

Mechanical Action	Chemical and Mechanical Action	Chemical Action				
Abrasion Tests	Marine Shore Sands	Subterranean Strata		Weathering (?)	Weathering of Rocks and Soil Material	
Freise (1931)	Thoulet (1913)	Pettijohn (1941)	Smithson (1941)	Sindowski (1949)	Goldich (1938)	L. & C. Dryden (1946)
		Rutile				
	Zircon	Zircon	Zircon	Zircon		Zircon
	Rutile		Rutile	Rutile		
Tourmaline		Tourmaline	Tourmaline	Tourmaline		Tourmaline
			Apatite			
		Monazite	Monazite			Monazite
Staurolite						
Augite						
Garnet		Garnet	Garnet			
	Biotite	Biotite			Biotite	
Olivine						
Apatite	Apatite	Apatite				
		Staurolite	Staurolite	Staurolite		
		Kyanite	Kyanite	Kyanite		
	Hornblende	Hornblende		Hornblende	Hornblende	Hornblende
			Ferro-magnesian Minerals			Staurolite
				Garnet		Garnet
	Augite	Augite		Augite	Augite	
				Apatite		
	Olivine	Olivine		Olivine	Olivine	
Monazite						

[1] Smithson, Frank, 1950, The Mineralogy of arenaceous deposits: *Sci. Progress,* vol. 38, no. 149, p. 14.

ered worthwhile to reproduce Smithson's table comparing the results of stability studies by several petrographers.

The most complete lists in the above table are those of Pettijohn, Smithson, Sindowski, and Thoulet, and the similarities in their stability series are striking, in spite of the fact that these investigators used different methods in arriving at their conclusions. (For a discussion of these methods see the original papers: Thoulet, 1913; Pettijohn, 1941; Smithson, 1941; Dryden and Dryden, 1946; Sindowski, 1949.)

Omitting apatite from the stability series because in heavy mineral investigations it may be destroyed by acid treatment, and also omitting a few minerals which have not been identified or counted in the Delaware sands so far, like biotite and olivine, the following list can be said to be representative of a stability series due to post-depositional decomposition:

Zircon, Rutile, Tourmaline	Very stable
Garnet, Staurolite, Kyanite	Moderately stable
Hornblende, Augite	Least stable

L. and C. Dryden's stability series based on a study of minerals in soils, shows a general agreement with the ones based on decomposition in subterranean strata, with the exception of the position of staurolite and garnet which are considered less stable than hornblende. Thus, the stability series due to decomposition of heavy minerals in the area of deposition (subterranean strata) and in the source area of the sediments (weathering of rocks and soil minerals) show essential, although not complete, agreement.

What deductions concerning stability can be made from the available heavy mineral data in the Coastal Plain of Delaware and nearby Maryland?

In the formations sampled in northern Delaware, there is some decrease in the number of mineral species with increase in age, but it is neither a general decrease nor an uninterrupted one. Minerals which are considered less stable than zircon, tourmaline, and rutile are abundant in the oldest sands (Patuxent zone), while in the younger Patapsco-Raritan zone the less stable minerals are nearly absent. Yet, the marine Upper Cretaceous formations, and particularly the Pleistocene sediments, do show a greater variety in their mineral content than the older non-marine Cretaceous deposits, and this feature should probably be ascribed partially to post-depositional decomposition. Moreover, in a continental deposit all or nearly all material is derived from the weathered

zone of the rocks of the source area, whereas in the case of marine sediments considerable material may be present from below the weathered zone, and consequently, from fresh parent rock. Thus, the greater variety of minerals in the marine formations is a result of a smaller degree of post-depositional as well as pre-depositional weathering as compared to that of the continental deposits. In addition, in the case of the marine Upper Cretaceous formations it is also due to mixing of mineral suites of two different source areas, as will be explained later.

It is clear, however, that post-depositional changes in mineral content play only a secondary role. When the average mineral frequencies of the very stable minerals zircon, tourmaline, and rutile are totaled for each mineral zone or formation (see table VI), the conclusion that the influence of provenance (here used in its broadest sense to include environmental conditions in the source area) predominates over post-depositional weathering as a function of the age of the deposits is inescapable.

In addition, the general trend of the average percentage of alterites in the various formations and zones can be considered. There is a slight general decrease in average alterite percentages, but there are major deviations from this trend, particularly in the Patapsco-Raritan zone and the Wenonah formation. (See table VI.)

TABLE VI

Average Total Percentages of Stable Minerals
(Zircon, Tourmaline, and Rutile) and Alterites

Formation or Zone	Percentage	Percentage (Excluding Alterites)	Percentage of Alterites
Red Bank	22	24	9
Mount Laurel-Navesink	30	33	8
Wenonah	31	34	12
Merchantville	28	31	9
Magothy	23	26	15
Patapsco-Raritan	62	87	29
Patuxent	29	31	12

Thus, no direct correlation is possible between the time elapsed since deposition, and alterite percentage. As a matter of fact, the alterite percentage of the Patuxent zone is much lower than that of the overlying Patapsco-Raritan zone, lower than that of the younger Magothy, and equal to that of the much younger Wenonah.

The heavy mineral work done by Bennett and Meyer (1952) in the Baltimore area, Maryland, indicates also that the total percentage of the stable minerals mentioned before is much higher in the Patapsco than in the older Patuxent deposits. Here again, provenance or pre-depositional conditions must have had a predominant influence on the heavy mineral suites.

The very rapid weathering of garnet *in situ* as found by Dryden and Dryden (1946) in the Piedmont of Pennsylvania and Maryland is of special interest, because this mineral is conspicuously absent in the non-marine Cretaceous deposits of northern Delaware, and present in only small percentages in Recent floodplain sands, whereas it is a very abundant mineral in the Wissahickon formation. Apparently, garnet is being rapidly destroyed in the *source area* at present, as it was during Patuxent to Magothy time.

The question concerning weathering in the source area versus post-depositional weathering is of special importance in the interpretation of paleogeographic problems. Therefore, it is necessary to consider in what manner an impoverished mineral suite, such as that of the Patapsco-Raritan zone, can originate. If the impoverished suite is derived from the source area, there are two alternative explanations. Firstly, the chemical weathering in the source area can be intensive and prolonged, and if this is the case, the paleogeographic condition implied is a warm, humid climate, and/or a source area of small relief, perhaps even a peneplane or pediment. Secondly, the deposit may have been derived from a source area of sedimentary rocks; thus, it may be of second or more sedimentary cycle origin. If, however, post-depositional weathering is the cause of the impoverished mineral suite, either intensive weathering during extremely slow deposition or intrastratal solution could be responsible.

Intrastratal solution undoubtedly exists, as pointed out by Pettijohn (1949). The question is, however, whether or not the Patapsco-Raritan zone can be impoverished by intrastratal solution, whereas the underlying, older, and lithologically similar sediments of the Patuxent zone have not suffered such a great degree of weathering. Thus, intrastratal solution may have eliminated many unstable heavy minerals in *both* zones, but the extreme poverty of mineral variety as well as mineral content in the Patapsco-Raritan zone can hardly be due to this cause.

Intrastratal solution is a part of diagenetic changes taking place in a sediment after deposition. It has been observed that such changes progress more rapidly in arenaceous deposits than in argillaceous ones. Sindowski (1939) stated (p. 469):

> Die Korngrösze des Sedimentes spielt bei weiteren diagenetischen Veränderungen eine wichtige Rolle, da in feinkörnigen Sedimenten die Schwermineralien besser erhalten sind.

Because the Patapsco-Raritan sediments are generally of finer texture than those of the older Patuxent zone, the high alterite percentages in the younger zone are the more remarkable, and additional proof that it is not primarily a result of intrastratal solution.

Post-depositional elimination of many mineral species as a result of weathering during extremely slow accumulation of the sediments is also unlikely, because the impoverished suite occurs not only in silts and clays which may be

considered floodplain or estuarine deposits subject to weathering during intervals of non-deposition, but also in the fine- and median-grained sands representing channel sands which are protected from the influence of the atmosphere by being saturated with water at the time of deposition.

If a second sedimentary cycle deposit were involved, most or all grains would be expected to be more or less rounded. In the Patapsco-Raritan, observation of the heavy mineral grains indicates that such is not the case. Indeed, the great majority of the tourmalines, for instance, displays beautiful angular to subangular prisms. The zircon grains are usually rounded, but because zircon may have been rounded in the source rock—as it often is in the Wissahickon schist for instance—this cannot be considered proof of second cycle origin.

In view of the above discussion intensive chemical weathering in the source area must be considered as the major cause of the impoverished Patapsco-Raritan suite.

So far, only the result of decomposition—or chemical action—has been considered, but some attention should also be given to the possible effects of mechanical action which might destroy some minerals. These effects were studied by Russell (1937), and he has shown that, in the lower Mississippi River at least, the selective destruction of minerals by abrasion is a relatively unimportant process. A mineral so little resistant to abrasion as kyanite is found in Pleistocene sands and in Recent beach sands which certainly have been transported by rather turbulent currents. Also, in marine sediments of Red Bank age which show considerable abrasion of the very resistant minerals, kyanite is present, often in large grains, in a larger percentage than in any other formation, indicating that the chances of complete destruction of a mineral are apparently small.

Finally, before discussing the significance of the mineral suites in terms of provenance, a few remarks should be made concerning the influence of grain size on mineral frequencies.

It should be stated that the great majority of the samples were obtained from sands, and only few from "clays". Actually, all samples contained sand, even those obtained from the so-called variegated clays of the Patapsco-Raritan zone. Most of these clays are really silts with considerable sand and clay. The presence of some sand in all these samples, and the use of a large fraction (500-40 microns, or medium sand to very coarse silt) in the analyses, may be responsible for the conclusion that the influence of the size frequency distribution on the mineral frequencies is not great enough to cast doubt on the question whether or not very fine-grained sediments belong to the same mineral association as coarse-grained ones of the same formation.

It is well known that in many sediments zircon and rutile occur as very small grains, and that they are found in higher percentages in fine-grained sediments than in coarse-grained deposits. In the Patapsco-Raritan sediments this same tendency can be observed, as shown by figure 15.

Staurolite usually occurs in large grains, and therefore percentages of this mineral are generally higher in coarse-grained sediments than in fine-grained ones. For example, the carbonaceous silts of the Magothy formation (samples 1272 and 1297) contain less staurolite than the fine and medium sands do. In the Patuxent zone, a similar situation must be expected, but it can not be dem-

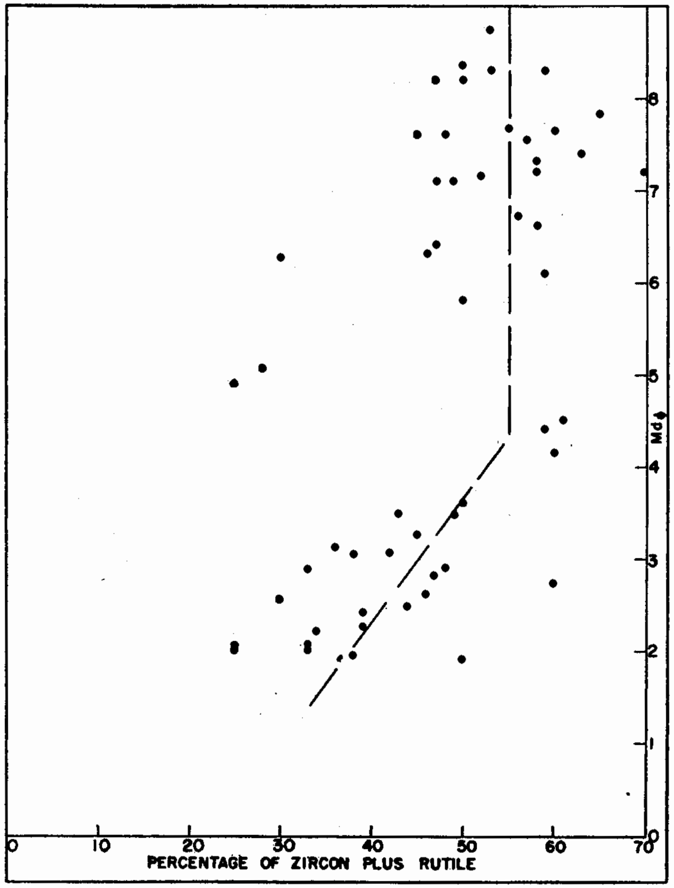


Figure 15. Rutile-zircon percentage as related to median grain size in the Patapsco-Raritan zone.

onstrated because no silts and clays were available for analysis. In the Patapsco-Raritan zone, however, practically no staurolite occurs even in fine and medium sands, and its absence can not be ascribed to the influence of grain size.

These findings are in agreement with those of Doeglas (1940) who stated (p. 103):

> After the examination of hundreds of samples derived from one source, however, we have found that deviations in mineralogical composition due

> to differences in grain size and laboratory methods lie within *narrow limits*. We have called these changes in mineralogical composition "chance variations", as they have no relation to the origin of the material. All other changes in the mineralogical composition are due to changes in the origin of the material.

The results of these considerations are fortunate, because if it had been found that post-depositional changes and texture were dominant factors in the composition of the mineral suites, deductions concerning provenance would have been impossible. It appears now, however, that the heavy minerals should provide a reliable guide to the interpretation of provenance and paleogeographic problems.

It has been pointed out by several sedimentary petrologists that a detailed study of varieties of one mineral may be just as valuable in making deductions concerning the provenance of sediments as the study of their mineral suites as a whole. Paul D. Krynine of the Pennsylvania State University has, in particular, emphasized detailed investigation of tourmaline in his paper "The Tourmaline Group in Sediments" (1946). Krynine stated (p. 65):

> Tourmaline occurs in all sediments of all types and ages. This wide distribution has resulted in tourmaline being taken for granted by many students of sediments who considered it as a mineral of no particular genetic or stratigraphic significance. However, precisely the opposite is true. This is due to the fact that tourmaline is not a simple—or single—mineral species but rather a complex isomorphous group, with an extremely elastic formula and possessing a series of very sensitive morphological characteristics which reflect very closely both the ontogeny and phylogeny of each grain and thus can act as excellent guides to the origin and history of each tourmaline grain and consequently of the sediment in which these grains are found. As a result, tourmaline can be used effectively as a guide mineral in the solution of paleogeographic and stratigraphic problems.

In the investigation of the sediments of the Coastal Plain the study of tourmaline proved to be very helpful. In order to arrive at conclusions relative to provenance, the following properties of tourmaline grains were observed: color and the nature of inclusions as indicators of possible source rocks; shape, degree of rounding, and size giving clues to their transportational history; and finally, the intensity of interference colors which differed markedly between the tourmalines of the non-marine and marine Cretaceous formations.

The results of the study of tourmaline grains are described in the discussion of the various mineral zones and formations in this chapter.

Patuxent Zone

Evidence from the Heavy Mineral Suite

The heavy mineral suite of the Patuxent zone is one primarily derived from metamorphic rocks, such as schists and gneisses, as indicated by the prevalence of such minerals as staurolite and kyanite, and metamorphosed carbonaceous shales, as evidenced by tourmaline and staurolite with carbonaceous inclusions. Some acid igneous rocks were also present in the source area because zircon and tourmaline with liquid and gaseous inclusions occur frequently. The presence of a fairly high percentage of opaque minerals may indicate basic igneous rocks in the area of provenance.

On the whole, the minerals show little sign of decomposition; staurolite, however, shows more signs of weathering than any of the other minerals of the suite. As mentioned previously, saw-tooth terminations of staurolite occur, and some alterites may have been derived from staurolite. Staurolite grains without inclusions appear to be quite fresh, however. In the deep test well near Salisbury, "cleaved" staurolite occurs in the Patuxent and the lower half of the Arundel-Patapsco formation. In northern Delaware, it is found in all Cretaceous sediments, although it deceases sharply in abundance in the marine Upper Cretaceous formations. According to Edelman and Doeglas (1934) staurolite with saw-tooth terminations can not be transported without being destroyed, and consequently, it must be a result of post-depositional weathering.

The composition of the mineral suite, and the small degree of rounding of even the large grains, particularly of tourmaline, suggest a deposit derived from the crystalline rocks located in a region close to the area of deposition and, consequently, transported over a relatively short distance. Thus, the source area is expected to be the nearby Piedmont.

Evidence from Tourmaline

The tourmaline in the Patuxent zone is mostly brown (about 83%) with some pink (13%) and green (4%). The brown and pink tourmalines generally have mineral or carbonaceous inclusions; some have liquid or gaseous ones. The green grains are remarkably free of inclusions of any kind. Most tourmalines were derived from pegmatized injected metamorphic terrane (Krynine, 1946, p. 68) consisting partly of metamorphosed black shales as indicated by the numerous grains with carbonaceous inclusions.

The vast majority of the tourmalines are prismatic and angular to subangular; some brown and green grains are prismatic and subrounded to rounded, and very few are irregularly shaped or oval, rounded grains. All pink grains observed are angular to subangular. This suggests that nearly all tourmaline grains are of first sedimentary cycle origin and derived mainly from metamorphic rocks in a source area not too distant from the basin of deposition. Moreover, the presence of a large number of broken angular prisms indicates short but rather violent transportation of the sediments. Thus, the nearby Piedmont should be regarded as the source area of the Patuxent sediments, with probably a minor contribution from the sedimentary rocks of the Folded Appalachian Mountains, as evidenced by a few oval (second or more cycle) tourmalines.

According to Dryden and Dryden (1946) the majority of the tourmaline grains found in the Patuxent and other non-marine Cretaceous sediments are identical in varietal characteristics with those of the Wissahickon formation of Delaware, Maryland and Pennsylvania. Thus, the Drydens' findings are in agreement with those presented here.

Evidence from Field Observations and Sample Study

One of the most significant features of the Patuxent sands is their feldspar content which is greater than that of any other Cretaceous formation in northern Delaware, although not high enough to warrant the term arkose.

It is generally agreed that feldspar is a rather unstable mineral that does not survive prolonged intensive weathering or long-distance transportation. Therefore, the consistent presence of feldspar indicates either a relatively dry climate hindering chemical weathering, or uplift of the source area causing streams to cut their valleys rapidly and allowing a relatively short time for the weathering processes under humid conditions.

The sediments of the Patuxent zone were deposited on the erosion surface of the crystalline rock of the eastern portion of the Piedmont, and, immediately above this basement rock, they are sometimes conglomeratic, indicating diastrophism rather than arid conditions. Also, the presence of some lignite suggests humidity, or high water table conditions, at least in the area of sedimentation.

Evidence regarding climatic conditions based on a thorough study of fossil plants has been described by Berry (Clark, *et al.*, 1911). He stated (p. 150):

> While the data are not conclusive it seems certain that the Potomac climate (the climate of Patuxent, Arundel and Patapsco times) was considerably warmer than that of today, with much less change from season to season, and with a very long growing period. The rainfall must have been ample and fairly well distributed, and the indications point to a rather high percentage of humidity throughout the major portion of the year.

Data obtained from well logs indicate that the Patuxent consists mainly of sands, with sediments of finer texture in the minority. Intraformational gravel layers of limited extent indicate frequent changes in the competency of the streams, which are believed to be due to variations in precipitation rather than to repeated uplifts.

Thus, all the available data indicate that Patuxent time was a period of active —although probably moderate—earth movements during which the eastern portion of the Piedmont was depressed, and the Appalachian region raised; furthermore, it is shown that climatic conditions differed from the present ones in that temperatures were somewhat higher; rainfall was abundant, possibly with seasonal variations.

Patapsco-Raritan Zone

Evidence from the Heavy Mineral Suite

The impoverished heavy mineral suite and high percentage of alterites of the Patapsco-Raritan zone make it somewhat difficult to state with certainty the types of source rocks from which the sediments were derived. Zircon, tourmaline, and rutile are the only abundant heavy minerals in this zone, and these are minerals which occur in all sediments. However, their predominance in this zone indicates long and intensive weathering in the source area, a condition which *may* occur when the area of provenance is in the stage of old age or is nearing a peneplane or pediment. The thorough weathering is also evidence of a humid climate which apparently continued during Patapsco-Raritan time. The influence of humid-tropical conditions on sedimentation is further discussed in Chapter VII.

The difference in the mineral composition between the Patuxent and Patapsco-Raritan zones is generally abrupt (See Chapter V). The sudden change from a mineral zone with abundant staurolite and few signs of decomposition, to a zone intensely weathered strongly suggests the presence of an unconformity. This point of view is supported by the fact that in Maryland the Patuxent is unconformably overlain by the Arundel formation, (Clark, *et al.*, 1911), which is missing in Delaware.

The sporadic presence of less stable minerals such as garnet, staurolite, sillimanite, kyanite, and epidote, often worn and pitted, also indicates that the Patapsco-Raritan suite is not a result of poverty of the source area, but is due to intensive decomposition in the area of provenance.

Attention should be called again to the significant differences between the heavy mineral suite of the Patapsco-Raritan of northern Delaware and that found in the Arundel-Patapsco and Raritan sections of the Hammond No. 1 well near Salisbury, Maryland, which were mentioned previously (see Chapter IV). The sections referred to in the Hammond well show actually two alternating mineral suites: one suite with very high percentages of epidote minerals, and another with a very high zircon content, and minor amounts of staurolite, tourmaline, and garnet, and traces of rutile. The epidote-rich suite greatly predominates, but through the entire upper portion of the Arundel-Patapsco and the Raritan section relatively thin beds containing the zircon-rich suite occur. For instance, Anderson's mineral chart (Anderson, 1948, fig. 2) shows zircon suites at the following depths: 1844-1894, 2044-2054, 2157-2167, 2313-2323, 2373-2383, 2938-2943, and 3183-3193 feet below surface. Thus, the Arundel-Patapsco and Raritan of the Hammond well show provincial alternation, as defined by Doeglas (1940). The zircon suite was probably derived from the Piedmont to the northwest of Salisbury, an area which also supplied northern Delaware and the Baltimore area with detrital material, whereas the epidote suite was probably mainly derived from the Piedmont to the west or southwest of Salisbury.

It is not surprising that the source area of most of the non-marine sediments of the Hammond well differs from that of the deposits of northern Delaware, because it can be expected that the streams descending from the Piedmont generally flowed in a direction perpendicular to the contours of the basement rocks. These contours run, in northern Delaware, approximately in a northeast-southwest direction, to change gradually to north-south in northern Virginia and finally even to northwest-southeast in the southern part of Virginia (see fig. 16).

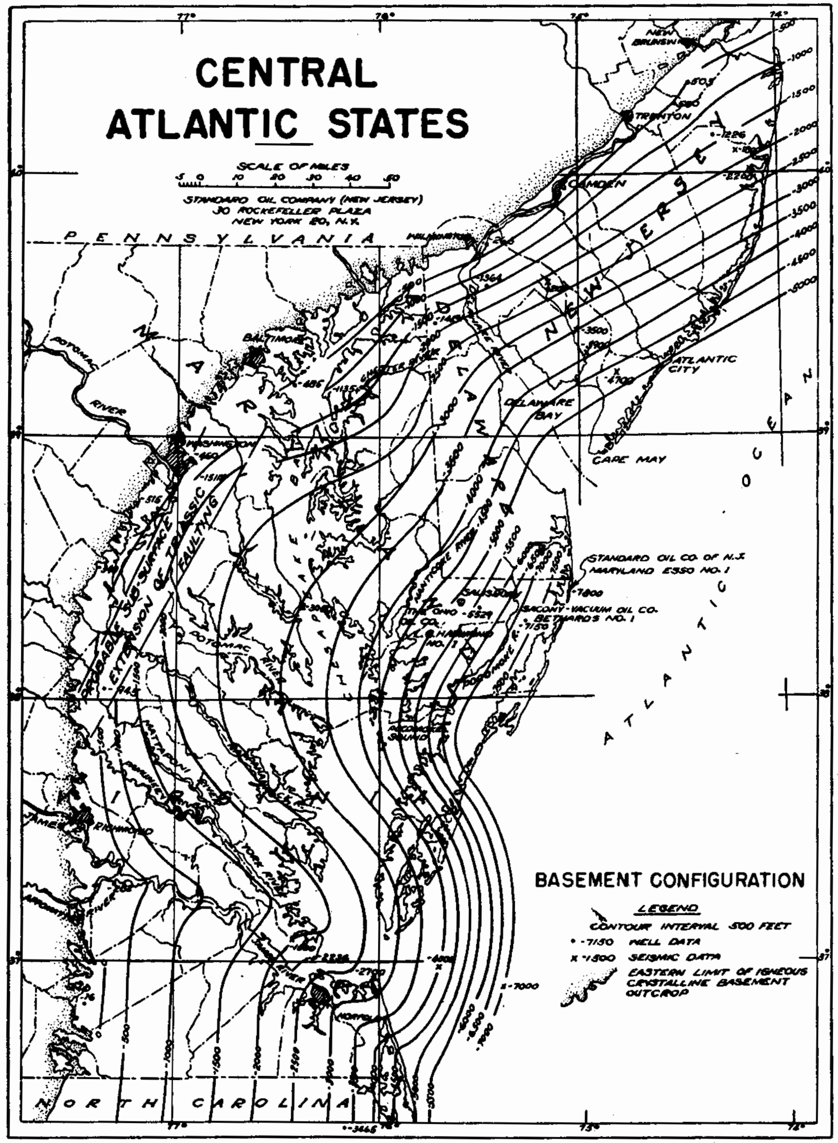


Figure 16. Basement configuration—Central Atlantic States. Reproduced from Spangler and Peterson, 1950.

The structure map of the top of the Raritan (Spangler and Peterson, 1950, p. 83) exhibits somewhat similar characteristics. Thus, pre-Cretaceous and Cretaceous topography supports the contention that most of the non-marine Cretaceous sediments of the Hammond well have a different source area from those of northern Delaware.

Evidence from Tourmaline

The study of tourmaline varieties indicates a sharp decline in the percentage of brown tourmaline, and an increase in green and pink varieties. Also, colorless tourmaline occurs, and a few yellow and one blue grain were observed.

As compared with the Patuxent sediments, the Patapsco-Raritan suite contains fewer tourmalines with carbonaceous inclusions, and a greater percentage with gaseous and liquid inclusions. This indicates that a larger portion of the minerals were derived from igneous terrane, and that most of the phyllites and slates which delivered these tourmalines during Patuxent time were eroded before the Patapsco-Raritan sediments were deposited.

The percentage of angular to subangular grains is smaller in this zone than in the underlying Patuxent zone. Particularly noticeable is an increase in oval and circular tourmaline grains of second or more cycle origin. This might, at first instance, be interpreted as an indication that the sediments of the Patapsco-Raritan zone were derived from those of the Patuxent zone. However, the great difference in tourmaline varieties between the two zones is evidence that this did not occur to any large extent in northern Delaware, although it may be true further down dip. Thus, the increase in second or more sedimentary cycle tourmaline is probably due to the presence of material derived from the Folded Appalachian Mountains in greater quantities than in Patuxent time owing to headward erosion of streams flowing in a southeasterly direction, probably accompanied by capture of new drainage basins.

Evidence from Field Observations and Sample Study

The predominant colors of the Patapsco-Raritan sediments are red, white and gray. The clays and silts are primarily red and white, and the sands white and light gray, although some red sands occur also.

There has been disagreement in the past as to the environmental conditions under which the red color of sediments originates. The difference in opinion concerns the climatic conditions, that is, it has been questioned whether or not the red color of a sediment can only occur under arid conditions. It was pointed out by Pettijohn (1949), and Krynine (1949) that aridity is not a necessary environmental condition. The red color of a sediment is commonly due to the presence of red ferric oxide pigment usually occurring as anhydrous hematite. Therefore, the only condition necessary to produce the red coloration is

> the prevalence of oxidation over reduction, a phenomenon that takes place most easily above the water table, thus explaining the great predominance of the continental red beds (Krynine, 1949, p. 60).

This prevalence of oxidation over reduction may occur under seasonal humid conditions, according to Krynine. He stated (1949, p. 61):

> At least 95 per cent of present day red soils are formed above 60°F. and 40″ (inches of rainfall). Most of the 5 per cent of so-called non-humid red soils were not formed at the present time, but were inherited from the pluvial Pleistocene period.

Red and gray soil profiles were also found in the humid tropics of Dutch Guiana by Bakker (1954). As a matter of fact, some of the profiles described contain red, white, gray and yellow variegated sandy clays, like the sediments of the Patapsco-Raritan zone in Delaware.

Krynine's opinion that aridity is no prerequisite for the formation of red-colored sediments is in agreement with the evidence of climatic conditions based on a study of the paleobotany of the non-marine Cretaceous sediments by Berry (Clark, *et al.*, 1911, 1916).

Even though it seems clear that the "red beds" of the non-marine Cretaceous formations in northern Delaware were formed under humid, warm conditions, the question remains whether these strata received their color before or after deposition, or, in other words, whether it is primary or secondary in origin.

It is believed that environmental conditions both in the source area of the sediments and in the sedimentation basin were favorable for the production of red beds. Intensive weathering under humid conditions, possibly on a surface of low relief, as indicated by the impoverished heavy mineral suite, should be able to produce a red regolith in the area of provenance; during short-distance transportation the hematite could survive and thus it could be found in the basin of deposition, except in some of the coarse channel sands where the water table was presumably high, and where reduction of the ferric iron oxide could take place. Thus, the channel sands could be expected to be light brown, gray, or white (as they usually are), and the finer materials, deposited away from the stream channels, which most of the time were above the water table, could be expected to have preserved their red color. However, oxidation may also have taken place after deposition in the interfluvial areas which were exposed to the oxygen of the atmosphere, while the channel sands were never red (or oxidized). Probably ferric iron oxide of both primary and secondary origin is responsible for the red colored silts, and some sands, in the non-marine Cretaceous of northern Delaware.

Bakker (1955), found that red is the predominant color in the higher terrace materials along the rivers in Dutch Guiana, whereas yellow-brown to reddish-brown colors occur in the younger sediments which are covered occasionally by water during floods. This difference in color is not due to variations in clay mineralogy, because it was found that all samples contained nearly exclusively kaolinite.

If the predominant red color of the Patapsco-Raritan deposits is of primary origin, chemical weathering in the source area must have been intensive, as already evidenced by the impoverished mineral suite.

Magothy Formation

Evidence from the Heavy Mineral Suite

The heavy mineral suite indicates that the Magothy sediments were derived primarily from metamorphic rocks. The staurolite grains which are present in all sizes and in some variety, make up the bulk of the heavy mineral suite as in the Patuxent zone, but they differ in their inclusions. In the Magothy, the staurolites, particularly the yellow grains, often have no inclusions; in the Patuxent, however, most grains do have inclusions, many of which are carbonaceous. In the Magothy, carbonaceous inclusions in staurolite are rare. Apparently, phyllites and slates were not predominant in the source area during Magothy time, and it must have consisted mainly of gneisses and schists.

The main source area was probably the nearby Piedmont again, as during Patuxent and Patapsco-Raritan time.

The degree of weathering of the minerals is much less than that of the Patapsco-Raritan zone, and probably a little greater than that of the Patuxent zone. Also, the percentage of alterites is considerably smaller than in the Patapsco-Raritan zone, and a little larger than in the Patuxent zone. Some staurolite with saw-tooth terminations was found in all samples.

These characteristics indicate that the weathering processes in the area of provenance were less intense, or were of shorter duration during Magothy time than during the preceding Patapsco-Raritan period. Thus, the heavy mineral suite indicates renewal of erosion by re-activated streams in the Piedmont and thus, indirectly, a seaward tilting of the Coastal Plain. Moreover, the suddenness of the change in mineral suites favors the assumption of an unconformity between the Patapsco-Raritan and the Magothy. The presence of an unconformity is also supported by stratigraphic evidence derived from wells.

Evidence from Tourmaline

The tourmaline grains in the Magothy formation are similar to those in the Patapsco-Raritan zone, although there are some small but significant differences. Firstly, the Magothy contains more subrounded prismatic brown grains than the older sediments do, and this slightly greater degree of rounding of otherwise similar tourmalines may be due to redeposition of some Patapsco-Raritan deposits. Secondly, the percentage of pink tourmalines which already increased from the Patuxent to the Patapsco-Raritan, shows an even greater abundance in the Magothy formation. Finally, about 80 per cent of the green tourmalines are rounded, circular or oval-shaped grains of second or more cycle origin, or about twice as many as in the underlying Patapsco-Raritan, and four times as many as in the Patuxent zone. Thus, further headward erosion of streams into the Folded Appalachian Mountains apparently took place in Magothy time.

The nature of the inclusions in the Magothy tourmalines does not differ much from that of the underlying zone. Carbonaceous inclusions are few, indicating that metamorphosed black shales did not contribute greatly to the Magothy sediments. Mineral inclusions in medium to small prismatic grains are predominant, and according to Krynine (1946, p. 68), were probably derived from injected metamorphic terrane (meta-quartzites, quartz-schists, and quartz-mica-schists). Fairly abundant liquid and gaseous inclusions in tourmaline grains are evidence that some igneous rocks were also present in the source area.

Evidence from Field Observations and Sample Study

The Magothy deposits consist mainly of angular to subangular, fine to medium quartz sands. This angularity of the sand grains—even the larger ones—is quite striking and many writers have referred to these sediments as "sugary" sands. It suggests relatively short-distance and probably violent transportation, as is also apparent from the presence of many broken tourmaline grains. Bakker (1955) found that under tropical conditions decomposition and disintegration of source rocks progress very rapidly, resulting in production of many angular fragments. Thus, the prevailing angularity of detrital material in the non-marine sediments may also be due to the warm, humid climate of the Cretaceous Period.

The color of the sands is usually white and light-gray, and no evidence of oxidation is found. Since these sediments were of lagoonal or paludal facies (see Chapter VI), reduction of iron oxides may have taken place. If the deposits contained any ferric oxide due to weathering in the source area, it could have been reduced, in the presence of abundant organic matter and in relatively stagnant water with a deficiency of oxygen, according to the following equation:

$$2Fe_2O_3 + 2C \rightarrow 4FeO + C + CO_2 \quad \text{(Krynine, 1946, p. 62)}$$

Thus, the lack of color is probably a post-depositional feature, and does not necessarily indicate absence of oxidation in the source area.

Marine Upper Cretaceous Formations

Evidence from the Heavy Mineral Suite

The heavy mineral suites of the marine Upper Cretaceous formations, with their abundance of epidote, and the consistent presence of chloritoid, is an indication of a significant change in provenance. Epidote and some zoisite are derived mostly from metamorphosed calcareous sediments and highly altered basic igneous rocks (Milner, 1952, p. 283 and p. 269), unless they are of second cycle origin. The colorless variety of garnet, which is particularly abundant in the Merchantville and Mount Laurel-Navesink, is considered to be frequently derived from metamorphosed limestones and crystalline schists (Milner, 1952, p. 293). In the Piedmont all these rock types are present and may have contributed to the marine Upper Cretaceous sediments.

The sudden appearance of a high percentage of epidote minerals is the most significant feature to be considered, however. It must be recalled that these minerals are abundantly present in the Arundel-Patapsco, Raritan, and Magothy sections of the Hammond Well No. 1 near Salisbury, Maryland (Anderson, 1948). With the introduction of a marine environment in Merchantville time it is possible, and likely, that considerable detrital material was derived from the sediments lying immediately south of Delaware, and that, therefore, at least a portion of the marine Upper Cretaceous deposits are of second sedimentary cycle origin. This interpretation, involving transportation of material in a northerly direction, is further substantiated by the greater degree of rounding of the detrital grains as compared with those of the non-marine Cretaceous formations, and by the fact that the percentage of epidote minerals decreases from northern Delaware to New Jersey (see fig. 17).

Samples from the Magothy-Raritan of New Jersey do not contain epidote, and it is considered very unlikely that a source area which did not provide epidote in Raritan-Magothy time would suddenly deliver large quantities of this mineral to the marine Upper Cretaceous deposits of Delaware, and smaller quantities to the same formations in New Jersey. Thus, transportation of material in a southerly direction does not appear to be within the realm of possibility.

The Englishtown of New Jersey, which is absent in northern Delaware, is partially non-marine, and in these deposits hardly any epidote minerals are found. Thus it appears that when the deposits were non-marine, and when the supply of epidote-containing material from the south was temporarily stopped, the mineral suite lacks epidote, and is characterized more by tourmaline, staurolite, kyanite, and sillimanite. This is another reason for suspecting that the source area of at least a portion of the marine Cretaceous detritals was located in the south.

It is of interest to note that Recent floodplain sands in northern Delaware have a mineral suite consisting mainly of hornblende, sillimanite, and staurolite; in addition many other heavy minerals are present in small percentages. Epidote is found in most samples, but only in very small amounts. Apparently, streams transporting detrital material derived from the Piedmont do not erode significant sources of epidote-containing rocks. Knowing that the non-marine Cretaceous sediments were mainly derived from the Piedmont and were lacking in epidote, and that the same is true for Recent floodplain sediments, the conclusion that the epidote-rich suite of the marine Upper Cretaceous was mainly derived from elsewhere is a logical one.

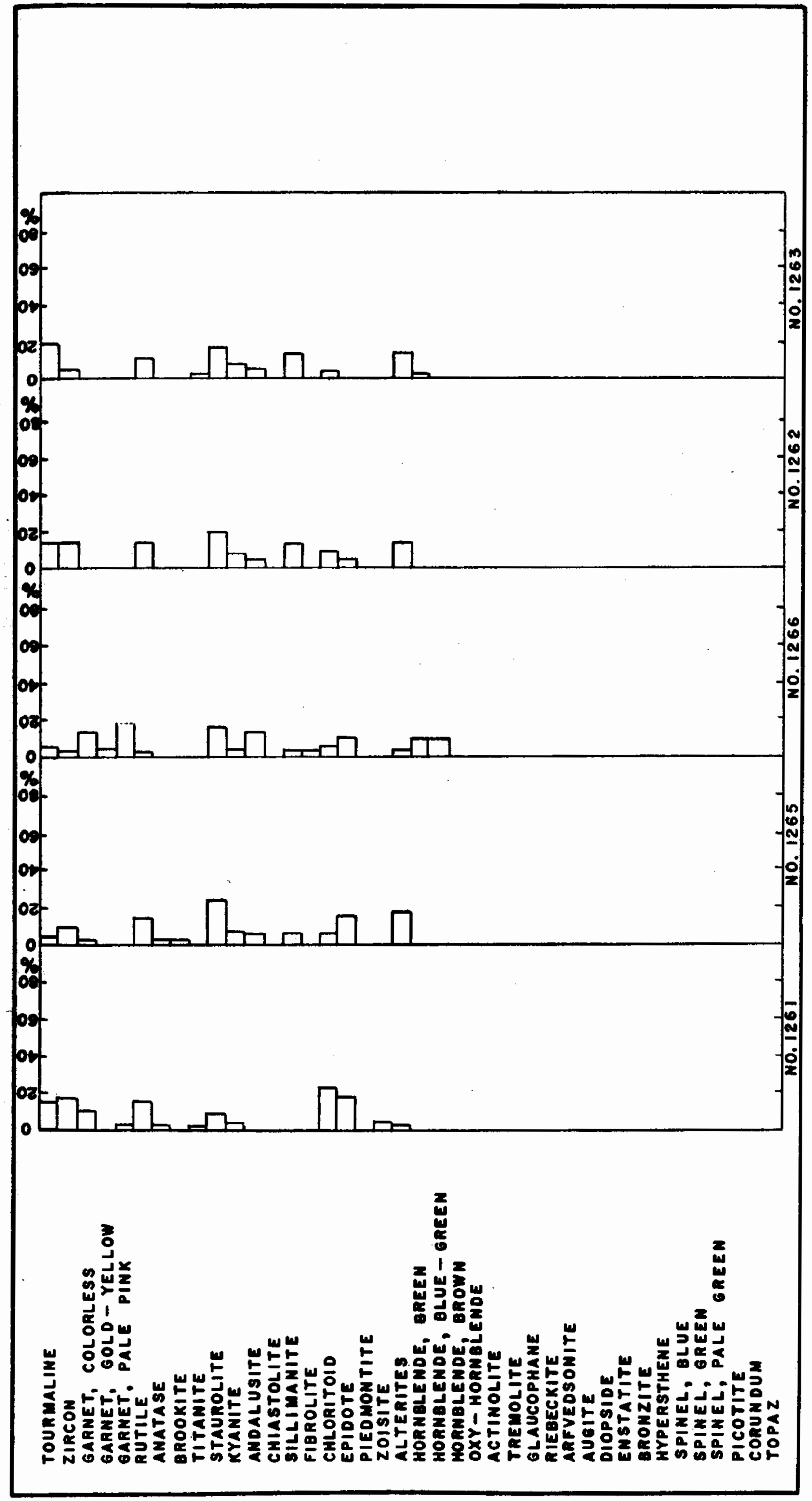


Figure 17. Bar diagrams of the heavy mineral content of marine Upper Cretaceous formations in New Jersey.

