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UNIVERSITY OF DELAWARE

DELAWARE GEOLOGICAL SURVEY

SELECTED PAPERS ON THE GEOLOGY OF DELAWARE

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Transactions
of the
Delaware Academy of Science

VOLUME 7

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Selected Papers on
The Geology of Delaware

Edited by JOHN C. KRAFT
and WENDY CAREY

1979
THE DELAWARE ACADEMY OF SCIENCE
Newark, Delaware

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FOREWORD

The Delaware Academy of Science has been instrumental in informing Delaware citizens about science and utilization of local resources. Since 1970 the annual meeting of the Delaware Academy of Science has been used as a time for presentation of ongoing research in various areas of science in the Delaware region. The proceedings of these meetings have resulted in publication of transactions of the Delaware Academy of Science. The 1976 annual meeting focused on aspects of the geology of Delaware. Members of the Delaware Geological Survey and the Geology Department at the University of Delaware contributed papers in their specific disciplines. This volume presents an overview of studies of geological features and processes of evolution of the geology of Delaware. Although this collection of papers does not represent an all-inclusive study of the subject, the selections included in this volume highlight past, present, and future trends in the study of Delaware's geology. It is hoped that the combined bibliographies of all the papers will provide a comprehensive view of the literature for further investigation into the geology of Delaware.

The Delaware Academy of Science wishes to thank the College of Marine Studies and Ms. Roslyn Foner and Ms. Sandra Graham for technical editing and composition of this volume. The Department of Geology thanks an anonymous contributor to the Department's program for her continued support, which made publication of this volume possible.

John C. Kraft
Chairperson and Professor, Department of Geology
Professor of Marine Geology

Wendy Carey
Graduate Student, College of Marine Studies
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TABLE OF CONTENTS

VOLUME 7

TRANSACTIONS OF THE ANNUAL MEETING OF THE DELAWARE ACADEMY OF SCIENCE AT NEWARK, DELAWARE

1976

SELECTED PAPERS ON THE GEOLOGY OF DELAWARE

Editors
JOHN C. KRAFT
WENDY CAREY

GEOLOGIC TIME SCALE

ERA	PERIOD		EPOCH	MILLIONS OF YEARS BEFORE PRESENT
CENOZOIC	QUATERNARY		HOLOCENE	LAST 10,000 YEARS
			PLEISTOCENE	2.5
	TERTIARY		PLIOCENE	7
			MIOCENE	26
			OLIGOCENE	38
			EOCENE	54
			PALEOCENE	65
MESOZOIC	CRETACEOUS			136
	JURASSIC			190
	TRIASSIC			225
PALEOZOIC	PERMIAN			280
	CARBONIFEROUS	PENNSYLVANIAN		325
		MISSISSIPPIAN		345
	DEVONIAN			395
	SILURIAN			430
	ORDOVICIAN			500
	CAMBRIAN			570
PRECAMBRIAN				4,600

MILLIONS OF YEARS: 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 4,600

(MODIFIED FROM D.L. EICHER, 1968)

1

The Impact of Geology in Delaware: Past, Present, Future

ROBERT R. JORDAN
State Geologist
Delaware Geological Survey

The Author: Robert R. Jordan is State Geologist of Delaware, Director of the Delaware Geological Survey, and Associate Professor of Geology at the University of Delaware. He has an A.B. from Hunter College and a M.A. and Ph.D. from Bryn Mawr College in geology. He has been with the Delaware Geological Survey and the University of Delaware since 1958. He is the author or coauthor of about 40 publications dealing mainly with the sedimentary rocks of the Atlantic Coastal Plain and applied geology. Dr. Jordan is a registered geologist in Delaware, a member of APGS, a fellow of GSA, and a member of several other scientific societies. He is a member of several Delaware boards and commissions and represents the state in the activities of several federal agencies.

THIS symposium is for me a very unusual and a very pleasurable experience. It is gratifying to find that the geology of Delaware is of sufficient interest to warrant a day of papers presented to a rather large and certainly attentive audience, especially because I know from experience that only a few years ago such a symposium would have been of interest to only a few specialists. Therefore, I must begin by congratulating the Academy and the organizers of this symposium and also thanking them for the opportunity to share some personal thoughts that this occasion has stimulated.

I find six elements in the title that has been assigned to me. The

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"impact of geology in Delaware" may be considered to be both the conditions dictated by the nature and configuration of the rocks in this area and the process and effects of studying those rocks. The title indicates that these two major elements will each be discussed in terms of three subdivisions: past, present, and future. This would require a review of the historical geology of the state and a summary of the history of the study of the geology of the state. Fortunately for me, and especially for the audience, my colleagues have presented herein a series of papers that have addressed most of these topics and permit me to be brief in summary.

Common to this discussion and the others in this volume is a concern with time, in this instance phrased as "past, present, and future." The geologist's emphasis on time unites students of the science and reflects the fact that geologists are basically historians of the earth; through science they attempt to construct stories connecting events in time from the sparse evidence observable today. George Gaylord Simpson (1963) has titled an essay on time and geology "Historical Science." He successfully argues that geology, in spite of its obvious debts to physics, chemistry, biology, and mathematics, is a unique and separate science distinguished by "a balance between historical and nonhistorical elements. . . " William H. Bradley (1963), in attempting to define the subject, has put it slightly differently: "Geology's spine is the history and the constitution of the earth, each to be understood in the broadest sense, and running through this spine is the thread of time."

In this context, then, we may consider the geologic past. The rocks of Delaware, as described by Thompson and by Spoljaric (this volume) represent one-half billion years of earth history. That may be only about one-tenth of earth's span, but it is still a significant amount of time. During this interval the Appalachian geosyncline evolved and was deformed to generate a major mountain system, and those mountains have been worn by the inexorable forces acting at the surface of the earth into particles, and transported into another trough off the Atlantic Coast, that is, another geosyncline. The half-billion years involved may seem like an enormous period of time, but when one considers the events portrayed in this volume, those years must have been packed with geologic action.

The geologic present is one instant, one frame in the continuum of time. From the perspective of the comparatively instantaneous period of men's lives Earth appears to be stable. However, our geologists view Delaware as balanced between the remnants of the Appalachian system –

to the west and pointing up – and its child by erosion – lying to the east and pointing down – the Atlantic Coast geosyncline. The balance seems to be static only because of the brevity of our period of observation. Kraft's paper presents evidence of the dynamic nature of the interface between the land and the ocean.

At present our activities are affected by the geologic events of the past which dictate the nature of the framework in which we live. Because our mountains exist only as roots or have not yet been elevated, we have difficulty in Delaware with such activities as skiing or mountain climbing; however, desirable mill sites, outstanding farmlands, and the subsurface architecture described by Woodruff as favorable to groundwater are more serious and positive impacts of the past on our present.

The next frame carries us into the geologic future. The geologic processes described by our authors are large in both power and duration. Therefore, we may expect the future to hold changes commensurate with those of the past. We may look a half-billion years ahead and state with conviction that the major geologic event will be the deformation of the geosyncline lurking offshore according to the tectonic principles referred to in Sheridan's paper. Those rocks will be welded to this continent as a new mountain system and it, then, will begin to erode into the sea.

Perhaps the evolution of the next mountain system is not of sufficient immediacy to be of primary concern. However, even in the more familiar time framework of generations of man, in the future before the end of this century, there will be important consequences resulting from the geologic past and present. Our scientific challenges lie in part in the delineation of natural processes and their interrelationships, and in determinations and projections of their rates. The rates of natural processes may differ from those that man may prefer. New minerals to replace those described by Leavens are born altogether too slowly. We have mined in the last hundred years infinitely more ore than has been created by nature. On the other hand, we find that the sea is encroaching too rapidly on Sussex County. The powerful forces acting to deform the crust of the earth generally act slowly, and we might become impatient if we did not recall the recent earthquakes in the Wilmington area, related, perhaps, to an acceleration of tectonic activity. A lesson from even a cursory examination of the geologic past, present, and future must be that not only do we need to understand geologic processes, but also their rates and the impacts resulting from differences between geologic rates and those rates that can be governed by men.

This collection of papers on Delaware's geology establishes that Delaware does have a geology (this has been questioned by those from more spectacular areas). The reader may also be convinced that geology is a valid and challenging subject for scientific inquiry. Finally, the condition of the rocks has contributed to the style and substance of the lives of Delawareans.

Three points remain: to discuss the past, present, and future of the study of geology in Delaware. My colleagues, in their papers, have summarized the current status of many aspects of the study of geology in Delaware and, in so doing, have also discussed the events of the past leading to our present circumstances. Pickett's paper deals with our geologist ancestors and Leavens' with others who have contributed to our knowledge. Pickett's history stops with the founding of the Delaware Geological Survey in 1951 and thus affords me the opportunity and the obligation to recall some of the more familiar names and events of the recent past. From this glance backward it is hoped that we may demonstrate how important the science of geology is to Delaware, as is illustrated by the growth of interest in the subject during the last quarter century. A quote from Edmund Burke adds dignity to this justification: "People will not look forward to posterity who never look backward to their ancestors."

There was a 110-year hiatus in the study of geology in Delaware between the publication of Booth's remarkable Memoir in 1841 and the founding of the present Delaware Geological Survey. That gap meant that while neighboring states and universities grew in geologic knowledge with the evolving understanding of geologic fundamentals, Delaware marked time and accumulated problems. The pressure of pent-up problems may have had some accelerating effect on the expansion of geologic efforts once begun, but it also forced us to start in comparatively primitive circumstances.

This chapter begins with the arrival of Johan J. Groot and his wife Catharina, also a geologist, at the University of Delaware in 1949. In 1951 the Delaware Geological Survey (DGS) was established by state statute. The DGS and the Department of Geology at the University of Delaware involved the same personnel. The Department offered up to three service courses to majors in other fields.

The establishment of the DGS was guided by a man to whom all Delawareans are indebted in many ways: the late George M. Worrilow. Dean Worrilow either was pursuaded by Dr. Groot or recognized from his own experience that there was a need for the study of Delaware's geology. He carried the message to Dover in his unique style; Governor Carvel and the General Assembly agreed and the DGS was founded. I have been told that in those earliest days the Survey's only piece of equipment was a typewriter and that there was not even a desk to place it on.