A minor portion of the marine Upper Cretaceous deposits was undoubtedly derived from more nearby sources. At least the presence of rutile and tourmaline in somewhat higher percentages than in the deposits of the Hammond well seems to indicate such a different source. Moreover, with the downward movement of the Coastal Plain and the consequent encroachment of the sea upon the land, which was already initiated in Magothy time, some contribution of nearby Piedmont materials and detritals from the Folded Appalachians can be readily expected.

Colorless garnet is present in most of the samples of the marine Upper Cretaceous formations, but primarily in the Merchantville and the Mount Laurel-Navesink, whereas the Wenonah and Red Bank contain only little garnet. The first two formations mentioned are fine-grained and calcareous, particularly the Mount Laurel-Navesink, whereas the Wenonah and the Red Bank consist chiefly of siliceous sands. According to Sindowski (1939), heavy minerals in general, and garnet in particular, are more subject to post-depositional weathering in coarse-grained, noncalcareous sediments than in fine-grained, calcareous deposits. Thus, it is likely that the very small garnet percentage in the Wenonah and Red Bank formations is due to post-depositional weathering and not to a difference in provenance.

Apart from the presence of garnet, the differences in the mineral suites of the marine Cretaceous deposits are small. There is a tendency, however, toward a slight decrease in the content of epidote minerals and an increase in staurolite, which is particularly noticeable in the Red Bank formation. This feature is probably due to an increasing influx of Piedmont and Appalachian detrital material and a decrease of material from the south. During Red Bank time most of the non-marine Cretaceous sediments were covered by the formations of the Matawan group and the Navesink, thus partially choking off the epidote supply contained in the Patapsco, Raritan and Magothy formations in the south. In addition, the Red Bank was deposited closer to the shore line than the underlying Mount Laurel-Navesink, and therefore, the former probably received a larger amount of Piedmont-derived material than the latter.

The increase in staurolite and the decrease in epidote percentages are not caused by grain size variations between the marine Upper Cretaceous formations. Increase in staurolite content is initiated in the Wenonah formation, and persists through the fine-grained Mount Laurel-Navesink and the fine- to medium-grained Red Bank.

Evidence from Tourmaline

The tourmaline grains differ significantly from those of the non-marine Cretaceous formations in the degree that they absorb light when the prisms are lying parallel to the horizontal crosshair of the microscope (perpendicular to the polarizer). The majority of the tourmaline grains of the older formations absorb, in this position, so much light as to appear almost black; but

those of the marine Cretaceous formations generally remain dark-brown, dark-green, etc. This phenomenon indicates a difference in provenance of these sediments, a conclusion which is not surprising considering what has been stated in the preceding pages concerning the source area of these detritals.

There are no great changes in the tourmaline varieties of the marine Upper Cretaceous, with the exception of an increase of "non-marine Cretaceous type" tourmaline in the Red Bank. Indications are that the Red Bank is a very shollow water deposit in which stream-transported material from the Piedmont and the Folded Appalachians to the west can be expected to occur in a larger percentage than in the older marine sediments. Further evidence of this possibility is that the number of rounded, oval- or circular-shaped grains sharply increases in the Red Bank over that of the earlier formations.

Evidence from Field Observations and Sample Study

All marine Upper Cretaceous formations contain small mica flakes (muscovite) and these appear in abundance particularly in the Merchantville and the Wenonah. In the Mount Laurel-Navesink and the Red Bank much less muscovite is present. Since muscovite is present in a rather wide range of rocks, and was also rather abundant in the non-marine Cretaceous deposits of the area of the Hammond Well No. 1 near Salisbury, Maryland, it is possible that the muscovite was derived both from the nearby Piedmont and the non-marine Cretaceous deposits of the Coastal Plain.

Feldspar is present in very small quantities in most samples of the marine sediments, but an increase in the amount of this mineral was noted in the Red Bank formation. This feldspar, which cannot have been transported very far, was probably derived from the nearby Piedmont. Therefore, this tends to support the conclusion—reached on the basis of the heavy mineral analyses—that there was a greater contribution of Piedmont-derived detrital material to the Red Bank than to the younger marine Cretaceous formations.

General Conclusions Regarding the Provenance of the Cretaceous Sediments of Northern Delaware

The non-marine Cretaceous sediments (those of the Patuxent and Patapsco-Raritan zones and those of the Magothy formation) were all derived from essentially the same source area, namely, the nearby Piedmont, and, to an increasing degree in the younger deposits, from the adjacent Folded Appalachians. Thus, although they are composed of detritals from a great variety of parent materials, such as metamorphic, igneous, and sedimentary rocks, they form a complex of sediments which, by their geographical distribution, age, and origin form a natural unit. Therefore they can be said to belong to *one sedimentary petrological province*, as defined by Baturin (1931), Edelman (1933), and Doeglas (1940).

The marine Cretaceous formations of northern Delaware, however, consist of a mixture of detrital materials from two sources. One source is located to the south providing an epidote-rich suite, and the second source is located to the northwest, and is actually the same source which supplied detrital materials to the non-marine Cretaceous sediments. Thus, the marine Cretaceous formations of northern Delaware form another sedimentary petrological province which differs from the first one by being composed of *mixed sediments.*

CHAPTER VI

THE ENVIRONMENT OF DEPOSITION OF THE CRETACEOUS SEDIMENTS OF NORTHERN DELAWARE

General Considerations

INTERPRETATION of the environment of deposition on the basis of mechanical analysis of the samples meets with many difficulties, because the grain size distribution of a sediment depends on many factors, such as the size of the grains available for transportation and deposition, their shape, roundness, and range in specific gravity, the agent of transportation, and the conditions under which deposition took place. In the Cretaceous deposits of northern Delaware some of these factors may be relatively unimportant, however, because they were derived partially from the Piedmont with its variety of igneous and metamorphic rocks, and partially from the Paleozoic rocks of the Appalachian region, and it is expected that a wide range in grain size would be available from these sources. In the sands, the influence of the specific gravity of the grains probably plays a minor role, because the Cretaceous sediments usually contain small percentages of heavy minerals, and consist largely of quartz grains, except the glauconitic Merchantville and Mount Laurel-Navesink formations. In the clayey silts and sands frequently occurring in the Patapsco-Raritan zone, the mixture of quartz sand and clay minerals may, perhaps, have a significant influence on the size frequency distribution, but, owing to the fact that no data on the distribution of grains smaller than 2 microns are available, such influence is not apparent.

Of greater importance is the possibility that a certain type of size frequency distribution can be produced in more than one environment. For instance, a comparison of the cumulative curves of beach and dune sands, and also of some river bed sands indicates that different environments *can* (although they not always do) produce sediments very much alike. Apparently, if transportation occurs by essentially the same medium, for instance by fluids of low viscosity, like coastal currents in the ocean, river currents, or air currents, the resulting sediments can be very similar in their mechanical composition although their environment of deposition is entirely different. Therefore, one or a few samples of a formation can never lead to reliable results in interpretation of environmental conditions; analysis of many samples of one formation, however, showing variations in mechanical composition, will produce curves of different types, a combination of which may be indicative of the environment of deposition. This will be discussed later in more detail.

It has become customary to describe the mechanical composition of sediments in statistical parameters, such as Md_ϕ, M_ϕ, $\sigma\phi$ and $\alpha\phi$ (see Chapter II). Although the usefulness of these values is recognized, it should be kept in mind that they are based only on a few points of the cumulative curve, and therefore cannot represent the distribution with the same degree of accuracy as the cumulative curve itself does. For this reason interpretation is based on the study of the cumulative curves as well as on statistical parameters.

As mentioned previously (see Chapter II) the results of the mechanical analysis were plotted on arithmetic probability paper, with the weight percentages of the sediment fractions on the probability scale, and the class intervals in phi (ϕ) units on the arithmetic scale. Because phi units are logarithmic, a straight curve on arithmetic probability paper indicates a *log* normal distribution rather than a normal one.

According to Doeglas (1950), many sediments approach a normal distribution, whereas Krumbein (Krumbein and Pettijohn, 1938) stated (p. 189):

> A type of graph paper of considerable value in analyzing cumulative curves is logarithmic probability paper, which has a logarithmic scale along one axis and a probability scale along the other. The probability scale is so designed that a symmetrical cumulative curve will plot as a straight line on the graph. Many sands show straight lines on this paper, and it affords an excellent method of comparing sedimentary data.

Thus, Krumbein found that sediments often approach a log normal distribution.

Doeglas (1950) analyzed the mechanical composition of beach sands of the Dutch coast and plotted them on arithmic probability paper. Some of Doeglas' samples are shown in figures 18 and 19, plotted, respectively, with particle diameter in microns and in phi units.

Neither Krumbein nor Doeglas stated why the size frequency distribution of a sediment should be or approach a normal or log normal one, although it is well known that some beach, dune, and river channel sands actually do. The possibility should be considered, however, that this phenomenon is not *directly* related to the type of deposit, or the environment of sedimentation, but to other factors.

The phi skewness (α_ϕ) is a valuable aid in studying the degree to which a size frequency distribution approaches the log normal. If the distribution is log normal, and therefore, the cumulative curve is a straight line, phi skewness is zero. The greater the skewness value, either positive or negative, the greater is the deviation from the log normal distribution.

It has been observed in the past that degree of sorting is related to grain size, and a glance at the skewness values suggested that there might also be a relationship between skewness and median grain size.

The relationship between median grain size (Md_ϕ) and skewness (α_ϕ) was plotted for all Cretaceous formations (see figs. 20-26).

In the Patuxent zone, the spread of the skewness values is considerable (see fig. 20); it should be noted, however, that in the coarse sands no low skewness

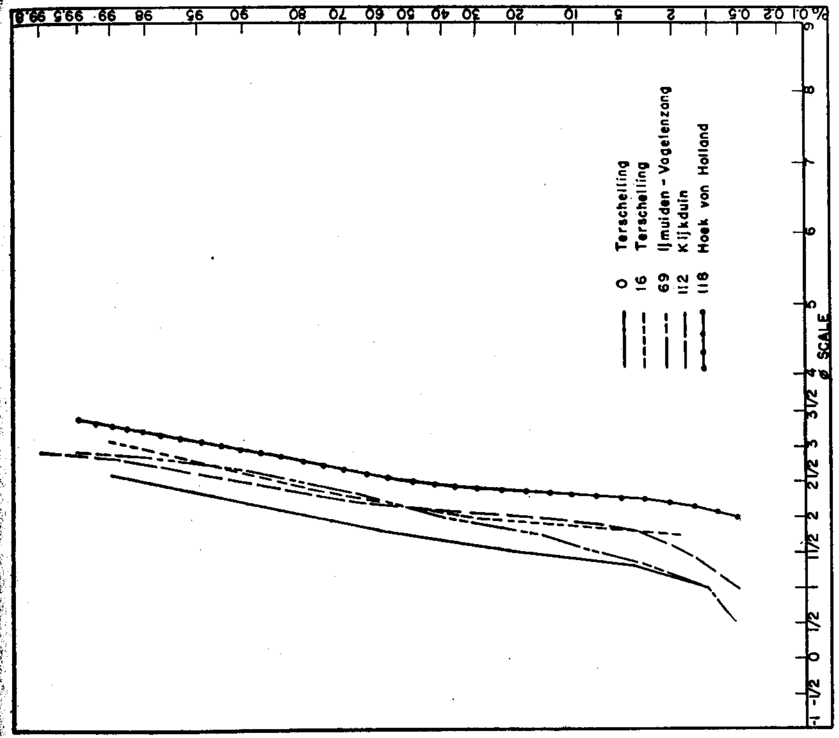


Figure 19. Mechanical analyses of beach sands of the Netherlands. Data from Doeglas (1950).

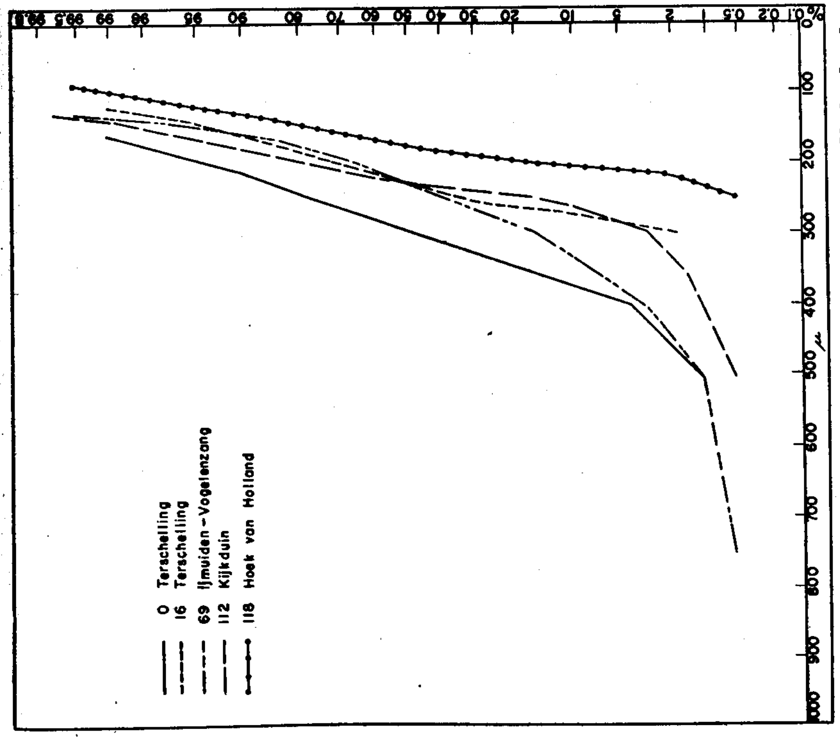


Figure 18. Mechanical analyses of beach sands of the Netherlands. Data from Doeglas (1950).

values occur, whereas these are frequent in the fine sands. Thus, there is a tendency toward increasing skewness when grain size increases from fine to coarse sand.

A wide range of values for median grain size and skewness is found in the samples of the Patapsco-Raritan zone, and the relationship between these values is clear (see fig. 21). In the sand sizes α_ϕ increases with decreasing Md_ϕ, but in the silt sizes the opposite is true. Thus, in the Patapsco-Raritan zone, the size frequency distribution has the greatest deviation from a symmetrical one on the boundary between sand and silt sizes, and the greatest degree of symmetry in the fine to medium sands and the fine silts.

In the Magothy formation, all median grain sizes but one fall within the sand fractions. Yet, there appears to be a tendency toward increasing skewness with decreasing grain size (see fig. 22).

A tendency similar to the one in the Patapsco-Raritan is found in the Merchantville formation. Again, skewness increases rapidly with decreasing medium grain size in the sand fraction, and it decreases again in the silt fraction (see fig. 23).

In the Wenonah samples, no correlation between Md_ϕ and α_ϕ is apparent (fig. 24), but all samples of this formation have a median grain size of about 3 phi units. The great range of α_ϕ of samples whose median grain size varies very little is due to the characteristic cumulative curve of these samples which invariably consists of a nearly straight curve with a long tail of silt (see figs. 69 and 70). If ϕ_{84} falls somewhere on this tail of the fine-grained fraction, it has a relatively high value, and consequently, α_ϕ is great. If, however, ϕ_{84} still falls on the straight curve itself, α_ϕ is relatively small.

In the Mount Laurel-Navesink formation the same trend in the relationship between median grain size and skewness is evident as in the Merchantville (fig. 25). Relatively few samples of the Red Bank formation were analyzed, but the trend of increasing skewness with decreasing median grain size is also apparent in this case (fig. 26).

The trend of increasing skewness with decreasing median grain size in the medium to very fine sand fraction and decreasing skewness with decreasing median grain size in the silt fraction occurs both in the marine and the non-marine Cretaceous formations, or in sediments of entirely different origin and environment of deposition. Since skewness is a measure of the degree to which the distribution approaches the log normal, at least within the boundaries of the parameters involved in determining α_ϕ, that is ϕ_{16} and ϕ_{84}, it appears that, generally, log normal distributions occur in medium to fine sands, and in medium to fine silts, irrespective of the environment of deposition.

In order to compare the results described above with data obtained from samples of known environments, mechanical analyses of floodplain and stream

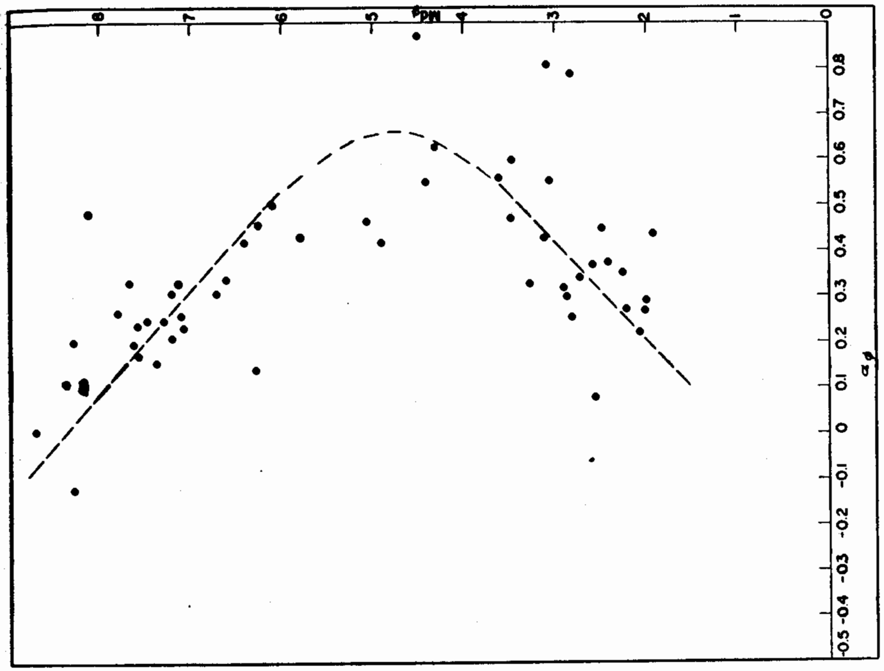


Figure 21. Relationship between median grain size and skewness, Patapsco-Raritan zone.

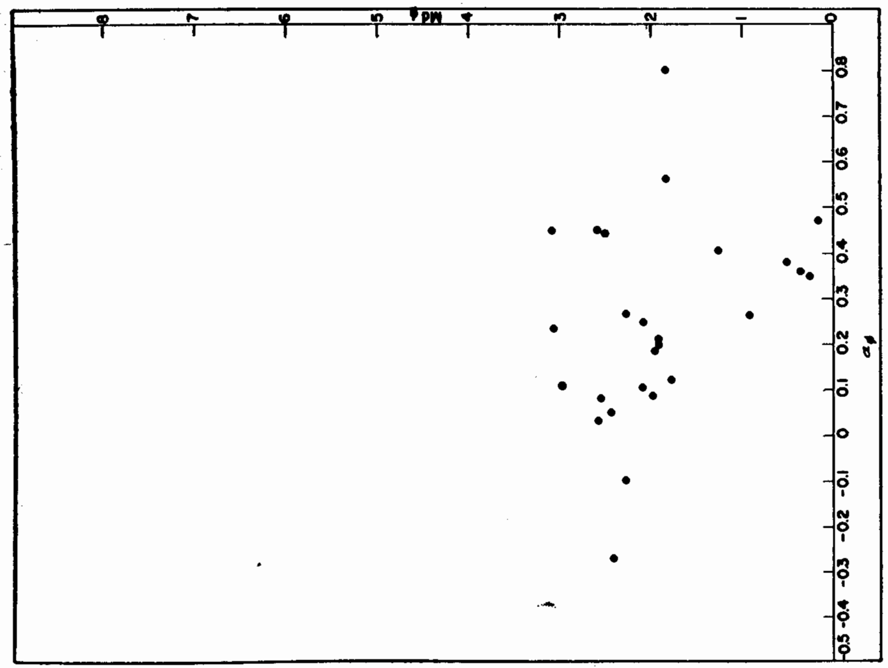


Figure 20. Relationship between median grain size and skewness, Patuxent zone.

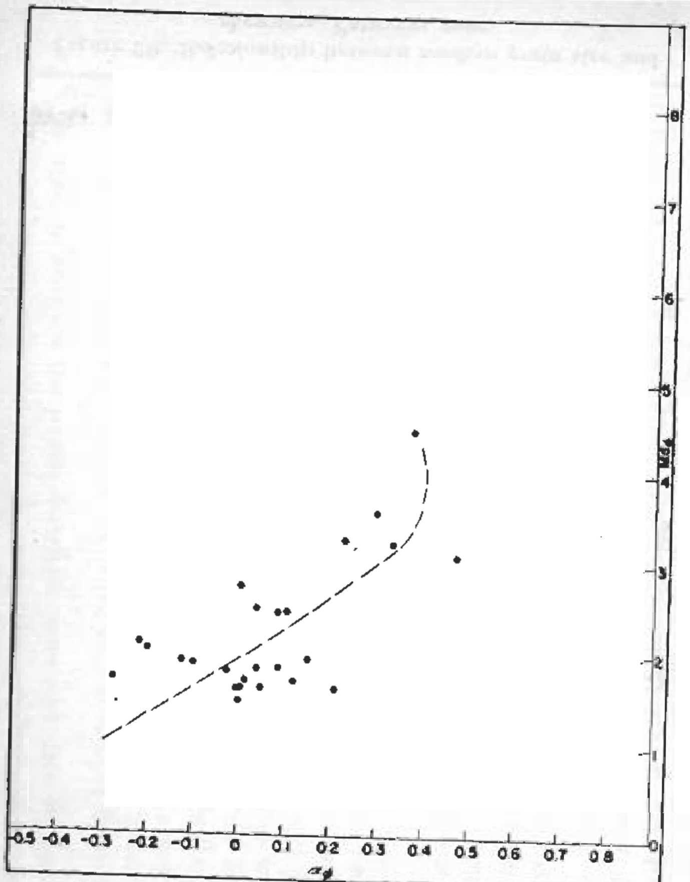


Figure 22. Relationship between median grain size and skewness, Magothy formation.

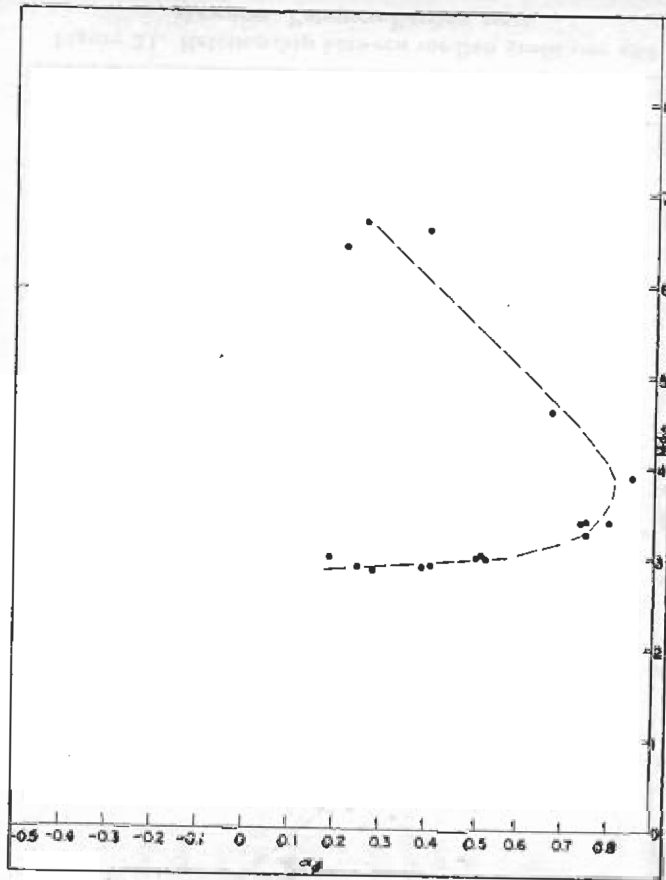


Figure 23. Relationship between median grain size and skewness, Merchantville formation.

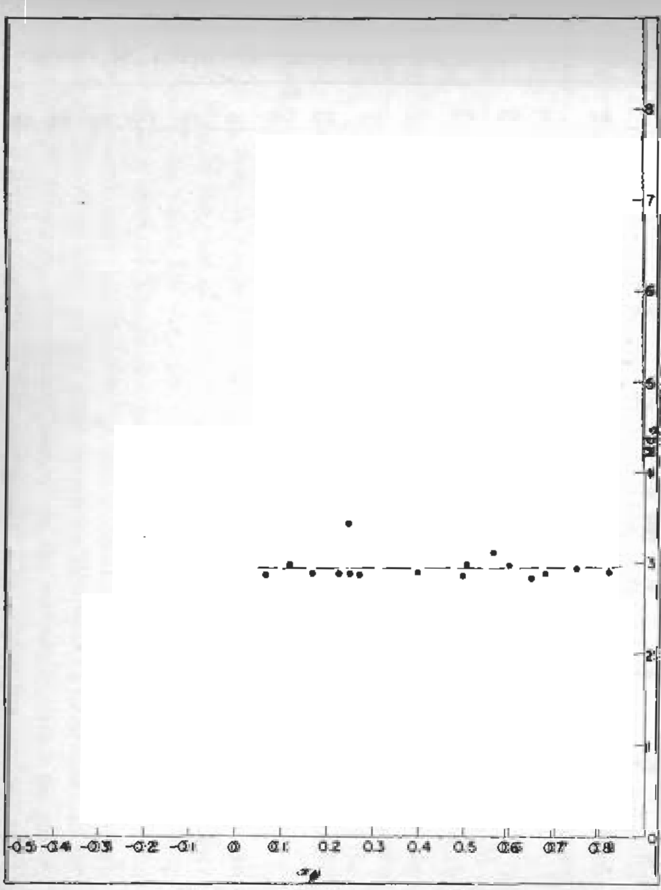


Figure 24. Relationship between median grain size and skewness, Wenonah formation.

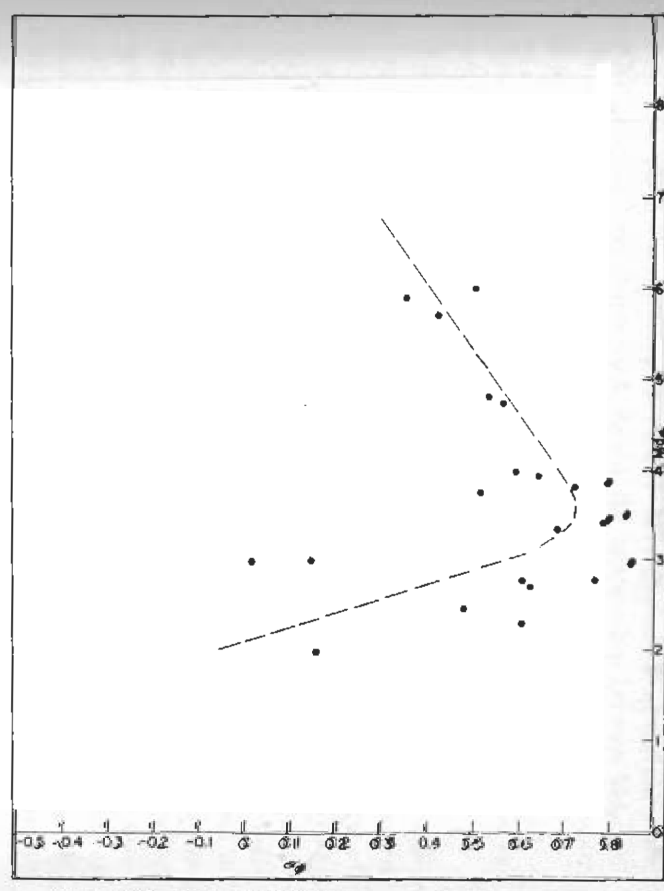


Figure 25. Relationship between median grain size and skewness, Mount Laurel-Navesink formation.

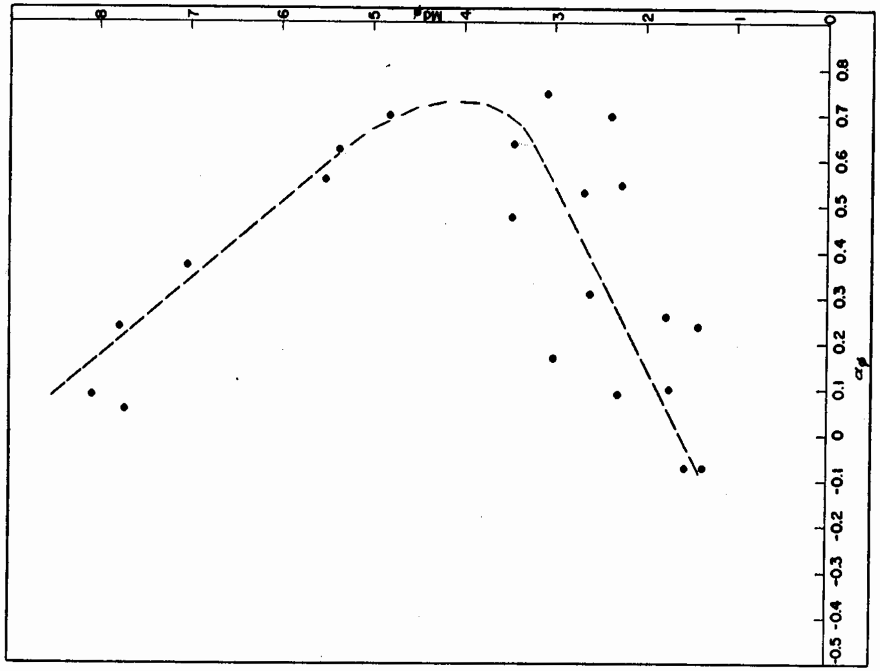


Figure 27. Relationship between median grain size and skewness, Recent floodplain sediments.

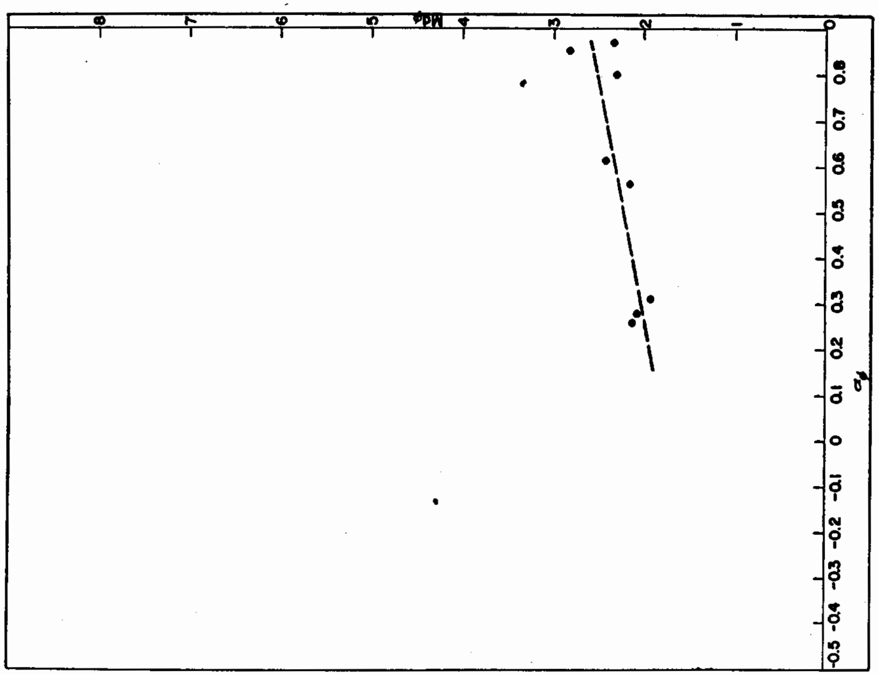


Figure 26. Relationship between median grain size and skewness, Red Bank formation.

bed samples published by Doeglas (1950) were plotted using the phi scale, and Md_ϕ and α_ϕ were determined. Again, the relationship between Md_ϕ and α_ϕ is similar to the one described for the Cretaceous sediments of Delaware (see fig. 27).

How can the relationship between skewness and median grain size be explained?

It has been noted that some sediments approach a log normal distribution, although the reason is not known. Apparently, when a sediment is transported for a sufficient time in a certain way, for instance by traction, a selection of particles takes place in such a manner that a log normal distribution is approached. The same may be true for sediments transported in suspension. Thus, if deposition of tractional particles alone takes place the resulting sediment may approach a log normal distribution, and the same may happen in the case of deposition of a suspension load. If, however, tractional and suspension particles are deposited at the same time—possibly both having a log normal distribution—the skewness will depend on the ratio between the tractional and suspension portions of the sediment. If about equal amounts of suspension and traction particles are present in a deposit, skewness phi will reach a high value, and the median grain size will range from fine sand to coarse silt.

Great variations in skewness values do not necessarily indicate differences in environment of deposition. In the Wenonah formation, for example, the ratio between body and tail of the cumulative curves, and therefore α_ϕ, varies considerably, but the similarity in the shape of the curves suggests strongly that there were no essential differences in the conditions under which the sediments were deposited. Slight differences in the velocity of the transporting currents must be responsible for this phenomenon.

Although the same trend in the relationship between Md_ϕ and α_ϕ was observed in the non-marine and marine formations, the increase of α_ϕ with decreasing Md_ϕ is more pronounced in the marine formations than in the non-marine ones. This feature is caused by the very sharp division between the body of fine sand and the fine tail of silt and clay which is very flat in the marine deposits. In the non-marine sediments, the curve usually bends toward the fine tail very gently.

Some caution is needed in the interpretation of the relationship between α_ϕ and Md_ϕ in the case of the very fine silts. If the median grain size becomes very small, the value for the 84th percentile can only be found by extending the curve as a straight line in the general direction of the last portion of the curve. If this extension is considerable, then a small skewness must be expected. Therefore, the reliability of the data shown in figures 20-27 depends on the accuracy with which ϕ_{84} was determined, or on the manner in which the cumulative curves were extended to that percentile. Yet, where the median grain size was in the coarse and median silt size, and the extension of the cumulative curve small, with little chance of a great error in determining the 84th percentile, the tendency of decreasing skewness was already evident.

Degree of sorting is also related to grain size. McMaster (1954), who studied the beach sands of the New Jersey coast, stated (p. 54):

> . . . . it appears that a general relationship exists between size and sorting for these beach sands. The sands having the smallest sorting values are those with median sizes between 0.2 mm. - 0.15 mm. (fine sand); while the medium and coarse sands have larger sorting values.

Inman (1949) found also that sediments with median diameter near the grade of fine sand are the best sorted, and sediments coarser and finer are not so well sorted.

The Cretaceous sediments of northern Delaware exhibit the same phenomenon. Median grain size (Md_ϕ) is plotted against the sorting factor (σ_ϕ) in figures 28-35. The tendency toward poor sorting in the fine-grained sediments is particularly noticeable in the samples of the Patapsco-Raritan zone (fig. 29), in the Merchantville (fig. 31) and in the Mount Laurel-Navesink formations (fig. 33).

Although the relationship mentioned above appears to apply to the non-marine as well as to the marine formations, it should be noted that the increase of the sorting factor (σ_ϕ) with decreasing median grain size (Md_ϕ) is much more rapid in the marine formations than it is in the non-marine sediments. Again, this is a result of the fact that σ_ϕ depends on ϕ_{84}, the value of which greatly varies with its position on the fine tail of the cumulative curve, as already mentioned in the discussion of the skewness of the grain size distribution.

A relationship between kurtosis (β_ϕ) and median grain size (Md_ϕ) can also be observed (see fig. 36-42). The greatest kurtosis values occur where β_ϕ is approximately between 2 and 3.5. In sands having a greater median grain size, and in the silts, β_ϕ is small. Evidently, those sediments which closely approach a log normal distribution (the medium to fine sands and the silts) have also small kurtosis values. Again, this relationship is true for both the non-marine and the marine sediments, although it is much more pronounced in the marine formations (see figs. 39-41).

Inman (1949) studied the transportation of sediments in the light of fluid mechanics. On the basis of theoretical considerations as well as experimental data, he found relationships between grain size, skewness and degree of sorting similar to the ones found for the Cretaceous sediments of northern Delaware.

The ability of a current to transport sedimentary particles in terms of size (competency) depends on the turbulence of the current, which is a function of current velocity and the degree of roughness of the bottom. If the bottom is smooth, a greater velocity is required to produce sufficient turbulence to move particles of a certain size than would be with a rough bottom. Inman

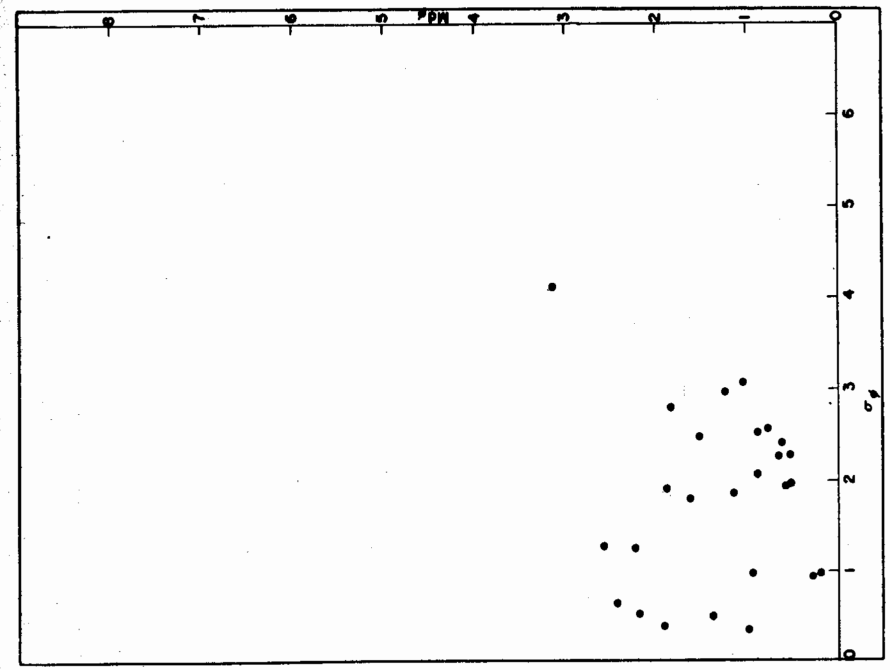


Figure 28. Relationship between median grain size and sorting coefficient, Patuxent zone.

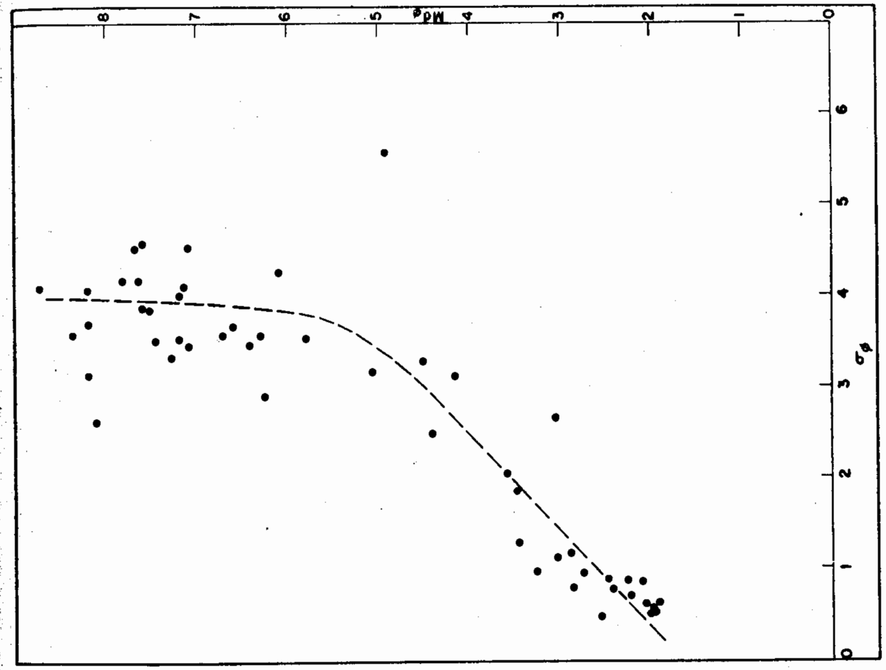


Figure 29. Relationship between median grain size and sorting coefficient, Patapsco-Raritan zone.

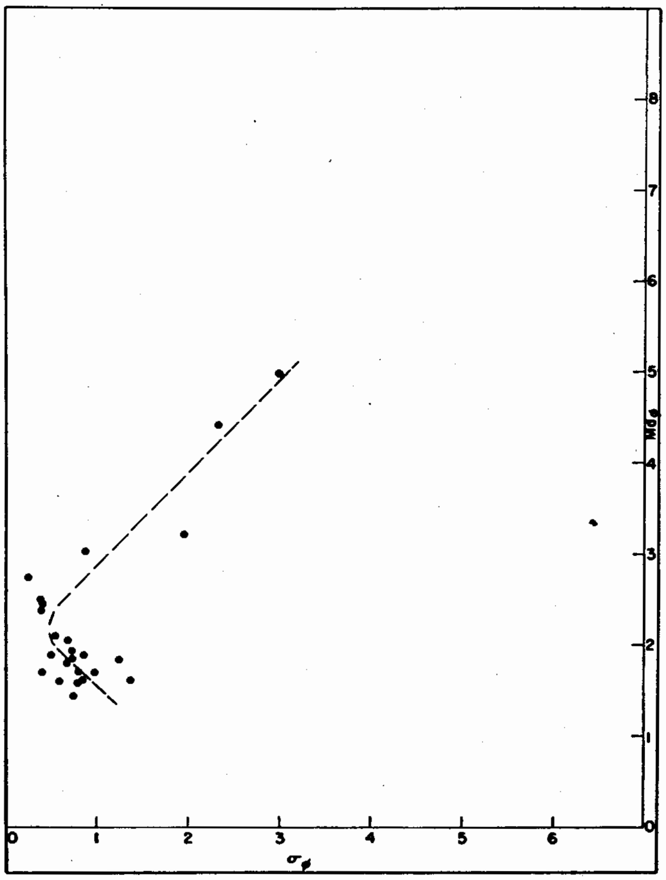


Figure 30. Relationship between median grain size and sorting coefficient, Magothy formation.

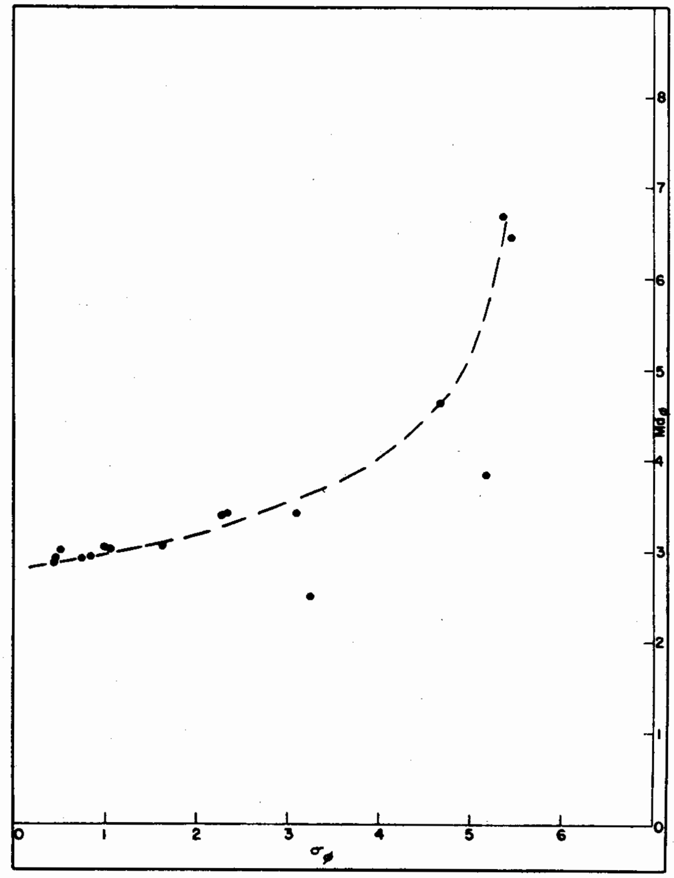


Figure 31. Relationship between median grain size and sorting coefficient, Merchantville formation.

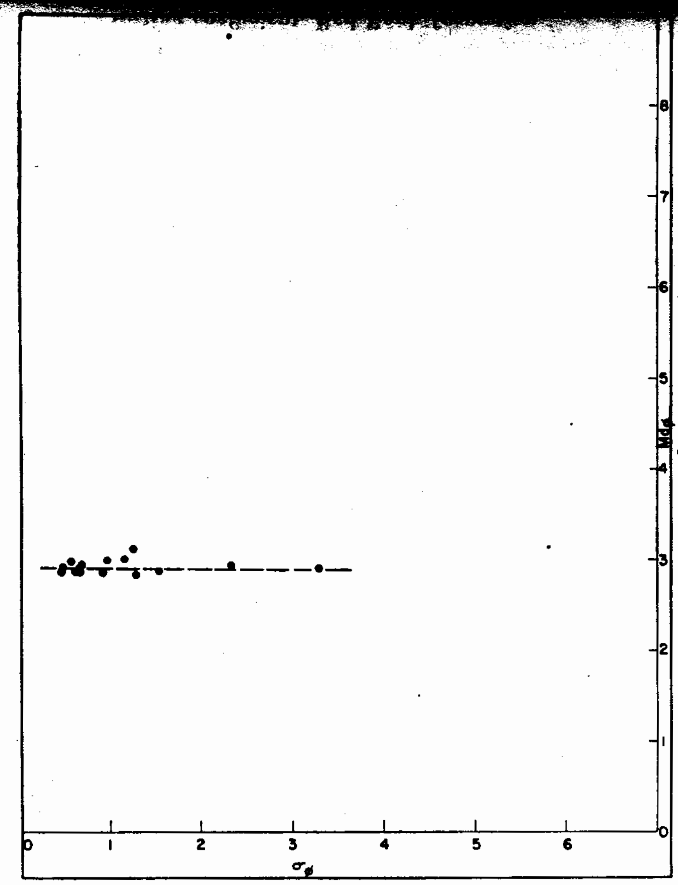


Figure 32. Relationship between median grain size and sorting coefficient, Wenonah formation.

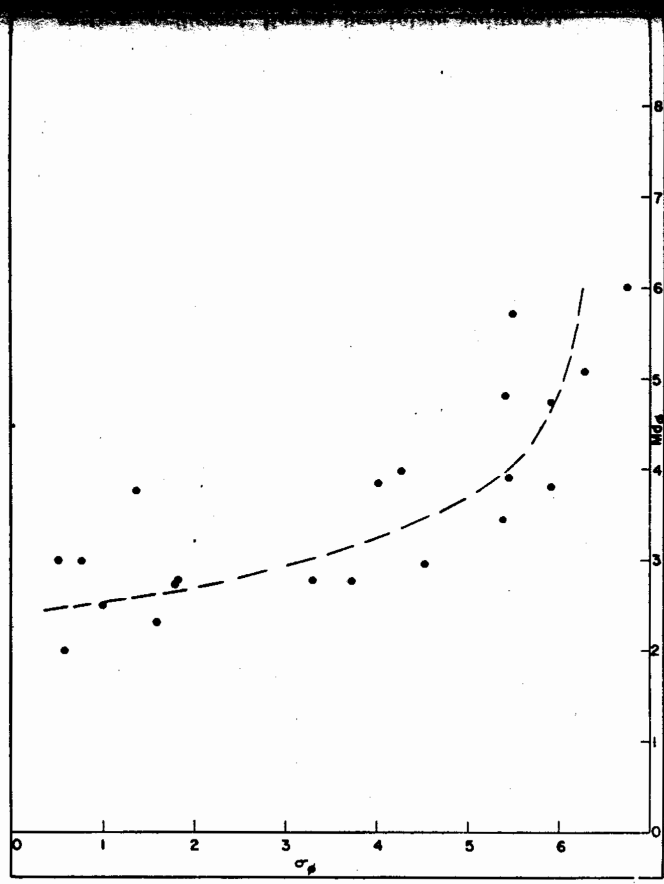


Figure 33. Relationship between median grain size and sorting coefficient, Mount Laurel-Navesink formation.

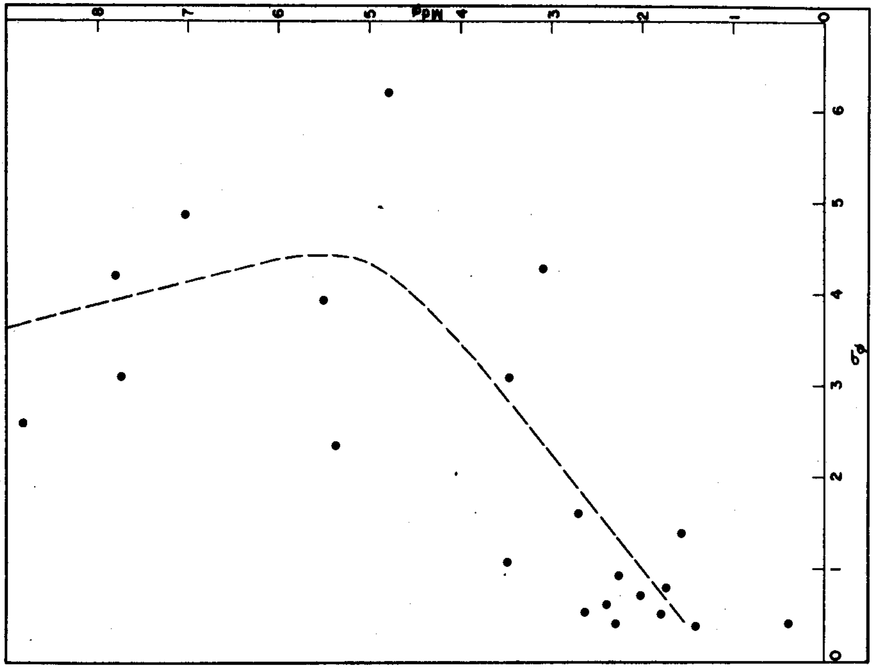


Figure 35. Relationship between median grain size and sorting coefficient, Recent floodplain sediments.

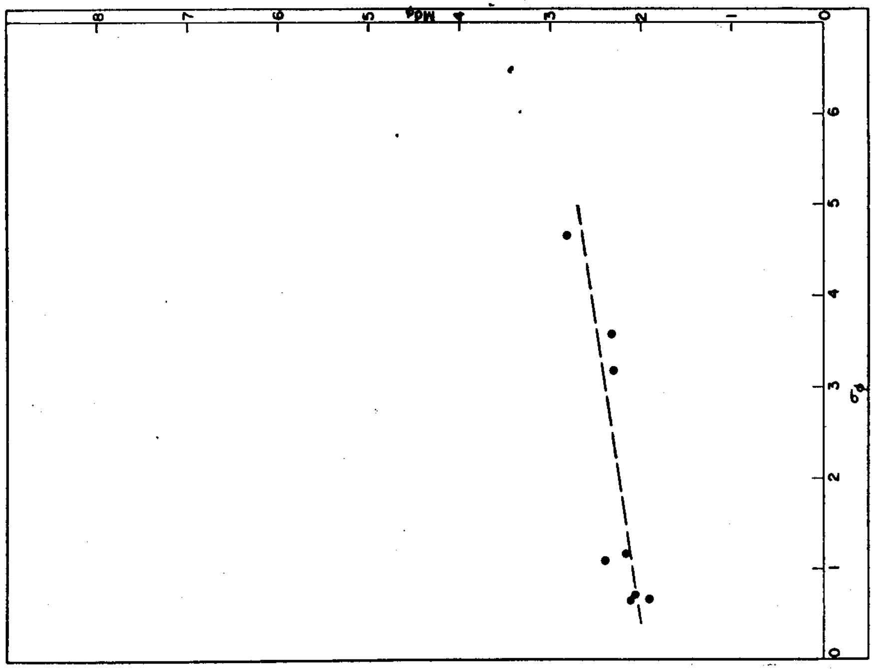


Figure 34. Relationship between median grain size and sorting coefficient, Red Bank formation.

(1949) found that the roughness velocity, or the critical friction velocity at which the character of the bottom changes from smooth to rough, is inversely proportional to particle diameter. For a bottom consisting of very small grains (fine silt, clay), the velocity required to cause significant turbulence is so great, however, that such particles will not begin movement unless the velocity is considerably greater than that required to move fine sand particles. Thus, the apparently anomalous situation exists that grains smaller than fine sand size require a greater velocity of the transporting medium to begin movement than those of fine sand size. Because larger grains also require greater velocity, the fine sand grains are unique in that they are the most easily moved particles.

Inman (1949) expressed this phenomenon by stating that the threshold velocity, or the critical velocity at which a particle begins to move owing to the drag force of the fluid, is smallest for particles of fine sand size (diameter about 0.18 mm), and increases for particles smaller *and* larger than this size.

For particles smaller than fine sand size the threshold velocity is considerably greater than the settling velocity. Thus, once a particle begins to move in a water current, it will tend to be transported in suspension rather than by traction. In the case of particles larger than fine sand, however, transportation will be by traction, unless the friction velocity of the current exceeds the settling velocity. These considerations support the contention—discussed previously—that the fine tail of a cumulative curve probably represents the suspension portion of a sediment, and the coarse body of the curve the tractional portion.

Inman's theoretical considerations were based on the assumption that the sediment particles are spherical and that they all have the same specific gravity. Obviously, this is not the case under natural conditions, and some deviations from theoretical conclusions must be expected. In general, very fine sand and silt particles are irregularly shaped and angular, and they can be more easily transported in suspension than spherical particles of the same weight. Medium and coarse sand particles, however, often are more or less spherical or ellipsoidal and rounded. As a result, the threshold velocity for small grains may be somewhat smaller in reality than in theory, whereas the theoretical and actual threshold velocities for median and coarse sand particles may coincide fairly closely.

It should be kept in mind that Inman's discussion relates primarily to friction velocities necessary to *start* the movement of sedimentary particles. Once this is accomplished, much lower velocities are needed to sustain particle transportation.

Inman (1949) emphasized the relationship between fluid mechanics and the transportation of sedimentary particles, and in particular, the current velocities at which particles of a certain size begin to move. For the purpose of studying environments of deposition, however, more stress should be put on

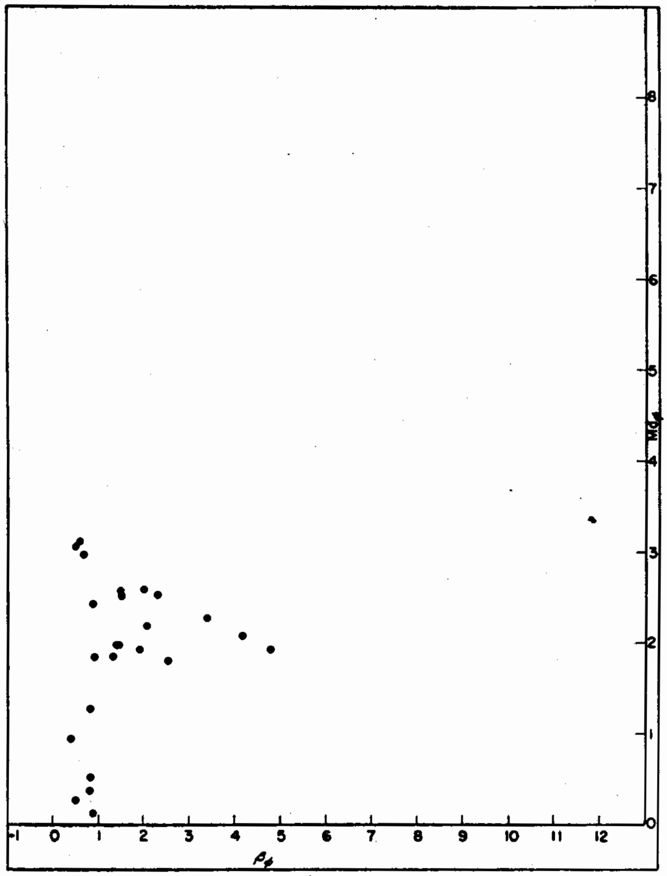


Figure 36. Relationship between median grain size and kurtosis, Patuxent zone.

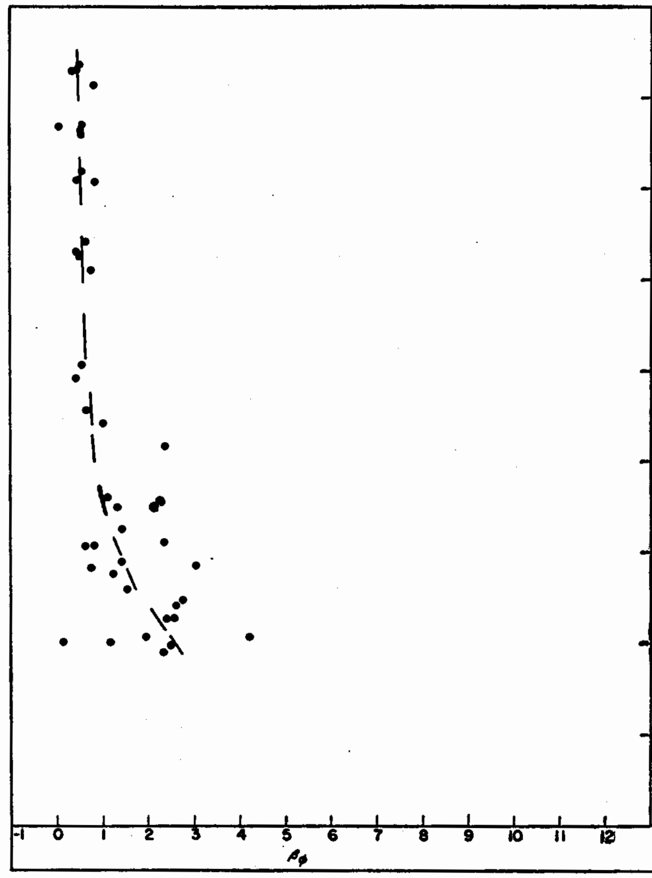


Figure 37. Relationship between median grain size and kurtosis, Patapsco-Raritan zone.

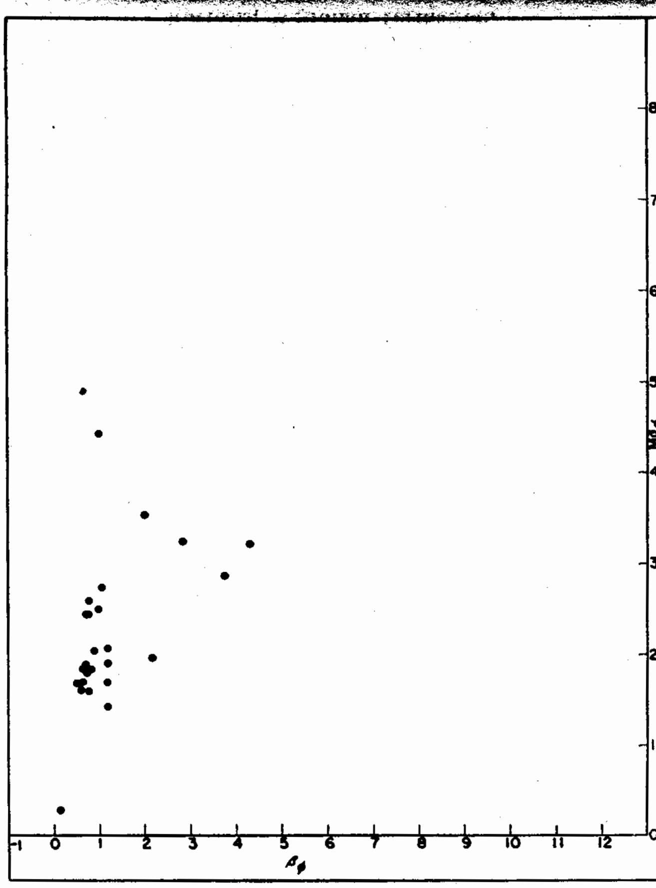


Figure 38. Relationship between median grain size and kurtosis, Magothy formation.

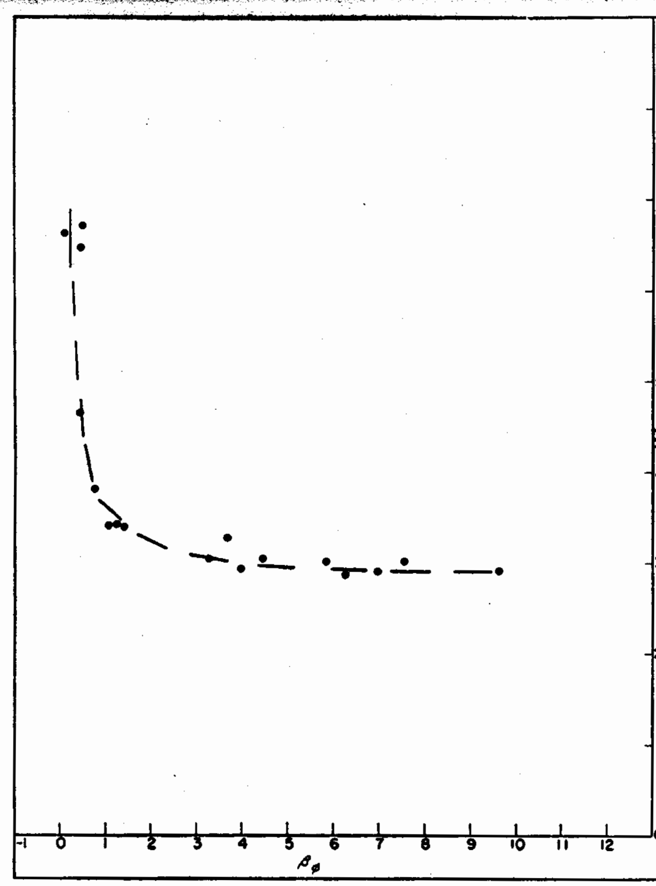


Figure 39. Relationship between median grain size and kurtosis, Merchantville formation.

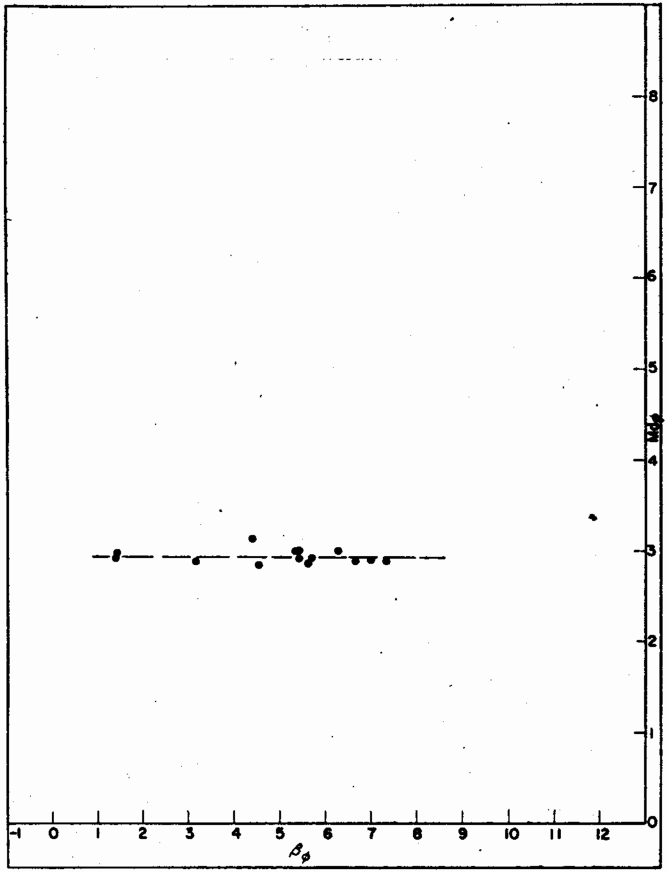


Figure 40. Relationship between median grain size and kurtosis, Wenonah formation.

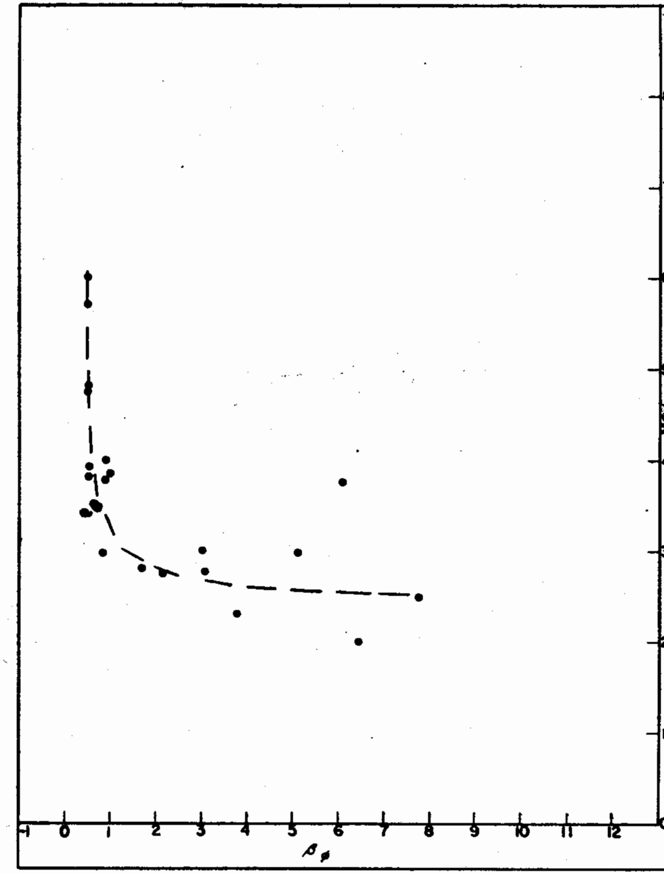


Figure 41. Relationship between median grain size and kurtosis, Mount Laurel-Navesink formation.

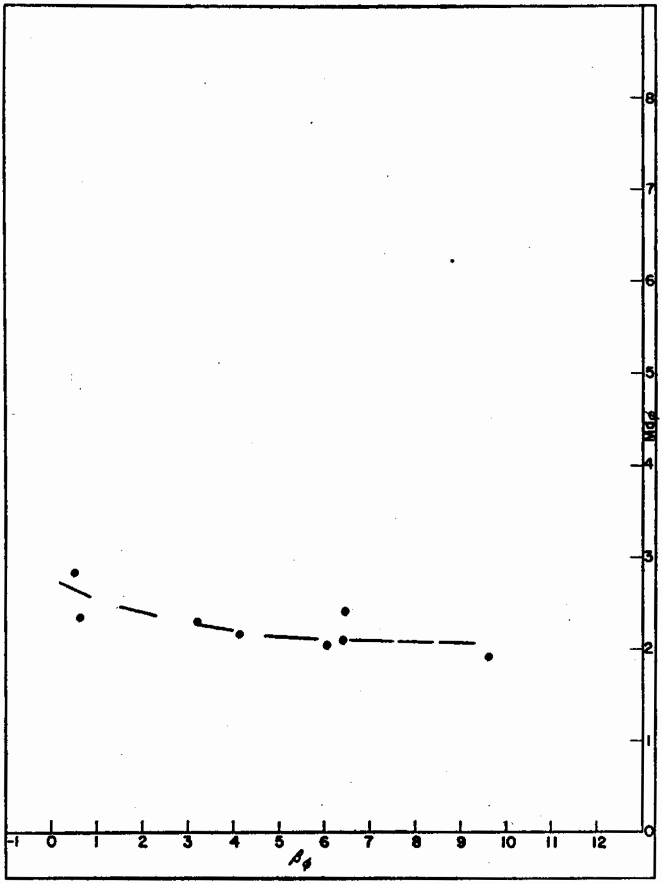


Figure 42. Relationship between median grain size and kurtosis, Red Bank formation.

the relationship between settling velocity and particle size. Indeed, sedimentary particles can start moving in areas at some distances from the basin of sedimentation, under conditions entirely different from those at the place they are deposited. Therefore, Inman's paper, although important with regard to problems of *transportation* of sediments, does not offer adequate explanations concerning their *deposition*. In this respect, a great deal can be learned from a study of the cumulative curves.

Assume a sediment having a log normal distribution as shown by curve A, figure 43. This sand was transported by a current having a competency great enough to move particles of 1 mm and smaller. When deposition took place due to a decrease in velocity all particles smaller than 0.125 mm were deposited. The range in particle size in the deposit (1 to 0.125 mm) is an indication of the change in competency of the transporting current. Deposit B, figure 43, has a range in particle size between 2 mm and 0.0625 mm. Thus, the competency required to transport the sediment represented by curve B is greater than that for the material of curve A. When all particles larger than 0.0625 mm were deposited, a decrease in competency must have occurred exceeding that of deposit A. Thus, the slope of the curves is a measure of the range of competencies of the currents transporting and depositing the sediments. The flatter the curve, the greater is the fluctuation of the competency of the current. Deposits A and B have log normal distributions and their phi skewness values are zero. Their sorting factors, however, vary; the flatter the curve, the poorer is the sorting.

Many sands have size frequency distributions as shown by curves C and D, figure 44. If A represents the tractional fraction of the sediment, and B the suspension fraction, their combined deposition results in sediments represented by curves C and D. Such a sediment can only form when considerable variations in current velocities take place, because the velocity required to transport particles of medium sand size, and the settling velocity of fine silt differ greatly.

With velocity changes of the transporting current and hence with changes in competency the possibility arises that after deposition a portion of the sediment is removed. When current velocity increases, it will reach initially the threshold velocity of fine sand, and consequently, particles of this size will be removed first. When higher velocities occur, the threshold velocity of coarser *and* finer materials will be attained, and medium and coarse sand as well as very fine sand and coarse silt will be removed. The effects on the cumulative curves of removal of particles are shown in figure 45. The greater the range in size of particles carried away, the smoother the bend in the cumulative curve becomes. If no medium and fine silts are removed, the tail end of the curve becomes slightly concave.

When a current reaches the threshold velocity for fine sand, and consequently this material is removed from a deposit, coarse and medium sand derived from an upstream area where threshold velocities are large can be deposited. Thus, addition of coarse grains can occur simultaneously with removal of fine and very fine sand. The effects of this phenomenon are shown in figure 46.

So far, consideration has only been given to sediments consisting of a tractional and a suspension fraction. Actually, a part of the sediment load of a current will be transported by saltation. If the velocity of the current fluctuates around the settling velocity for grains of a certain diameter, say 0.2 mm, then particles of approximately this size will most likely move by saltation.

Patuxent Zone

The Patuxent zone consists primarily of fine to coarse sands; some silts and clays occur also, but because they were not found in outcrop in Delaware, and were not available from cored drill holes, no analyses of these fine-grained deposits were made.

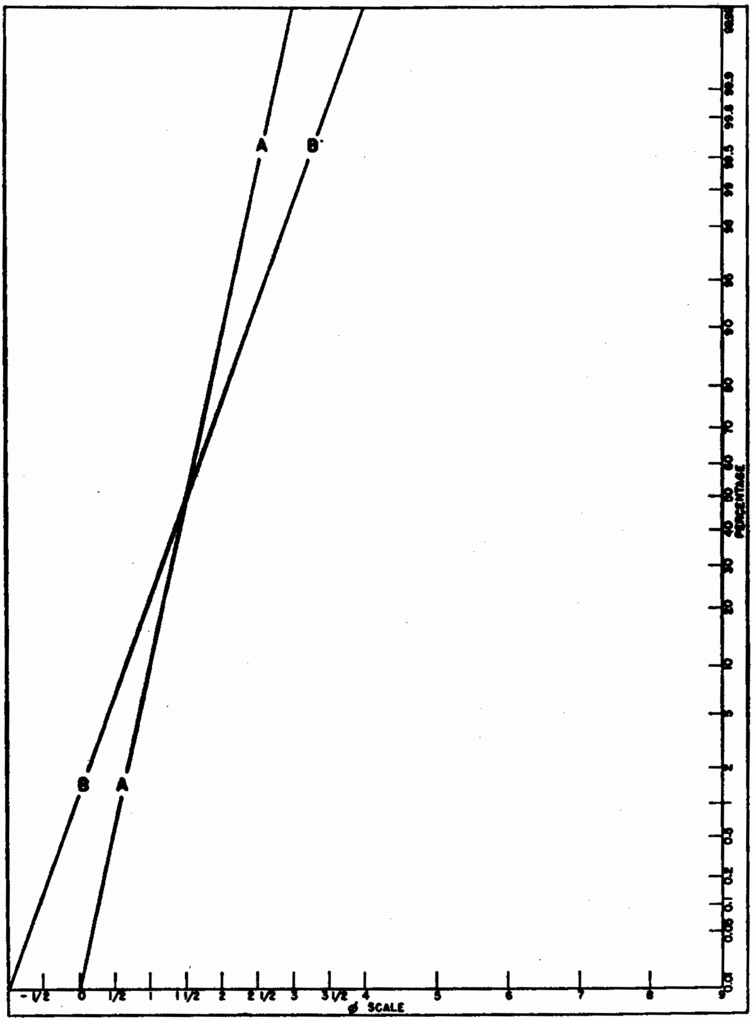


Figure 43. Cumulative curves of two deposits with log normal size frequency distributions and different sorting coefficients.

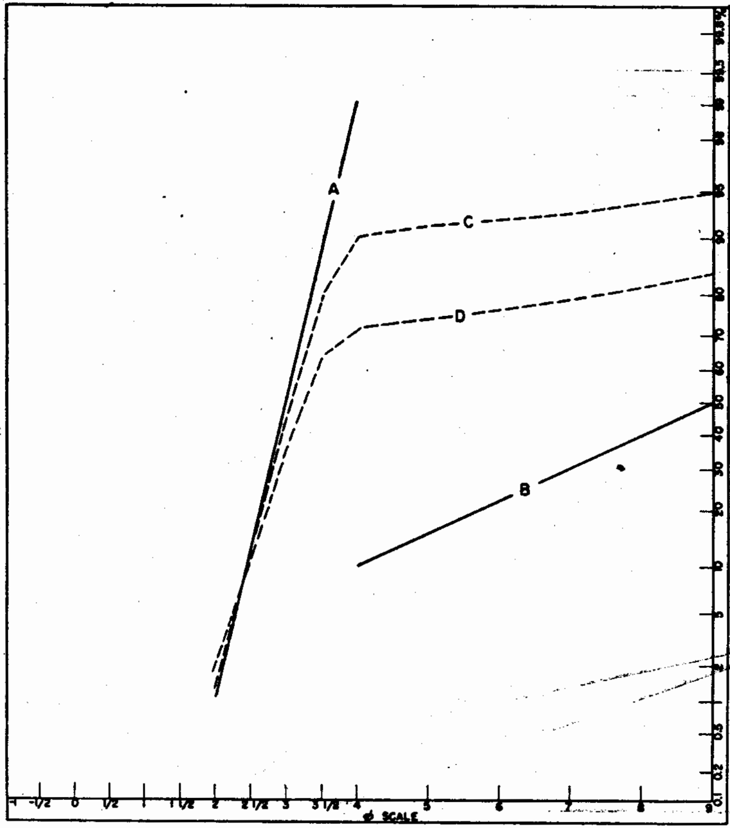


Figure 44. Combined deposition of tractional and suspension particles, each having a log normal distribution.

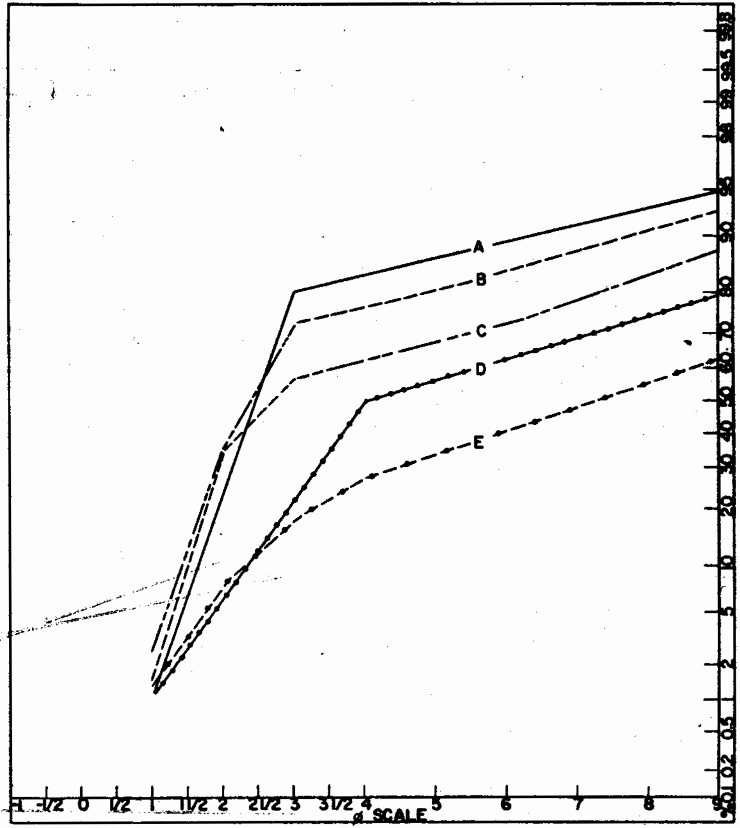


Figure 45. Effects of removal of sedimentary particles from a deposit by increase of current velocity.

and fine material added to the body of medium and fine sand. It should be noted that the break in the curve, presumably the transition from the tractional to the suspension material, takes place in the very fine sand fraction.

Very common types of size frequency distributions of the sediments of the Patuxent zone are shown in figures 49, 50 and 51. Long tails of silt and clay, constituting 10 to 20 percent of the sediment, are present, indicating deposition of considerable suspension material. Apparently, the friction velocity of the transporting current was small, resulting in the deposition of considerable silt and clay.

Usually, when deposition of tractional and suspension material takes place, the cumulative curves have a definite break or bend in the fine or very fine sand size. The curves of samples 2010, 2019, and 2039, however, are slightly convex in most of the sand fraction, only to become nearly straight in the very fine sand and silt fractions (see fig. 52). Possibly, a large portion of the sediment was removed after deposition, and consequently, the curves are similar to curve E of figure 45.

The mechanical analyses show that the sediments of the Patuxent zone were transported and deposited by water currents varying considerably in competency within short distances and small intervals of time, resulting in heterogeneity of their mechanical composition. Although the sorting of the sands is usually good, the sorting coefficient as well as the skewness value have a great range and they are generally higher than those of beach and dune sands, and of marine deposits.

These phenomena indicate that most of the Patuxent sands are fluviatile or estuarine deposits.

Bakker (personal communication) has noticed in Dutch Guiana that in young continental-fluviatile sediments the silt fraction is very small; thus, the ratio of material smaller than 2 micron to material smaller than 16 micron, expressed as a percentage, is usually about or over 80 percent. In young marine deposits, this ratio usually varies between 60 and 80 percent, and in sediments laid down in brackish water it ranges from 28 to 50 percent. It is possible, however, that in older sediments these ratios are somewhat different due to post-depositional changes or diagenetic processes.

A study of the histograms (fig. 53) reveals also the great variation in the mechanical composition of the sediments. Some samples clearly show bimodal sediments, for instance nos. 2001, 2008, 2010 and 2016. It is known that bimodal sediments are of fluviatile origin, but because the ratio of material smaller than 2 micron to material smaller than 16 micron is usually below 60 percent, a brackish-water, estuarine environment is suggested for at least a portion of the Patuxent deposits.