Only a few benchmark events and a few names can be noted here to attempt to convey the essence of 25 years of hard work. Because of the necessary selectivity, there may be unintended omissions.

The first *Bulletin* of the DGS was published in 1953. It reported a practical application of geology and hydrology to highway construction. The Cooperative Program of the DGS and the United States Geological Survey (USGS) were first organized at about this time. The former has continued to emphasize water resources. Also in 1953, the DGS became involved in some of the first regulatory work in this region dealing with water. Delaware geologists were deeply involved with litigation that eventually resulted in the Supreme Court Decree of 1953 apportioning the waters of the Delaware River among the four states of the Basin and New York City. To this day we attempt to protect the Delaware Estuary from adverse effects from the reservoirs upstream. The year 1954 was marked by the publication of the fourth *Bulletin,* the first statewide treatment of Delaware geology since Booth (1841), and the only such treatment of water resources. Ira Wendell Marine and the late William C. Rasmussen of the USGS Cooperative Program were its authors.

The staff of the DGS in those early years included Groot, Donna M. Organist, and Richard F. Ward. In 1958 Marlene Carucci took charge of our office and ever since kept us on an even keel. In that year there was no significant differentiation between the staff of the DGS and the faculty of the budding Department of Geology; the personnel were, in fact, the same: Groot, John K. Adams, and myself. We had the audacity to suggest that we should have a full geology major. After all, we were three in number and we were spending two-thirds of our time on Survey projects, thus leaving one-third of our time for the academic department. The answer from the administration, as the story was told, was: "You may have a geology major but it must not cost the University anything." Our resources were limited but we had, possibly, more than normal measures of enthusiasm and conviction. The first classroom was of such a size that it later became a one-man office. The second classroom ("laboratory," we said proudly) was carved from a former coal bin in the basement of Robinson Hall. The first students who majored in geology at

Delaware, the first who dared to become involved with that den of improvisation, really wanted to be geologists. They had to!

The period 1958 through 1964 produced basic research in the stratigraphy, petrology, and paleontology of Delaware, which built a foundation for the study of geology. The undergraduate Department struggled but flourished. The first pieces of modern equipment were acquired. National Science Foundation-sponsored programs for now-evolving secondary school earth science teachers were run. In the turbulent activity of the interval the staff changed a number of times; the net result was steady, moderate expansion.

Some important natural events emphasized geology. In March, 1962, Delaware lost beaches and buildings to a major coastal storm. Some research efforts were diverted to the beaches and some of the processes and predictable effects were identified. Kraft, of course, later greatly expanded and detailed our knowledge of Delaware's shores. The DGS anticipated another need in 1963 by proposing the first oil and gas exploration legislation for Delaware. At the time it was ridiculed and did not pass, but similar measures were included in the 1966 Water and Air Resources Act. The areas of our research extended beyond the outcrops of the Piedmont and Chesapeake and Delaware Canal to the farthest corners of the state, beneath it to new subsurface areas, and into the Delaware Bay.

The next period, the mid- and late 1960s, will probably be best remembered as the drought years. Rainfall decreased and so did streamflows, but, except for marginal wells, ground water supplies sustained us. The value of that protected resource hidden in the ground – water – became more apparent. Woodruff's paper summarizes our knowledge of Delaware's vast groundwater assets and Varrin's reminds us of the delicate quality of that resource and the need for vigilance to assure its protection.

Perhaps stimulated by the combination of growth in the undergraduate academic program and by the results of geologic research applied to major problems, many of our present colleagues joined us. Among the authors represented herein, Varrin, Spoljaric, Pickett, and Woodruff joined the DGS and Kraft, Leavens and Thompson, and Sheridan came to the department in the mid-1960s. Now growth of both programs began to require separate appointments to the department or the DGS. As the programs grew we began to anticipate the next phase of our story.

On the department side plans were laid for a graduate program. The preparation was long and thorough and the proposal generated only a few snickers. When it was over, in 1968, the Department of Geology had been authorized to grant both master's and doctoral degrees. By then we had chased the competition out of the basement of Robinson Hall. Eventually, the combined space needs of the DGS and the department were satisfied when we moved into Penny Hall. The extensive renovation of the facility and its dedication to geology represent a tangible monument to the success of our various programs. The move to adequate facilities permitted additional growth in both programs as well as the acquisition of the technical tools essential to modern geologic inquiry. In 1977 we overfilled Penny Hall. Of course the University of Delaware itself expanded greatly during the time since the initiation of our undergraduate major, but the Department's programs satisfied a long-neglected need and its growth outstripped the University's in rate until now there are 120 undergraduate majors and 30 graduate students in the Department of Geology.

The DGS, meanwhile, dealt with the floods that inevitably followed the drought and began to contribute in many ways to what has become known as "environmental geology." In order to provide useful, immediate information under flood hazard conditions, we sought to bring together for the first time rainfall data from the National Weather Service and a network of observers and streamflow data from our system of stream gages operated under the Cooperative Program of the DGS and USGS. "Environmental" concepts and functions were brought together in Delaware by the creation in 1966 of the Water and Air Resources Commission. The DGS worked closely with that body and its successor, the present Department of Natural Resources and Environmental Control, and so participated in the development of many of the protective measures operating today in Delaware.

The basic data collection programs and some of the efforts in basic research culminated in what for the DGS was a major event in 1970: publication of the first modern geologic map of Delaware, which Pickett prepared for the Chesapeake and Delaware Canal area.

The DGS also applied the products of geologic research to such issues as major alternative water supply systems for the state, potential refinery and other oil-related sites along Delaware Bay, and to siting conditions for proposed nuclear power plants.

The applications of geology and the efforts of geologists found fertile soil in Delaware. In addition to the research, basic data collection, and provision of geologic services, the DGS, in less visible fashion, now relates to about 30 state, federal, and interstate agencies. Formal agreements cover some of these relationships; others are by appointment or may be less formal. During the last period of this study of geology's "past" in Delaware – the last few years – we continue to find new and sometimes startling applications for geology, some of great potential significance. We have dealt recently with earthquakes, municipal water supply shortages, and major pollution problems. At this writing, much effort is being devoted to the subject of offshore oil and gas exploration. It is important to note that many of the problems that geologists in Delaware have faced in the period discussed here were coincident in time. Geologic problems do not tend to be solved easily. The tendency, rather, is to meet each challenge and to incorporate its solution into an ever-growing workload.

As the work in geology in Delaware increased in scope and intensity, the number of geologists has also increased. We have seen that there was in 1951 a single geologist serving the Department of Geology and the DGS. There also seem to have been about five in the state working with industry. Today we count six at the DGS, eight in the department, several more in other parts of the University, about seven in industry, five in other state units, two with the USGS in the Cooperative Program, and several in private practice, plus those who operate here only on temporary assignment. About 125 geologists have met qualifications for professional registration in Delaware and have registered with the State Board of Registration of Geologists, although they do not all live here. This provides some measure of the size of the niche that geology has found in Delaware during the past quarter-century.

The University of Delaware has provided us with more than mere sustaining support once geology's potential here became clear. The Unidel Foundation and the University of Delaware Research Foundation have contributed significantly to our successes. Other foundations have also recognized the virtues of our proposals and supported our efforts. The General Assembly has been steadfast in its support of the DGS and many governmental units and private entities have provided contracts and grants. The Irénée du Pont Mineral Collection is an asset to the entire community. The Getty Oil Company contributed the first geophysical equipment that permitted study of subsurface Delaware. Many others have, of course, contributed in numerous ways and the general cooperation of the people of Delaware has been gratifying.

The present status of the study of geology in Delaware is the focus of much of this volume. We may also turn our attention to the future. I suggest that, just as with the forces of geology, the future of the study of geology will contain elements of the past and present. The fundamental attributes necessary for quality teaching, productive research, and effective application of geology will not change. The nature of the rocks is not expected to change suddenly, nor will requirements for new, advanced technology. There will be new discoveries, however, and the context in which our work is done may change unexpectedly. The future may be predicted to be more of the same, but with many surprises.

The most visible geology-related activity in the immediate future will, I suspect, be oil and gas development, especially oil and gas exploration on the Atlantic Outer Continental Shelf and perhaps much closer to shore. In addition to the basic geologic problems involved, there are also major elements of economics, technology, law, and sciences other than geology.

It is clear that we will have critical problems in the future with all energy and mineral resources. As has been noted, the rates of consumption exceed rates of replenishment. Even in the case of a renewable resource such as water, rates of consumption in some areas continue to increase beyond those of renewal. Such problems are unlikely to be solved by new technology or large-scale spending before the new century, if then; the demands for mineral resources will be similar to those at present, but will intensify over the next 25 years. Coping with this situation will demand all of our dedication, all of our science. Delaware is involved and our geology, our geologists, and those to be trained here as geologists will make significant contributions during this challenging period.

The problem was succinctly summarized by geologist H. H. Read some years ago: Rocks do not have baby rocks. Will Durant has written: "The present is the past rolled up for action, and history is the present unrolled for our understanding." We have tried to unroll some history, earth history, from the rocks that preserve it. That history is ready for action; the processes will continue according to natural law and are not to be changed in course by wishful thinking. It will benefit us to understand such history and the forces it represents and to respect it in areas where the future presents options.

In preparing for the future I believe my colleagues may derive satisfaction from their past accomplishments and the indication that their efforts are appreciated from the fact of this symposium.

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2

The History of the Science Of Geology in Delaware

THOMAS E. PICKETT
Senior Geologist
Delaware Geological Survey

The Author: Thomas E. Pickett received his B.S. degree in geology from Duke University in 1959; he earned his M.S. and Ph.D. from the University of North Carolina in 1962 and 1965, with a dissertation on the sediments of Pamlico Sound, N.C. He worked for a year in oceanography at the Smithsonian Institution before joining the Delaware Geological Survey at the University of Delaware. Dr. Pickett's main research interests are stratigraphy and sedimentation of the Atlantic Coastal Plain, trace fossils, and the history of the science of geology, especially in the Delaware area.