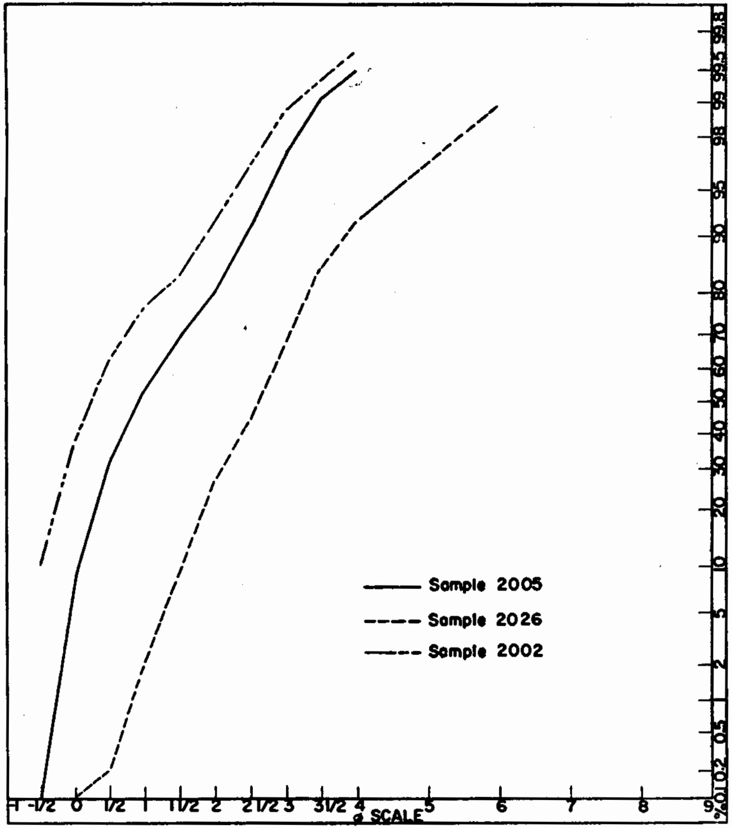


Figure 47. Cumulative curves of representative samples of the Patuxent zone.

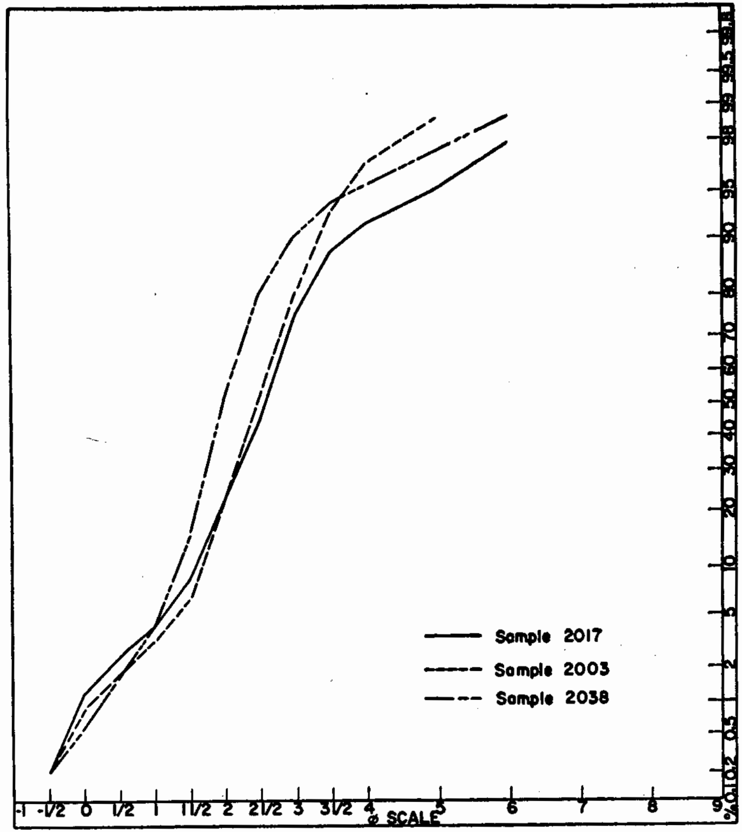


Figure 48. Cumulative curves of representative samples of the Patuxent zone.

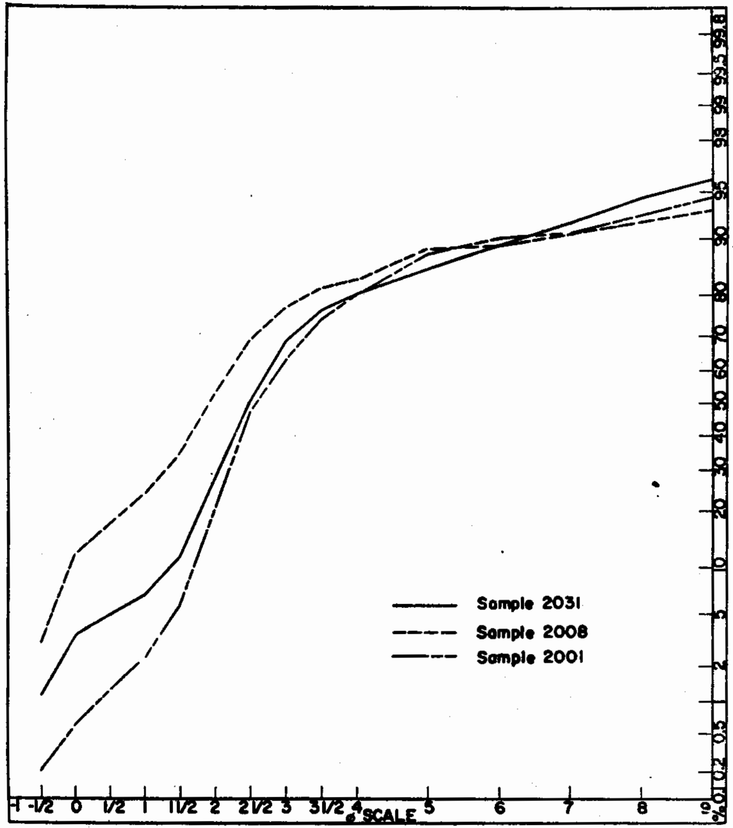


Figure 49. Cumulative curves of representative samples of the Patuxent zone.

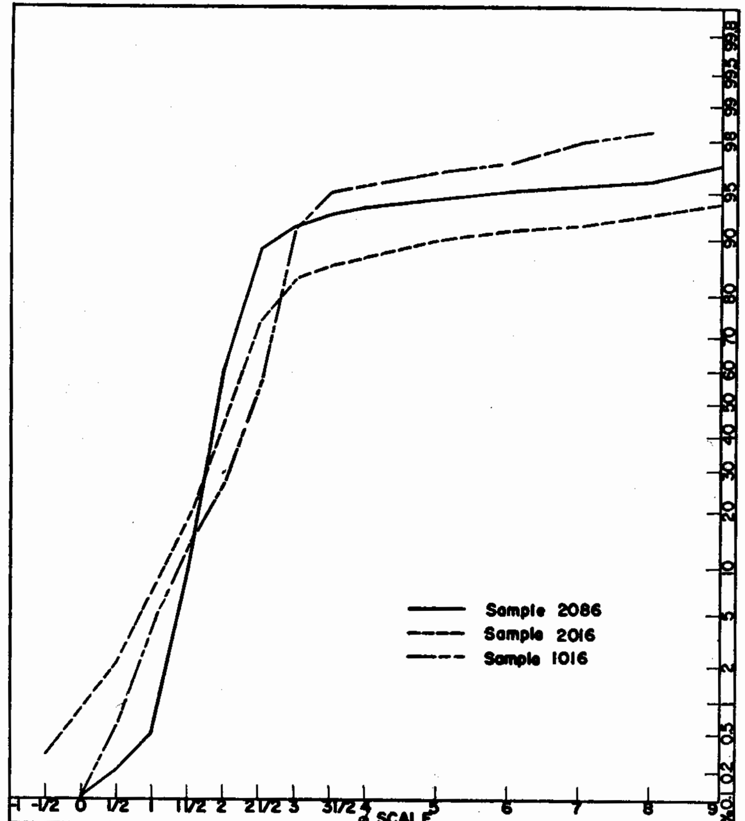


Figure 50. Cumulative curves of representative samples of the Patuxent zone.

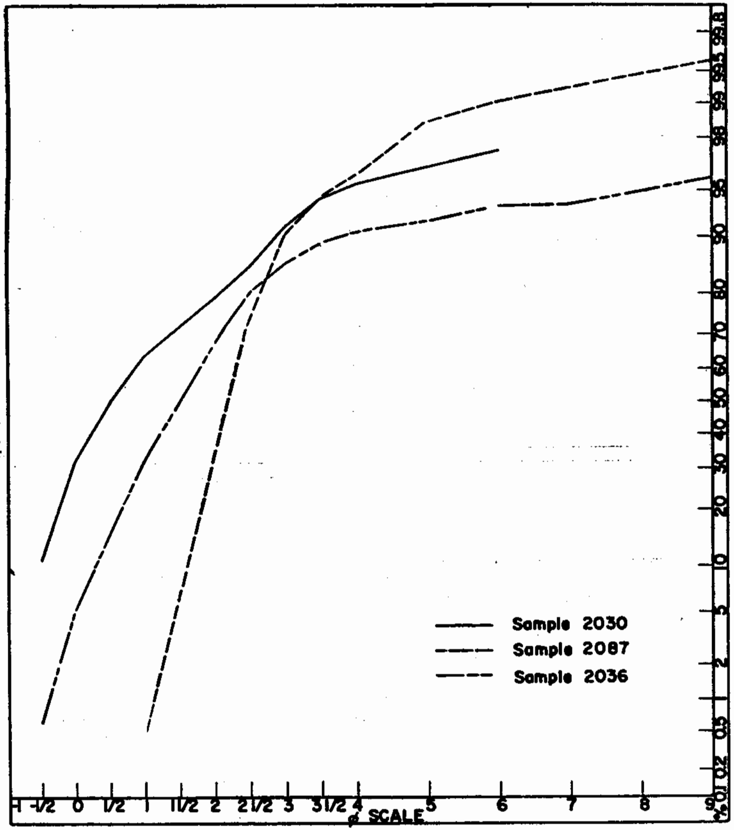


Figure 51. Cumulative curves of representative samples of the Patuxent zone.

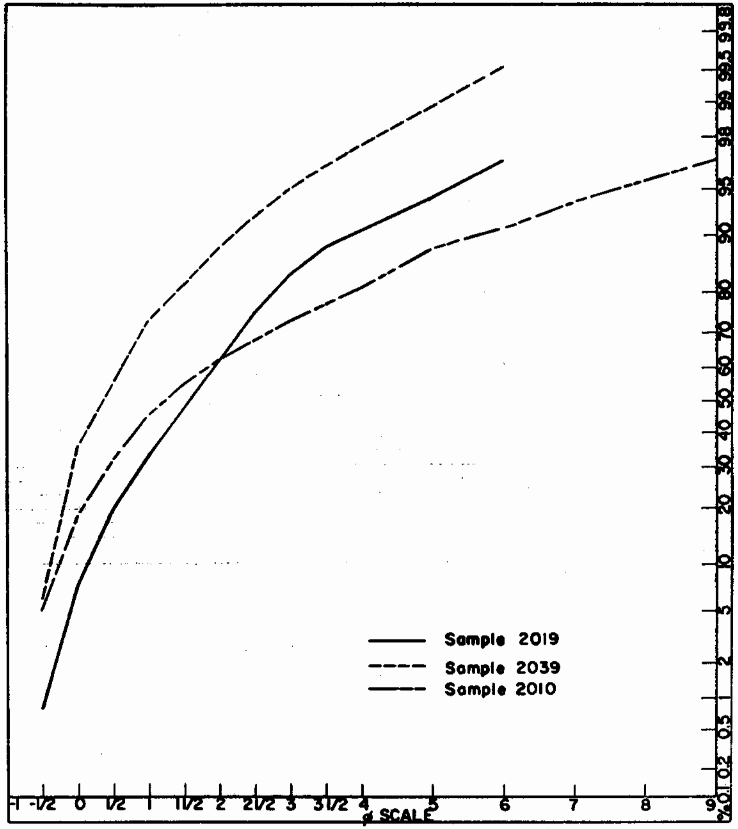


Figure 52. Cumulative curves of representative samples of the Patuxent zone.

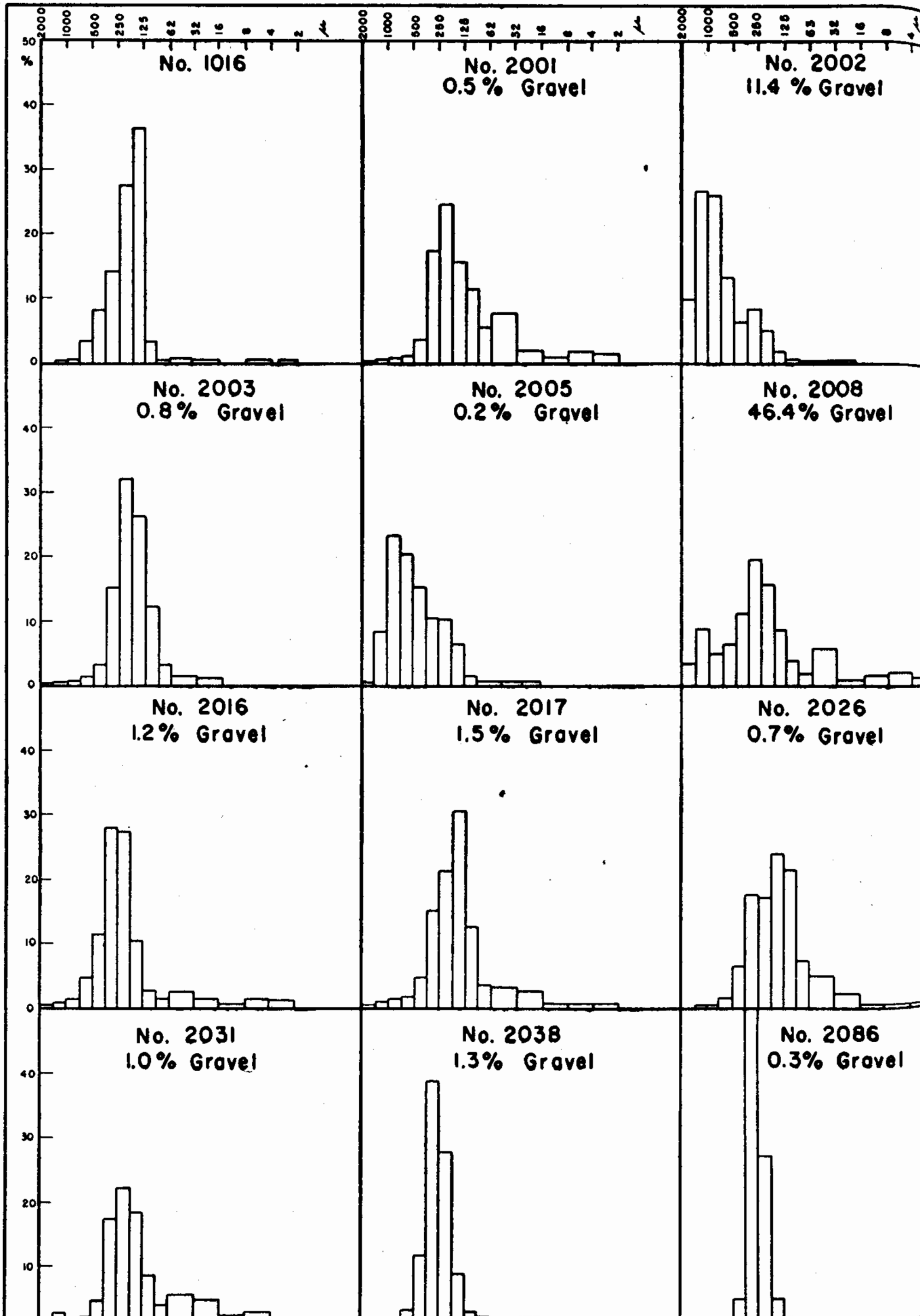


Figure 53. Histograms of samples of the Patuxent zone.

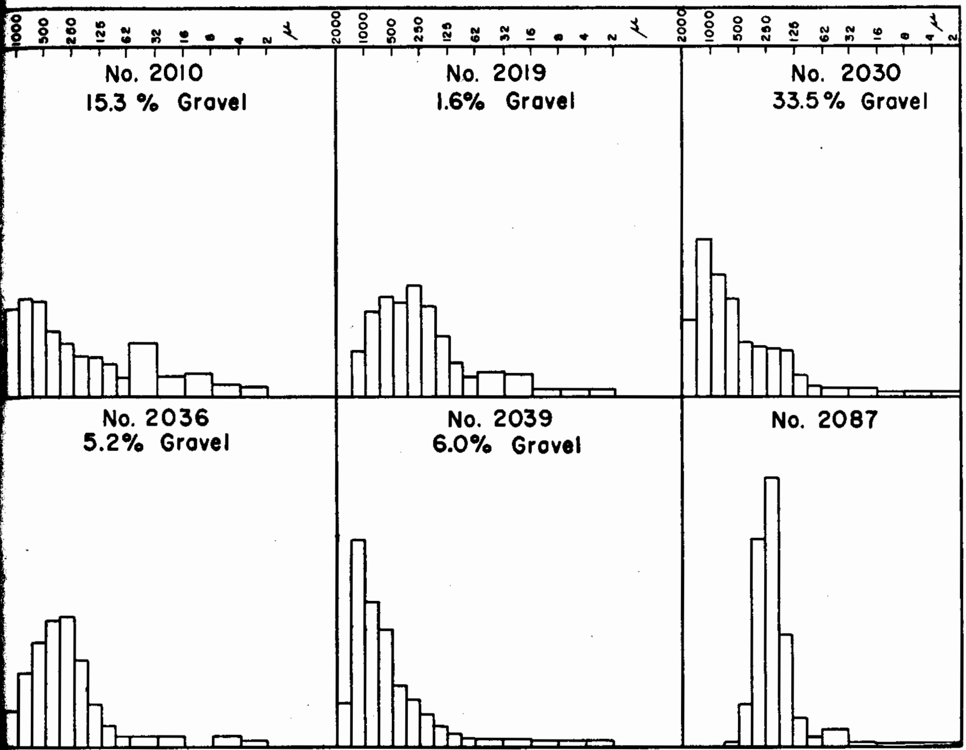


Figure 53 (continued). Histograms of samples of the Patuxent zone.

Where lignite occurs in the Patuxent, it is often associated with pyrite or marcasite. It has been pointed out by van der Spek (1934) that pyrite forms in brackish water primarily, because only saline water contains enough sulphur to account for the forming of pyrite. Thus, the occurrence of pyrite is additional evidence of brackish-water conditions.

The well-sorted sands presented in figures 47 and 48 were obtained from a channel deposit which was outlined with the aid of numerous test borings in the Patuxent zone.

The above discussion does not exclude the fact that a part, and perhaps a major part, of the Patuxent is continental-fluviatile in origin as suggested by the presence of cross-bedded sands and the occurrence of rolled clay balls.

In summary, it can be stated that the Patuxent sediments are non-marine, and that their environment of deposition must be considered partially continental and partially estuarine. The estuarine character especially indicates a downward movement of the land relative to sea level. This conclusion is not surprising in view of the fact that tilting, and reactivated erosion of the Appalachian region was deduced from the study of the heavy mineral content of the Patuxent sediments. Thus, the results of the mechanical analysis and the mineralogical evidence point to the same paleogeographic interpretation.

Patapsco-Raritan Zone

The mechanical composition of the Patapsco-Raritan deposits is even more heterogeneous than that of the underlying Patuxent zone. These sediments range from clays to medium sands usually containing considerable amounts of silt and clay.

Representative cumulative curves of Patapsco-Raritan sediments are shown in figures 54-59. Typical fine silts and clays with only small amounts of sand are represented in figure 54. These fine-grained sediments have small skewness values, and therefore, closely approach a log normal distribution; they are probably the result of the deposition of suspension material. As in practically all silts, their sorting is poor.

The median and fine silts represented by the cumulative curves of figure 55 are similar to those of figure 54, except for the addition of small percentages of coarse sand. Whether this is due to deposition of some tractional material or to the mixing of two sedimentation units in the core samples cannot be determined.

Median and fine silts and clays are also shown in figure 56. All contain high percentages of suspension materials, are poorly sorted, and have low skewness values, except sample 2014.

The Patapsco-Raritan sands are nearly all fine-grained and silty (see figs. 57-59). Their cumulative curves indicate that they consist of log normal distributions of tractional and suspension materials. Again, the bend in the cumulative curves is found in the very fine sand fraction, near the critical sand size mentioned by Inman (1949).

The great variation in the mechanical composition of the sediments of this zone again points to fluviatile deposition. Investigation of outcrops and well logs reveals that the lower portions of the Patapsco-Raritan zone consists chiefly of silts and clays, whereas in the upper portion fine sands become more abundant. However, even in this upper part the sands rapidly change to silts and clays within very short distances.

Examples of the mechanical composition of the Patapsco-Raritan sediments are also presented in a number of histograms (fig. 60). A great number of samples clearly show bimodal sediments (for instance nos. 1306, 1307, 2013, 2081, 1285, 1289, 2015) and some others exhibit the same feature to a smaller degree (for instance nos. 1309, 1288, 1249,1218, 1219, 1274). Some of these samples (nos. 1288, 1289, 1249, fig. 57) have relatively high values for the clay/silt ratio (about 77%), and, according to Bakker (personal communication) they are probably river sands deposited in fresh water. Many samples, however, have low clay/silt ratios, for instance nos. 1306, 1307, 2013, and others; they were probably deposited in relatively quiet, brackish water, such as a lagoon. A few well-sorted sands with very little silt, like no. 1218, and no. 1249 also occur, and these could represent sediments deposited on lagoonal or estuarine beaches.

The mechanical analyses as well as other evidence indicate that the environment of deposition was a low-lying, swampy coastal plain, in which fluviatile, bimodal sediments were deposited, some in brackish, swampy lagoons and estuaries, and some in stream channels and floodplains.

Magothy Formation

Typical size frequency distributions of Magothy sediments are shown in figures 61-63, and in the histograms of figure 64.

The majority of the samples are of the type represented by figure 61. They are fine to medium, well-sorted sands lacking silt and clay fractions, and closely approaching a log normal distribution.

Magothy sands immediately overlying the Patapsco-Raritan zone (nos. 1080, 1082, 1269, 1271) have a mechanical composition resembling that of the sediments of that zone. Their cumulative curves indicate that current velocities ranged widely (see fig. 62). They probably represent fluviatile sands having a very high clay/silt ratio (about 86-90%). However, these sands are apparently found only at the base of the formation.

Black, lignitic silts are represented by samples 1272 and 1297 (fig. 63). The clay/silt ratio of these samples is relatively low (49 and 43 respectively) suggesting brackish water estuarine or lagoonal conditions. The well-sorted sands probably indicate considerable reworking of sediments by waves. Thus the environment of deposition was probably that of a lagoon containing brackish water, probably open to the sea and with considerable wave action. In the more quiet places of the lagoon abundant vegetation occurred, which is partially preserved in the lignitic clays containing abundant pyrite or marcasite. At some places, rivers entered the lagoon, as indicated by some fluviatile sands.

Marine influence increased in Magothy time as compared to Patuxent or Patapsco-Raritan time. Apparently, further eastward tilting of the region took place during the Magothy, as was already concluded from the study of the mineral suite. Thus, the Magothy environment is transitional between that of the non-marine Patapsco-Raritan and that of the marine Upper Cretaceous formations.

The Marine Upper Cretaceous Formations

The mechanical composition of the marine Upper Cretaceous formations is strikingly different from that of the non-marine Cretaceous sediments in

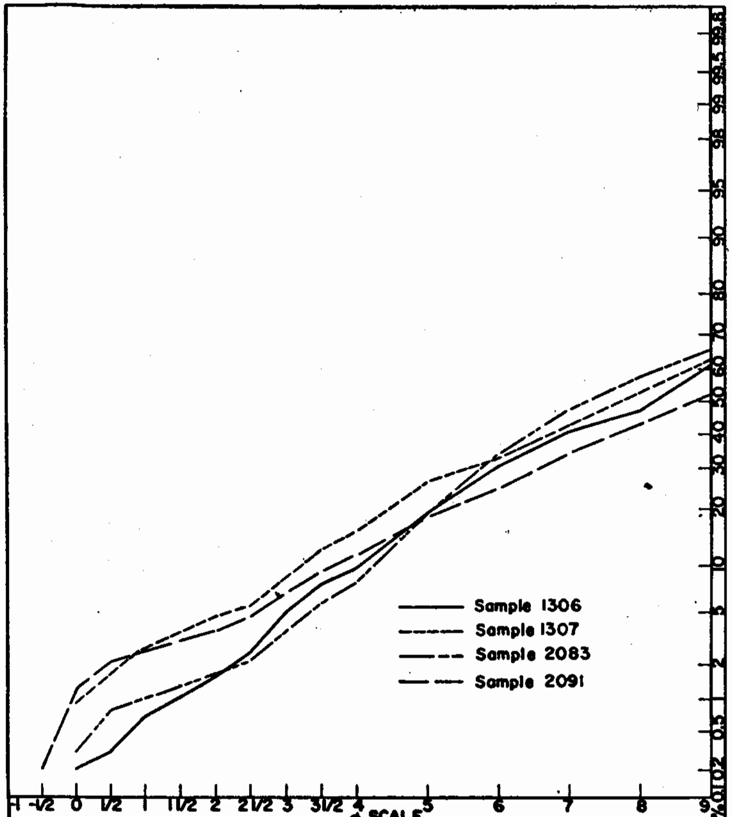


Figure 54. Cumulative curves of representative samples of the Patapsco-Raritan zone.

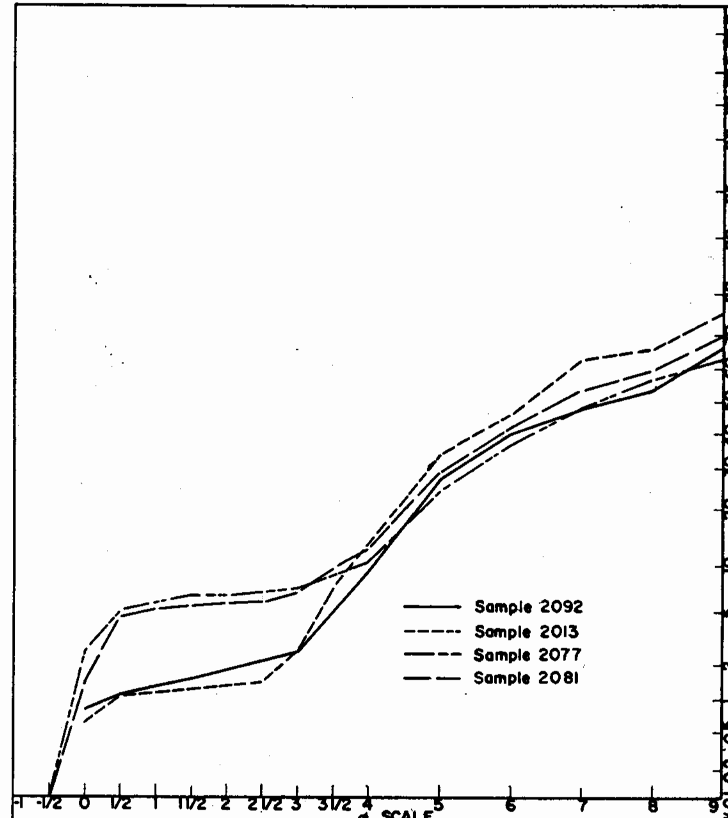


Figure 55. Cumulative curves of representative samples of the Patapsco-Raritan zone.

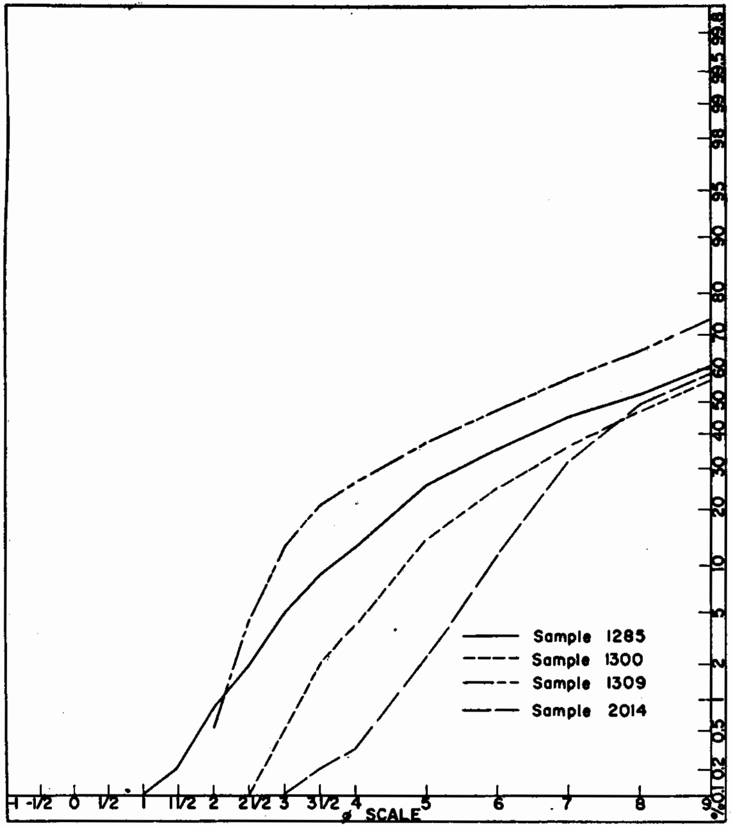


Figure 56. Cumulative curves of representative samples of the Patapsco-Raritan zone.

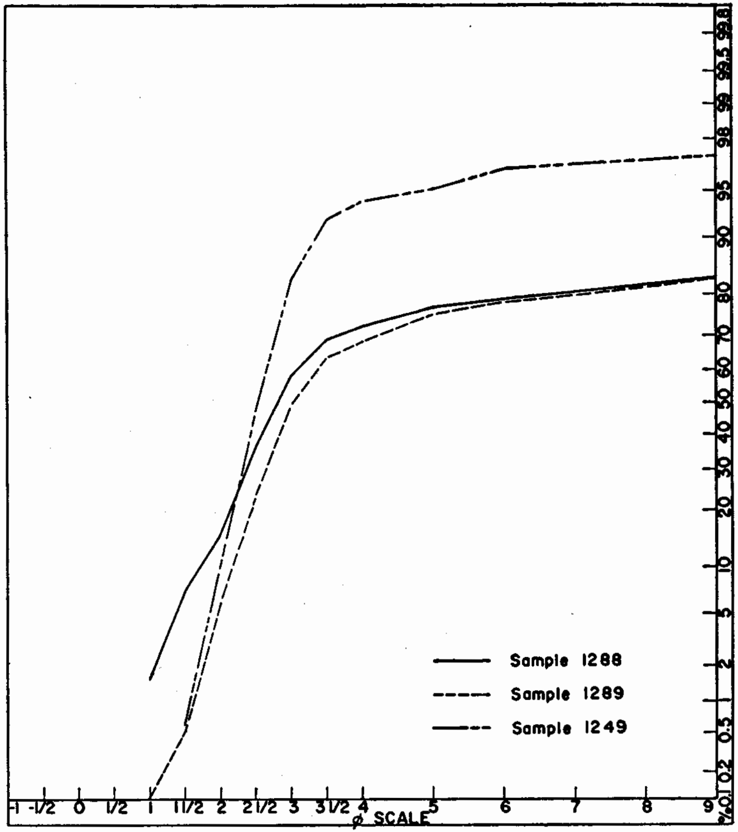


Figure 57. Cumulative curves of representative samples of the Patapsco-Raritan zone.

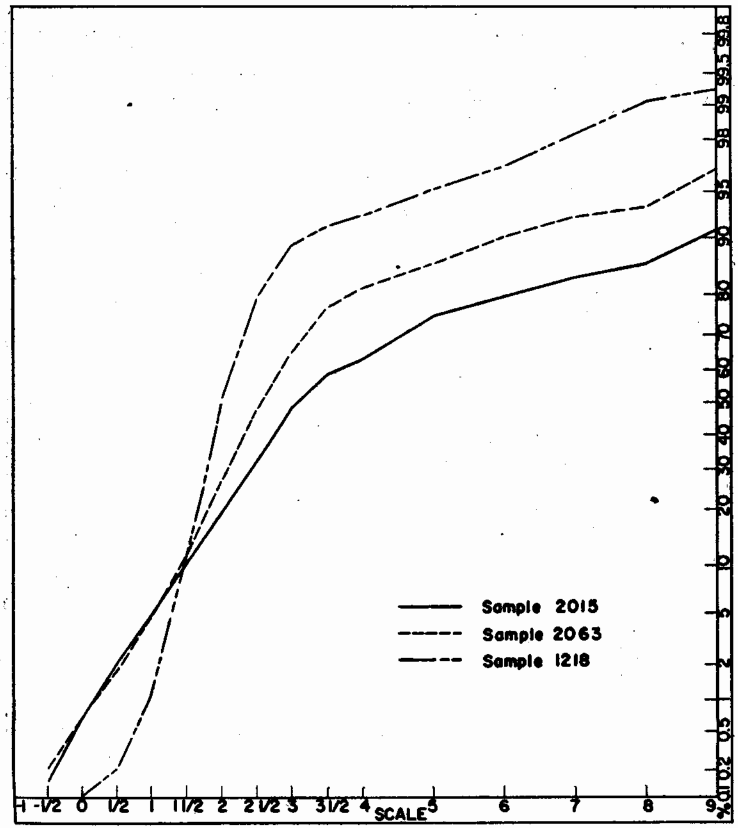


Figure 58. Cumulative curves of representative samples of the Patapsco-Raritan zone.

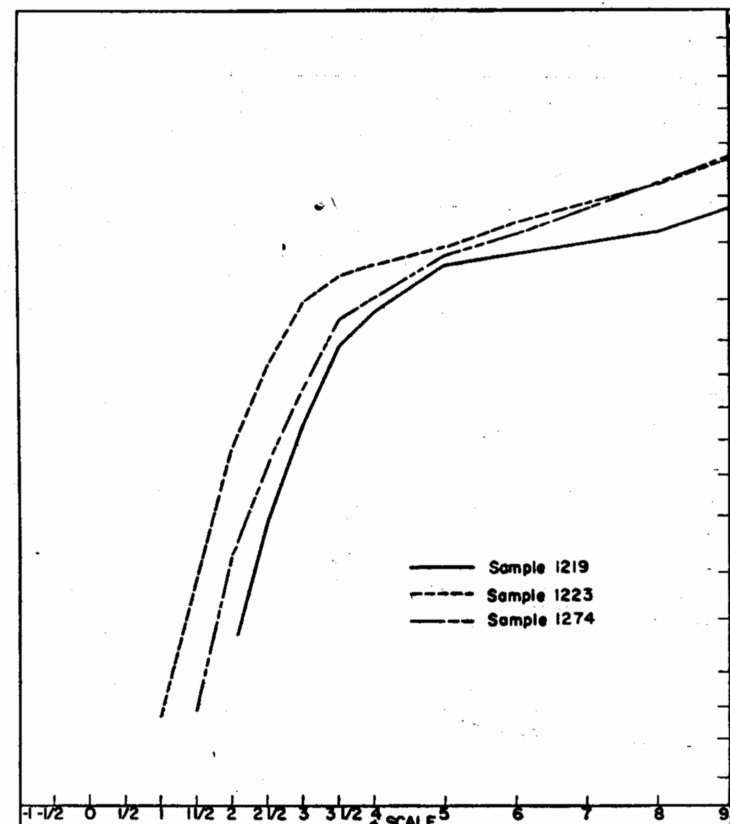


Figure 59. Cumulative curves of representative samples of the Patapsco-Raritan zone.

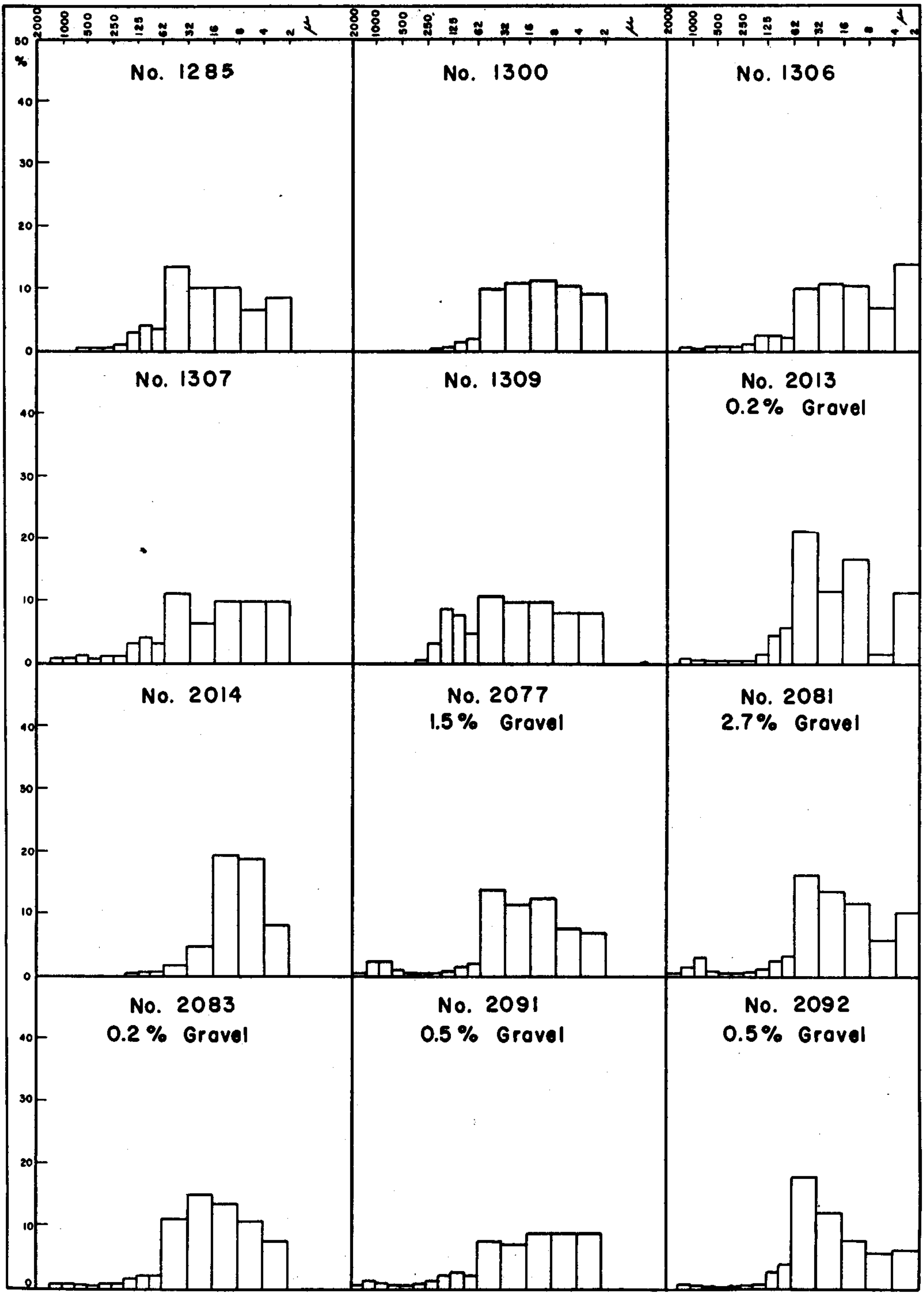


Figure 60. Histograms of samples of the Patapsco-Raritan zone.