GEOLOGY in Delaware did not start, in a modern sense, until the nineteenth century; however, the foundations for scientific studies were laid by earlier observers. For example, Augustine Herrman put Iron Hill, Delaware, on his map of Maryland and Virginia (which includes Delaware) at the early date of 1673. Also, bog iron ore beds in Sussex County were known and utilized starting in early colonial times. Kaolin clay near Hockessin-Yorklyn, stone on the Brandywine, and greensand marl in southern New Castle County were all located, described, and used in early Delaware. Eighteenth-century travelers, such as John Bartram, published descriptions that included the natural history of the Atlantic Coastal Plain, of which Delaware is a part. Lewis Evans (1749), of Philadelphia, made a map of New Jersey, New York, Pennsylvania,

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and the Delaware counties which differentiated mountainous and flat-lying topographic provinces. In 1752, Jean Guettard, a Frenchman who never visited America but assimilated reports from his agents, made a very rudimentary geologic map (probably the first) which described the Atlantic Coastal area and the Appalachian mountains. From his map it is unclear whether or not he recognized a coastal plain. Johann Schöpf was a Hessian surgeon who remained in America after the Revolution; in 1787 he published his observations on the geology of eastern North America. Schöpf recognized the Atlantic Coastal Plain and Fall Line. In 1804 Constantin F. Volney, a Frenchman, published an account in Philadelphia that discussed the Atlantic Coast Plain in simplistic terms as a flat of sand left by the sea.

Benjamin Latrobe, the noted architect and engineer, made engineering feasibility studies for a proposed Chesapeake and Delaware Canal in the first decade of the nineteenth century. Some geologic descriptions of materials to be excavated were made by him (Latrobe, 1803).

The descriptions made by these early observers provide a general foundation upon which nineteenth-century scientists were able to develop a geologic history of the Atlantic Coastal Plain and Piedmont.

The first important American nineteenth-century geologist was William Maclure, who in 1809 published a colored geologic map of the United States and a paper entitled "Observations on the geology of the United States." This map shows Delaware's Coastal Plain as "alluvial" and the Piedmont as "primitive." Maclure's text included perhaps the first specific, practical geologic observations on Delaware:

> Delaware, the smallest state, almost all consists of Alluvial, the part formed by the depositions of the Delaware will most probably be good soil, while that formed by the washings of the Sea will be light and sandy. . .

While this is an oversimplification when considered in hindsight by modern geologists, it nevertheless was a good beginning for modern geologic mapping. It is interesting that Maclure explained the presence of bog iron ore in Delaware and New Jersey by the proximity of red beds in Pennsylvania which could serve as source material.

In 1823 Professor John Finch from England differentiated the Alluvial of the Atlantic Coastal Plain described by Maclure into the Secondary and Tertiary Formations and correlated these formations with similar ones in Europe. This was a noteworthy step because it was the first attempt to subdivide the formations of the Atlantic Coastal Plain.

The excavation of the Chesapeake and Delaware Canal, finished in 1829, was a major stimulus for geologic science. The exposures created were of major importance because they were more extensive than natural outcrops found between northern New Jersey and the western shore of Chesapeake Bay. Fossils were found in abundance at the Canal and were as major an attraction to geologists in the nineteenth century as they are today.

Lardner Vanuxem, of Philadelphia and later South Carolina, made the first definite recognition of Cretaceous age sediments in the Atlantic Coastal Plain in 1829. This initial work was expanded in the 1830s by Dr. Samuel G. Morton of Philadelphia, who studied fossils from the Chesapeake and Delaware Canal and elsewhere, and attempted to differentiate the Cretaceous sediments.

An essay on the mineralogy of Delaware by Henry du Pont was written in 1831 for the "Lyceum," presumably the Wilmington Lyceum. This manuscript is available in the Winterthur papers. It discusses some mineral localities no longer in existence.

Timothy A. Conrad, starting in 1830, studied fossils from the Tertiary of the Atlantic Coastal Plain, including the mid-Atlantic states.

Booth's Geologic Survey of Delaware

On February 18, 1837, the Delaware Legislature passed an act "to procure to make a geologic and mineralogic survey of the State." Three commissioners, one from each county, were named to hire a geologist: Thomas Stockton, Jonathan Jenkins, and Dr. Henry F. Hall. The commissioners were also to spend some time in the field with the geologist. Stockton spent 40 days; Hall, 28; and Jenkins, 11. They were paid $3 a day.

One June 1, 1837, they hired James Curtis Booth, a Philadelphia chemist-mineralogist, as the Delaware State Geologist at a salary of $1200 a year. He was paid at this rate for 2 years. In addition to the requirements of the act of the legislature, Booth agreed to give information on any useful discovery to the owner of the land and to collect and deposit with the commissioners specimens of all the minerals he found. The location of these samples is unknown today.

Booth started his field work in the summer of 1837. In the winter of 1837-1838, he analyzed samples he had taken. He returned in the field season of 1838 with an auger capable of drilling up to 20 feet, which he used for greensand evaluation. He was assisted by John F. Frazer, his former co-investigator in the Pennsylvania survey. The field work was apparently concluded by the fall of 1838. Booth analyzed more samples, becoming more oriented toward geology for agricultural purposes as he realized that most of Delaware's mineral wealth was in the soil, suitable for crops.

In 1839-1840 he wrote his *Memoir of the Geological Survey of Delaware: Including the Application of the Geological Observations to Agriculture* (1841a) which he formally submitted to the Legislature on May 4, 1841.

In a letter with his report, Booth (1841b) concluded that there was no formation of special value except some "excellent clay," which modern tests have confirmed; that there was a "moderate amount of iron ore" (mostly bog iron); and "that the 2,000 square miles of Delaware should be devoted to agriculture, because the whole state is peculiarly well adapted to it, and because there is no other general object to which it is as well adapted." Booth saw his main purpose, during his field investigations, as "a travelling instructor in agriculture, without exhibiting the formality of teacher among the people to be taught."

Geologic formations delineated by Booth in his 1841 report were divided into: 1) Primary (modern Piedmont crystalline rocks); 2) Upper Secondary (modern Cretaceous formations and lower Tertiary greensands); 3) Tertiary (modern Miocene); and 4) Recent (modern Quaternary). This was the first effort in describing Delaware's stratigraphy.

Booth's colleague John Frazer constructed a geologic map of Delaware to go with the survey based on "an old but excellent map of the state by Mr. Varley." However, Booth declined to publish the map, saying that the minute descriptions of the survey alleviated the need somewhat, and recommending that Maryland, Delaware, and Virginia cooperate in publishing a map of the Delmarva Peninsula, since the entire area contained similar geologic formations. The Commissioner's report on the survey to Charles Marim, Secretary of State, said that the "map which was to accompany the Memoir is still in the hands of Mr. Booth, but will be forwarded to you in a few days." A search by the author and others revealed no trace of this map, which could be very useful in locating some of Booth's outcrops that are now obscure. Perhaps it was never completed. A generalized attempt to reconstruct Booth's map, based on discussions in his *Memoir,* is shown in Figure 1.

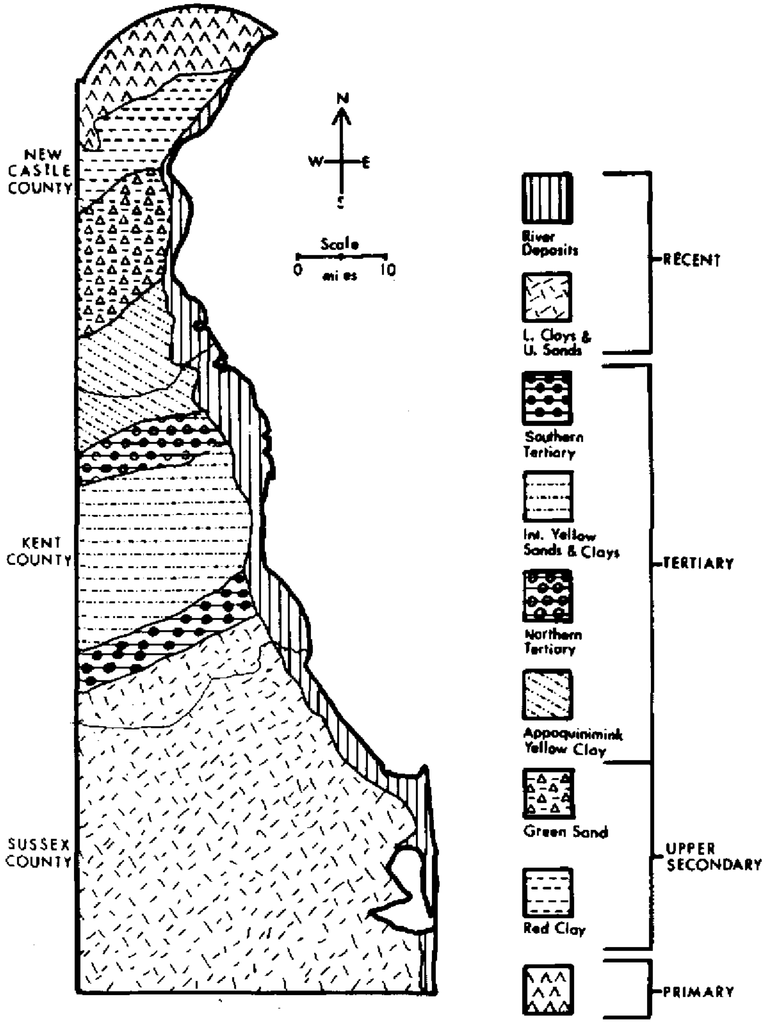


Figure 1. A possible reconstruction of Booth's 1841 map by T. E. Pickett (1976).

James C. Booth has been overlooked as a contributor to American regional geology, largely because of his identification as a chemist. His practical application of geologic data to agriculture provided an invaluable service to Delawareans.

Of great value to the modern Delaware Geological Survey, which was founded in 1951, are his outcrop descriptions and analyses. Natural outcrops are rare in Delaware's Coastal Plain; therefore Booth's report is a useful guide to rediscovering long-lost outcrops. This has had direct application to the Geologic Quadrangle Mapping Program. Other state surveys may find it useful to study carefully the original surveys of their states.

In his *Memoir,* Booth revealed his great interest in promoting the use of greensand (glauconite) as a natural source of potash for fertilizer. He devoted many pages to this subject and to chemical analyses of Delaware greensands. Today the Delaware Geological Survey has a grant from the United States Bureau of Mines to investigate the interesting ability of greensand to remove objectionable metallic ions from wastewater. Delaware has one of the purest glauconite deposits in the United States.

The origin of the Delaware Piedmont crystalline rocks is today viewed as enigmatic. Booth reasoned that they are, at least in part, sedimentary in origin because of the sedimentary structures he observed in the weathered rocks. Booth's reasoning coincides more with the ideas of modern geologists than it does with the ideas of geologists of the intervening years between 1841 and now. Booth (1841b) wrote:

> . . .the value of the splendid Bay and Ocean Front, directly contributing food to man, of the best quality, in ample supply, and through all the time, only needing proper legislative influence to regulate it, for the welfare of the citizens of the State.

Thus it seems that Booth was ahead of his time in calling for legislative regulation of Delaware's important coastal wetlands. Delaware was one of the first states to do this, long after Booth's time. The Delaware Coastal Zone Act was passed in 1971.

In the 110 years from Booth's *Memoir* in 1841 until the establishment of the modern Delaware Geological Survey in 1951, Delaware geology was largely overlooked because there was no Delaware State Survey and the geologists of adjacent Maryland and New Jersey ventured into Delaware only occasionally. Delaware geology was usually mentioned in passing or in connection with a special note about fossils from the Chesapeake and Delaware Canal.

Modern Geology in Delaware

In 1884, F. D. Chester of the Academy of Natural Science in Philadelphia attempted to update Booth's work and indicate in more detail the stratigraphic order of sediments. His map of northern Delaware is similar to modern maps in showing distribution of rock types (Figure 2). Chester also had the very modern idea that sediments south of the Murderkill River might be Pliocene, not Pleistocene in age.

William B. Clark included Delaware in his geologic investigations of the mid-Atlantic states at the turn of the twentieth century. He mapped the Matawan, Monmouth, and Rancocas Formations in Delaware and Maryland. The Rancocas was considered to be Cretaceous in age. We now consider it to transcend the Cretaceous-Tertiary boundary.

Some other geologists who engaged in studies in Delaware early in the twentieth century were: Berry from Johns Hopkins, a paleobotanist; Weller, a paleontologist from New Jersey; and Shattuck from Maryland, who "spilled over" into Delaware. B. L. Miller (1960), mapped the Dover area and discussed the geology in a United States Geological Survey (USGS) folio. Florence Bascom and B. L. Miller (1920) published a USGS folio on the Elkton-Wilmington area.

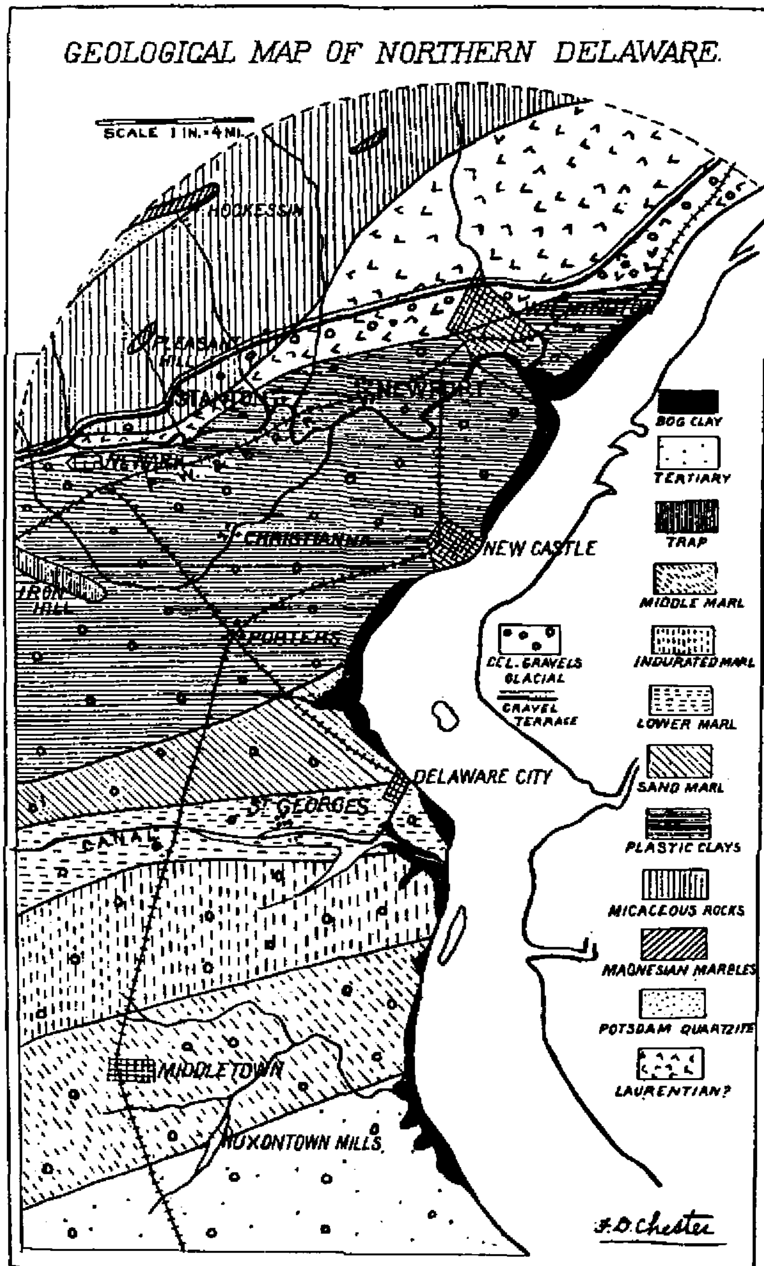
In 1937, Charles W. Carter, from Maryland, published a paper on the Upper Cretaceous deposits in the Chesapeake and Delaware Canal. He had the advantage of studying new excavations after a period of widening the canal. Carter's interpretations are similar to the present interpretations by the Delaware Geological Survey.

Horace G. Richards of the Academy of Natural Science in Philadelphia included Delaware in a discussion of the geology of the Atlantic Coastal Plain in 1945 and subsequent studies.

Spangler and Peterson (1950) wrote a synthesis of Coastal Plain geology of New Jersey, Delaware, Maryland and Virginia.

In 1951, Delaware passed legislation establishing the present Delaware Geological Survey. The geologic research done since 1951 by the Delaware Geological Survey and the University of Delaware Department of Geology is discussed in other chapters. The latest geologic map (see end papers) is the culmination of many years of geologic investigations.

The study of the history of geology is very important so that we do not continue to "re-invent the wheel." Early geologists frequently did very accurate work. We find that in some cases they knew of outcrops, processes, and geologic relationships that we assumed were first discussed


GEOLOGICAL MAP OF NORTHERN DELAWARE.
SCALE 1 IN.=4 MI.
HOCKESSIN
PLEASANT HILL
STANTON
NEWPORT
WILMINGTON
NEWARK
CHRISTIANNA
NEW CASTLE
IRON HILL
PORTERS
DELAWARE CITY
ST. GEORGES
CANAL
MIDDLETOWN
NOXONTOWN MILLS
BOG CLAY
TERTIARY
TRAP
MIDDLE MARL
CEL. GRAVELS GLACIAL
GRAVEL TERRACE
INDURATED MARL
LOWER MARL
SAND MARL
PLASTIC CLAYS
MICACEOUS ROCKS
MAGNESIAN MARBLES
POTSDAM QUARTZITE
LAURENTIAN?
F.D. Chester

processes, and geologic relationships that we assumed were first discussed by modern geologists. A careful reading of early geologic reports and maps is recommended as a foundation for those interested in the geology of Delaware.

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Figure 2. (opposite) Chester's (1884) geological map of Delaware is similar to modern maps because it shows distribution of rock types.

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3

The Coastal Environment

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BASICALLY, two different regions make up the coastal plain of Delaware: the low-lying Delmarva Peninsula in the south, and the broad, rolling country of northern Delaware. The northern portion of the coastal plain in Delaware is a relatively high, deeply incised region that extends from the Fall Zone at the boundary with the Piedmont province southward to the vicinity of Odessa. The northernmost portion includes a narrow fringe of Delaware's coastal zone extending from Wilmington along the Delaware River northward to the Pennsylvania border. Thus Delaware is much affected by the ocean, since its tidal shoreline starts

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at the Pennsylvania border and extends along the coast of Delaware Bay to Cape Henlopen, thence southward to the Delaware-Maryland border at Fenwick Island. Approximately 13% of Delaware consists of coastal tidal wetlands. Obviously, tidal waters of Delaware Bay, the lower Delaware River, and the Atlantic Ocean dominate life in Delaware, and it is therefore appropriate to call attention to the many varied aspects of the geology of this coastal zone.

From Odessa-Smyrna southward, the Delaware coastal plain is low in elevation and becomes increasingly flat and poorly drained. In reality, the Delaware coastal plain is the emergence of a larger geomorphic feature known as the Atlantic continental shelf. The coastal plain protrudes outward across the shelf approximately halfway to the edge of the continental slope (Figure 1). Farther to the south, in the Carolinas, narrow bands of land reach the outer edge of the shelf, whereas to the north, in Rhode Island and Massachusetts, nearly the entire continental shelf is submerged by the Atlantic Ocean. Thus the present geomorphology of the Delmarva Peninsula and Delaware coast is a geologic coincidence of position of land versus sea in time and space as related to a large geologic feature known as the Baltimore Canyon Trough geosyncline, which forms the Atlantic continental shelf. This immensely long and over 150 km wide geologic feature received sediments eroding off the continent of North America over the past 150 to 200 million years. Robert E. Sheridan discusses the geosyncline in detail in the next chapter.