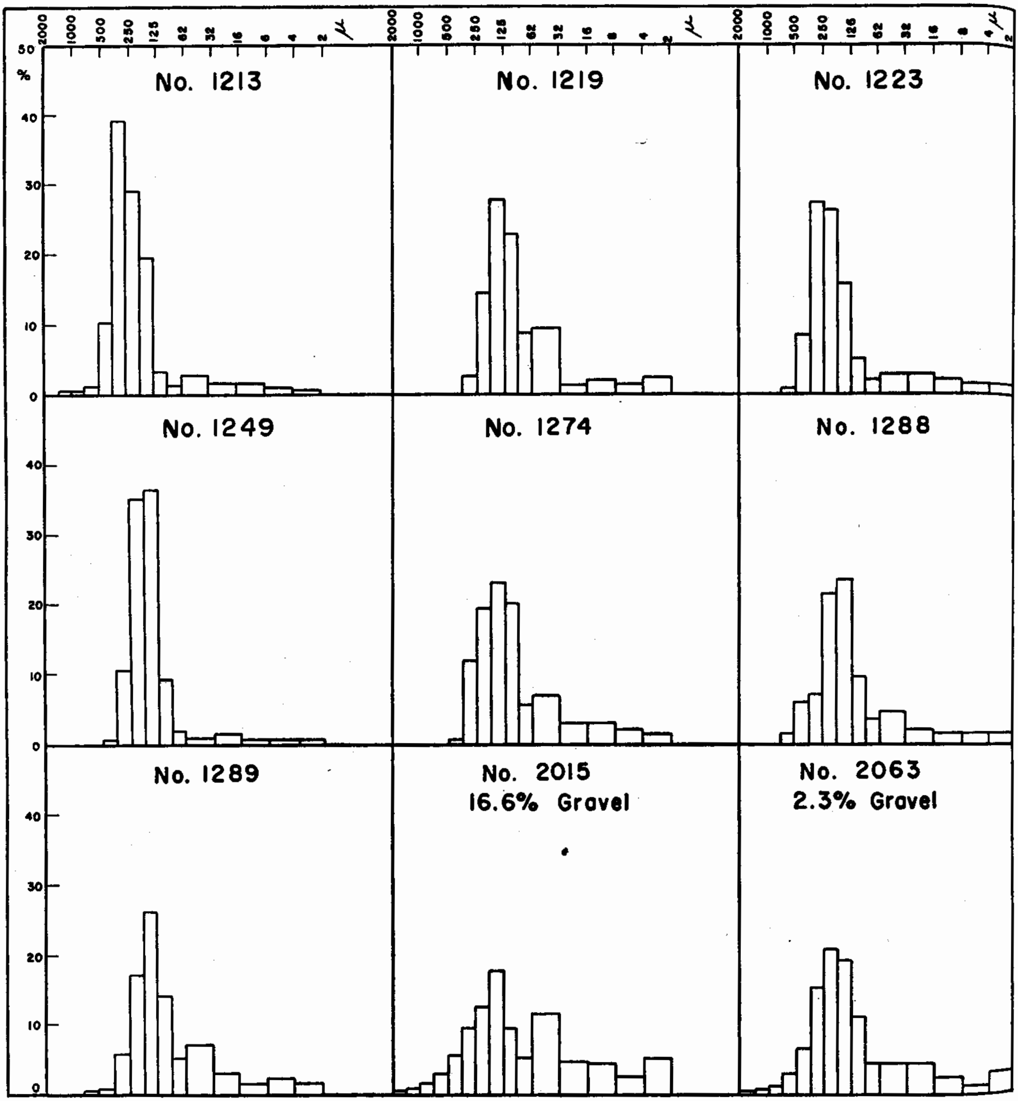


Figure 60 (continued). Histograms of samples of the Patapsco-Raritan zone.

that it exhibits a great degree of uniformity. Nearly all samples within one formation, and even those of different formations, are similar in their size frequency distribution (see figs. 65-77). Only minor differences occur.

Generally the cumulative curves show a fine to very fine sand with varying amounts of silt and clay, indicating transportation and deposition of tractional material of relatively small grain size, and in addition, deposition of a fine suspension load. Thus, the currents must have been strong enough to move medium sand, and in some cases, small quantities of coarse sand, while velocities must have decreased periodically to zero in order to deposit the suspension load. Such conditions exist where tidal currents are present, and consequently, flood and ebb currents alternate with periods of slack water in between. Thus, the medium to fine sands were deposited by tidal currents, and the silts and clays during slack water.

Tidal currents of sufficient competency to transport medium sand cannot be expected in the deep ocean, but in the relatively shallow water near the coast. Thus, the mechanical composition of the marine Upper Cretaceous formations indicates that these formations are shallow, open sea deposits. Thus, the sediments are generally of neritic facies.

The ratios of material smaller than 2 micron to that smaller than 16 micron are generally high (60-80%), which, according to Bakker (personal communication) is also indicative of a marine environment.

Samples 1104, 1105 and 1253 (fig. 67), obtained from the base of the Merchantville formation, deviate from the general size frequency distribution of the formation. These samples are poorly sorted, sandy and clayey silts with a bimodal distribution. Possibly, they were deposited in an estuarine or tidal flat environment, suggesting the initial stage of the Upper Cretaceous transgression.

The sands of the Wenonah formation (figs. 69-70) have a size frequency distribution similar to that of the upper portion of the underlying Merchantville. Again, the clay/silt ratios indicate a marine environment. Some ratios are very high (samples 1166 and 1256 have ratios exceeding 80%) and these occur near the top of the formation, in the transition zone to the Mount Laurel-Navesink, which consists of marine sands and silts with high values for the clay/silt ratio. According to Bakker (personal communication) such sediments either indicate fluviatile influence, or occur in a shelf environment. If fluviatile influence is strong, the deposit should be very close to shore, and probably subject to wave action. Although very few fossils occur in the Wenonah formation, probably due to post-depositional solution, the macro-fossils in the lower and middle portions of the Mount Laurel-Navesink show considerable abrasion; in addition, many shell fragments occur suggesting near-shore wave action. In the upper part of the Mount Laurel-Navesink formation, however, even fragile shells have been well preserved. Apparently, the Wenonah and lower and middle portions of the Mount Laurel-Navesink formations were deposited very close to the shore, whereas the upper portion was deposited in slightly deeper water. Abundant forminifera occur in the Mount Laurel-Navesink, and these are well preserved, but even non-abraded forams are found on present day beaches subject to considerable wave action.

The Mount Laurel-Navesink formation is highly glauconitic, but even near shore sediments can contain an abundance of glauconite due to in-shore transportation. Therefore, this cannot be considered proof of deposition in deeper water.

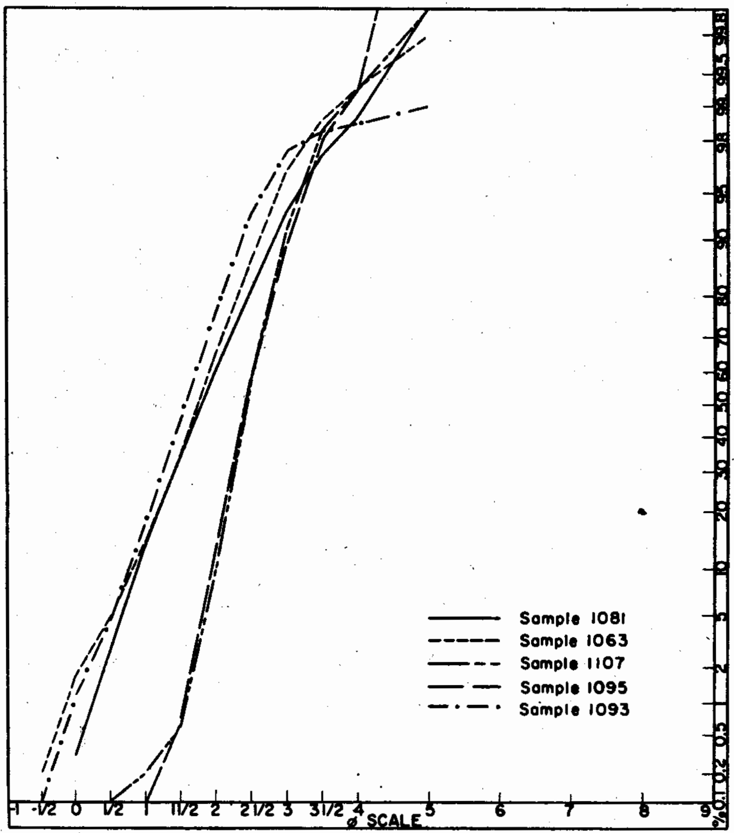


Figure 61. Cumulative curves of representative samples of the Magothy formation.

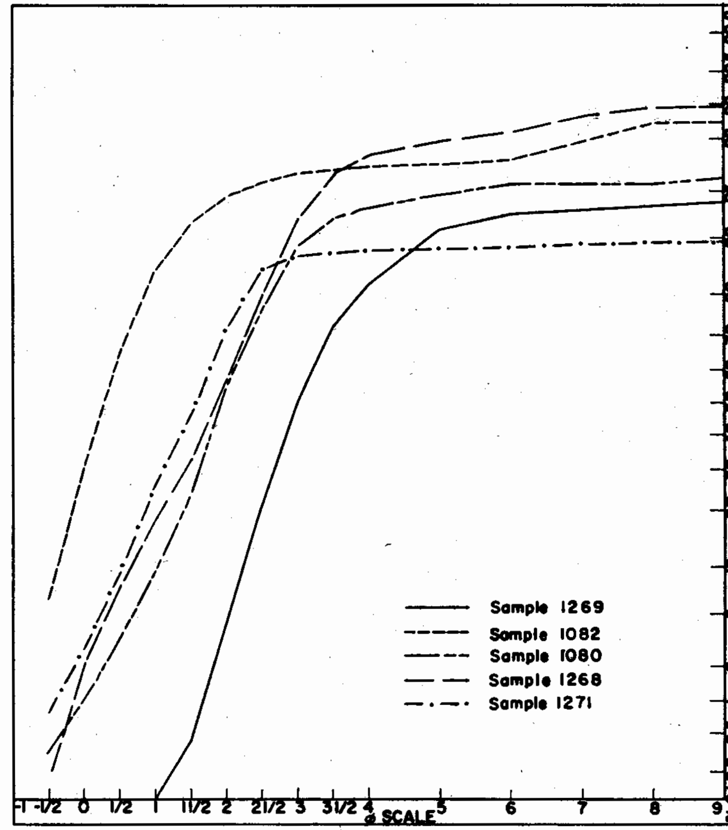


Figure 62. Cumulative curves of representative samples of the Magothy formation.

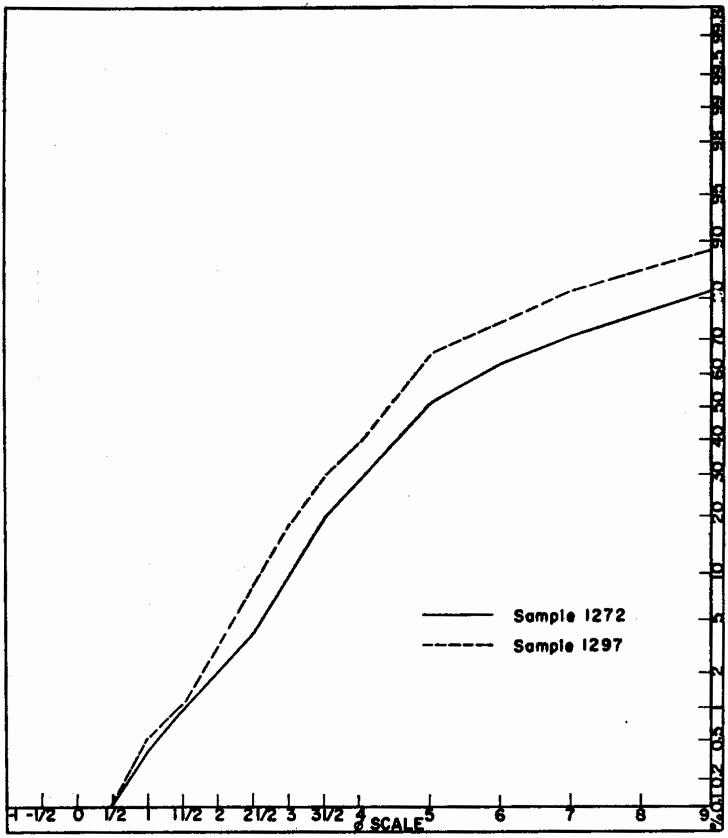


Figure 63. Cumulative curves of representative samples of the Magothy formation.

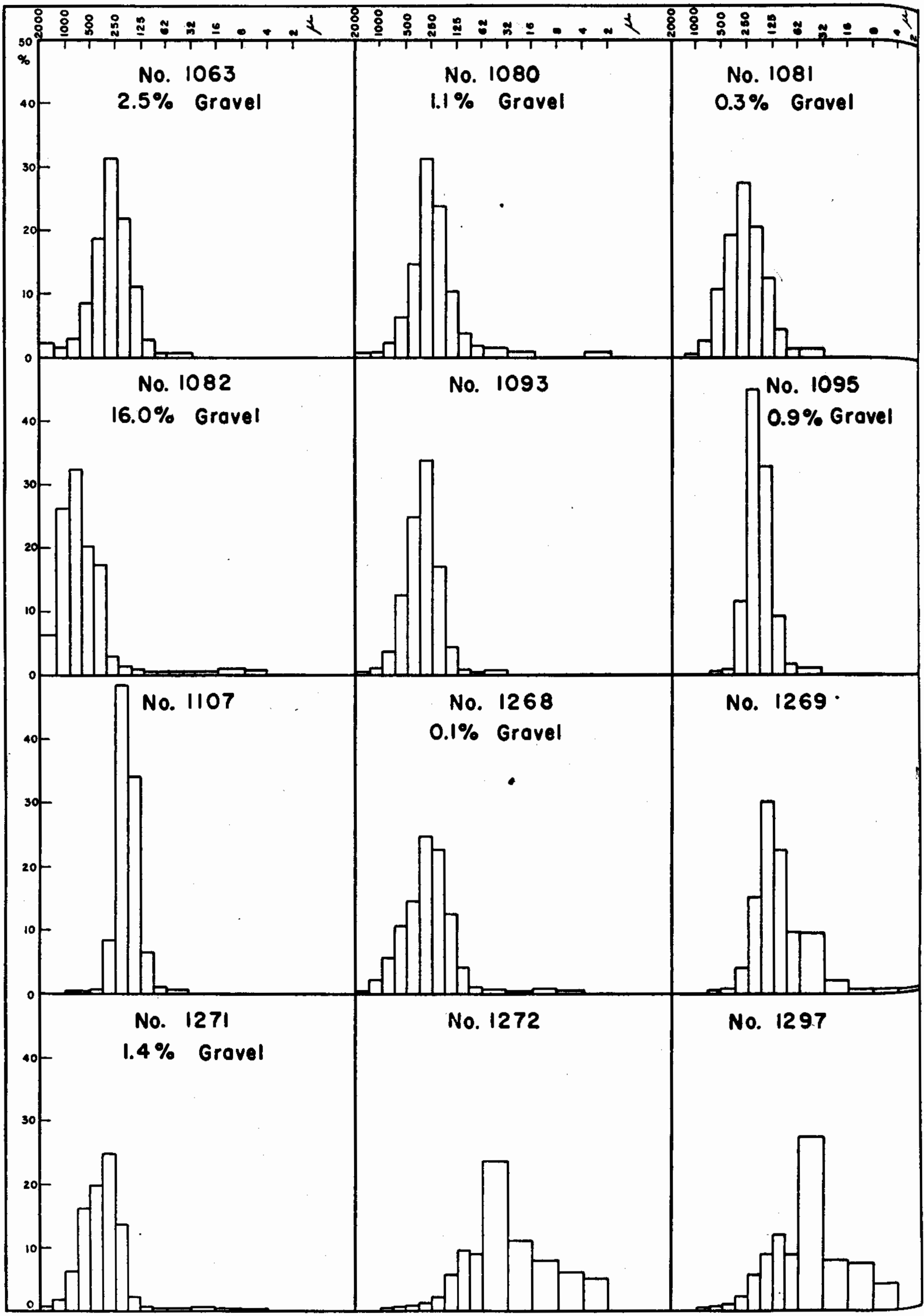


Figure 64. Histograms of samples of the Magothy formation.

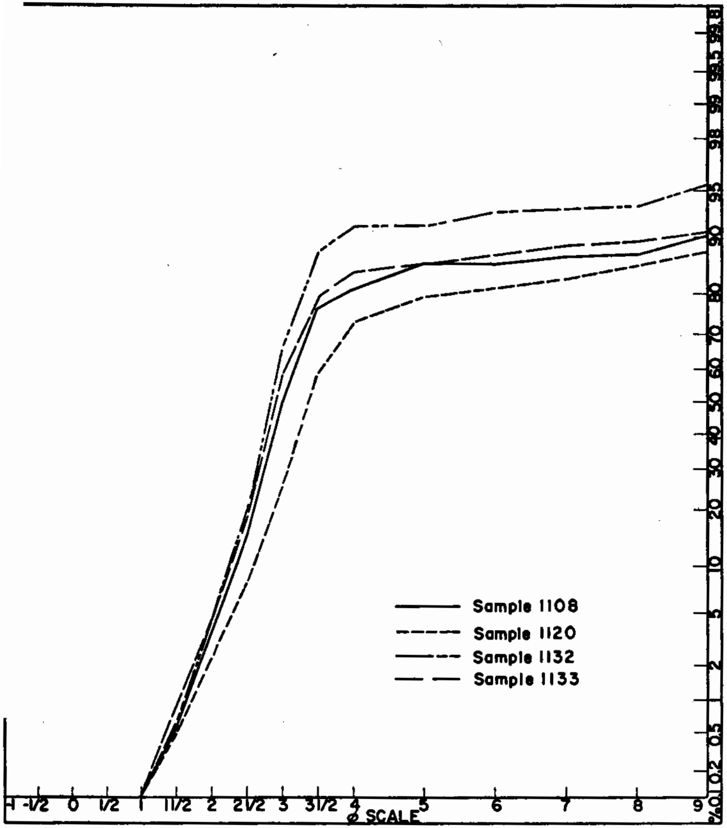


Figure 65. Cumulative curves of representative samples of the Merchantville formation.

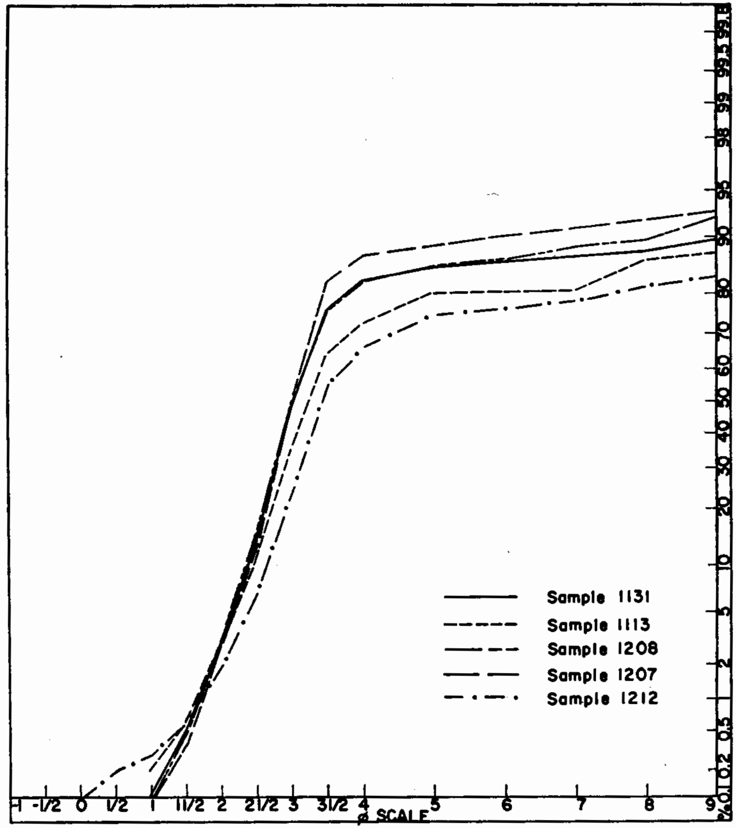


Figure 66. Cumulative curves of representative samples of the Merchantville formation.

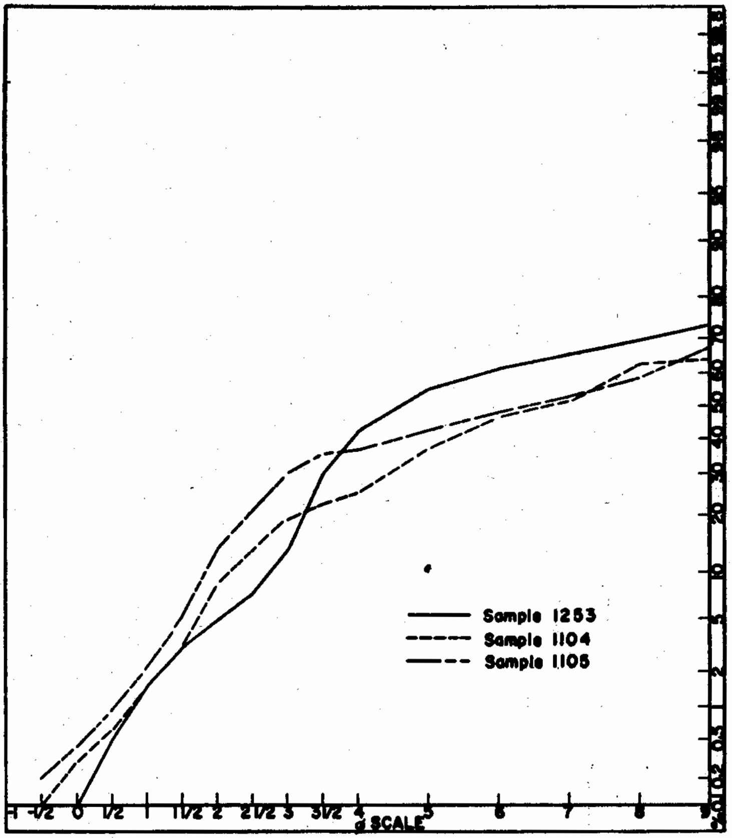


Figure 67. Cumulative curves of representative samples of the Merchantville formation.

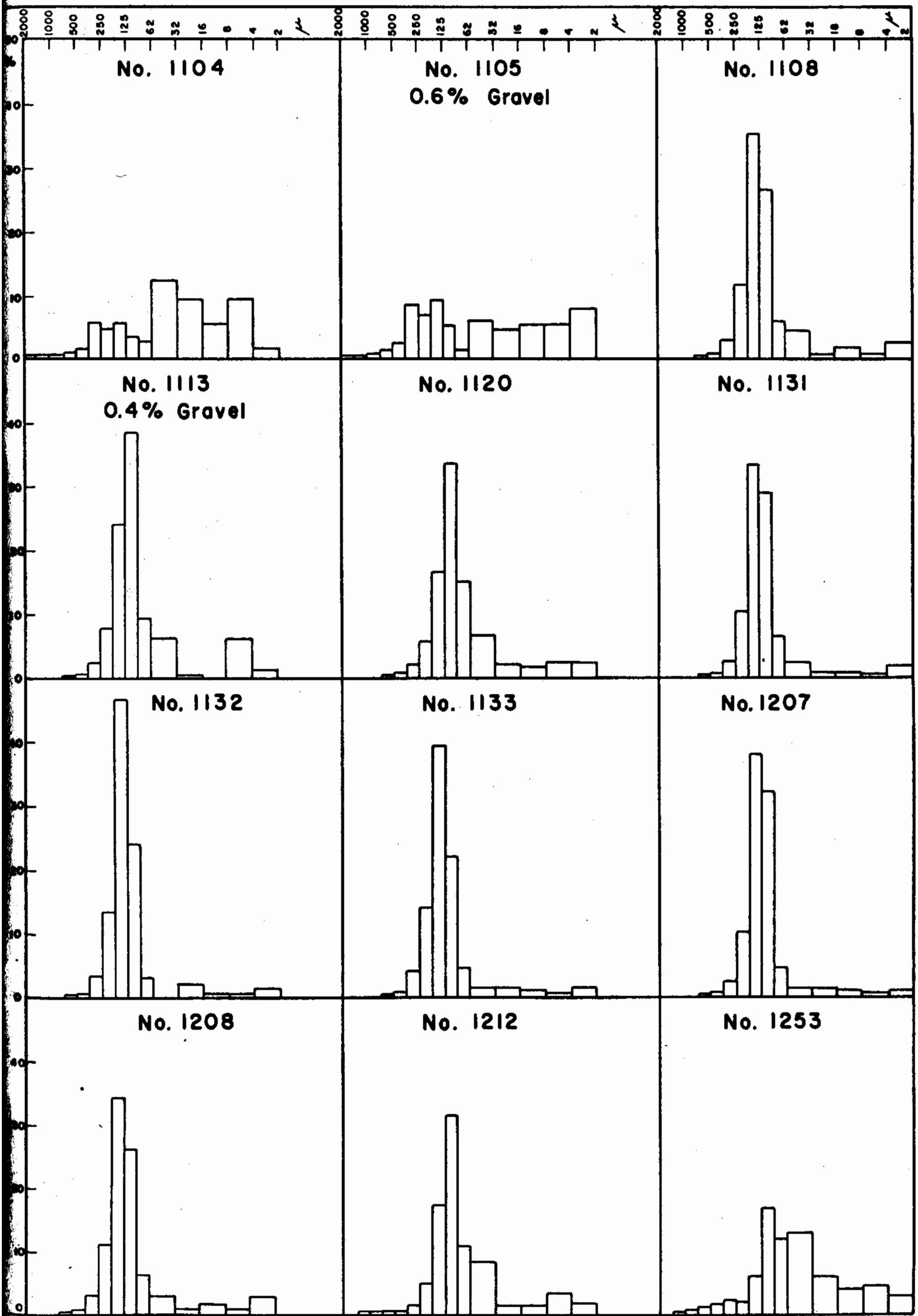


Figure 68. Histograms of samples of the Merchantville formation.

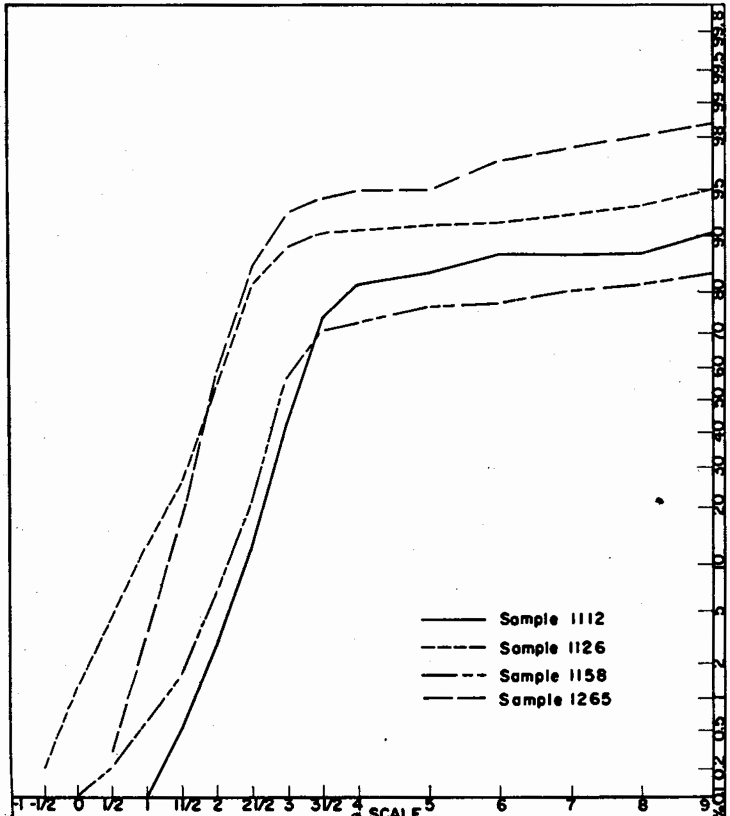


Figure 69. Cumulative curves of representative samples of the Wenonah formation.

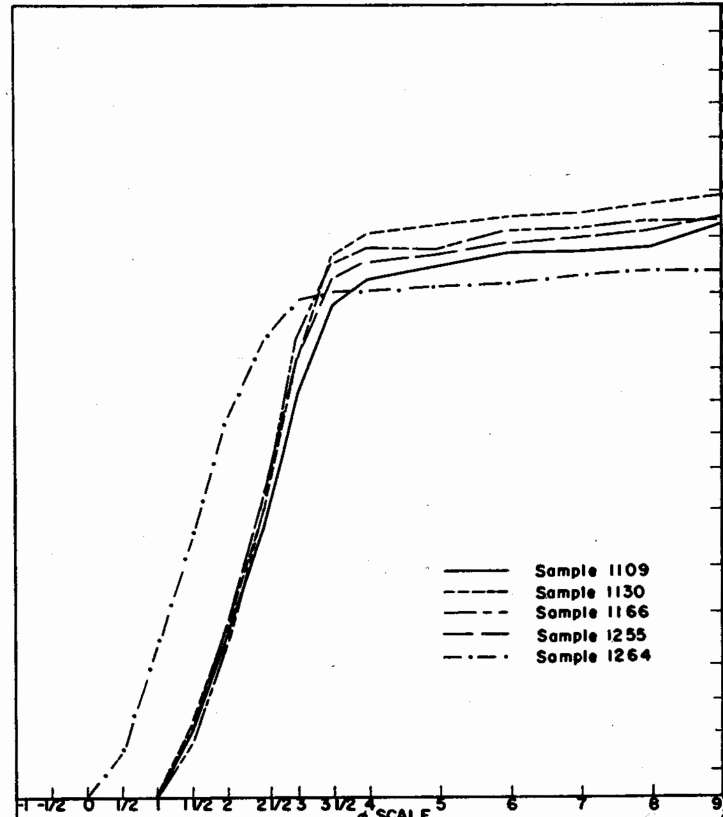


Figure 70. Cumulative curves of representative samples of the Wenonah formation.

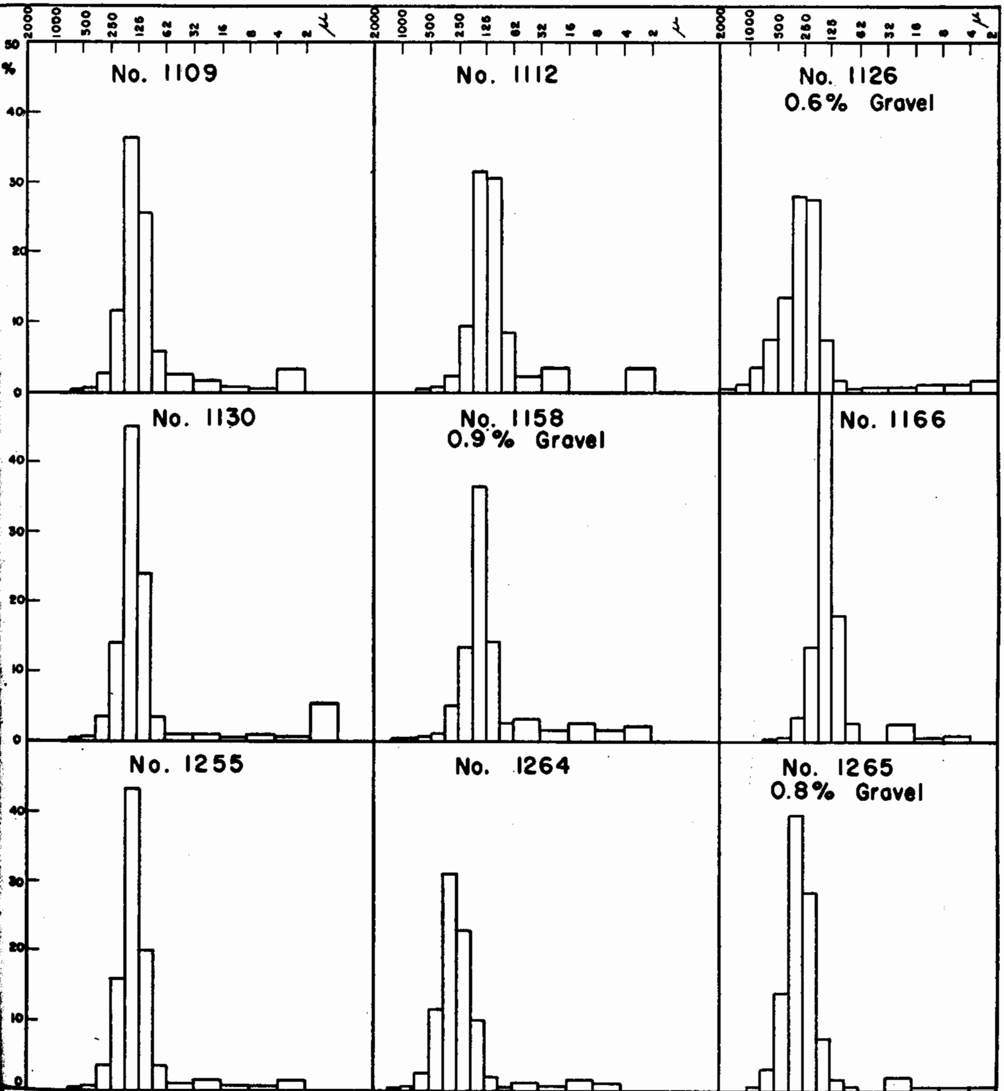


Figure 71. Histograms of samples of the Wenonah formation.

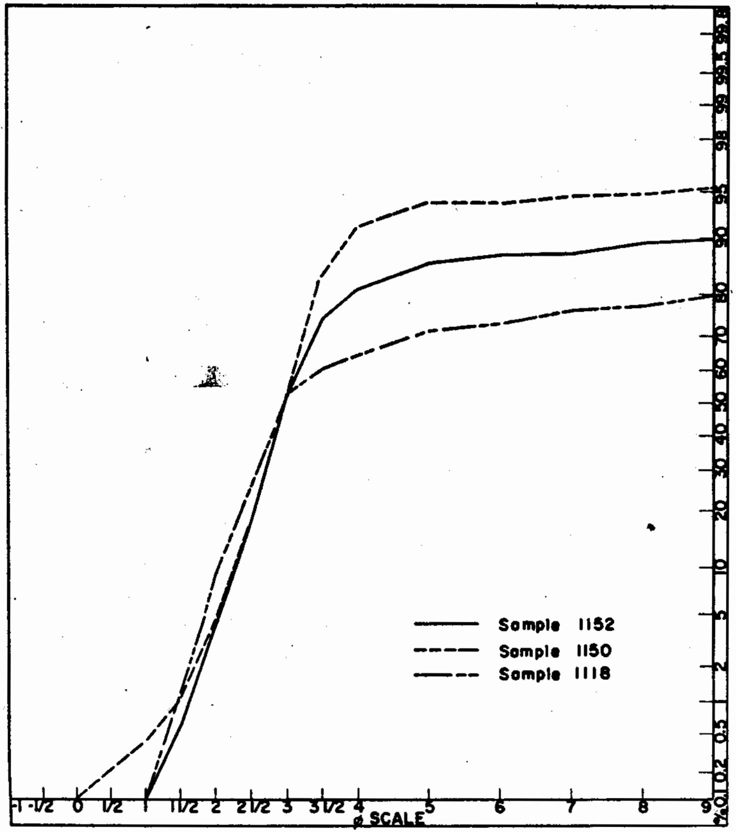


Figure 72. Cumulative curves of representative samples of the Mount Laurel-Navesink formation.

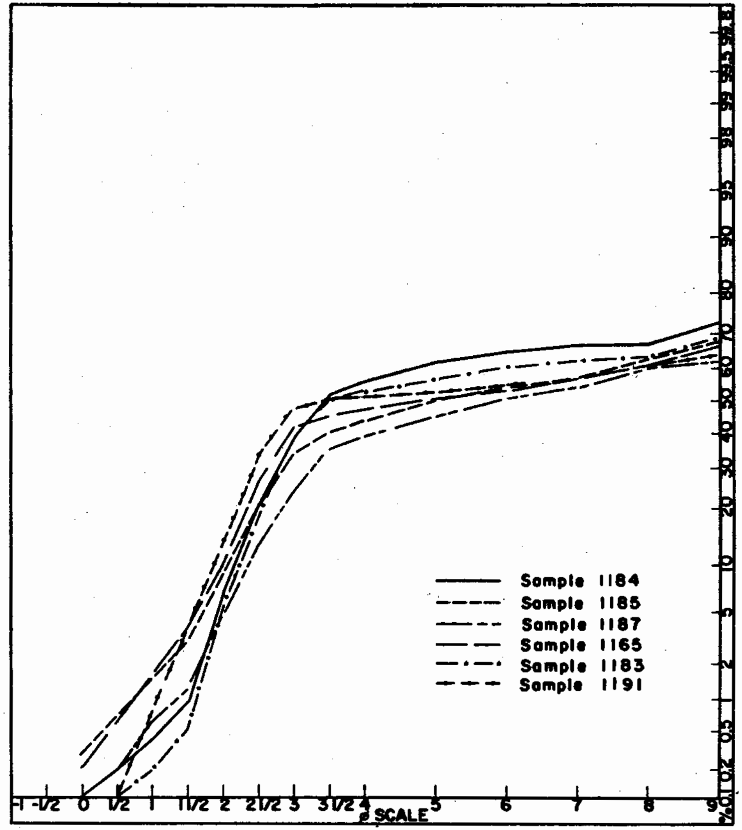


Figure 73. Cumulative curves of representative samples of the Mount Laurel-Navesink formation.

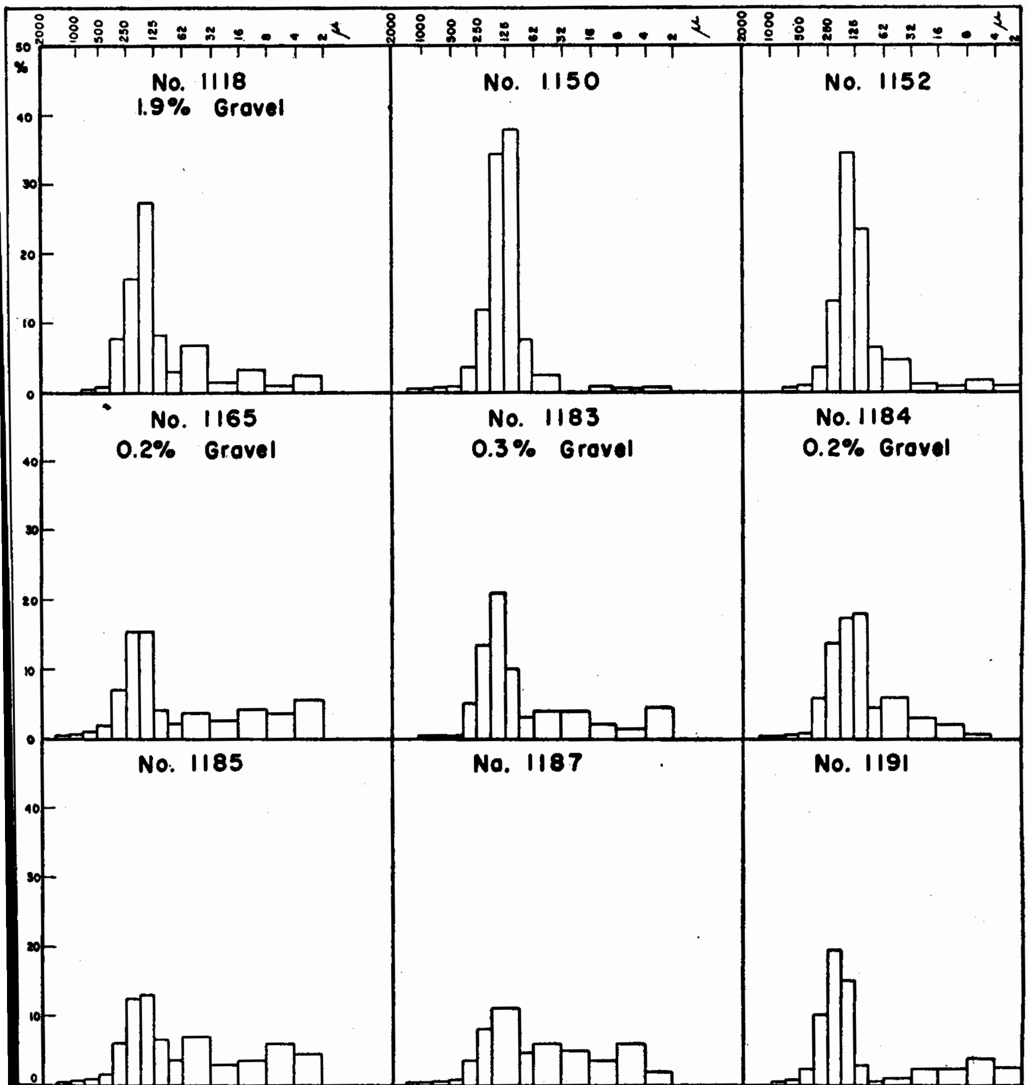


Figure 74. Histograms of samples of the Mount Laurel-Navesink formation.

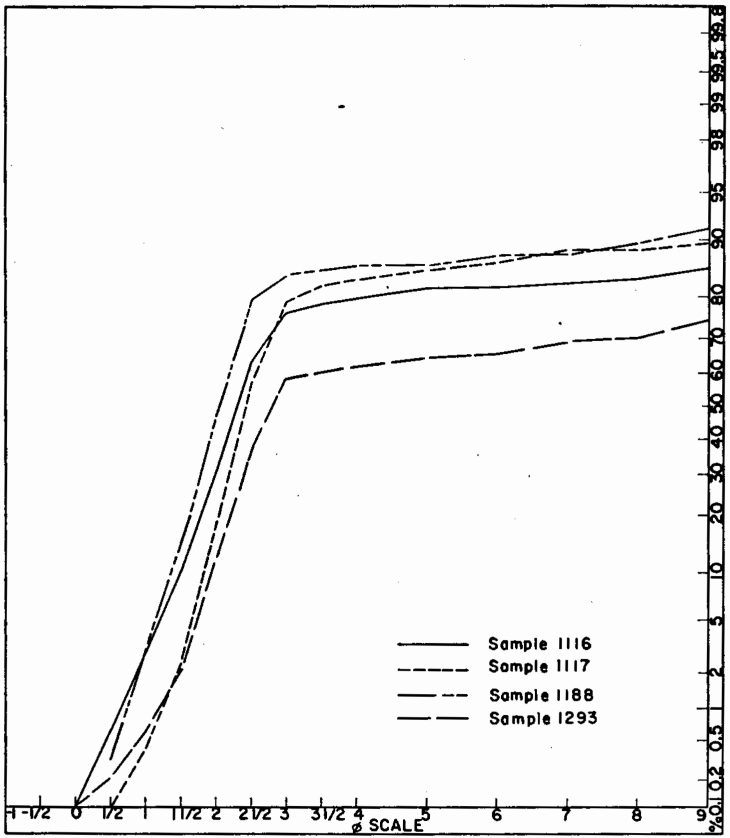


Figure 75. Cumulative curves of representative samples of the Red Bank formation.

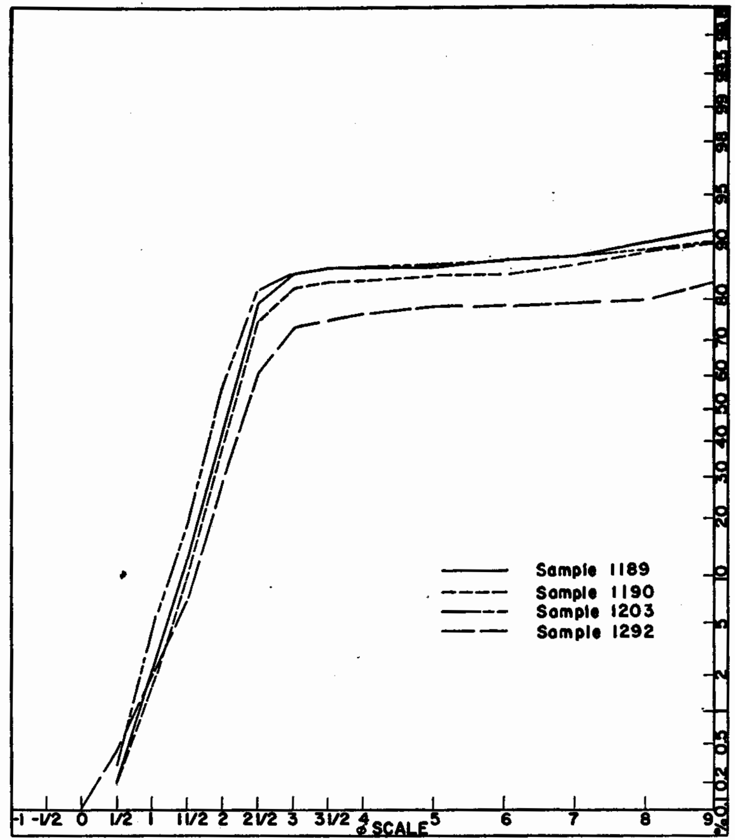


Figure 76. Cumulative curves of representative samples of the Red Bank formation.

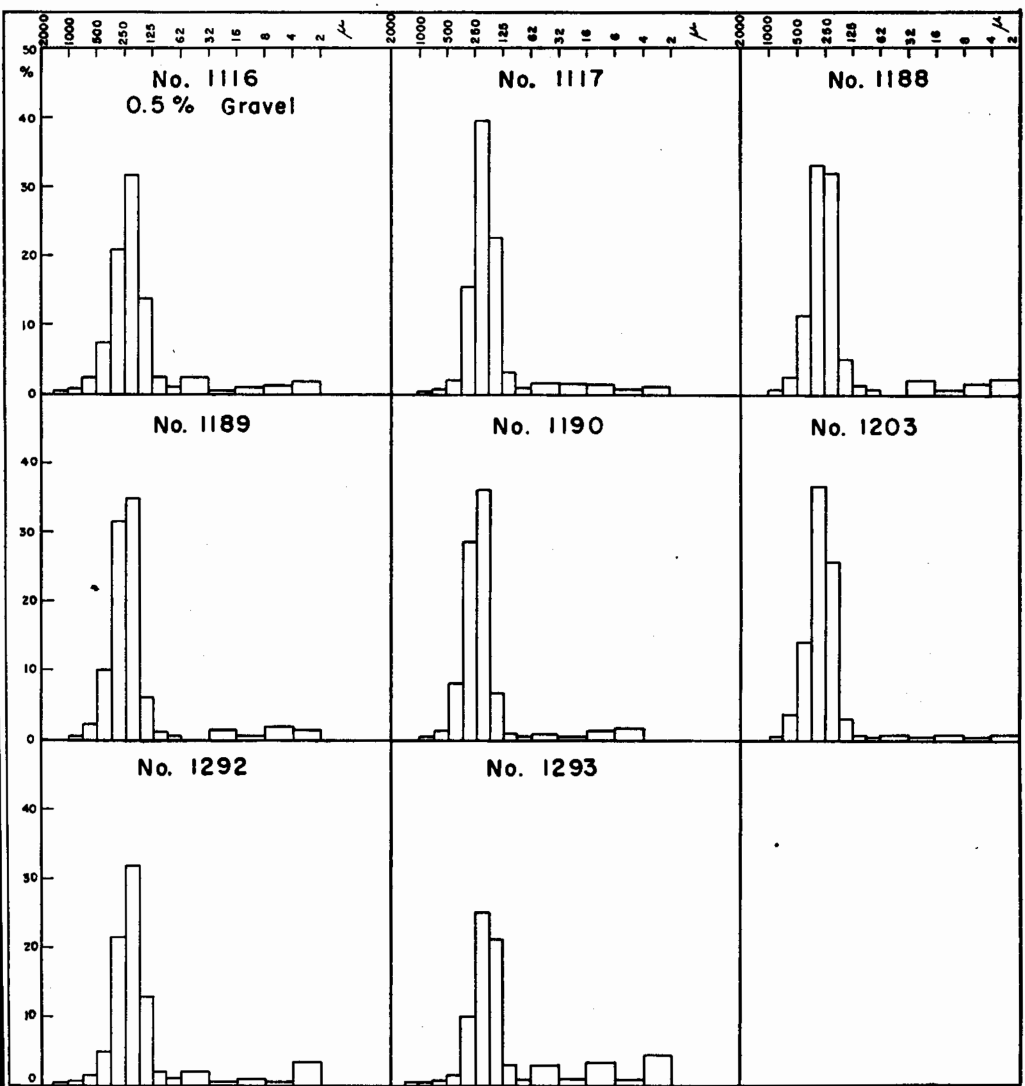


Figure 77. Histograms of samples of the Red Bank formation.

The sands of the Red Bank are somewhat coarser than those of the other marine formations. The few fossils preserved are usually broken, indicating wave action near shore. Thus the Red Bank was deposited in very shallow water, and is possibly even a beach deposit in northern Delaware.

CHAPTER VII

THE CRETACEOUS DEVELOPMENT OF THE APPALACHIAN MOUNTAIN SYSTEM IN THE LIGHT OF THE SEDIMENTARY RECORD OF THE COASTAL PLAIN

Main Problems

SINCE OESTREICH (1899) many authors have assumed that earth movements which have taken place in mountains are reflected in the sedimentary record of adjacent basins of deposition. Particularly in Europe many workers have applied the principle of "correlative strata", that is the correlation of sedimentary strata with the diastrophic history of adjacent mountains. Thus, the study of the Cretaceous sediments of the Coastal Plain should afford an opportunity to examine what clues can be derived from the sedimentary record with regard to the diastrophic and erosional history of the Appalachian region which furnished much of the detrital material of the Coastal Plain.

Twenhofel (1950) discussed what he called the "environmental factors" which have a bearing on the origin of a sediment, and he mentioned as the most important factors physiography, diastrophism, source rock and climate. If all these factors are not considered, the interpretation of the correlative strata may lead to oversimplification, if not erroneous results. Because climate has great influence on weathering processes, and therefore, on the *production* of detrital material, its effects on the sediments of the Coastal Plain should be given adequate consideration before an attempt is made to describe the diastrophic and erosional history of the Appalachian region during the Cretaceous Period.

The main problems discussed in the literature on the post-Triassic development of the Appalachian region are:

1. Reversal of the drainage system which apparently took place after the folding and uplift, presumbably during the Cretaceous Period.
2. Origin of wind gaps and water gaps in the Appalachian region.
3. Recognition of peneplane remnants in various stages of completion or destruction as indicators of crustal stand-still and crustal movement in the eastern United States.

Numerous papers regarding these problems have been published in the past, but very little agreement has been reached by the investigators concerning their solution. Some bold and imaginative hypotheses have been proposed, notably Johnson's hypothesis of the superposition of the Appalachian drainage system on a sedimentary cover which extended perhaps 200 miles west of the present Fall Line (Johnson, 1931). However, the lack of positive data concerning this sedimentary cover has prevented general acceptance of Johnson's ideas.

The study of Appalachian peneplanes and their significance in terms of earth movements has suffered because of disagreement on the recognition or correlation of erosion surfaces, and also because a study of the sediments of the Coastal Plain in relation to the Appalachian region was never attempted in detail, and in fact, was completely omitted by several investigators.

Reversal of Appalachian Drainage

The concept that the divide between east-flowing and west-flowing streams in the Appalachian Mountain System was located somewhere in the area of crystalline rocks east of the present Great Valley has been generally accepted. Whether this divide was located on the crystalline rocks of old Appalachia, or on Paleozoic metamorphosed sediments and intrusives forming the culmination of the Appalachian region, is a question outside the scope of this report. In either case a considerable change in drainage must have taken place, because at present the divide is beyond the Ridge and Valley Province in the Appalachian Plateau.

Two major hypotheses have been advanced, one involving regional superposition, and one involving headwater piracy.

The hypothesis of regional superposition of the drainage system, proposed by Johnson (1931), is briefly, as follows:

Following folding and uplift, and Triassic faulting, the Appalachian region was peneplaned in pre-Cretaceous time. This peneplane was submerged beneath the water of the ocean and received Cretaceous sediments as far west as the present Alleghany Front; marine deposition was followed by uplift with the maximum elevation occurring near the present divide. On the surface thus exposed a consequent drainage pattern developed, the streams flowing eastward and westward from the culmination created by the uplift.

Johnson's hypothesis was critically examined by Thompson (1949). He exposed certain basic difficulties inherent in Johnson's theory. One difficulty pertains to the fact that, when peneplanation of the uplifted Appalachian region took place, two peneplanes should be formed, sloping gently from the divide on the crystalline rocks, one in a westward, and the other in an eastward direction. Thompson (1949) stated (p. 34-35):

> If the divide was asymmetric, with shorter streams on the Atlantic side, as it may well have been, then the two peneplanes would have been separated from each other by a scarp similar to that now found along the east face of the Blue Ridge in the south.
>
> From which direction did the sea transgress the west-sloping peneplane, from the east or from the west? If from the east, as seems to be implied, the entire region must have been tilted eastward before, or concurrently with, submergence. The eastward tilting would require an axis far to the west of the crystallines and would have to be considerable in order to reverse the original westward slope on the west side of the divide. The

reversal of slope by eastward tilting would in itself solve the main problem, that of reversal of drainage, without submergence.

In addition, Thompson (1949) discussed the question of the source of supply for the marine sediments which supposedly covered the pre-Cretaceous peneplane. If the peneplaned Appalachian region were covered by the sea where would be the landmass supplying detritus to that sea? Johnson (1931), realizing this difficulty, stated (pp. 47-48):

> —it seems quite possible that while the sea was encroaching upon certain portions of the beveled land mass other portions were still undergoing reductions and contributing significant amounts of sediment to the advancing waters. Large areas in the Appalachian interior may have remained high until long after those portions of the Fall Zone peneplane now observable had been brought low. The part of the extended coastal plain responsible for superposition of the southeast-flowing streams need not have been very thick, so the quantity of sediments needed to form it was not necessarily great.

These arguments are not very convincing. Firstly, Johnson postulates the existence of a peneplane—that is, an extensive area of very small relief—but in order to have a source area for the sedimentary rocks needed for the hypothesis of superposition, he is willing to assume large areas which remain high during the advance of the sea. Secondly, if peneplanation took place as described by Thompson (1949), producing one westward-sloping and another eastward-sloping peneplane, tilted seaward during or before transgression, the sediments deposited on the eastward-sloping peneplane would probably form a wedge-like series like the sediments of the present Coastal Plain; consequently, they would have reached a considerable thickness, and therefore, a substantial quantity of sediment would be required.

What evidence pertaining to the question of superposition is available on the basis of the investigation of the Cretaceous sedimentary rocks of the Coastal Plain of Delaware?

1. The Cretaceous sediments lying directly on the crystalline basement rock are non-marine in character (see Chapter VI), not only in the area adjacent to the Fall Zone, but also further to the south, at considerable distance from the Fall Zone, in the deep Hammond No. 1 well near Salisbury, Maryland. No marine Cretaceous sediments have ever been found in the Piedmont of Delaware, and there is no indication that a blanket of marine Cretaceous sediments ever existed.

2. As indicated in Chapter V, there is considerable evidence that the non-marine Cretaceous sediments were primarily derived from the crystalline rocks of the Piedmont, and this area must have been exposed to the processes of weathering and erosion. Thus, a continuous or complete sedimentary cover did not exist there in Patuxent to Magothy time.

The conclusion that Patuxent and younger non-marine Cretaceous sediments were primarily derived from the nearby Piedmont, is supported by Clark (Clark, *et al.*, 1911). He stated (p. 82):

> The Patuxent deposits, like those of the succeeding Arundel and Patapsco formations, reflect in a large measure the character of the Piedmont materials which lie immediately to the westward.

Clark's statement implies, although he does not specifically mention it, that these sediments never covered the Piedmont far to the west of the present Fall Zone. Thus, the conclusions based on heavy mineral analysis in Delaware, and on the general lithologic character of the sediments in Maryland, are in agreement with each other.

If the marine sedimentary cover assumed by Johnson ever existed in Lower Cretaceous time, it must have been entirely removed by erosion before deposition of the Patuxent took place. Thus, in the relatively short time interval between the beginning of the Cretaceous Period and Early Cretaceous deposition of non-marine sediments, tilting, marine deposition, and complete removal of deposits should have been accomplished.

3. There is evidence that in Patapsco-Raritan time more material was derived from the rocks of the Folded Appalachian Mountains than in previous Patuxent time due to headward erosion of the streams on the Atlantic slope and the westward expansion of their drainage basins, gradually including larger areas of the Folded Appalachians (see Chapter V).

4. On the basis of the foregoing discussion, it is considered impossible that the great transgression assumed by Johnson took place in Early Cretaceous time. However, Johnson (1931) did not specify exactly when during the Cretaceous Period the great submergence took place. He discussed the possibility that some of the Upper Cretaceous greensands were deposited in "fairly deep water" (p. 51), and that, therefore, the Cretaceous sea may have reached far inland. In northern Delaware, such a Cretaceous greensand is the Mount Laurel-Navesink formation, which, near St. Georges, is about 25 feet thick. It is conformably overlain by the Red Bank formation and conformably underlain by the Wenonah. The thickness of the Mount Laurel-Navesink mentioned above represents, therefore, the original thickness of the deposit, and is not influenced by erosion.

   It is difficult to assume that a formation which is thin in northern Delaware, and which thickens considerably toward the southeast, would have extended very far to the northwest. The presence of abundant large shells of *Exogyra cancellata* and *Exogyra costata*, and the analysis of the mechanical composition as discussed in Chapter VI, also indicate relatively shallow water conditions.

For the reasons mentioned above, it is believed that Johnson's hypothesis of superposition is not in accordance with the sedimentary record of the Coastal Plain of Delaware, and that headward erosion must be responsible for the shift of the divide between the westward and eastward flowing streams in the Appalachian region.

Origin of Wind and Water Gaps in the Appalachian Mountains

This problem is only briefly discussed here, because the sedimentary petrology of the Coastal Plain sediments does not contribute positive evidence as to the origin of the gaps. However, the investigation of the provenance of the sediments of the Coastal Plain revealed that the non-marine Cretaceous deposits were derived mainly from the Piedmont and the Appalachian region, and that therefore the Appalachian streams did not originate on a marine sedimentary cover as proposed by Johnson. It is this assumed cover which made the explanation of the gaps a simple one, because the present drainage would be inherited from the consequent stream courses developed on it. If a marine cover never existed, the gaps should be explained in some other way.

It is possible that the gaps can be compared to the pediment passes observed by Howard (1942) in the Sacaton Mountains. If gaps are formed as low places which resulted from denudative altiplanation as defined by Bakker (1948, p. 20), and if the lower portions of the Appalachian region became gradually covered by some continental deposits, particularly during Patapsco-Raritan time, some streams may have chosen these gaps as natural eastward courses in the process of headward erosion. Thus, the presence of gaps is not inconsistent with the results of the heavy mineral investigation.

The Age of Appalachian Peneplanes in the Light of the Sedimentary Record

The importance of studying the sediments of the Coastal Plain in relation to the erosional history of the Appalachian region was recognized by Bascom (1921). She stated (p. 541):

> In any investigation of the cycles of erosion, complete or incomplete, that collectively constitute the erosional history of the Piedmont Province of the Appalachian Highlands, the stratigraphic record preserved on the margin of the province must furnish the data by which the succession and age of such erosion cycles stand or fall.

Bascom apparently based her age determination of peneplanes or partially completed peneplanes entirely on the stratigraphy of the Coastal Plain, unconformities indicating periods of erosion during which peneplanation took place, and the sedimentary formations indicating periods of deposition in the Coastal Plain and uplift in the Appalachian Mountains. Thus, the eroded crystalline basement represents one peneplane (the Kittatinny), whereas the next peneplane (the Schooley) passes beneath the base of the Patapsco formation which unconformably overlies the Patuxent. Because Bascom considered the Patapsco to be of Early Cretaceous age, the Schooley peneplane must be of the same age.

The correlation of peneplanes or pediments with unconformities, without any reference to the nature of the sediments, seems to be an over-simplification which can lead to misinterpretation. There is no good reason to assume that during a period of peneplanation in the Appalachian region no deposition would take place in the Coastal Plain. In fact, whenever the Appalachians approached an area of low relief, gradients of eastward-flowing streams would be small, and *deposition* of clastic sediments would be expected in the Coastal Plain rather than erosion. During active uplift of the Appalachian region erosion may also have taken place in the Coastal Plain, although not necessarily so. With moderate or slow uplift and a slight increase in competency of streams, deposition in the Coastal Plain, possibly of somewhat coarser sediments, could still continue. Thus, earth movements and erosional history of the Appalachian region should not be based on the stratigraphic record alone, but also on the record of the sediments themselves.

Stose (1940) did consider the sedimentary record, although not in detail. He stated (p. 474):

> An examination of the Coastal Plain deposits may throw some light on the subject. The sediments of the Lower Cretaceous in Maryland and Delaware are largely arkosic sands with kaolinized feldspar and clays, derived from disintegrated crystalline rocks exposed on the adjacent part of the peneplane surface. The Upper Cretaceous beds are of similar composition but of finer texture, with less arkose and more clay, and the uppermost beds are largely marl with still less detrital material.

On the basis of this record Stose was of the opinion that all during Cretaceous time (and also during a part of the Tertiary) the land of the Appalachian region stood relatively low and that no major uplifts took place; thus, the peneplane which was formed during Jurassic time on the pre-Cambrian and Paleozoic crystalline rocks and Triassic sedimentary rocks was never severely uplifted and dissected until mid-Tertiary time, and consequently, remnants of this peneplane have been preserved until the present. Thus, opinions concerning the development of the Appalachian region based on the record of the Coastal Plain differ widely, Bascom (1921) finding numerous erosion cycles and peneplanes, and Stose (1940) essentially one peneplane, which he called the Schooley peneplane. Stose's conclusions have some appeal, because the development of a peneplane certainly involves a long time interval, while Bascom's multiple erosion cycles would allow very little time for peneplane development.

What deductions can be made from the sedimentary record of the Coastal Plain of Delaware?

In evaluating the data concerning the Cretaceous sediments in terms of their usefulness as correlative strata, it should be remembered that the climate of the Cretaceous Period was warm and humid, as evidenced by the fossil flora of the non-marine Cretaceous deposits described by Berry (Clark, *et al.*, 1911), the remains of large reptiles in the Arundel formation of Maryland, and the fauna of the marine Upper Cretaceous formations. Consideration should be given to the effects of this climate on the weathering processes in the source area before the record of the sediments is interpreted in terms of earth movements which took place in the Appalachian region.

The significance of correlative strata in a tropical, humid climate has been discussed by Bakker (1955), mainly on the basis of recent investigations of soils and sediments in Dutch Guiana which indicate that thorough decomposition and disintegration of source rocks can take place even in regions with considerable relief and fairly steep slopes. Bakker stated:

> Sur les pentes inclinées inférieures à 25-50° les roches-mères ont l'occasion de se décomposer parfaitement. Ce sont les domaines où, dans une région tropicale humide, les profils du sol peuvent avoir une épaisseur remarquable. Néanmoins il est plus important que l'horizon C du profil du sol, qui s'étend sur l'ensemble des roches sousjacentes, n'échappe pas aux phénomènes de migration et à une désagrégation préparatoire très intensive. La profondeur de cet horizon C plus ou moins décomposé peut dépasser 10-20 mètres. C'est pourquoi les filons de quartz et les quartzites—qui souvent ne sont pas trop compacts—se décomposent, aussi plus ou moins. Ça veut dire, que l'activité mécanique des ruisseaux rapides et pas trop courts, suffit à briser les blocs en gravillons et sables grossiers. Sur les pentes inclinées à 25-50°, souvent un profil du sol bien développé fait défaut, mais la désagrégation préparatoire de l'horizon C est aussi tellement forte, que les filons de quartz et les quartzites n'échappent pas. En général, il faut conclure que la désagrégation préparatoire *in situ*, tellement intensive ét profonde sous un climat tropical humide, est moins favorable à la conservation des cailloux quartzeux et quartziteux pendant le transport fluvial que celle des climats tempérés. En d'autres termes, la décomposition sous un climat tropical humide des roches-mères et le transport des eaux produisent bien de grands quantités de gravillons et de sables grossiers, mais non pas de graviers grossiers. Néanmoins une partie de ces gravillons et sables grossiers anguleux semble être assez résistante, aussi bien dans les profils du sol de nature kaolinitique que dans les sédiments fluviaux et côtiers.

An important conclusion is reached by Bakker on the basis of these observations, that is, that the sediments produced under tropical humid conditions do not necessarily differ greatly in their mechanical and mineral composition whether produced on steep slopes or in areas of small relief, due to the thorough weathering taking place in the C horizon of the soils of the source area.

In view of the fact that warm and humid conditions prevailed during the Cretaceous in the area discussed in this report, some caution is necessary as to the interpretation of the sediments in terms of earth movements and physiographic conditions in the Appalachian region. The impoverished mineral suite of the Patapsco-Raritan zone, as well as the predominantly fine-grained character of these sediments, are not necessarily an indication that during this time the source area was reduced to a peneplane or pediment. However, the mineralogical and mechanical composition of the Patapsco-Raritan zone do indicate reduction of relief *relative* to that existing during Patuxent and Magothy time, assuming no significant changes in climate during that period. This reduction of relief should have taken place at least in the eastern portion of the Appalachian region, not very far from the basin of deposition, while the region beyond may still have had considerable relief.

Much of the material of the marine Upper Cretaceous sediments was derived from a source located to the south, and therefore the mechanical composition and heavy mineral content do not necessarily reflect conditions in the Appalachian region. However, certain deductions regarding paleogeographic problems can be made on the basis of study of the environment of deposition.

With these considerations in mind, attention can be turned to the development of the Appalachian region during the Cretaceous Period.

The sediments of the Patuxent zone were deposited on an erosion surface, which bevels pre-Cambrian, lower Paleozoic and Triassic rocks. This erosion surface has a relief of only a few hundred feet, and may be called a peneplane. It was formed after the Triassic, and before deposition began on it during Early Cretaceous time. Thus, its age can best be described as Jurassic.

In Early Cretaceous time the eastward-flowing streams from the Appalachian region were activated by a slight seaward tilting of the Jurassic peneplane, which was probably somewhat dissected before deposition of Patuxent sediments began. This reactivation of the streams is indicated by the relatively fresh staurolite suite and the arkosic character of the Patuxent sands, and the presence, at least in Maryland, of a basal conglomerate in this formation. Moreover, the Patuxent sands are somewhat coarser than those of younger non-marine Cretaceous sediments (see Chapter VI). Probably, deposition on the Jurassic peneplane began at some distance to the east of the present Fall Zone, and the decrease of stream gradients resulting from this deposition caused sedimentation to move gradually westward. In that way, the upper part of the Patuxent in the eastern portion of the Coastal Plain would have been deposited simultaneously with Patuxent deposits near the Fall Zone. This would be in accord with the predominance of staurolite in the upper portion of the Patuxent in the Hammond No. 1 well near Salisbury, Maryland.

The tilting of the Jurassic peneplane is also indicated by the estuarine character of a part of the Patuxent sediments suggesting encroachment of the sea on the continent in Patuxent time.

At the close of Patuxent time some erosion of the Coastal Plain sediments took place, probably due to an increase in the rate of seaward tilting of the area. (Actually, this movement must have been a nearly continuous one throughout Cretaceous time, because great thicknesses of sediments were deposited, all of which are either of non-marine, or of neritic facies.) Because the Patuxent sediments never overlapped the Piedmont much farther to the west than they do today, and because the adjacent Piedmont did not stand much higher than the Coastal Plain, the amount of Patuxent removed by erosion may have been relatively small.

During Patapsco-Raritan time deposition of fine-grained fluviatile and estuarine sediments took place. Intensive weathering in the source area prevailed under warm, humid conditions, resulting in an impoverished mineral suite. The virtual absence of metamorphic minerals as opposed to the prevalence of staurolite and kyanite in the underlying and overlying sediments strongly suggests lowering of relief in the source area, and perhaps even the forming of a peneplane or pediment. Along the major streams continental sediments may have been deposited and redeposited accounting for the worn character of the mineral suite as a whole. However, the occurrence of much angular and subangular tourmaline (of Wissahickon type) indicates that much of the Piedmont was not covered by sediments but functioned as source area. An increasing percentage of well-rounded, oval tourmaline grains as compared to the underlying Patuxent sediments indicates that the Appalachion streams expanded their drainage basins in a westward direction, deriving an increasing amount of detritus from the Folded Appalachian region. At the end of this period, more rapid tilting took place, causing some erosion of the Patapsco-Raritan deposits, and submerging a portion of the Coastal Plain, resulting in swampy coastal areas. Thus, the Magothy formation, with a mineral suite similar to that of the Patuxent zone, is a lagoonal or paludal (swamp) deposit, and in some places, a marine deposit. (It is known to have marine tongues in New Jersey, and in deep wells in Bridgeville, Delaware, and Salisbury, Maryland.)

The tilting of the Coastal Plain increased again at the end of Magothy time, and, as a result, the Magothy formation was eroded, at least for a relatively short period, before deposition took place in the shallow sea gradually submerging nearly the entire Coastal Plain. The marine sediments deposited in the advancing sea were partially derived from the Appalachian region to the northwest, and partially brought in from an area to the south, presumably by coastal currents. The ratio between the amounts of stream-transported and current-transported material slightly varies from one formation to another. When deposition took place very close to the shore, as in Red Bank time, the ratio was in favor of stream-transported material, and when deposition took place in somewhat deeper water, as during part of Mount Laurel-Navesink time, the ratio was in favor of current-transported material.

All during this time seaward tilting of the Appalachian region must have been in progress. There are indications that the tilting may have been accompanied by slight warping or folding of the Cretaceous beds and the underlying basement rocks. A very gentle anticlinal structure may be seen in the south bank of the Chesapeake and Delaware Canal; and slight variations in dip of marine Upper Cretaceous formations can be deduced from well records. In addition the presence of marine tongues in the Raritan formation of New Jersey, which is strictly non-marine in northern Delaware, and the variations in thickness of marine Upper Cretaceous formations, notably the Merchantville, in outcrops, indicate that the rate of subsidence of the Coastal Plain varied from place to place, and that, consequently, some warping occurred.

It is obvious from the sedimentary record that subsidence of the Coastal Plain was gradual, and usually balanced by sedimentation. Sometimes sedimentation seemed to gain a little on subsidence, and at other times subsidence gained on deposition. At the same time the Appalachian region was uplifted gradually to supply detrital materials for the Coastal Plain. Probably it never stood very high during Cretaceous time, and the uplifted Jurassic peneplane was dissected during Patuxent time and relief reduced again during Patapsco-Raritan time. Very gradual tilting, at varying rates, took place during the remainder of the Cretaceous.

In summary, up to the close of the Cretaceous Period, development of at most two peneplanes or pediments can have taken place, one of Jurassic age, and one of Patapsco-Raritan or middle Cretaceous age. However, it is possible that during the last mentioned period the peneplane or pediment had only a limited extent, and that farther from the basin of deposition a region of considerable relief persisted.

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APPENDIX A

Heavy mineral content of the sediments of the Coastal Plain of northern Delaware

NOTE: Not all heavy mineral analyses made for this report are incorporated in the appendix. Additional data may be obtained from the Delaware Geological Survey. Some analyses of Recent and Pleistocene are included for the purpose of comparison with data concerning the Cretaceous deposits. Location of samples may be found on plate I. Those marked with an asterisk (*) are shown on plate II.

Recent

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
*1	23	5	6	2	2	1	—	2	—	—	—	8	3	—	—	1	17	—	4	—	—	9	20	12	—	—	—	—	—	—	—	—	—	5	—	3	—	—	—	—	—	—
*2	64	4	22	2	1	1	—	2	—	—	—	6	1	—	—	12	2	1	21	—	—	2	8	5	1	—	2	1	—	—	—	2	—	1	—	—	1	—	—	—	1	1
*3	31	8	3	1	1	—	—	3	—	—	—	1	6	—	—	8	12	—	20	—	—	13	17	2	1	—	2	—	—	—	—	1	—	1	—	—	—	—	—	—	—	—
*4	71	9	19	2	1	1	—	2	—	—	2	9	2	1	—	13	2	1	14	—	—	7	5	4	—	—	1	2	—	—	—	1	—	1	—	1	—	—	—	—	—	—
*5	41	7	10	2	—	—	—	1	2	—	4	3	2	—	—	17	9	—	11	—	—	6	9	8	—	—	4	1	—	—	—	1	2	—	—	—	1	—	—	—	—	—
*6	24	4	5	4	1	5	—	1	—	—	2	6	5	—	—	9	—	—	12	—	—	4	18	9	6	—	2	1	—	—	1	2	1	—	—	2	—	—	—	—	—	—
*7	24	9	4	1	2	2	—	4	—	—	2	8	1	2	—	6	3	1	15	—	—	3	8	19	6	—	—	1	—	—	—	1	1	1	—	—	—	—	—	—	—	—
*8	35	5	9	5	1	6	—	3	—	—	1	9	4	—	—	8	1	—	9	—	—	4	8	14	5	—	2	1	—	—	—	—	1	1	—	1	—	1	—	—	—	1
*101	12	6	1	1	—	4	—	—	—	—	—	12	4	—	—	5	16	—	3	—	1	7	11	13	3	—	2	1	—	—	—	1	1	5	—	3	—	—	—	—	—	—
*102	80	3	40	2	3	—	—	3	—	—	4	8	3	—	—	8	1	1	9	—	—	5	1	2	—	—	2	1	—	—	—	2	—	1	—	—	—	—	1	—	—	—
*103	68	4	28	2	1	1	—	4	—	—	2	9	7	—	—	10	5	1	7	—	—	5	2	2	1	—	3	1	—	—	—	1	1	1	—	1	—	1	—	—	—	—
*104	60	7	25	4	1	1	—	4	—	1	3	9	3	—	—	11	2	1	10	—	—	6	2	2	—	—	2	1	—	—	—	1	—	1	—	1	—	—	1	—	—	1
*105	40	2	5	1	—	4	—	—	—	—	—	2	—	1	—	8	7	—	7	—	1	7	21	21	—	—	6	3	—	—	—	2	1	—	—	1	—	—	—	—	—	—
*106	17	4	2	4	1	—	2	2	—	—	1	8	4	1	—	10	4	1	14	—	—	4	9	20	2	—	2	1	—	—	—	—	1	—	1	2	—	—	—	—	—	—
*108	17	3	1	3	1	2	—	—	1	—	1	3	1	—	—	6	7	2	10	—	—	5	25	16	2	—	4	—	—	—	—	1	1	4	—	1	—	—	—	—	—	—
201	5	1	1	2	3	15	—	—	—	—	—	—	—	—	—	—	33	—	—	—	—	2	17	20	—	—	1	3	—	—	—	1	1	—	—	—	—	—	—	—	—	—
*202	11	1	1	1	1	3	—	—	—	—	4	1	1	—	—	5	10	1	6	1	—	1	35	16	2	—	5	1	—	—	—	1	1	1	—	1	—	—	—	—	—	—
*203	21	1	1	—	7	17	—	—	—	—	1	5	1	—	—	2	6	1	5	—	—	2	29	13	2	—	3	1	—	—	—	1	1	—	—	1	—	—	—	—	—	—
204	11	1	1	3	—	6	—	—	—	—	1	4	—	—	—	2	6	—	6	—	1	2	39	22	1	—	3	1	—	—	—	1	—	—	—	—	—	—	—	—	—	—
*205	47	18	12	—	—	1	—	5	5	1	1	14	2	—	—	1	2	—	3	—	—	21	2	9	—	—	2	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
206	48	9	18	1	—	—	—	1	2	1	1	17	1	—	—	3	5	—	3	—	—	9	7	17	1	—	3	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
207	—	—	—	—	—	—	—No Heavy Minerals—					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Pleistocene

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1003	27	—	1	—	—	1	—	—	—	—	1	—	1	—	—	1	1	—	2	—	—	1	14	23	24	—	1	—	—	—	—	3	3	10	1	12	—	—	—	—	—	—
1004	7	—	1	—	—	—	—	—	—	—	—	—	1	—	—	1	1	—	3	—	1	2	37	19	24	—	1	1	—	—	—	1	2	4	1	1	—	—	—	—	—	—
1012	52	1	4	—	—	—	—	—	—	—	3	3	2	—	—	5	1	—	14	—	—	5	17	23	15	—	1	—	—	—	—	2	2	2	—	—	—	—	—	—	—	—
1013	29	1	6	1	—	—	2	—	—	—	1	12	3	—	—	2	1	—	5	—	—	2	23	24	12	—	1	2	—	—	—	2	—	—	—	—	—	—	—	—	—	—
1014	83	1	23	1	—	—	—	3	—	—	2	10	5	—	—	3	1	—	12	—	—	1	5	18	8	—	2	2	—	—	—	2	1	—	—	—	—	—	—	—	—	—
1015	56	2	10	1	—	1	—	1	—	—	2	6	3	—	—	8	—	1	17	—	—	—	12	21	5	—	4	4	—	—	—	2	—	—	—	—	—	—	—	—	—	—
1033	70	2	17	1	—	—	—	1	1	—	—	15	7	—	—	2	16	—	16	—	—	4	6	5	1	—	1	3	—	—	—	1	1	—	—	—	—	—	—	—	—	—
1034	61	6	12	3	1	1	—	5	1	—	1	8	9	—	—	4	7	—	14	—	—	6	4	7	—	—	3	5	—	—	1	1	1	—	—	—	—	—	—	—	—	—
1035	48	9	19	1	—	1	—	8	1	—	—	3	7	—	—	22	2	1	1	—	—	10	3	2	—	—	1	5	—	—	1	1	1	—	—	—	—	1	—	—	—	—
1936	37	9	21	1	—	—	—	5	1	—	—	2	10	—	—	14	7	—	1	—	—	12	4	2	1	—	3	6	—	—	—	—	1	—	—	—	—	—	—	—	—	—
1053	49	2	7	1	1	—	—	2	1	—	—	8	11	1	—	10	3	4	25	—	—	3	10	4	—	—	3	3	—	—	—	—	—	—	—	—	—	—	—	1	—	—
1054	65	11	11	1	—	—	—	4	—	—	—	9	3	—	—	16	2	—	19	—	—	11	2	4	—	—	1	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1055	75	7	20	4	—	—	—	7	1	—	—	3	9	1	—	14	1	2	19	—	—	6	2	1	—	—	1	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1056	46	2	12	2	—	1	—	5	1	—	1	4	10	1	—	11	1	2	12	—	—	2	15	10	3	—	1	5	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1084	75	7	9	2	1	1	—	5	—	—	1	17	8	—	—	3	3	—	25	—	—	4	4	1	1	—	1	5	—	—	—	1	1	—	—	—	—	—	—	—	—	—
*1085	59	2	9	6	—	—	—	6	—	—	—	22	9	—	—	7	5	2	16	—	—	7	4	2	—	—	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1086	48	8	3	—	1	—	—	3	—	—	—	14	10	—	—	16	3	—	16	—	—	10	7	1	—	—	—	6	—	—	—	1	—	—	—	—	—	1	—	—	—	—
*1087	15	7	5	5	—	1	—	2	—	—	1	6	8	—	—	5	1	2	13	—	—	5	7	16	—	—	4	12	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1088	33	11	11	6	—	—	—	2	—	—	2	4	9	—	—	17	1	—	10	—	—	4	4	3	—	—	6	6	—	—	—	2	1	1	—	—	—	—	—	—	—	—
2041	45	2	48	—	1	—	—	2	1	—	—	5	3	—	—	12	2	—	10	—	—	3	5	1	—	—	—	1	—	—	—	1	1	—	—	1	—	1	—	—	—	—
2043	47	9	52	—	1	—	—	11	4	—	1	3	—	—	—	2	1	—	5	—	—	9	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2058	26	4	27	1	—	—	—	12	3	—	—	6	1	—	—	5	2	5	17	—	2	9	3	1	—	—	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2060	34	5	19	4	—	—	—	5	2	—	2	9	2	2	—	5	1	1	18	—	1	9	8	3	—	—	1	—	—	—	—	—	—	1	—	1	—	1	—	—	—	—
2065	46	3	20	2	1	—	—	4	—	—	—	2	2	1	—	11	1	—	22	—	2	5	15	4	1	—	2	1	—	—	—	—	1	—	—	—	—	—	—	—	—	—
2066	60	6	25	—	—	—	—	9	1	—	—	15	5	1	—	11	1	1	13	—	—	4	5	1	—	—	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Red Bank