Geomorphic Elements of Delaware's Coastal Zone

Delaware's coastal zone lies on the northwesterly flank of a subsiding geosyncline, and highly varied processes of coastal change impinge upon this zone. Therefore the morphology of the coastal zone is highly diverse (Figure 2). In the north, a very narrow tidal salt marsh impinges against the Piedmont province of the uplands of northern Delaware. This coastal area is no longer in its natural state due to the intensity of man's development of the area. From the south of the Fall Zone (Wilmington-Newark) to the vicinity of Odessa the irregular coastal salt marshes fringe the tidal Delaware River along this higher element of the Delaware coastal plain. The Delaware coastal plain may be higher in this region as a result of a slight tectonic upwarp or a lesser rate of downwarp than toward the axis of the Baltimore Canyon Trough geosyncline, which lies seaward on the outer continental shelf. Southward from the

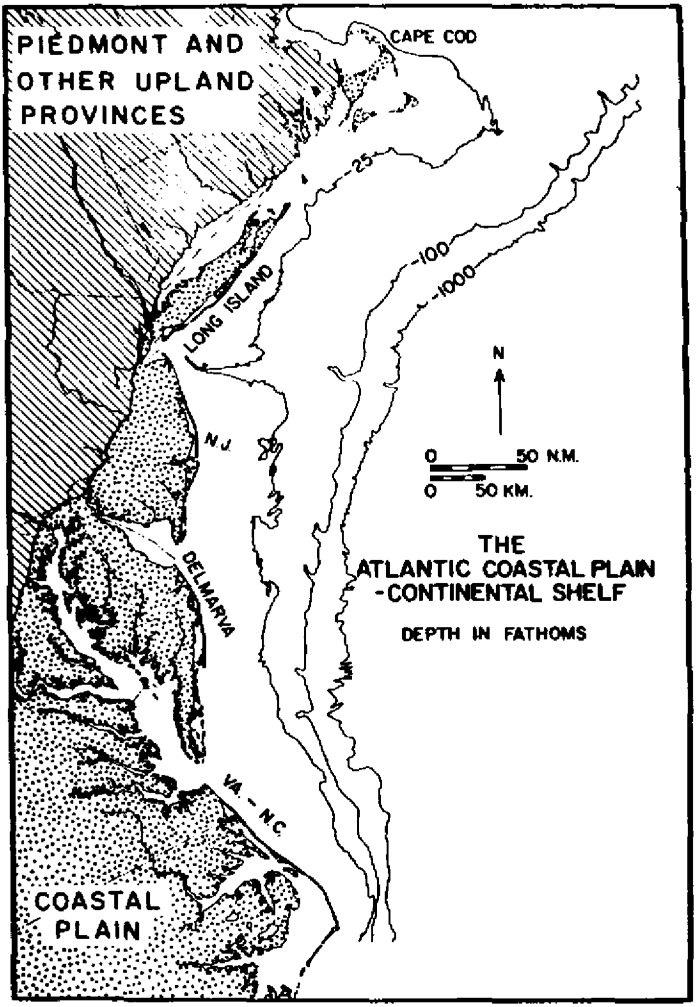


Figure 1. Index map to the mid-Atlantic Bight showing the relationship to the Atlantic coastal plain and Delmarva Peninsula to the submerged continental shelf.

Chesapeake and Delaware Canal to approximately the vicinity of Bowers, Delaware broad coastal marshes and isolated minor sandy barriers dominate the shoreline of Delaware. Little sand is available to form beaches.

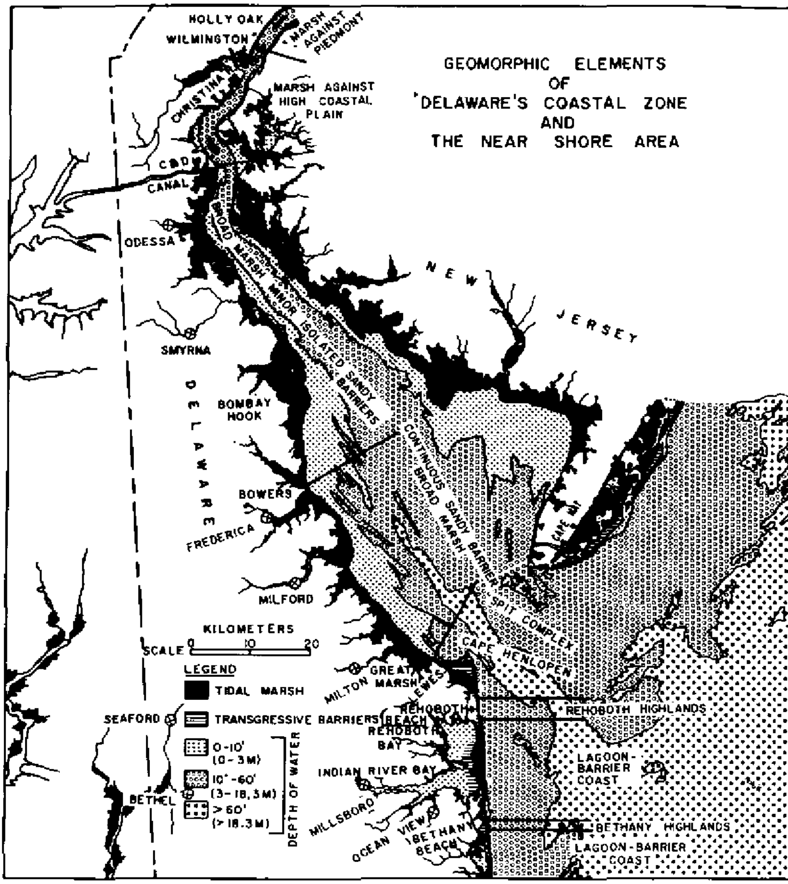


Figure 2. Geomorphic provinces of coastal Delaware as related to the shallow marine area of Delaware Bay and the Atlantic Ocean nearshore area.

This is because of a lack of sand sources transported by the river or available from the erosion of sands of the Delaware coastal plain. Accordingly, this is an area of broad coastal marshes in direct contact with the tidal waters of the lower Delaware River and the upper Delaware Bay. Small villages lie along this shoreline in those areas where thin, ephemeral beaches have established themselves.

From the town of Bowers south to Cape Henlopen, Delaware Bay is also fringed with typical wide salt marshes. However, in this area, a supply of sand has been available over a longer period of geologic time; it moves as a stream of sediment transported along the shoreline by wave action, leading to the formation of a narrow sand-gravel beach. Thus this area includes a continuous sandy barrier with broad coastal tidal marshes (Figure 2).

At Cape Henlopen, a great complex and interplay of coastal environments occur. At the towns of Lewes, on the bay, and Rehoboth Beach on the Atlantic Ocean, the low-lying sandy coastal plain of southern Delaware impinges against the bay and the sea. Thus a higher land area, formed in the past, is undergoing erosion at present. Between Lewes and Rehoboth, a triangular spit complex of approximately 25 square km has formed. The tip of this area is named Cape Henlopen. Actually, the triangular area is a complex of spit, beach, fresh-, and saltwater tidal marshes, dunes parallel to the ocean, and the giant dune of Lewes (perpendicular to the Atlantic Ocean shore). It is a very complex geomorphic area and has been discussed in detail by Kraft (1971a), Kraft and Caulk (1972), and Kraft et al. (1978).

To the south of the Rehoboth highlands lies Delaware's lagoon-barrier coast. Here the broad coastal lagoons, Rehoboth Bay, Indian River Bay, and Assawoman Bay, are cut off from the ocean by the relatively thin and narrow Atlantic Ocean coastal barriers. These lagoons are fringed by tidal salt marsh. At Bethany Beach, another highland area protrudes to the shoreline. These Atlantic coastal upland areas are believed to be part of a low-lying undulating plain formed in a shallow marine environment approximately 40,000 to 100,000 years ago, in a time known to geologists as the Wisconsin Epoch and Sangamon Epoch. A precise knowledge of these sediments is not yet known. At those times, sea level stood at 12 m above present sea level. Farther inland, and throughout the entire Peninsula, the surficial sediments of the coastal plain of Delaware have been studied in some detail by Jordan (1964, 1974). Details of the internal structure of the underlying sediments and development of the coastal plain are presented in Chapter 5 by Spoljaric. The offshore area of the inner shelf, surrounding the coasts of Delaware, provides major clues to the origin of the present coastal features. The Delaware Bay estuary is being filled in part by a thin veneer of sediment as the tidal waters of the Atlantic Ocean rise over the Delmarva Peninsula (Weil, 1977). Delaware Bay and its river are formed along the axis of the ancestral Delaware River, which was eroded to depths of greater than 70 m in the vicinity of Delaware approximately 15,000 years ago (Moody and van Reenan, 1967; Owens et al. 1974; Twichell et al., 1977). This bay and its sediments and geologic structures have been studied in detail by Moose (1973) and Weil (1977). The subsurface geology of the immediate offshore area of Delaware has also been studied by Field and Duane (1976), Sheridan et al. (1974), Swift (1974), and Twichell et al. (1977). These studies provide important clues to the origin and evolution of the present coastal zone.

Figure 2 shows subsurface contours or depths of water. Note the similarity between the shapes of the various water depth areas and the present shoreline. The line of 10 feet (3 m) water depth is very similar to the shape of the present coastal area of Delaware Bay. Equally, the line of 60 feet (18.5 m) water depth is very similar to the Atlantic coast of Delaware and New Jersey, including Cape May. This suggests that these coastal features formerly lay to the south and east and have been buried as sea level rose and migrated northwestward across the Atlantic coastal plain, which was an exposed area 15,000 years ago, during the last great ice age, known as the Wisconsin Age.

A large number of studies have been made of Delaware's coast. In view of this, the remainder of this chapter is relatively short but includes a large number of illustrations that explain graphically and visually the geology of the Delaware coastal zone. The reader with more detailed interests is referred to the many references cited at the end of this article, and in particular to Kraft (1977a, b), Kraft et al. (1976), and Kraft and John (1976).

Coastal Processes

Many types of coastal processes impinge upon the coastal zone of Delaware, leading to highly varied coastal environmental forms. Delaware is undergoing a small but continuous tectonic subsidence as a result of its location on the northwest flank of the Baltimore Canyon Trough geosyncline. In addition, coastal sedimentation is occurring along the barriers and in the coastal lagoons and marshes. These sediments are subject to compaction and subsidence. Delaware's shoreline area is undergoing a continuous, pervasive rise of sea relative to land. In part this is eustatic, caused by the melting of the world's ice caps (Belknap and Kraft, 1977; Kraft et al. 1976). Figure 3 shows a relative sea level rise curve derived from data in the Delaware coastal zone. The curve is drawn based on data from basal tidal salt marsh sediments, believed to be the most stable points upon which to base a relative sea level rise curve. Over the past 2000 years, the sea has been rising relative to the land in the Delaware coastal area at a rate of approximately 18 cm per century. This may seem like a small amount, but over the longer term, it is a serious matter. From 6000 to 2000 years ago, sea level was rising at a rate of nearly 1/3 m per century. Before that time, rates of relative sea level rise of up to a meter per century possibly occurred. Even though the relative sea level rise curve (Figure 3) is definite for the coast of Delaware, much argument remains regarding changes in world sea level. It is generally agreed that the world's sea levels have risen approximately 100 m since the beginning of the waning of the last great ice caps that developed across the northern and southern portions of the globe about 15,000 years ago.

Possibly of more importance to our generation is the fact that

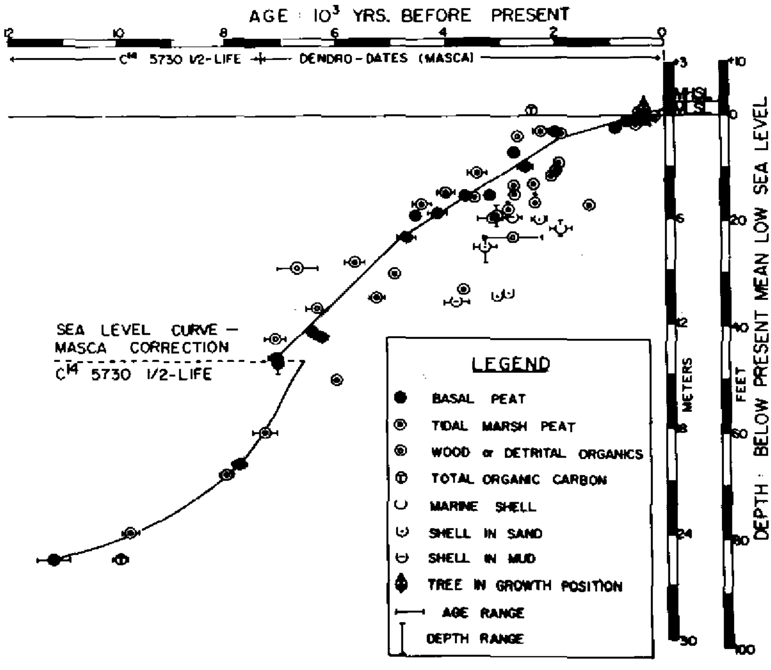


Figure 3. A local relative sea level rise curve derived from radiocarbon evidences in the Delaware coastal area.

Hicks and Crosby (1974), upon examining tidal gauge records of the past 70 to 90 years along the North American coast, observed a sharp increase in rate of relative sea level rise. Figure 4 shows a curve of relative sea level rise for the Delaware coastal area, based on data from Lewes Harbor, Delaware. The data are spotty and irregular, but there is absolute proof that relative sea level is presently rising at a much greater rate than the long-term geologic average. It is not known why this is so. It may be a minor upward cycle on the longer term geologic curve, or the rate of relative sea level rise may have speeded up as a result of increasing global temperatures brought on by the industrial revolution. The curve shown in Figure 4 is cyclic but ever upward. Should sea level continue to rise, into the indefinite future, it spells great danger to man in terms of his occupation of the coastal zone.

The most visible and most important coastal processes, as they affect man, are those of coastal erosion and deposition. Massive changes have occurred in Delaware's coastline since European man's first occupancy of the area. Details of these processes are discussed in Kraft (1971a, b) and Kraft et al. (1976). Predominate winds attack the coast from the northwest through northeast-to-southeast quadrants. The average waves hitting the coast of Delaware come from the east or southeast, causing a gradual movement of sand by a process known as littoral transport to the north toward Cape Henlopen. Major storms frequently hit the Delaware coast from the northeast, causing erosion, which may send sand flowing in the littoral transport system to the south toward Maryland. However, over the long-term average, it has been estimated that there is an annual net flow of 350,000 cubic yards of sand along the Delaware Atlantic Ocean coast to the north (Turner, 1968), and a resultant northward building of Cape Henlopen into southern Delaware Bay into the area of Lewes Harbor. Figures 5 and 6 are summary diagrams showing rates of change along coastal Delaware (Kraft et al., 1976). Regardless of cause, a very high rate of erosion is occurring, varying from 3 m per year at Cape Henlopen to 2/3 to 1 m per year from Rehoboth to Bethany Beach averaged over the past century.

The Delaware shoreline is advancing landward at an extremely rapid rate. We must assume that these erosion rates will continue into the long-term future. Thus a question is raised regarding man's ability to occupy the coastal zone. During normal weather, waves approach from the southeast and impinge upon the beach; slowly they move sand grains in an ever-continuing stream to the north. This is the dominant direction of sand movement along the Delaware coast. During an excep-

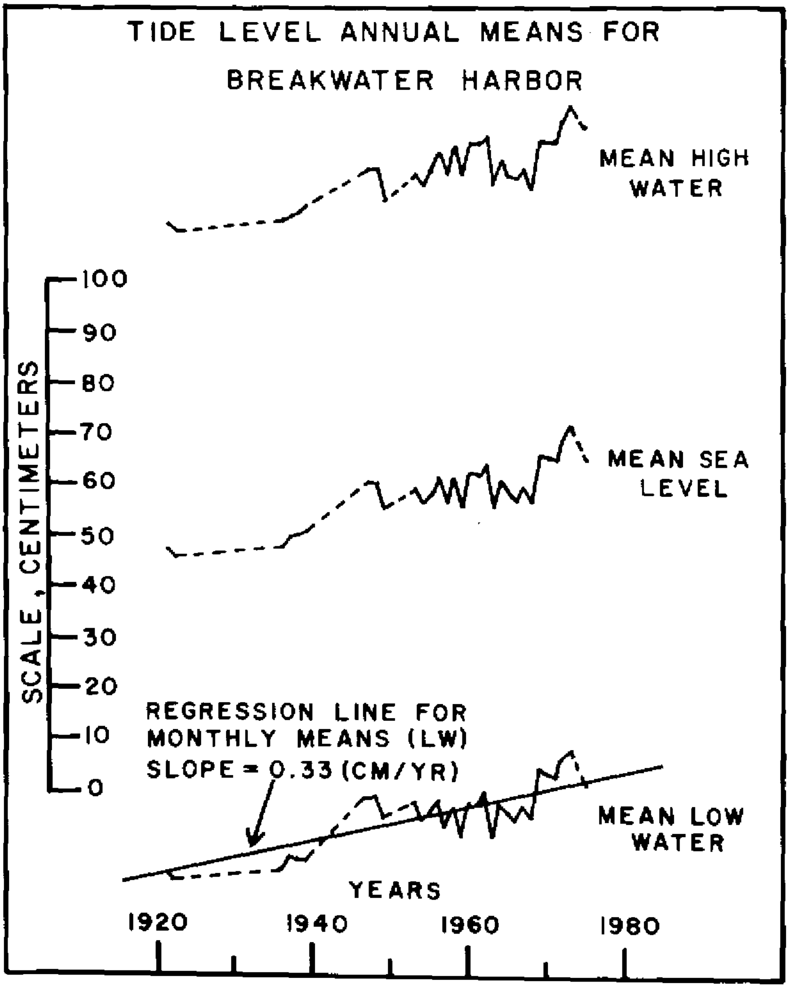


Figure 4. Short-term accelerated sea level rises indicated by tidal gauge records. (From Demarest, 1978, based on Hicks and Crosby, 1974).

tional storm, the sand may be moved in the southerly direction, depending upon the direction of the incoming waves. During storms, massive erosion occurs. The sand may be eroded and deposited in the nearshore shelf area in an offshore bar, washed across the berm and dunes and into the coastal lagoons, or moved to Cape Henlopen by littoral transport and dumped into the deep (20 m) channel at the tip of the Cape. Some of this sand is eventually eroded away from the tip of the Cape to the southeast onto the ebb-tidal shoal, known as Hen and Chicken Shoal. At low tide, and when the beach surface is dry, strong winds may move

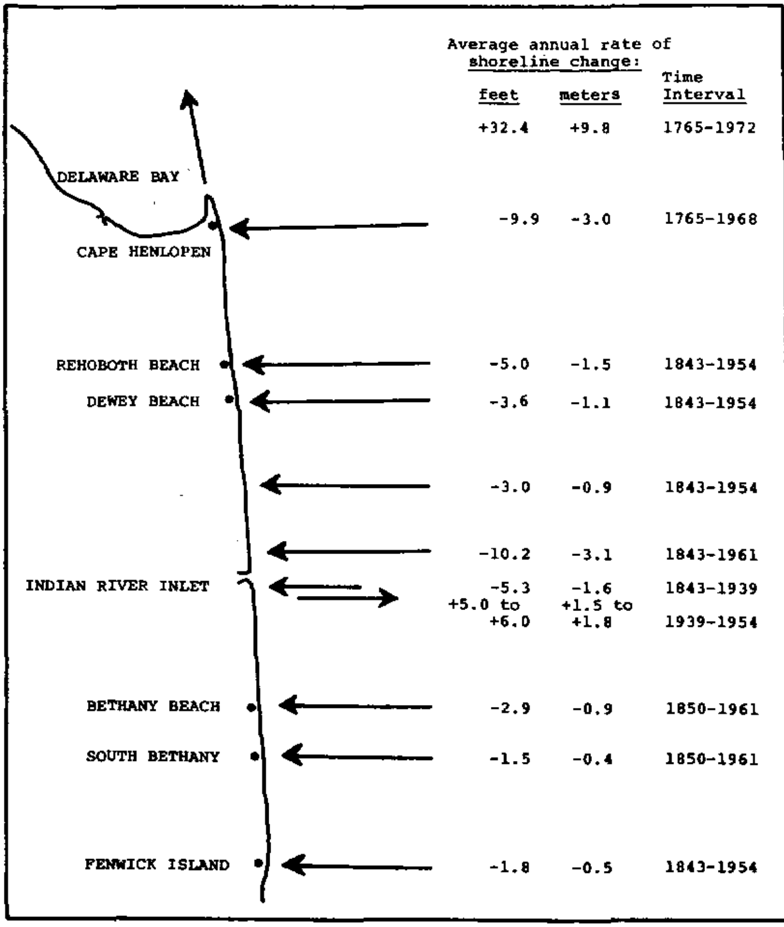


Figure 5. Average annual rates of shoreline change along the Atlantic coast of Delaware from Cape Henlopen to Fenwick Island: 1842-1972. Based on work of E. M. Maurmeyer from map data of the U.S. Coastal Survey and U.S. Coast and Geodetic Survey (Kraft et al., 1976).