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites
1116	49	12	4	—	—	—	—	7	1	—	—	30	7	2	—	4	—	3	20	—	—	8
1117	56	6	5	2	—	1	—	6	—	—	1	23	3	2	—	6	—	5	25	—	—	12
1188	51	16	4	—	—	—	—	12	1	—	—	31	10	3	—	4	—	3	11	—	—	5
1189	54	10	1	1	—	—	—	11	—	—	—	34	10	2	—	6	—	3	15	—	—	5
1190	40	8	5	3	—	1	—	8	—	—	1	21	8	4	—	9	—	4	15	—	—	10
1203	37	6	7	3	1	—	—	6	—	—	1	30	7	3	—	2	—	2	17	—	—	15
1292	42	11	7	1	—	—	—	5	—	—	—	21	6	3	—	4	1	4	21	—	—	16
1293	50	7	5	1	—	—	—	5	2	—	1	20	7	2	—	5	—	7	25	—	1	11

Sample Number	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1116	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1117	—	2	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1188	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1189	—	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1190	1	—	1	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1203	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1292	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1293	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Mount Laurel-Navesink

Number Sample	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites
1118	45	13	16	2	—	—	—	6	1	—	1	17	3	2	—	2	—	6	22	—	—	8
1149	58	10	11	8	1	1	—	10	1	—	1	17	3	—	—	2	—	5	15	—	—	15
1150	40	6	22	9	—	1	—	18	2	—	1	5	1	—	—	1	—	6	18	—	1	8
1151	37	6	15	13	2	—	—	10	4	1	1	4	1	1	—	2	—	12	20	—	1	7
1152	35	10	12	3	1	1	—	11	2	—	1	8	1	1	—	2	—	9	24	—	1	10
1153	30	10	14	7	1	1	—	12	3	—	1	2	—	—	—	2	—	9	26	—	1	8
1161	59	7	6	5	1	1	—	13	1	—	1	13	4	1	—	5	—	8	22	—	1	9
1162	55	4	11	14	4	1	—	8	2	1	1	9	4	—	—	4	—	9	20	—	1	7
1163	53	9	17	20	1	1	—	8	—	—	1	5	1	1	—	1	—	4	16	—	1	12
1164	56	12	10	10	2	4	—	6	2	—	—	17	4	1	—	2	1	4	18	—	1	5
1165	45	8	12	5	3	—	—	8	1	—	—	20	2	6	—	3	—	4	21	—	1	6
1170	25	7	11	10	3	2	—	9	3	—	—	9	—	1	—	3	—	8	22	—	3	5
1183	49	11	8	10	1	2	—	12	2	—	—	12	3	2	—	1	—	3	21	—	1	11
1184	49	10	14	10	—	4	—	10	2	—	—	11	3	—	—	1	—	5	22	—	1	7
1185	48	8	11	13	—	3	—	7	2	—	—	28	3	2	—	4	—	2	12	—	2	3
1187	30	9	19	9	1	1	—	8	1	—	—	8	2	—	—	1	—	8	21	—	1	10
1191	52	9	10	11	—	11	—	9	2	—	—	17	3	—	—	2	—	5	16	—	—	3
1204	25	14	5	7	1	5	—	4	1	—	1	24	2	5	—	3	—	1	14	—	—	6
1209	42	12	3	13	1	2	—	6	—	—	—	13	1	2	—	4	—	5	26	—	1	11
1290	46	11	12	3	—	1	—	13	3	—	1	9	1	1	—	5	1	11	18	—	—	9
1303	63	8	10	4	—	1	—	12	2	—	1	24	7	2	—	2	—	7	13	—	1	6
1304	66	7	21	2	1	—	—	14	1	—	—	17	6	—	—	3	—	4	15	—	1	8

Number Sample	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1118	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1149	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1150	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1151	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1152	1	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1153	—	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—
1161	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1162	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1163	—	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1164	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—
1165	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1170	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—
1183	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1184	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1185	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1187	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1191	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1204	3	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1209	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1290	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1303	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1304	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Wenonah Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1109	58	5	12	—	1	—	—	8	2	—	2	11	2	2	—	1	—	9	38	—	—	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1110	64	9	16	2	—	—	—	14	4	—	—	13	3	2	—	1	—	7	15	—	—	14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1112	58	8	10	1	—	1	—	10	5	—	1	13	2	—	—	1	—	11	24	—	—	12	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1119	42	16	2	1	—	—	—	7	—	—	1	5	3	3	—	3	—	11	25	—	1	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1130	49	12	14	3	—	—	—	9	1	—	2	10	3	—	—	2	—	12	25	—	1	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1146	53	8	14	2	1	—	—	12	2	—	—	11	3	1	—	3	—	7	26	—	1	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1154	32	9	7	3	1	—	—	12	4	—	2	11	2	1	—	3	—	14	18	—	1	11	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1155	46	8	16	1	1	1	—	14	2	—	1	9	2	1	—	4	—	8	22	—	—	8	1	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
1158	56	13	12	1	—	—	—	11	1	—	1	11	2	1	—	4	—	9	26	—	1	5	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1166	17	10	7	5	1	—	—	12	4	—	—	12	2	1	—	5	—	11	17	—	—	12	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1168	44	9	8	—	—	—	—	6	2	—	1	14	5	2	—	7	—	11	17	—	2	15	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1206	27	11	6	9	—	2	—	13	2	—	—	12	1	—	—	—	—	10	26	—	1	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1255	33	9	4	1	—	—	—	14	3	—	—	4	4	—	—	2	—	13	22	—	1	23	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1256	41	8	6	1	—	—	—	7	2	—	1	8	4	—	—	4	—	15	30	—	—	14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1257	19	10	7	—	—	—	—	16	—	—	1	14	3	1	—	2	—	8	23	—	1	14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1305	35	10	12	1	—	—	—	12	1	—	1	11	3	2	—	2	—	8	23	—	—	13	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Merchantville Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1104	60	8	14	1	1	—	—	11	—	—	1	20	7	1	—	5	—	10	10	—	—	10	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—
1105	59	8	15	10	1	5	—	9	1	—	1	14	3	1	—	1	—	10	14	—	1	4	1	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—
1108	52	5	9	13	1	2	—	11	3	—	1	7	1	1	—	1	—	12	21	—	1	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1113	48	3	12	17	—	1	—	10	3	—	1	7	1	—	—	2	—	7	25	—	1	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1120	44	5	9	13	—	2	—	10	1	—	1	11	4	1	—	1	—	9	26	—	1	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1124	46	3	7	15	—	3	—	11	1	—	1	6	1	1	—	—	—	11	28	—	—	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1125	48	9	12	11	1	1	—	12	1	[illegible]	—	8	2	2	—	1	—	12	22	—	1	5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—
1131	49	9	19	9	2	1	—	4	1	—	1	9	1	—	—	3	1	15	19	—	1	5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1132	43	11	2	13	2	1	—	11	1	—	1	6	4	1	—	3	—	12	19	—	1	10	1	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1133	36	12	6	12	2	—	—	13	1	—	1	11	1	1	—	3	—	6	18	—	1	12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1134	40	6	9	11	2	—	—	9	—	—	1	10	2	—	—	2	—	9	24	—	1	13	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1135	50	7	13	13	4	1	—	10	1	—	2	6	2	—	—	1	—	9	22	—	—	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1207	4	12	7	8	—	4	—	6	3	—	—	7	3	—	—	1	—	13	21	—	4	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1208	9	7	6	12	—	3	—	14	1	—	1	6	3	1	—	2	—	9	25	—	—	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1212	15	12	12	9	1	1	—	8	2	—	—	7	2	2	—	2	—	4	27	—	3	8	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1253	34	10	2	12	—	1	—	9	3	—	—	11	—	3	—	1	—	9	28	—	1	10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Magothy Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1063	25	9	3	—	—	—	—	1	—	—	—	78	4	—	—	1	2	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1080	54	15	10	—	—	—	—	2	1	—	—	57	4	—	—	1	—	—	1	—	—	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1081	21	14	5	—	—	—	—	6	1	—	—	64	3	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1082	28	12	7	—	—	—	—	1	1	—	—	68	6	—	—	1	4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1092	23	19	6	—	—	—	—	2	1	—	—	63	5	—	—	—	—	—	1	—	—	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1093	20	11	2	—	—	—	—	1	1	—	—	80	2	—	—	—	1	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1095	37	13	8	—	—	—	—	3	2	—	—	50	1	—	—	—	—	—	1	—	—	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1096	25	7	23	—	—	—	—	4	1	—	1	40	—	—	—	—	—	—	1	—	—	23	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1099	31	21	3	—	—	—	—	2	1	—	—	62	2	—	—	—	—	—	—	—	—	9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1103	39	3	11	—	—	—	—	13	1	—	—	26	2	—	—	—	—	—	—	—	—	44	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1106	13	15	4	—	—	—	—	2	2	—	—	68	2	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1107	19	16	5	—	—	—	—	2	2	—	—	61	1	—	—	—	—	—	—	—	—	13	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1230	19	9	1	—	—	—	—	4	—	—	1	74	—	—	—	—	—	—	—	—	—	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1231	18	16	2	—	—	—	—	1	1	—	—	61	2	—	—	—	1	—	—	—	—	16	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1232	29	5	15	—	1	—	—	3	—	—	—	54	7	—	—	—	2	1	1	—	—	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1250	8	12	2	—	—	—	—	1	—	—	—	72	2	—	—	—	—	—	—	—	—	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1251	15	12	14	—	—	—	—	3	—	—	—	42	1	—	—	1	—	—	—	—	—	27	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1268	5	20	1	—	—	—	—	—	—	—	—	73	5	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1269	28	11	14	—	—	—	—	1	6	—	1	39	1	—	—	—	—	—	—	—	—	27	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1271	24	8	1	—	—	—	—	1	—	—	—	80	2	—	—	—	4	—	—	—	—	4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1272	8	11	24	1	—	—	—	8	1	—	—	32	1	—	—	—	—	—	—	—	—	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1277	33	4	17	—	—	—	—	5	1	—	1	61	3	—	—	1	—	—	—	—	—	6	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1282	16	27	7	—	—	—	—	4	—	—	—	53	2	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1283	4	6	5	—	—	—	—	1	1	—	—	84	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1297	22	12	24	—	—	—	—	14	3	—	—	22	1	—	—	—	1	—	—	—	—	22	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1298	17	8	8	—	—	—	—	—	—	—	—	76	5	—	—	—	—	—	—	—	—	2	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Patapsco-Raritan Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1007	54	9	20	—	—	1	—	5	—	—	1	9	—	—	—	1	—	—	2	—	—	51	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1046	31	15	15	—	—	—	—	13	6	—	—	14	—	—	—	—	—	—	1	—	—	36	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1216	40	11	19	1	1	—	—	6	3	—	1	6	—	—	—	—	—	1	4	—	—	46	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1217	31	13	27	—	—	—	—	11	7	—	3	1	—	—	—	—	—	—	1	—	—	37	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1218	31	14	19	—	—	—	—	6	1	—	—	1	—	—	—	—	—	—	—	—	—	58	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1219	16	6	22	—	—	—	—	14	6	—	—	1	—	—	—	—	—	—	—	—	—	50	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1220	4	12	30	—	—	—	—	19	2	1	1	—	1	—	—	—	—	—	—	—	—	34	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1221	10	4	35	—	—	—	—	15	4	—	1	1	—	—	—	—	—	—	—	—	—	40	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1222	18	14	23	—	—	—	—	10	4	—	—	—	—	—	—	—	—	—	—	—	—	49	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1223	30	8	32	—	—	—	—	7	3	—	—	—	—	—	—	—	—	—	—	—	—	50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1224	21	14	24	—	—	—	—	10	1	—	—	—	—	—	—	—	—	—	—	—	—	51	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1225	20	4	29	—	—	—	—	4	3	1	1	—	—	—	—	1	—	—	—	—	—	56	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1248	6	6	33	—	—	—	—	12	4	—	—	—	—	—	—	1	—	—	—	—	—	44	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1249	12	12	23	—	—	—	—	7	2	1	1	—	—	—	—	—	—	—	—	—	—	54	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1270	15	3	45	—	—	—	—	16	6	—	—	2	—	—	—	—	—	—	—	—	—	28	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1273	23	11	43	—	—	—	—	17	3	1	—	1	—	—	—	—	—	1	—	—	—	23	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1274	19	19	38	—	—	—	—	10	6	1	—	—	—	—	—	—	—	—	—	—	—	26	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1275	37	18	28	—	—	—	—	11	5	1	—	1	—	—	—	—	—	—	—	—	—	36	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1276	47	9	30	—	—	—	—	14	5	3	—	—	—	—	—	—	—	—	1	—	—	38	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1278	22	9	36	—	—	—	—	14	1	—	—	2	—	—	—	1	—	—	—	—	—	37	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1279	48	3	27	—	—	—	—	6	1	—	—	1	—	—	—	—	—	—	—	—	—	62	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1280	17	3	38		—	—	—	21	5	2	1	—	—	—	—	—	—	—	—	—	—	30	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1281	21	4	33	—	—	—	—	10	3	2	—	—	—	—	—	—	—	—	—	—	—	48	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1284	19	10	38	—	—	—	—	11	4	—	—	1	—	—	—	—	—	—	—	—	—	36	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1285	15	7	48	—	—	—	—	12	6	—	—	1	—	—	—	—	—	—	—	—	—	26	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1286	23	5	43	—	—	—	—	16	7	—	—	3	—	—	—	—	—	—	—	—	—	24	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1	—	—	—
1287	9	4	37	—	—	—	—	21	8	1	—	1	—	—	—	—	—	—	—	—	—	28	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1288	30	11	29	—	—	—	—	18	1	—	—	—	—	—	—	—	—	—	1	—	—	40	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Patapsco-Raritan (Cont'd)

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites
1289	26	5	32	—	—	—	—	10	5	—	—	—	—	—	—	—	—	—	—	—	—	48
1296	18	14	30	—	—	—	—	15	7	—	—	1	—	—	—	—	—	—	—	—	—	33
1300	18	13	34	1	—	—	—	16	5	—	—	1	—	—	—	—	—	—	—	—	—	30
1301	12	4	42	—	—	—	—	13	5	—	1	—	—	—	—	—	—	—	—	—	—	35
1302	10	2	35	—	—	—	—	12	8	1	1	—	—	—	—	—	—	—	—	—	—	41
1306	16	23	22	—	—	—	—	25	1	—	1	3	—	1	—	3	—	—	—	—	—	20
1307	29	14	17	—	—	—	—	33	10	—	2	1	—	—	—	—	—	—	1	—	—	22
1308	21	17	33	—	—	—	—	27	2	—	—	2	—	—	—	—	—	—	—	—	—	19
1309	23	14	23	—	—	—	—	23	6	—	—	3	1	—	—	—	—	2	—	—	—	28
1310	16	23	55	—	—	—	—	4	—	—	—	8	—	—	—	—	—	—	2	—	—	8
2013	23	6	18	—	—	—	—	12	13	—	—	—	—	—	—	—	—	—	—	—	—	51
2014	—	—	—	(No heavy minerals)				—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2015	38	18	23	—	—	—	—	15	8	—	—	1	—	—	—	—	—	—	—	—	—	35
2047	10	15	18	1	—	—	—	29	4	1	—	7	1	—	—	—	—	—	1	—	—	23
2063	44	25	36	—	—	—	—	10	4	1	—	4	—	—	—	—	—	1	1	—	—	18
2068	11	24	39	1	—	—	—	14	4	1	—	2	1	—	—	—	—	—	3	—	—	9
2074	2	18	30	—	—	—	—	18	5	—	1	1	—	—	—	—	—	—	—	—	—	27
2075	6	8	47	1	—	—	—	18	2	—	—	2	—	—	—	—	—	—	—	—	—	22
2077	8	3	56	1	—	1	—	14	3	—	—	2	—	—	—	—	—	—	1	—	—	15
2078	8	13	37	—	—	—	—	15	7	—	—	3	—	—	—	—	—	—	—	—	—	23
2079	7	8	32	1	—	—	—	25	3	—	—	1	—	—	—	—	—	—	1	—	—	28
2080	6	3	34	—	—	—	—	24	2	2	—	4	—	—	—	—	—	1	1	—	—	28
2081	3	4	40	—	—	—	—	16	7	—	—	2	2	—	—	—	—	—	1	—	—	24
2082	20	9	32	—	—	—	—	18	2	—	1	3	—	—	—	—	—	—	—	—	—	35
2083	7	25	43	—	—	—	—	15	3	—	—	1	—	—	—	1	—	—	—	—	—	10
2091	26	15	43	2	1	—	—	10	4	—	—	6	—	—	—	—	—	—	1	—	—	15
2092	11	9	45	—	—	—	—	18	3	—	1	—	—	—	—	—	—	—	—	—	—	24

Sample Number	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1289	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1296	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1300	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1301	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1302	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1306	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1307	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1308	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1309	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1310	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2013	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2014	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2015	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2047	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2063	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2068	1	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
2074	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2075	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2077	1	—	—	—	—	—	—	—	—	1	1	—	—	1	—	—	—	—	—	—
2078	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2079	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
2080	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—
2081	1	1	—	—	—	—	—	—	—	1	—	—	—	1	—	—	—	—	—	—
2082	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2083	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2091	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2092	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Patuxent

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites
1016	14	8	5	—	—	—	—	1	2	—	—	67	5	—	—	—	—	—	—	—	—	12
1017	17	7	3	—	—	—	—	1	1	—	—	69	1	—	—	—	—	—	—	—	—	18
2001	49	19	14	—	—	—	—	12	6	—	—	24	—	—	—	—	—	—	—	—	—	25
2002	34	9	7	—	—	—	—	2	2	1	—	69	6	—	—	—	—	—	—	—	—	4
2003	43	21	22	—	—	—	—	3	4	—	—	28	2	—	—	—	—	—	1	—	—	18
2004	20	14	14	1	—	—	—	5	2	—	—	51	5	—	—	—	—	—	1	—	—	7
2005	26	10	8	—	—	—	—	1	—	—	—	68	8	—	—	—	—	—	1	—	—	4
2008	42	13	8	—	—	—	—	1	1	—	1	64	3	—	—	—	—	—	1	—	—	8
2009	35	9	13	—	—	—	—	6	3	—	2	47	4	—	—	—	—	—	—	—	—	16
2010	12	12	11	—	—	—	—	1	1	—	—	[illegible]	14	—	—	1	—	—	—	—	—	3
2011	17	15	4	—	—	—	—	1	—	—	—	[illegible]	5	—	—	—	—	—	—	—	—	5
2016	47	14	24	—	—	—	—	4	2	—	—	42	7	—	—	1	—	—	—	—	—	6
2017	37	14	22	—	—	1	—	11	4	—	—	19	1	—	—	—	1	—	1	—	—	26
2019	46	14	27	1	—	—	—	3	3	—	—	36	7	—	—	1	—	—	2	—	—	6
2020	15	3	2	—	—	—	—	—	—	—	—	81	11	—	—	—	—	—	—	—	—	3
2021	30	5	6	—	—	—	—	—	—	—	—	69	17	—	—	—	—	—	—	—	—	3
2026	45	18	25	—	—	—	—	4	6	1	—	32	3	—	—	1	—	—	1	—	—	9
2029	28	8	7	—	—	—	—	1	1	—	—	68	13	—	—	—	—	—	—	—	—	2
2030	22	16	4	—	—	—	—	2	2	—	—	62	9	—	—	—	—	—	—	—	—	5
2031	60	13	43	—	—	—	—	4	2	—	—	31	3	—	—	—	—	—	—	—	—	4
2035	51	6	8	—	—	—	—	18	6	—	—	37	1	—	—	—	—	1	—	—	—	22
2036	26	6	3	—	—	—	—	1	—	1	1	83	3	—	—	—	—	—	—	—	—	—
2037	63	26	11	—	—	1	—	10	4	1	—	24	2	—	—	—	—	—	—	—	—	20
2038	42	22	6	1	—	—	—	6	5	1	—	37	1	—	—	1	—	—	—	—	—	19
2039	3	4	4	—	—	—	—	1	—	—	—	80	10	—	—	—	—	—	—	—	—	1
2040	41	14	15	—	—	—	—	6	4	—	—	46	3	—	—	—	—	—	—	—	—	12
2065	35	25	8	—	—	—	—	12	4	—	—	26	2	—	—	—	—	—	—	—	—	23
2066	24	28	18	—	—	—	—	7	2	1	—	30	5	—	—	1	—	—	—	—	—	8
2067	42	12	11	—	—	—	—	9	1	—	—	31	5	—	—	—	—	—	2	—	—	29

Sample Number	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
1016	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1017	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2001	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2002	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2003	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—
2004	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2005	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2008	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2009	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2010	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2011	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2016	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2017	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2019	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2020	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2021	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2026	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2029	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2030	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2031	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2035	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
2036	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2037	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—
2038	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2039	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2040	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2065	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2066	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2067	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

APPENDIX B

Heavy Mineral content of the Cretaceous sediments of the Coastal Plain of New Jersey

Location of samples marked with an asterisk (*) are shown on plate II.

Sample Number	Opaque	Tourmaline	Zircon	Garnet, colorless	Garnet, golden yellow	Garnet, pale pink	Garnet, green	Rutile	Anatase	Brookite	Titanite	Staurolite	Kyanite	Andalusite	Chiastolite	Sillimanite	Fibrolite	Chloritoid	Epidote	Piedmontite	Zoisite	Alterites	Hornblende, green	Hornblende, green-blue	Hornblende, brown	Oxy-Hornblende	Actinolite	Tremolite	Glaucophane	Riebeckite	Arfvedsonite	Augite	Diopside	Enstatite	Bronzite	Hypersthene	Spinel, blue	Spinel, green	Spinel, pale green	Picotite	Corundum	Topaz
Navesink																																										
*1266	23	5	2	11	4	15	—	1	—	—	—	14	4	11	—	2	2	3	9	—	—	3	7	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Wenonah-Mount Laurel																																										
*1264	52	10	5	—	—	—	—	4	—	—	1	29	4	—	—	4	—	5	24	—	—	11	1	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1265	39	4	7	1	—	—	—	12	1	1	—	24	6	5	—	5	—	5	13	—	—	16	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
English-town																																										
*1262	65	12	12	—	—	—	—	12	—	—	—	20	7	3	—	11	1	6	3	—	—	13	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1263	37	20	5	—	—	—	—	10	—	—	2	19	8	5	—	12	—	3	—	—	—	15	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Merchant-ville																																										
*1261	6	13	14	8	—	2	—	9	1	—	1	7	2	—	—	—	—	22	18	—	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Raritan-Magothy																																										
*1258	45	15	17	—	—	—	—	4	2	1	—	13	3	—	—	—	—	—	2	—	—	43	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1259	52	4	16	—	—	—	—	6	1	—	1	9	—	—	—	—	—	—	2	—	—	61	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
*1260	46	15	18	—	—	—	—	1	1	—	—	16	3	—	—	—	2	—	—	—	—	44	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

APPENDIX C

Mechanical composition of the sediments of the Coastal Plain of Northern Delaware

Location of samples may be found on plate I. Those marked with an asterisk (*) are shown on plate II.

Recent

Mechanical composition in weight percentages

Sample Number	>2 mm in % of total	2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	Statistical Parameters: 5	16	50	84	95	σ	α	β
* 1	tr.	—	0.5	8.7	45.25	33.7	8.7	1.7	0.4	0.1	0.25	—	—	—	—	—	—	0.37	0.61	0.95	1.42	1.84	0.405	0.16	0.81
* 2	2.4	0.2	5.4	33.85	26.75	12.0	11.2	7.1	2.4	0.3	0.1	—	—	—	—	—	—	−0.03	0.23	0.70	1.72	2.35	0.745	0.369	0.597
* 3	—	—	0.9	2.1	40.5	38.8	9.85	4.4	2.6	0.6	0.25	—	—	—	—	—	—	0.58	0.77	1.08	1.56	2.28	0.395	0.215	1.151
* 4	tr.	0.2	0.3	1.5	6.8	17.2	43.9	25.7	3.5	0.15	0.1	—	—	—	—	—	—	0.80	1.24	1.77	2.21	2.46	0.485	−0.092	0.711
* 5	9.5	5.25	15.1	18.8	44.8	11.7	2.9	0.4	0.2	0.1	0.15	—	—	—	—	—	—	−0.55	−0.10	0.61	1.00	1.42	0.55	−0.290	0.791
* 6	29.1	7.0	16.0	9.5	5.9	8.8	24.1	21.6	6.7	0.4	0.1	—	—	—	—	—	—	−0.60	−0.16	1.55	2.26	2.60	1.21	−0.413	0.322
* 7	10.4	0.8	6.1	12.05	17.4	20.35	32.0	9.4	1.1	0.1	0.15	—	—	—	—	—	—	−0.09	0.40	1.35	1.90	2.25	0.75	−0.266	0.560
* 8	tr.	0.2	1.45	4.1	17.15	24.5	34.7	13.9	3.0	0.5	0.1	—	—	—	—	—	—	0.43	0.84	1.53	2.05	2.44	0.605	−0.140	0.661
*101	—	—	—	2.0	26.7	48.7	20.7	1.0	0.1	0.1	0.05	—	—	—	—	—	—	0.64	0.87	1.22	1.60	1.83	0.365	0.04	0.63
*102	tr.	0.1	0.2	2.1	16.3	32.6	36.3	9.6	1.9	0.2	0.1	—	—	—	—	—	—	0.64	0.95	1.47	1.94	2.32	0.495	−0.05	0.69
*103	—	—	0.4	3.8	30.45	37.2	18.4	6.7	2.0	0.3	0.2	—	—	—	—	—	—	0.53	0.77	1.20	1.78	2.30	0.505	0.148	0.75
*104	—	—	—	0.2	3.9	15.4	41.2	31.3	6.55	0.5	0.1	—	—	—	—	—	—	1.04	1.42	1.88	2.31	2.66	0.445	0.03	0.82
*105	tr.	—	0.5	7.1	47.05	34.5	8.0	1.4	0.6	0.2	0.1	—	—	—	—	—	—	0.42	0.64	0.96	1.39	1.80	0.375	0.18	0.84
*106	—	—	0.1	0.2	4.5	18.8	46.8	21.6	4.2	0.3	0.1	—	—	—	—	—	—	1.02	1.36	1.80	2.21	2.50	0.425	−0.03	0.74
*108	tr.	0.1	1.55	8.2	25.75	25.0	25.8	9.1	3.3	0.4	0.15	—	—	—	—	—	—	0.28	0.66	1.25	1.92	2.46	0.63	0.06	0.73
201	1.8	1.5	6.4	8.9	14.7	16.2	18.3	10.8	6.8	3.1	1.25	2.6	2.6	0.6	2.9	0.2	3.0	−0.13	0.45	1.57	3.06	7.37	1.305	0.141	1.873
*202	—	—	0.2	0.1	0.1	0.1	0.4	0.9	1.9	3.35	3.05	12.7	17.8	17.5	11.85	6.1	23.9	3.23	4.52	6.52	10.40	13.8	2.94	0.329	2.595
*203	7.0	1.1	3.4	5.7	10.6	12.05	10.8	6.0	4.6	3.7	2.4	6.7	7.7	6.8	4.7	3.25	10.5	0.05	0.80	2.54	7.52	11.40	3.36	0.482	0.687
204	—	—	—	0.1	0.1	0.4	1.1	1.85	3.3	3.7	2.9	10.5	16.5	13.3	13.4	7.4	25.3	2.74	4.27	6.71	10.40	13.3	3.065	0.208	0.722
*205	1.2	—	0.2	0.1	0.2	0.2	0.3	1.0	5.5	6.8	4.7	14.5	13.15	12.4	11.1	8.6	21.5	2.84	3.70	6.25	9.70	12.08	3.00	0.15	0.54
206	—	—	0.3	0.3	0.2	0.2	0.5	0.9	1.1	0.8	0.4	3.3	15.3	20.0	16.0	8.3	32.3	4.15	5.60	7.44	11.52	14.56	2.96	0.395	0.758
207	—	—	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	2.8	13.6	25.2	25.2	13.95	9.25	33.1	5.04	5.87	7.48	11.81	13.62	2.97	0.457	0.410

Pleistocene

Sample Number	>2 mm in % of total	2000-1400µ	1400-1000µ	1000-710µ	710-500µ	500-350µ	350-250µ	250-177µ	177-125µ	125-88µ	88-62µ	62-32µ	32-16µ	16-8µ	8-4µ	4-2µ	<2µ	5	16	50	84	95	σ	α	β
		Mechanical composition in weight percentages																Statistical Parameters							
1003	11.9	2.9	12.8	20.65	27.4	17.8	0.2	3.45	2.05	0.9	0.55	—	1.0	—	—	0.8	1.0	0.35	0.02	0.76	1.64	2.91	0.81	0.086	1.012
1004	tr.	0.5	3.7	13.1	24.4	19.2	17.3	9.2	3.6	1.2	0.5	—	1.6	1.0	1.4	—	3.5	0.17	0.46	1.21	2.30	6.56	0.92	0.184	2.472
1012	6.5	1.2	4.9	9.2	15.0	14.7	10.1	5.1	2.6	1.2	0.7	6.4	7.8	4.2	3.5	1.2	11.6	−0.08	0.54	1.77	7.30	17.79	3.38	0.636	1.643
1013	9.4	0.7	3.5	4.9	7.8	8.6	6.0	2.6	1.6	0.7	0.5	7.5	23.4	12.0	4.6	4.4	10.8	0.10	0.93	5.23	7.90	11.10	3.48	−0.233	2.156
1014	50.8	1.9	7.2	8.4	12.5	13.1	10.2	6.9	4.2	2.2	1.1	3.5	8.8	4.45	2.6	2.6	10.6	−0.20	0.42	1.87	6.90	13.61	2.73	0.656	1.54
1015	10.2	1.9	11.1	20.0	26.9	13.8	7.6	2.1	1.8	1.3	0.8	1.2	1.3	1.5	2.15	1.5	3.8	−0.28	0.08	0.83	2.62	9.03	1.27	0.409	2.665
1033	46.6	1.1	3.5	5.1	9.0	10.7	13.0	10.7	7.4	3.3	1.4	5.3	8.7	3.8	2.3	1.2	13.5	0.06	0.87	2.35	7.43	17.13	3.28	0.548	1.602
1034	0.6	—	0.55	3.1	16.4	38.4	20.0	4.25	2.0	1.2	0.7	1.65	1.65	0.5	2.4	1.6	5.6	−0.58	0.92	1.41	2.81	9.35	0.94	0.481	3.64
1035	—	2.0	9.7	15.0	20.0	17.8	10.5	6.3	5.8	1.4	0.7	2.1	0.7	1.8	1.5	1.8	3.0	−0.27	0.16	1.09	2.72	7.76	1.28	0.273	2.137
1036	0.6	—	0.2	5.6	42.4	33.3	6.6	1.8	1.05	0.9	0.4	1.0	0.7	1.0	1.6	1.25	2.2	0.47	0.69	1.02	1.65	7.03	0.48	0.312	5.833
1053	2.3	0.5	8.2	23.5	37.6	14.7	4.0	1.9	1.1	0.6	0.3	0.5	0.9	0.5	2.6	—	3.4	−0.10	0.20	0.75	1.49	7.20	0.645	0.147	0.466
1054	2.3	0.2	1.5	2.4	3.4	2.8	17.9	41.0	10.1	2.6	1.0	2.6	2.3	4.2	2.2	1.1	4.1	0.65	1.70	2.27	4.45	8.25	1.375	0.585	1.765
1055	tr.	—	0.2	0.5	0.7	0.7	8.6	46.5	19.6	3.5	1.2	2.0	3.3	2.8	4.5	1.2	4.5	1.75	2.10	2.45	5.16	8.64	1.53	0.771	1.25
1056	—	3.8	15.3	21.5	28.2	17.6	4.4	0.9	0.6	0.5	0.3	0.5	0.9	2.0	0.9	0.5	2.0	−0.41	−0.06	0.65	1.40	6.20	0.73	0.0274	3.53
*1084	6.5	1.1	5.7	11.8	24.4	26.4	15.6	4.4	1.2	0.5	0.3	0.4	1.0	1.1	1.9	—	4.2	−0.09	0.42	1.11	1.99	7.58	0.785	0.121	3.89
*1085	32.8	3.1	11.6	20.1	26.0	20.4	7.6	1.4	1.1	0.8	0.5	1.2	0.5	2.2	0.5	—	2.9	−0.38	0.05	0.80	1.65	6.25	0.80	0.0625	3.143
*1086	11.7	2.7	11.0	18.2	23.1	24.3	10.6	1.2	0.8	0.6	0.4	0.1	1.5	—	1.8	—	3.6	−0.32	0.10	0.90	1.70	6.45	0.80	0	3.24
*1087	—	0.2	2.3	8.0	37.9	33.1	9.1	1.9	1.0	*0.7	0.4	0.7	0.2	1.3	1.3	—	1.7	0.21	0.60	1.01	1.62	4.50	0.51	0.197	3.21
*1088	tr.	0.1	2.4	11.2	36.1	26.5	9.4	3.9	1.9	1.2	0.6	1.8	—	—	2.5	—	2.4	0.19	0.55	1.00	1.90	4.90	0.675	0.334	2.49
2041	10.1	0.3	2.5	6	11	12	11	7	5	4.5	3	9.5	7.5	6.5	2	2	10	.26	.86	2.57	6.72	12.5	2.93	.41	1.09
2043	16.6	0.8	1.5	3	5	6	6	6.5	10	8.5	4.5	11	10.5	6	3	3.5	14.5	.45	1.46	3.90	8.5	13.4	3.52	.31	.83
2058	5.0	0.1	0.5	0.8	1.5	2	2	1	0.7	0.8	0.9	18	32	13.5	6	5	15	1.56	4.40	5.70	8.81	11.9	2.20	.41	1.30
2060	5.0	0.3	0.7	1.5	3	4.5	7	5	3.5	2.5	2	8.5	14	12	6.5	5.5	23	.37	1.94	5.81	10.5	14.2	4.28	.09	.54
2065	20.1	0.8	2.5	5.5	12	28	18.5	9.5	5.5	2.5	1.5	3.5	1.5	2.5	1	3	2.5	.20	.82	1.54	3.4	8.1	1.29	.44	2.06
2066	2.5	0.1	1	3.5	7.5	17	38.5	9.5	3.5	2	1	2	2.5	2.5	2	2	5	.56	1.12	1.79	4.2	9.2	1.54	.56	1.80

Red Bank

Sample Number	>2 mm in % of total	2000-1400µ	1400-1000µ	1000-710µ	710-500µ	500-350µ	350-250µ	250-177µ	177-125µ	125-88µ	88-62µ	62-32µ	32-16µ	16-8µ	8-4µ	4-2µ	<2µ	5	16	50	84	95	σ	α	β
		Mechanical composition in weight percentages																Statistical Parameters							
1116	0.5	—	0.1	0.5	2.2	7.1	20.8	31.8	13.7	2.3	0.9	2.2	0.3	0.9	1.1	1.4	14.8	1.20	1.69	2.30	8.10	28.4	3.205	0.809	3.24
1117	tr.	—	—	0.1	0.3	2	15.5	39.5	22.5	3	0.9	1.5	1.5	1.5	0.6	1	10	1.65	1.97	2.4	4.2	18.3	1.11	.61	6.49
1188	—	—	—	0.3	2.5	11.5	33	32	[illegible]	1	0.4	—	2	0.3	1.5	2	8	1.16	1.53	2.05	3.00	11.5	.73	.28	6.08
1189	—	—	—	0.2	2	10	31.5	35	[illegible]	1	0.3	—	1.5	0.7	2	1.5	8.5	1.21	1.60	2.10	2.96	11.3	.68	.26	6.41
1190	—	—	—	0.2	1.5	8.5	29	36.5	7	1	0.4	1	0.5	1.5	2	0.9	10	1.30	1.63	2.15	4.00	13.4	1.18	.56	4.12
1203	—	—	—	0.3	4	14.5	37	26	3.5	0.7	0.3	0.5	0.3	1	0.9	1	10	1.06	1.45	1.92	2.82	15.5	.68	.31	9.61
1292	—	—	0.1	0.3	1.5	5.0	21.5	32.0	13.0	2.0	1.0	2.0	0.5	1.0	0.5	3.5	15.5	1.37	1.77	2.34	9.00	13.40	3.615	0.869	0.664
1293	—	—	0.1	0.1	0.4	1.5	10.0	25.0	21.0	3.0	0.8	3.0	1.0	3.5	0.8	4.5	25.0	1.73	2.12	2.81	11.50	16.20	4.69	0.852	0.544

Mt. Laurel-Navesink

Sample Number	>2 mm in % of total	Mechanical composition in weight percentages															Statistical Parameters							
		2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	5	16	50	84	95	σ	α	β
1118	1.9	—	—	—	0.1	0.9	8	16.5	27.5	8.5	3	7	1.5	3.5	1	2.5	20	1.83	2.27	2.95	11.4	19.0	4.56	.85	.88
1149	0.2	—	0.2	0.4	0.9	2	10	22.5	28.5	10	3.5	5	1.5	2	—	2	11.5	1.62	2.08	2.74	5.70	13.2	1.81	.63	2.19
1150	tr.	—	0.1	0.1	0.2	0.6	3.5	12	34.5	38	7.5	2.5	—	0.8	0.1	0.5	4.5	2.03	2.48	2.98	3.50	8.30	.51	.02	5.13
1151	1.1	0.1	0.4	0.4	0.6	0.9	1.5	3	8	23.5	16	12.5	5	2	2.5	2.5	20.5	2.25	3.03	3.85	11.1	18.5	4.03	.80	1.01
1152	tr.	—	—	—	0.1	0.5	3.5	13	34.5	23.5	6.5	4.5	1	0.6	1.5	0.7	9.5	2.06	2.48	3.0	4.5	19.8	1.01	.48	7.78
1153	—	—	—	—	0.1	0.3	1.5	3	8	26	21.5	21.5	3	2	0.3	0.7	12	2.51	3.05	3.75	5.86	22.5	1.39	.52	6.19
1161	—	—	—	0.3	2.5	8	22	30	15.5	2.5	0.9	2.5	0.6	2	0.9	0.9	12	1.20	1.67	2.3	4.90	16.7	1.61	.61	3.81
1162	1	—	0.1	0.1	0.3	2	12	23	25	7	2.5	5.5	1.5	3.5	1	0.9	16	1.67	2.03	2.78	8.70	20.0	3.33	.77	1.75
1163	0.2	—	—	0.1	0.4	1	4	9	18.5	8	2	2	7	4.5	5.5	4	33	1.95	2.55	5.70	13.6	18.8	5.52	.43	.52
1164	0.5	0.1	0.3	0.5	1	2	8	16	14	6	3	4.5	4	5	4.5	4	27	1.60	2.18	3.92	12.1	17.5	4.96	.65	.60
1165	0.2	—	0.2	0.4	1	2	7	15.5	15.5	4	2	3.5	2.5	4	3.5	5.5	33	1.64	2.21	4.74	14.1	19.7	5.94	.57	.52
1170	—	—	—	—	0.1	0.7	6.5	15	28.5	26.5	8	5	0.5	—	2	5.5	2	1.89	2.32	2.99	3.90	8.3	.79	.15	3.05
1183	0.3	—	—	0.1	0.1	0.3	5	13.5	21	10	3	4	4	2	1.5	4.5	31.5	1.99	2.42	3.50	16.1	25.0	6.84	.84	.68
1184	0.2	—	0.1	0.1	0.2	0.5	6	14	17.5	13	4.5	6	3	2	0.4	6	27	1.91	2.38	3.45	13.2	20.4	5.41	.80	.70
1185	—	—	0.3	0.4	0.8	1.5	6	12.5	13	6.5	3.5	7	3	3.5	6	4.5	31.5	1.71	2.31	4.82	13.2	18.5	5.44	.54	.54
1187	3.8	—	0.1	0.1	0.4	0.6	3.5	8	11	11	4.5	6	5	3.5	6	2	37.5	2.05	2.69	6.00	16.2	22.7	6.75	.51	.52
1191	0.6	—	—	0.1	0.7	2.5	10	19.5	15	3	0.9	1	2.5	2.5	4	3	34.5	1.63	2.09	3.41	15.2	21.2	6.55	.79	.49
1204	—	—	—	—	3	13.5	36	30	4.5	1	0.5	1	—	1	1	2	6	1.14	1.49	1.99	2.69	10.1	.60	.16	6.46
1209	2.5	—	0.4	0.7	1.5	2.5	9	19	31	11	3	3.5	3.5	2	0.4	1.5	11	1.50	2.06	2.77	5.72	16.6	1.83	.61	3.12
1290	—	0.5	1.0	1.5	3.0	3.5	4.0	5.0	7.5	15.5	9.0	11.0	7.5	6.0	1.5	3.0	19.5	0.86	2.27	3.98	10.90	17.60	4.315	0.599	0.939
1303	—	—	0.3	0.5	1.0	1.5	7.0	18.0	17.0	4.0	1.5	2.5	4.0	2.0	3.5	4.0	33.0	1.65	2.20	3.80	14.05	20.2	5.925	.729	0.565
1304	—	0.2	0.5	1.0	2.5	3.5	10.5	19.0	24.0	7.0	2.5	4.5	2.0	2.5	1.0	2.5	16.0	1.13	1.92	2.78	9.40	15.35	3.74	.770	0.927