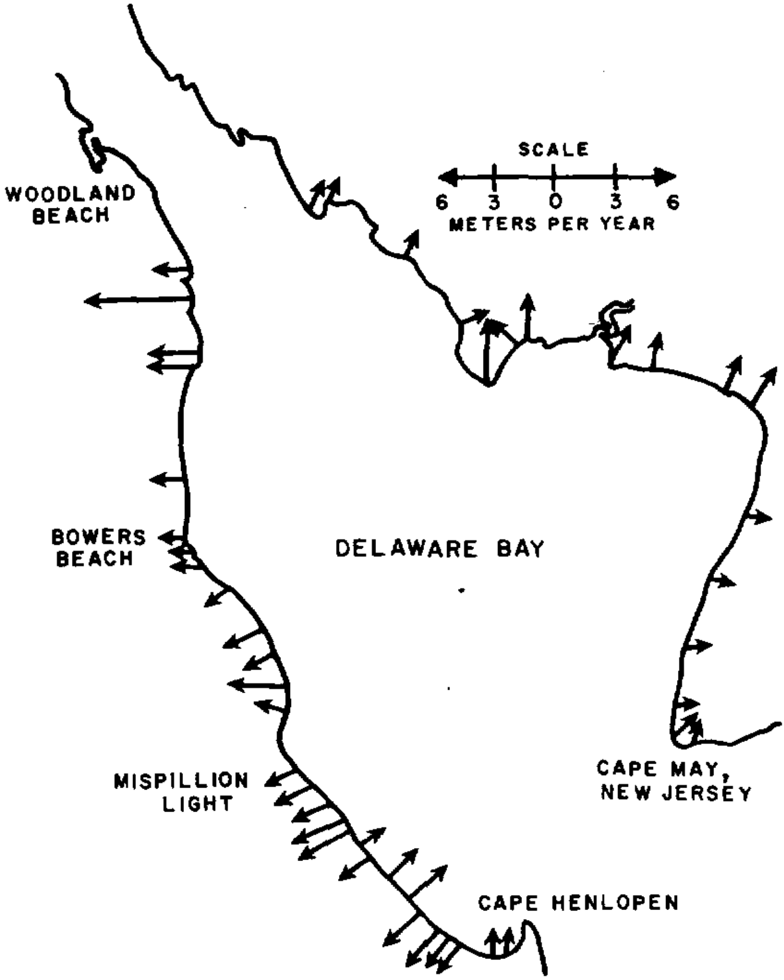


Figure 6. Average annual rates of shoreline change in Delaware Bay: 1848-1972. Based on work of C. B. Weil and E. M. Maurmeyer from map data of the U.S. Coastal Survey and U.S. Coast and Geodetic Survey (Kraft et al., 1976).

the sands across the tidal flats and berm into coast parallel dunes which have formed to elevations of up to 27 m in the Cape Henlopen area. In the early 1800s, while the inner breakwater was undergoing construction in Lewes Harbor, the giant sand dune at Lewes formed and began to migrate south (Kraft and Caulk, 1972).

Man's construction in the coastal zone has had a major impact on the movement of sediment in the littoral transport system. One important example is that of the jetties at the tidal inlet at Indian River. As sand moves by the inlet on the flood tide, it is rapidly transported into the eastern end of Indian River Bay and deposited in a flood tidal delta. With the ebbing of tides, a narrower, smaller ebb-tidal delta forms the shoals around the outer edge of the jetties in the Atlantic Ocean. Sand is trapped on the beach on the southern side of Indian River Inlet. However, wave refracting around the jetties plus the deposition of sand in the tidal deltas and entrapment south of the jetties leads to a deficit of sand to the north of the Indian River jetties. Here wave energies are focused and massive erosion occurs (Figure 7). Without constant replenishment of this sand by state and federal agencies, the coastal highway at the foot of the bridge across the Indian River Inlet would be undermined and collapse. Similar effects of groins and jetties may be observed elsewhere along the Delaware coast. Some sand is migrating along the inner shelf area of the Atlantic Ocean and, after storms, tends to move from the first offshore bar back onto the beach and rebuild the beach-berm. However, after every storm, there is a net loss of sand and movement of the shoreline landward.

Geomorphic Coastal Forms

A few examples showing the highly varied geomorphic coastal forms in the Delaware coastal zone follow. They are only briefly discussed and the reader is referred to the many sources in the references for more detailed information. Figure 8 shows a paleogeomorphologic construction of the Piedmont-Delaware River coastal plain from Wilmington northward to the Pennsylvania border. Six thousand years ago, the tidal Delaware River was much lower. Since then, with the gradual rise of sea level relative to land, the fringing marsh has migrated upward along the edge of the Piedmont Crystalline Province. Geologic drill hole studies of this area enable us to examine the layers of sediment forming the coastal zone and to make interpretations of what occurred geologically over the past 40,000 years. This area is particularly important in that one of the earliest evidences of man's occupancy of the coastal zone was discovered in this area over a century ago. The story of Holly Oak and the Holly Oak mastodon is complex, and subject to some question

(Kraft and Thomas, 1976). However, at present, the area is one of nearly total fill from highways, the railroad, and other works of man.

Farther to the south, in the vicinity of Bowers, Delaware, lies a typical broad coastal marsh with a very thin, narrow, sand-gravel washover barrier and a narrow highland neck of land protruding from the coastal plain to the beach area. Figure 9 is an aerial photograph oblique of the Bowers-South Bowers coastal zone showing the very narrow washover barrier, broad tidal salt marshes, and inland surface of the low-lying coastal plain of central Delaware. The Island Field Archaeological Site lies between the Murderkill River and a small freshwater pond toward the rear of the photograph. The shoreline of Delaware Bay is eroding so rapidly in this area that the salt marsh is being overridden by the barrier and eroded by wave action in the intertidal zone. Thus erosion of the coastal salt marsh sediments contributes a large quantity of organic materials and muds to the turbid Delaware Bay waters. This area is also of considerable archaeological interest, in view of the location of the Island Field Site on a highland to the south side of the Murderkill

Figure 7. Aerial photograph showing extreme coastal erosion at Indian River Inlet, the result of man's intrusion, disrupting normal littoral transport systems.

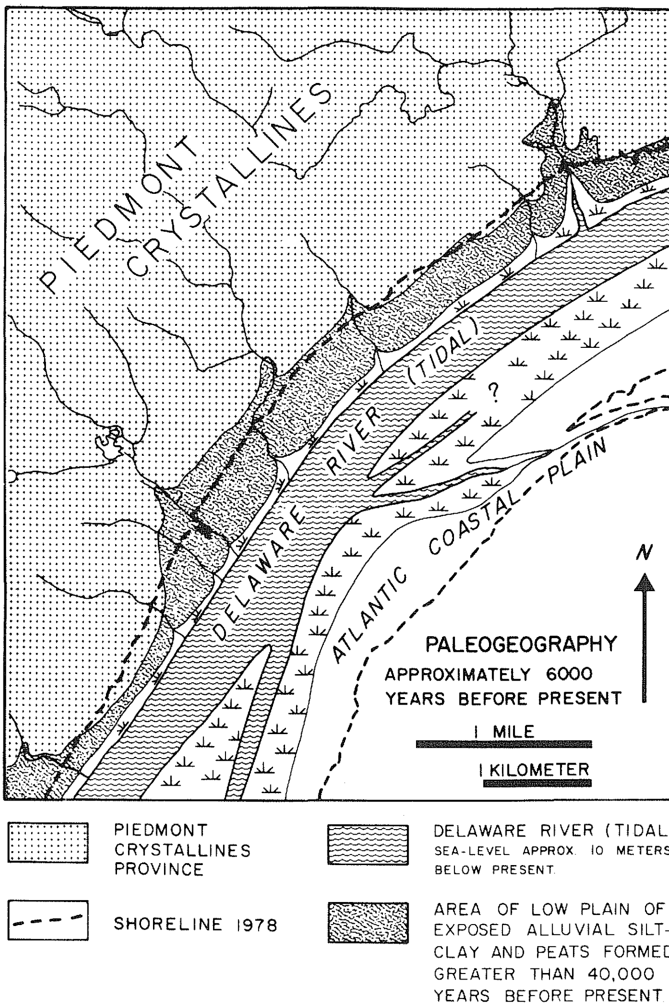


Figure 8. A paleogeomorphologic reconstruction of the Piedmont-Delaware River geomorphic provinces 6000 years ago, when sea level was much lower. See Kraft and Thomas (1976) for details.