Wenonah

Sample Number	>2 mm in % of total	Mechanical composition in weight percentages															Statistical Parameters							
		2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	5	16	50	84	95	σ	α	β
1109	tr.	—	—	—	0.1	0.4	2.9	11.8	36.3	25.5	5.9	2.5	1.8	0.7	0.5	3.2	8.4	2.11	2.51	2.99	4.50	14.90	0.995	0.518	5.44
1110	—	—	—	—	0.1	0.4	2.6	10.6	38.8	23.2	4.8	4.1	0.9	1.3	0.5	1.9	10.8	2.15	2.54	2.99	4.85	16.90	1.155	0.61	5.39
1112	tr.	—	—	—	0.1	0.4	2.3	9.3	31.2	30.2	8.2	2.1	3.4	—	—	3.1	9.7	2.20	2.59	3.12	5.10	15.9	1.255	0.578	4.45
1119	—	—	—	—	0.1	0.4	3	13	45	24	3	1	0.9	1	0.7	0.3	7	2.10	2.50	2.90	3.48	15.2	.49	.18	12.39
1130	tr.	—	—	—	0.1	0.5	3.5	14	45	24	3.5	1	1	0.4	1	0.7	5.5	2.05	2.45	2.88	3.40	9.30	.47	.08	6.70
1146	0.1	—	—	0.1	0.3	1	5.5	12.5	35.5	21	3	2.5	1	1.5	1.5	2	13	1.90	2.40	2.95	7.10	13.5	2.35	.76	1.46
1154	tr.	—	—	—	0.2	0.8	5	14	42	18	2	2	—	1.5	0.8	1.9	11.5	1.93	2.40	2.87	5.50	15.0	1.55	.69	3.21
1155	tr.	—	—	—	0.2	0.8	4.5	14	44.5	16	2	2	0.6	0.8	1	1.5	12	1.95	2.40	2.84	5.0	16.5	1.30	.66	4.59
1158	0.9	—	0.1	0.1	0.4	1	5	13.5	36.5	14	2.5	3	1.5	2.5	1.5	2	16.5	1.90	2.36	2.91	9.0	18.2	3.32	.83	1.45
1166	—	—	—	—	0.1	0.3	3.5	13.5	50.5	18	2.5	—	2.5	0.2	1	0.1	8	2.12	2.46	2.82	3.44	15.5	.49	.26	12.65
1168	—	—	—	—	0.1	0.5	5	11.5	36.5	28.5	5.5	1.5	1.5	1	0.5	1.5	6	1.97	2.47	2.98	3.66	10.6	.59	.13	6.31
1206	—	—	—	—	0.1	0.6	4.5	15	38.5	23	4.5	2	1	1.5	1.5	0.9	6.5	2.00	2.41	2.90	3.75	10.7	.67	.26	5.49
1255	—	—	—	—	0.1	0.4	3.5	16	43	20	3.5	1	1.5	0.9	0.7	1.5	7.5	2.07	2.42	2.88	3.70	12.3	.64	.28	7.00
1256	0.3	—	—	—	0.1	0.5	4.5	16.5	41	20	3.5	0.5	2	1	1	—	9	2.0	2.38	2.88	3.70	13.0	.66	.24	7.33
1257	tr.	—	0.1	0.1	0.2	0.7	4	15.5	44	18.5	3	1	1.5	0.5	1.5	1	9	2.0	2.40	2.86	4.30	14.5	.95	.51	5.68
1305	—	—	—	—	0.2	0.3	2.5	12.5	43.5	22.5	3.0	2.5	0.4	1.0	1.5	1.5	8.0	2.15	2.51	2.92	3.90	11.50	.695	.410	5.726

Merchantville

Sample Number	>2 mm in % of total	2000-1400µ	1400-1000µ	1000-710µ	710-500µ	500-350µ	350-250µ	250-177µ	177-125µ	125-88µ	88-62µ	62-32µ	32-16µ	16-8µ	8-4µ	4-2µ	<2µ	5	16	50	84	95	σ	α	β
		Mechanical composition in weight percentages																Statistical Parameters							
1104	—	0.1	0.2	0.3	0.8	1.7	5.5	4.6	5.6	3.3	2.8	12.2	9.3	5.4	9.7	1.6	36.7	1.71	2.75	6.69	13.45	17.76	5.35	2.64	0.50
1105	0.6	0.2	0.2	0.5	1.3	2.8	8.5	7.0	9.7	5.2	1.7	6.0	4.8	5.5	5.7	8.0	32.7	1.50	2.20	6.45	13.10	17.70	5.45	2.20	0.487
1108	—	—	—	—	0.1	0.4	2.9	11.5	35.1	26.1	5.4	4.2	0.3	1.5	0.4	2.5	9.6	2.11	2.51	3.00	4.60	16.50	1.045	0.53	5.89
1113	0.4	—	—	—	0.2	0.4	2.4	8.0	24.3	28.9	9.6	6.3	0.2	—	6.1	1.3	12.3	2.19	2.63	3.26	7.60	25.5	2.485	0.745	3.68
1120	tr.	—	—	—	0.1	0.4	2	5.5	16.5	33.5	15	6.5	2	1.5	2.5	2.5	12	2.30	2.80	3.39	7.40	13.3	2.30	.74	1.39
1124	tr.	—	—	0.1	0.2	0.4	1.5	2.5	8.5	27.5	16.5	10.5	2.5	2	3	1.5	23.5	2.54	3.07	3.80	13.4	23.0	5.18	.85	.97
1125	tr.	—	—	—	0.1	0.4	2	5	15	33.5	15.5	6.5	1.5	3	3	2.5	11	2.30	2.83	3.40	7.50	12.9	2.33	.75	1.27
1131	—	—	—	—	0.1	0.4	2.5	10.5	33.5	29	6.5	2.5	1	1	0.7	2	10	2.15	2.54	3.03	4.60	13.4	1.03	.52	4.45
1132	tr.	—	—	—	0.1	0.5	3.5	13.5	46.5	24	3	—	2	0.3	0.3	1.5	5	2.05	2.48	2.86	3.40	8.75	.46	.28	6.28
1133	tr.	—	—	—	0.1	0.7	4	14	39.5	22	4.5	1.5	1.5	1	0.8	1.5	9	2.04	2.45	2.91	3.98	14.2	.76	.39	7.00
1134	—	—	—	—	0.1	0.4	3	13	41	26	4.5	0.5	2	0.2	0.9	1	7.5	2.10	2.50	2.90	3.54	12.1	.47	.25	9.63
1135	tr.	—	—	—	0.1	0.5	4	13.5	38	22.5	5	3.5	—	3.5	—	2	8	2.02	2.44	2.93	4.15	10.5	.85	.41	3.99
1207	—	—	—	—	0.1	0.3	2.5	10	38	32	4.5	1.5	1.5	1	0.9	1	6.5	2.18	2.58	3.00	3.63	11.1	.52	.19	7.57
1208	—	—	—	—	0.1	0.4	3	11.5	34.5	26.5	6.5	3	1	2	1	3	7.5	2.11	2.53	3.02	4.56	10.8	1.01	.51	3.29
1212	—	—	0.1	0.1	0.1	0.3	1.5	5	17.5	31.5	11	8.5	1.5	1.5	3.5	2	15.5	2.36	2.80	3.40	9.00	15.1	3.10	.80	1.05
1253	tr.	—	0.1	0.4	1	1.5	2	2	6	17	12	13	6	4	4.5	3	27.5	2.0	3.11	4.63	12.5	18.2	4.69	.67	.72

Magothy

Sample Number	>2 mm in % of total	2000-1400µ	1400-1000µ	1000-710µ	710-500µ	500-350µ	350-250µ	250-177µ	177-125µ	125-88µ	88-62µ	62-32µ	32-16µ	16-8µ	8-4µ	4-2µ	<2µ	5	16	50	84	95	σ	α	β
		Mechanical composition in weight percentages																Statistical Parameters							
1063	2.5	2.2	1.4	3.0	8.7	18.9	31.2	21.8	11.0	2.6	0.5	0.5	—	—	—	—	—	0.55	1.10	1.79	2.45	2.90	0.675	−0.0233	0.741
1080	1.1	0.3	0.7	2.2	6.0	14.5	31.0	23.7	10.2	3.5	1.3	1.2	0.8	—	—	0.5	4.1	0.70	1.29	1.93	2.80	5.50	0.755	0.1521	2.18
1081	0.3	—	0.3	2.5	10.7	19.1	27.6	20.5	12.4	4.4	1.3	1.2	—	—	—	—	—	0.68	1.10	1.82	2.60	3.20	0.75	0.04	0.68
1082	16.0	6.1	26.1	32.1	20.1	7.1	2.8	1.2	0.6	0.3	0.2	0.2	0.2	0.9	0.6	—	1.5	−0.54	−0.23	0.29	1.00	2.23	0.615	0.161	0.125
1092	—	—	0.1	0.3	4.4	26.6	50.0	12.8	3.1	1.2	0.8	0.7	—	—	—	—	—	1.10	1.29	1.69	2.10	2.74	0.405	0.0125	1.025
1093	tr.	0.1	1.1	3.7	12.7	24.7	33.9	17.0	4.4	0.8	0.2	0.3	—	—	—	—	—	0.51	0.98	1.59	2.19	2.66	0.605	−0.0083	0.778
1095	0.9	—	—	—	0.1	0.5	11.2	44.9	32.3	9.0	1.3	0.7	—	—	—	—	—	1.82	2.06	2.44	2.89	3.25	0.415	0.0845	0.723
1096	0.8	0.2	1.2	2.5	4.5	5.4	7.4	6.7	11.6	23.1	10.5	9.5	2.4	—	3.4	1.7	9.8	0.65	1.69	3.22	5.65	16.0	1.98	0.227	2.875
1099	tr.	—	—	0.1	0.3	0.5	8.7	41.6	38.6	5.9	0.8	0.2	0.1	0.8	—	—	2.2	1.84	2.11	2.49	2.90	3.42	0.395	0.038	1.00
1103	3.3	—	—	—	—	—	—	0.4	10.3	38.0	27.9	18.4	—	—	—	3.7	1.3	2.85	3.10	3.52	4.29	6.50	0.595	0.294	2.085
1106	3.1	0.7	4.6	7.6	11.2	15.1	29.1	24.4	5.1	1.3	0.4	0.5	—	—	—	—	—	−0.02	0.67	1.69	2.27	2.69	0.80	−0.275	0.694
1107	—	—	—	0.1	0.1	0.4	8.6	48.3	34.0	6.8	1.0	0.6	—	—	—	—	—	1.88	2.11	2.44	2.85	3.20	0.37	0.105	0.784
1230	0.4	0.3	2	3.5	4.5	8	27.5	39	12.5	1.5	0.3	—	0.6		—0.6—		—	.43	1.40	2.07	2.50	2.86	.55	−.22	1.20
1231	—	0.1	1	4	7.5	11.5	25.5	34	13.5	2	0.3	0.3	—	—	—	—	tr.	.50	1.18	2.02	2.59	3.21	.70	−.20	.93
1232	1.8	0.3	2.5	6.5	14.5	22.5	24.5	16	7.5	2.5	0.7	—0.9—				—1.5—		.23	.78	1.59	2.40	3.15	.81	—	.80
1250	—	—	0.4	1.5	6	15	36.5	32	7.5	0.7	0.1	0.3	—	—	—	—	tr.	.83	1.32	1.88	2.33	3.03	.50	−.12	1.20
1251	—	—	—	—	—	—	0.7	19	65	12.5	1	0.6	—	—	—	—	1	2.26	2.46	2.72	2.99	3.35	.26	—	1.07
1268	0.1	0.2	2	5.5	10.5	14.5	24.5	22.5	12.5	4	1	0.6	0.4	0.5	0.2	—	1	.31	.91	1.87	2.65	3.32	.87	−.10	.72
1269	—	—	—	—	0.1	0.3	4	15	30	22.5	9.5	9.5	2	0.4	0.4	0.2	5.5	2.03	2.42	3.02	4.23	11.80	.90	.33	4.31
1271	1.4	0.8	2	6.5	16.5	20	25	14	2.5	0.6	0.3	0.2	0.3	0.5	0.1	—	10.5	.23	.79	1.60	2.49	34.0	.85	.05	18.86
1272	—	—	—	0.1	0.3	0.5	1	2	5.5	9.5	9	23.5	11	8	6	5	18.5	2.64	3.39	4.98	9.5	12.9	3.05	.47	.68
1277	9.9	0.6	3.5	8	13	14	17.5	14.5	10.5	6	3.5	5	0.9	0.3	0.9	—	1.5	.07	.68	1.82	3.21	4.75	1.26	.09	.86
1282	0.1	—	1.5	6.5	15.5	20.5	19	10	16	7	2	1	0.3	—	—	0.6	0.3	.35	.81	1.68	2.80	3.40	.99	.12	.53
1283	37.7	5	14	9.5	9.5	9.5	15.5	17	10	3.5	1.5	3	0.1	0.7	0.7	—	0.4	−.50	−.07	1.60	2.69	4.0	1.38	−.21	.63
1297	—	—	—	0.1	0.4	0.6	2.0	5.5	9.0	12.0	9.0	27.5	8.0	7.5	4.0	3.0	11.5	2.23	2.94	4.42	7.64	11.70	2.35	.370	1.014
1298	—	1.0	3.0	8.0	17.0	24.0	26.0	11.0	3.5	1.5	0.6	1.0	—	1.0	—	1.5	1.0	0.08	0.65	1.43	2.20	3.50	.775	.006	1.206

Patapsco-Raritan

Mechanical composition in weight percentages

Sample Number	>2 mm in % of total	2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	Statistical Parameters 5	16	50	84	95	σ	α	β
1007	1.2	0.85	2.2	2.8	4.0	4.25	6.05	6.1	6.45	5.0	3.0	10.05	2.45	3.6	4.4	6.3	32.25	0.80	1.66	4.91	12.80	17.30	5.57	0.418	0.463
1046	tr.	—	0.1	—	0.1	—	0.1	1.35	6.7	11.05	8.05	22.2	9.7	9.6	4.8	6.0	20.2	2.83	3.36	5.07	9.79	13.07	3.215	0.468	0.592
1216	—	—	—	—	0.6	10	46.5	25.5	7.5	2.5	1	2	1.5	0.6	1.5	0.6	0.5	1.34	1.59	1.93	2.58	4.68	.49	.30	2.41
1217	tr.	—	—	0.1	0.6	9.5	46.5	25	7.5	2.5	1	2.5	1	1.5	0.5	1.5	—	1.35	1.61	1.96	2.63	4.94	.51	.31	2.51
1218	—	—	0.1	0.1	1	10	39	29	9.5	3	1	2.5	1.5	1.5	0.9	0.2	0.5	1.31	1.60	2.00	2.72	4.90	.56	.29	2.19
1219	—	—	—	—	—	—	2.5	14.5	28	23	9	9.5	1.5	2	1.5	2.5	6	2.17	2.48	3.11	4.72	9.65	1.12	.43	2.34
1220	—	—	—	—	—	—	1	6	19	25.5	15	16.5	2.5	2.5	1.5	3	7.5	2.39	2.79	3.48	5.40	10.5	1.30	.47	2.11
1221	—	—	—	—	—	—	0.5	5.5	21.5	21	12	17.5	4.5	2	3	3	10	2.48	2.80	3.60	6.90	11.2	2.05	.61	1.12
1222	—	—	—	—	—	0.2	5.5	20	34.5	20	5	4	1.5	2	1.5	2	4	1.99	2.32	2.87	3.90	8.40	.79	.30	3.05
1223	—	—	—	—	0.8	8.5	27.5	26.5	16	5	2	3	3	2	1.5	1.5	3	1.35	1.68	2.25	3.47	7.44	.89	.35	2.41
1224	—	—	—	—	0.6	8	28.5	29.5	16	5	2	3	1.5	1.5	0.8	1	2	1.39	1.69	2.21	3.13	6.56	.72	.27	2.58
1225	—	—	—	0.1	1	11.5	34	27	14	4	1.5	2	1.5	0.8	1.5	0.4	1	1.29	1.58	2.06	2.83	5.00	.62	.22	1.98
1248	—	—	—	—	—	0.1	2	10.5	26	21.5	11	19.5	3	1.5	1	1	3	2.21	2.60	3.96	4.58	7.00	.99	.33	1.41
1249	—	—	—	—	—	0.6	10.5	35	36.5	9.5	2	1	1.5		0.6		2.5	1.84	2.12	2.56	3.08	5.00	.48	.08	2.29
1270	—	—	—	—	—	0.1	0.1	0.2	1.5	5.5	7	28.5	14	7.5	6	5.5	24	3.34	4.09	4.52	10.7	14.5	3.30	.87	.69
1273	—	—	—	0.1	0.1	0.9	11.5	24	27.5	14	5.5	11	0.2	2	0.9	0.7	2	1.79	2.10	2.74	4.04	6.10	.97	.34	1.21
1274	—	—	—	—	—	0.9	12	19.5	23	20	5.5	7	3	3	2	1.5	3	1.80	2.11	2.90	4.45	7.52	1.17	.32	1.44
1275	—	—	—	—	0.2	2	18.5	34.5	21.5	7.5	2.5	4.5	2.5	0.7	1.5	—	4	1.65	1.92	2.41	3.50	7.40	.79	.38	2.63
1276	—	—	—	—	0.1	1.5	17	33	21.5	9	3.5	4.5	2.5	2	—	0.9	4.5	1.71	1.99	2.48	3.80	8.50	.90	.45	2.76
1278	0.8	—	0.1	0.1	1	12.5	45.5	20.5	7.5	3	1	3	1.5	0.8	0.3	0.2	2.5	1.29	1.56	1.91	2.80	5.50	.62	.44	2.39
1279	tr.	—	0.1	0.2	0.7	8	41.5	30	10	2.5	0.9	2.5	1	0.9	0.3	0.6	1	1.35	1.63	2.0	2.65	4.40	.51	.27	.19
1280	—	—	—	—	—	—	—	0.6	6.5	15.5	14.5	31	7.5	4	3.5	3	13.5	2.90	3.31	4.42	8.33	13.1	2.51	.55	1.03
1281	—	—	—	—	—	—	0.6	6.5	23.5	20.5	11	16.5	4	3	2.5	3	9	2.42	2.75	3.49	6.50	11.1	1.87	.60	1.32
1284	—	0.1	0.8	1.5	1.5	1	1	0.8	0.8	1.5	1.5	12	15.5	11	10	7.5	32.5	1.55	4.52	7.1	11.5	14.25	3.49	.26	.82
1285	—	—	—	—	0.1	0.1	0.6	1	3	4	3.5	13.5	10	10	6.5	8.5	39.5	3.04	4.30	7.65	12.7	15.8	4.20	.20	.52
1286	1.4	0.1	0.7	0.4	0.3	0.6	0.8	0.5	2	5	6	22.5	10.5	9	6	5	30.5	2.92	3.98	6.10	12.5	17.0	4.26	.50	.77
1287	0.3	—	0.1	0.1	0.2	0.3	0.3	0.3	1.5	3.5	4	16.5	12	11	9	8.5	32	3.35	4.42	7.20	11.5	14.5	3.54	.21	.57
1288	—	—	—	—	1.5	6	7	21.5	23.5	9.5	3.5	4.5	2	1.5	1.5	1.5	17	1.37	2.04	2.82	9.5	21.0	3.73	.79	1.63

Patapsco-Raritan—continued

Mechanical composition in weight percentages

Sample Number	>2 mm in % of total	2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	Statistical Parameters 5	16	50	84	95	σ	α	β
1289	—	—	—	—	0.1	0.4	5.5	17	26	14	5	7	3	1.5	2	1.5	16.5	1.97	2.36	3.07	9.90	20.0	3.77	.81	1.38
1296	—	—	—	—	0.1	0.2	0.3	0.9	2.5	3.5	3.0	18.5	2.5	13.5	9.0	8.0	38.0	3.18	4.40	7.60	12.18	15.10	3.89	0.177	0.532
1300	—	—	—	—	—	—	—	0.1	0.4	1.5	2.0	10.0	11.0	11.5	10.5	9.5	43.5	4.18	5.22	8.37	12.42	15.00	3.60	.125	0.502
1301	—	—	—	—	—	—	0.1	0.4	0.8	2.0	2.5	15.5	14.0	9.5	8.0	6.5	40.5	3.89	4.64	7.68	13.75	17.80	4.555	.332	0.526
1302	—	—	—	—	—	—	—	0.6	5.0	9.5	5.0	14.0	8.0	7.5	8.5	6.0	36.0	2.98	3.61	7.10	12.74	16.57	4.565	.235	0.488
1306	—	—	0.2	0.1	0.4	0.3	0.5	1.0	2.5	2.5	2.0	10.0	10.5	10.5	7.0	14.0	38.0	3.01	4.69	8.20	11.02	12.90	3.165	.109	0.562
1307	—	—	0.9	0.8	1.0	0.8	1.0	1.0	3	4	3	11	6.5	10.0	10.0	10.0	37.0	5.75	4.04	8.20	11.50	13.90	3.73	.115	0.065
1308	—	—	0.1	—	0.2	0.1	0.3	3.0	12.5	19.5	12.0	18.5	5.5	3.0	4.0	4.0	17.5	2.60	2.99	4.15	9.32	13.30	3.165	.633	2.38
1309	—	—	—	—	—	—	0.5	3.5	9.0	8.0	5.0	11.0	10.0	10.0	8.5	8.5	26.0	2.58	3.22	6.30	10.40	12.90	3.59	.142	0.438
1310	—	—	0.3	0.9	1.5	2.5	4.5	6.0	7.0	5.5	3.5	7.5	2.5	4.0	3.0	4.5	47.0	1.47	2.54	8.30	16.90	22.50	7.18	.204	0.478
2013	0.2	—	0.6	0.4	0.1	0.1	0.1	0.1	1.1	4.7	5.8	21.1	11.5	16.6	1.5	11.2	25.1	3.32	4.18	6.26	10.06	12.29	2.94	0.462	0.525
2014	—	0.05	—	—	—	—	—	—	0.05	0.1	0.1	1.9	9.8	19.25	18.6	8.0	42.2	5.45	6.27	8.13	12.60	15.50	2.66	0.489	0.885
2015	16.6	0.15	0.55	1.3	2.9	5.3	9.3	12.2	17.7	9.2	5.0	11.35	4.5	4.3	2.45	5.0	8.9	1.04	1.86	3.05	7.23	10.09	2.68	0.556	0.647
2047	0.2	—	0.2	0.1	0.3	0.4	0.6	0.6	1	3	4	18	16	12.5	8	6.5	29	3.30	4.39	6.42	11.4	15.0	3.50	.42	.61
2063	2.3	0.2	0.5	1	3	6.5	15	20.5	19	11	4.5	4.5	4.5	2.5	1	3	3	1.06	1.70	2.59	4.55	8.4	1.42	.37	1.58
2068	—	0.1	0.1	0.1	0.2	0.2	0.3	0.7	3	5.5	4.5	12	7.5	8	5.5	9	43	3.02	4.12	8.3	12.3	15.0	4.09	-.02	.46
2074	0.4	0.1	0.7	0.9	0.8	0.7	0.8	1	2.5	4	3.5	12.5	9.5	8.5	8	5.5	40	2.50	4.10	7.60	13.3	17.0	4.60	.24	.57
2075	tr.	—	0.3	0.4	0.3	0.1	0.2	0.2	0.6	2	2.5	13.5	13	11.5	7	7.5	41	3.70	4.76	7.84	13.2	16.85	4.22	.27	.55
2077	1.5	0.1	2.5	2.5	0.8	0.4	0.3	0.2	0.5	1.5	2	14	11.5	12.5	7.5	7	36.5	.49	4.45	7.21	12.5	15.85	4.02	.31	.91
2078	tr.	—	2	3.5	0.8	0.2	0.1	0.1	0.2	1.5	2	16.5	11	11	7.5	7	36.5	.43	4.40	7.15	12.63	16.20	4.11	.33	.91
2079	0.4	0.1	1.5	2.5	0.4	0.2	0.1	0.1	0.2	1	1.5	14.5	11.5	12	8.5	7.5	38	3.0	4.65	7.54	12.4	15.6	3.87	.25	.62
2080	0.6	—	0.2	0.3	1	0.2	0.1	0.2	1.5	4	4	18	13	12	8.5	5.5	32	3.22	4.32	6.63	11.7	15.2	3.69	.34	.62
2081	2.7	0.1	1.5	3	0.8	0.1	0.1	0.2	1	2.5	3	16	13.5	11.5	5.5	10	31	.87	4.28	6.72	11.45	14.50	3.58	.31	.90
2082	2.0	—	0.2	0.2	0.2	0.2	0.2	0.3	3.5	7.5	7	21.5	12	10	6.5	4.5	26	3.02	3.79	5.80	10.9	14.6	3.55	.43	.63
2083	0.2	—	0.3	0.5	0.2	0.2	0.4	0.6	1.5	2	2	11	15	13.5	10.5	7.5	34	3.40	4.80	7.30	11.5	14.3	3.35	.25	.62
2091	0.5	0.2	1	0.9	0.6	0.4	0.6	1	2	2.5	2	7.5	7	9	9	9	47.5	2.60	4.70	8.72	12.9	15.6	4.10	.01	.58
2092	0.5	—	0.8	0.3	0.2	0.2	0.3	0.3	0.5	2.5	4	18.5	12.5	8	6	6.5	39	3.47	4.44	7.40	11.5	14.3	3.53	.16	.50

Patuxent

Sample Number	>2 mm in % of total	2000-1400μ	1400-1000μ	1000-710μ	710-500μ	500-350μ	350-250μ	250-177μ	177-125μ	125-88μ	88-62μ	62-32μ	32-16μ	16-8μ	8-4μ	4-2μ	<2μ	5	16	50	84	95	σ	α	β
		Mechanical composition in weight percentages																Statistical Parameters							
1016	—	—	0.1	0.5	3.5	8.55	14.7	27.7	36.6	3.4	0.6	0.7	0.6	—	1.0	0.3	2.05	1.08	1.66	2.42	2.86	3.50	0.60	−0.266	1.016
1017	tr.	—	0.1	0.3	2.3	6.9	20.8	34.4	28.9	3.4	0.6	—	1.7	—	—	0.4	0.4	1.24	1.71	2.29	2.77	3.18	0.53	−0.094	0.830
2001	0.5	0.2	0.4	0.6	1.0	3.6	17.1	24.8	15.9	11.3	5.3	7.7	2.0	1.0	2.0	1.7	5.4	1.43	1.86	2.58	4.47	9.32	1.30	0.448	2.022
2002	11.4	9.95	26.95	26.15	13.45	6.6	8.5	5.2	2.0	0.55	0.2	0.45 (62-16μ)		—	—	—	—	−0.73	−0.36	0.26	1.54	2.28	0.95	0.347	0.584
2003	0.8	0.2	0.7	0.8	1.6	3.25	15.6	32.3	26.5	12.45	3.7	1.6	1.3	—	—	—	—	1.29	1.84	2.43	3.09	3.68	0.625	0.056	0.912
2004	18.0	8.75	33.6	23.6	10.15	6.8	4.75	2.8	3.05	2.6	1.4	1.3	1.2	—	—	—	—	−0.63	−0.35	0.17	1.62	3.25	0.98	0.472	0.969
2005	0.2	0.1	8.6	23.1	21.4	15.1	11.3	11.2	6.6	1.7	0.4	0.5 (62-16μ)		—	—	—	—	−0.08	0.21	0.93	2.17	2.76	0.98	0.265	0.448
2008	46.4	3.1	8.8	4.9	6.1	11.0	19.3	15.3	8.5	3.9	1.9	5.4	0.8	1.5	1.7	1.0	6.8	−0.34	0.43	1.92	4.22	10.91	1.89	0.213	1.968
2009	0.6	—	0.1	0.2	1.7	5.6	11.45	13.0	18.15	17.15	9.65	16.75	2.3	0.5	0.9	0.5	2.05	1.32	1.89	2.98	4.34	5.50	1.22	0.110	0.706
2010	15.3	5.0	12.8	14.0	13.6	9.2	7.4	5.8	5.6	4.3	2.7	7.8	2.7	3.1	1.6	1.4	3.1	−0.50	−0.06	1.26	4.39	7.59	2.22	0.406	0.847
2011	1.5	1.1	4.4	6.4	6.3	7.1	8.6	8.2	7.0	3.9	2.6	8.6	5.5	5.9	3.9	4.0	16.5	0.07	0.84	3.10	9.11	13.50	4.13	0.453	0.640
2016	1.2	0.3	0.5	1.3	4.8	11.1	27.7	27.2	10.2	2.7	1.3	2.7	1.2	0.6	1.3	1.0	6.1	0.85	1.42	2.08	3.16	9.97	0.87	0.252	4.241
2017	1.5	0.2	1.0	1.3	1.6	4.9	15.0	21.2	30.4	12.6	3.6	3.4	2.6	3.0 (16-<2μ)				1.13	1.77	2.57	3.34	4.93	0.77	−0.038	1.532
2019	1.6	0.8	6.3	12.1	14.0	13.2	15.8	12.8	8.4	4.8	2.6	3.2	3.0	2.2 (16-<2μ)				−0.09	0.39	1.61	3.06	5.27	1.335	0.086	1.007
2020	13.0	4.1	14.3	14.2	11.2	7.8	7.8	6.6	6.8	5.2	3.2	8.7	3.4	1.5	1.3	1.3	2.6	0.46	0.08	1.42	4.22	6.55	2.15	0.30	0.63
2021	14.0	2.8	14.7	15.0	11.4	7.8	7.3	6.5	6.8	5.1	3.1	9.2	3.4	3.0	2.2	1.0	0.7	−0.35	−0.05	1.42	4.3	6.55	2.18	0.33	0.58
2026	0.7	—	0.1	0.1	1.9	6.7	17.6	17.3	23.9	16.8	7.3	5.0	2.2	1.1 (16-<2μ)				1.28	1.74	2.53	3.47	4.57	0.86	0.086	2.381
2029	1.3	2.9	11.1	10.7	9.8	8.7	10.9	8.2	7.5	5.8	3.6	11.6	1.1	2.4	2.1	1.1	2.5	−0.34	1.11	1.82	4.35	7.28	1.62	0.561	1.388
2030	33.5	10.6	22.4	17.2	13.9	7.6	7.0	6.6	6.1	2.9	1.2	1.9 (62-16μ)		2.6 (16-<2μ)				−0.78	−0.35	0.50	2.39	3.77	1.37	0.379	0.807
2031	1.0	1.1	2.4	1.35	1.7	4.5	17.0	22.0	18.1	8.3	3.6	5.25	4.55	2.05	2.5	1.5	4.1	0.57	1.67	2.50	4.69	8.38	1.51	0.450	1.586
2035	0.3	—	0.1	0.1	0.1	0.4	6.7	17.8	22.25	17.95	9.8	19.0	2.3	2.0 (16-2μ)			1.5	1.91	2.29	3.07	4.34	5.29	1.025	0.239	0.551
2036	5.2	0.6	4.9	10.05	14.7	18.1	19.35	12.25	6.1	3.0	1.4	1.6	1.5	—	1.4	0.8	4.15	−0.03	0.51	1.79	2.79	8.05	1.14	0.122	2.552
2037	1.7	0.1	0.3	0.4	0.4	2.8	24.4	40.2	14.5	3.9	1.7	1.6	2.7	2.0	1.2	1.0	2.8	1.55	1.83	2.28	3.06	7.00	0.615	0.268	3.430
2038	1.3	0.2	0.4	0.7	2.8	11.6	38.6	27.6	8.9	3.3	1.55	3.1 (62-16μ)		1.52 (16-<2μ)				1.04	1.51	1.96	2.62	3.79	0.55	0.189	1.474
2039	6.0	6.0	29.6	20.7	16.7	8.6	6.65	4.1	2.8	1.6	0.9	1.9 (62-16μ)		0.45 (16-<2μ)				−0.55	−0.27	0.35	1.67	3.00	0.97	0.360	0.829
2040	0.2	—	0.9	0.1	1.4	12.9	36.5	31.75	8.6	2.4	1.0	2.5 (62-16μ)		1.95 (16-<2μ)				1.18	1.52	1.98	2.53	3.71	0.505	0.089	1.504
2085	tr.	—	0.5	0.5	4	27.5	26	4.5	2	2	2	7.5	5	3	2.5	2.5	10.5	1.00	1.28	1.83	6.90	12.1	2.81	.80	.97
2086	0.3	—	0.1	0.1	0.3	9.5	50	27	4.5	1.5	0.6	0.7	0.8	0.3	0.5	1	3.5	1.36	1.60	1.91	2.39	5.90	.39	.20	4.82
2087	—	—	—	—	0.5	6	29.5	38.5	16	4	1.5	2.5	0.5	0.6 (16-2μ)			0.4	1.45	1.73	2.18	2.77	3.65	.52	.13	2.11

APPENDIX D

Selected Outcrop Descriptions

1. Location: Abandoned sand pit, ¼ mile east of Newport, about 700 feet north of Pennsylvania Railroad tracks

	Feet
Pleistocene series	
Brown, mostly coarse, poorly-sorted, poorly-stratified, "dirty" sand with little silt and some pebbles. At the base a gravel layer varying from 6 inches to 2 feet in thickness, containing many small boulders	0–6
Brown, fairly well-sorted, "dirty", cross-bedded, subangular to rounded sand with very little silt. At the base a layer of gravel ½ to 1 foot thick (sample nos. 1018 and 1019)	6–12
Unconformity	
Upper Cretaceous series	
Patuxent zone	
White, very fine to fine, well-sorted, well-stratified quartz sand (sample nos. 1016 and 1017)	12–18

2. Location: South bank of Chesapeake and Delaware Canal, east of navigation light No. 12

	Feet
Pleistocene series	
Gray, hard silt with little sand, with at the base some pebbles and an occasional cobble	0–3
Unconformity	
Upper Cretaceous series	
Patapsco-Raritan zone	
Light brown and buff, mostly fine, angular, cross-bedded quartz sand becoming slightly coarser toward the base of this layer; samples 1216-18	3–10
Variegated, mostly red and white clay	10–11
Light brown, reddish brown, and buff very fine sand; sample 1219	11–14
Light yellow to white, very fine sand with some muscovite; sample 1220	14–15
Slump	15–28

3. Location: South bank of Chesapeake and Delaware Canal, 150 feet east of navigation light No. 41

	Feet
Pleistocene series	
Reddish brown, poorly stratified sand, with a pebble layer at the base	0–6
Unconformity	
Upper Cretaceous series	
Magothy formation	
Black clay with finely disseminated organic material	6–9
White and some light brown sand; sample 1095	9–13
Alternating laminae of white sand and black clay with abundant organic matter and considerable marcasite	13–17
Dark gray and black sand with abundant lignite; sample 1096	17–19

4. Location: South bank, 1000 feet west of the Pennsylvania Railroad bridge

Height of outcrop: 50 feet

	Feet
Pleistocene series	
Buff and tan, medium to coarse, subrounded to rounded, well-sorted, "dirty", quartz sand; little feldspar and black minerals; some silt, pebbles and cobbles.	0–5
Buff and rust brown, coarse to very coarse, subrounded to rounded, quartz sand; some grit but no pebbles or cobbles. Cross-bedding is a prominent feature of this layer.	5–6
Buff and tan, medium to coarse, subrounded to rounded, poorly-sorted, "dirty" quartz sand. Pebbles or cobbles up to 12 inches in di-	

ameter are scattered throughout this layer but are more heavily concentrated near the bottom. Boulders are found scattered on the beach and on land surface.	6–10
Unconformity	
Upper Cretaceous series	
Monmouth group	
Red Bank formation	
Predominantly gray, some thin bands of rust brown, fine to medium, well-sorted, subangular, "dirty" quartz sand; little glauconite and mica. This layer contains numerous fragile sand casts, smaller than yet similar to *Halymenites major*.	10–12
Predominantly rust brown, some streaks of gray, fine, subangular, well-sorted, "dirty" quartz sand; little glauconite and mica. Numerous sand casts as in previous layer.	12–15
Slightly greenish-brown, fine, subangular, well-sorted, "dirty", quartz sand; little feldspar, glauconite and mica; very little silt. A mottled appearance is caused by the spotty weathering of the glauconite to a rust-brown color.	15–17
Greenish-brown, some rust brown spots, very fine to fine, well-sorted, subangular, quartz sand; some feldspar, mica, glauconite and silt; very little clay. The sand casts become less numerous and the sand more argillaceous toward the base of the formation, thus grading into the mount Laurel-Navesink formation.	17–20
Mount Laurel-Navesink formation	
Dark greenish-brown with numerous rust brown spots, very fine to fine, poorly-sorted, subangular, glauconitic, quartz sand; some silt and clay; little mica.	20–21
Dark green, with brick-red spots, very fine, poorly-sorted, subangular, very glauconitic, quartz sand; considerable silt and clay; little mica.	21–25
Greenish-black with rust brown and brick-red spots, very fine, poorly-sorted, very glauconitic, clayey, quartz sand; grades into a very coarse to coarse silt with abundant glauconite. The surface of this layer weathers to a greenish-white hard silt.	25–30
Matawan group	
Wenonah formation	
Light gray to greenish-white with some rust brown spots, medium, well-sorted, "sugary", quartz sand; some mica; little glauconite.	30–32
Predominantly gray with thin bands of rust brown, fine, well-sorted, subangular, quartz sand; some mica; little glauconite. This layer contains some tubes of *Halymenites major*	32–34
Predominantly rust brown with some gray streaks, fine, well-sorted, subangular, quartz sand; some mica; little glauconite. This layer has a stratified appearance from a distance. Abundant *Halymenites major*.	34–39
Merchantville formation	
Gray with very little rust brown, fine to very fine, well-sorted, subangular, quartz sand; some mica and glauconite. This layer represents a gradational change from the Wenonah above to the Merchantville below.	39–40
Dark greenish-brown with some rust brown spots, very fine, poorly-sorted, subangular, quartz sand; considerable silt and clay; some glauconite.	40–43
Dark blue, poorly-sorted, heavily micaceous, very fine, quartz sand; grades into a very coarse silt.	43–50

APPENDIX E

Depth of core drill samples

Test Hole No.	Sample No.	Depth below land surface (ft.)
16	2001	34–35
	2002	54–55
	2003	74–75
	2004	94–95
	2005	99–100
20	2008	73–74
	2009	88–89
	2010	121–122
	2011	141–142
24	2074	17–18
	2075	26–27
	2013	39–40
	2014	60–61
	2015	63–64
	2016	100–101
	2017	129–130
25	2077	14–15
	2078	19–20
	2079	24–25
	2080	39–40
	2081	44–45
	2082	49–50
	2019	58–59
	2020	107–113
	2021	117–123
27	2083	39–40
	2085	59–60
	2086	64–65
	2087	69–70
	2025	74–75
	2026	134–135
29	2029	59–60
	2030	64–65
	2031	74–75
30	2035	20–21
	2036	147–148
32	2091	14–15
	2092	29–30
	2037	54–60
	2038	79–80
	2039	114–115
	2040	139–140
	2041	1.5–2.5
	2043	2 –2.5
	2047	6.2–6.6
	2058	4.5–5.7
	2063	9.0–9.9
	2065	9.0–9.9
	2066	4.0–5.4
	2068	4.0–5.2