River (Kraft, 1977b). At the time of major occupancy of the Island Field Site, the shoreline was not in its present position; rather, it lay considerably farther seaward. Figure 10 is a cross section showing some of the geologic evidences of lower sea level and seaward positions of the coastal environments over the past 10,000 years. With the continual rise of sea and erosion of the coast, the tidal marsh has tended to move landward and upward in space and time. Radiocarbon dates of many of the tidal marshes encountered by drilling into the subsurface prove that the coastal sedimentary environments have been constantly migrating landward and upward relative to present sea level. It is interesting to note that 2740 years ago, a coastal marsh existed over 1 mile seaward from the present coast. Major coastal erosion has occurred in a very short time in the South Bowers area (Kraft 1977a). Figure 11 shows the present geomorphology of the Bowers region of the Delaware Bay shoreline with a number of paleogeographic reconstructions of coastal positions over the past 10,000 years.

Still farther to the south, the size of the barrier between lower Delaware Bay and the broad fringing marshes increases as it approaches Cape Henlopen and the Atlantic Ocean, where the barriers become typical large Atlantic coastal barriers. Many studies have been made of the Delaware coast in this area. These include a study of the Great Marsh at Lewes by Elliott (1972); a study of the nearshore submarine

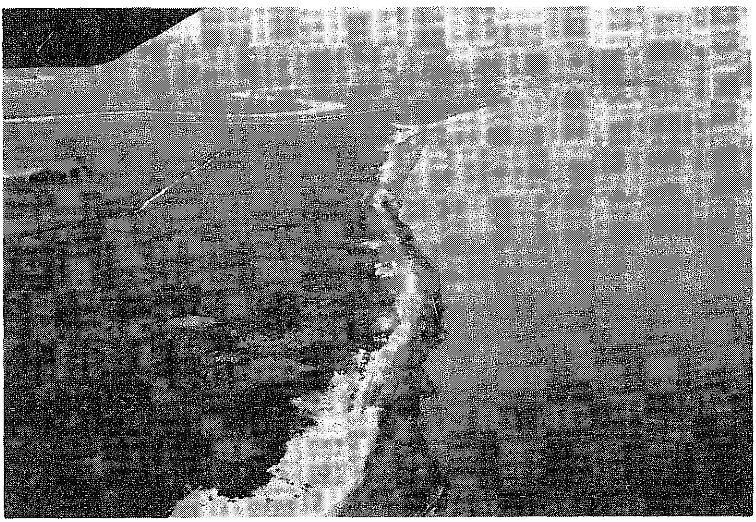


Figure 9. An aerial photograph oblique of the Bowers-South Bowers coastal zone.

area from Cape Henlopen to Fowler Beach by Strom (1972); a study of the thickness of the mud infill of the various ancestral valleys that have undergone transgression as sea level rose by Richter (1974); a study of the short-term development of the simple spit, Cape Henlopen,

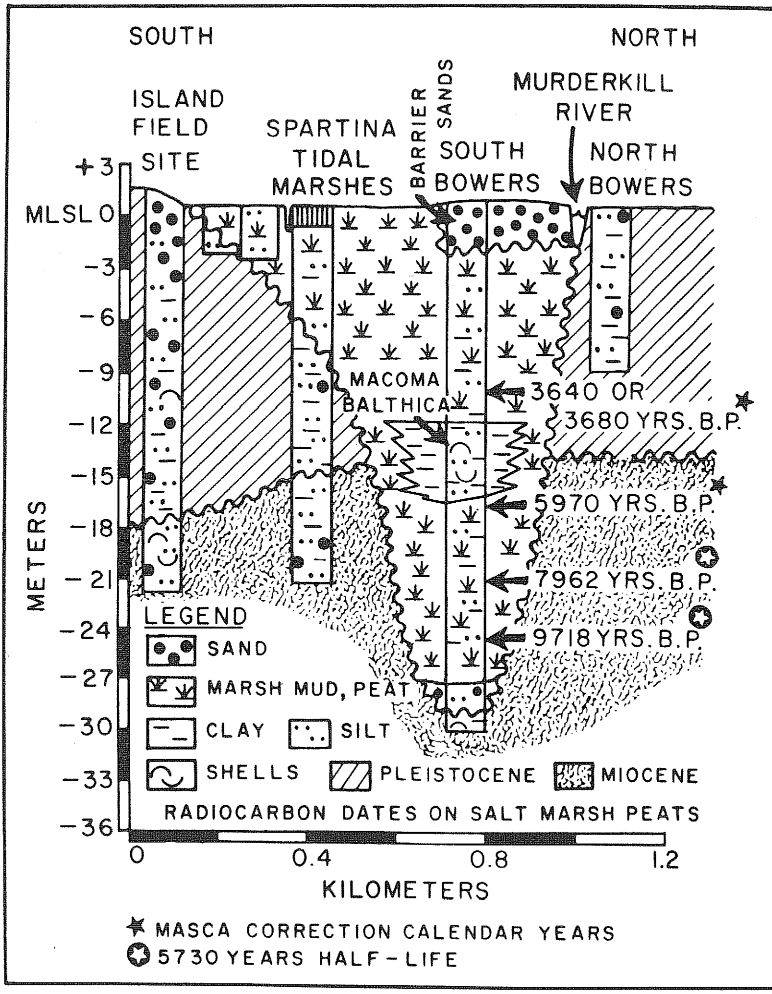


Figure 10. A surface-subsurface cross section showing geologic evidences of lower sea levels over the past 10,000 years.

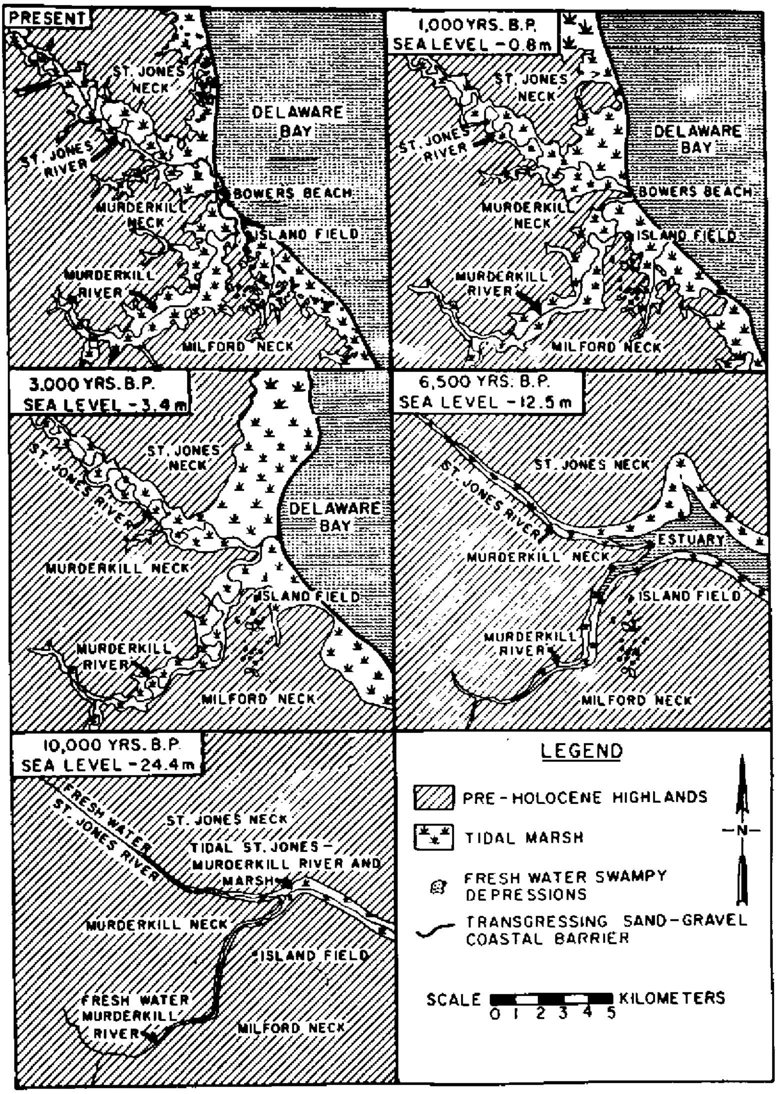


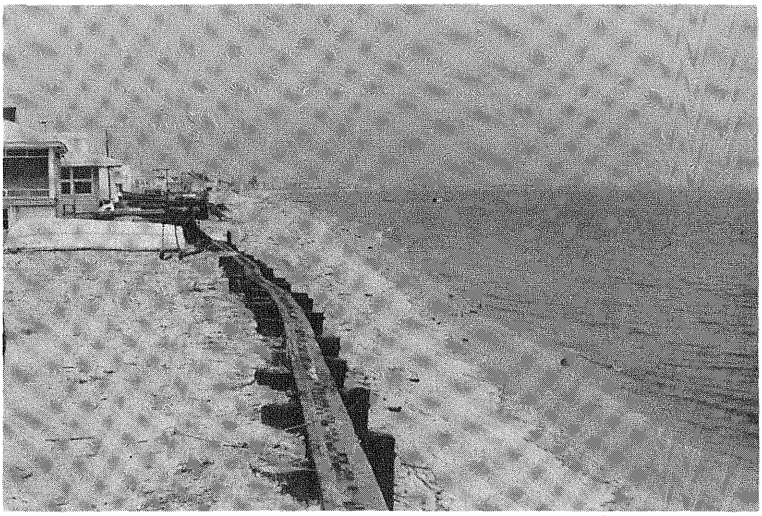
Figure 11. The geomorphology of the Bowers region of the Delaware Bay shoreline showing coastal positions over the past 10,000 years.

by Maurmeyer (1974); a study of the Lewes Creek Marsh, which overlies an infilled coastal lagoon behind older recurved spits of Cape Henlopen, by Allen (1974); a study of the evolution of marsh flora of the broad coastal marshes of Delaware Bay by Allen (1977); and summaries of geology of the area by Kraft (1971b) and Kraft et al. (1976).

Coastal erosion and sediment transport in the littoral transport system along lower Delaware Bay is pervasive and has continued for many thousands of years. Figure 12 shows the effects of this erosion and man's attempts to counter long-term geologic processes. At Slaughter Beach, a bulkhead has been placed between the houses of the village and the beach area. After storms, the sands and gravels of the beach erode away. Frequent beach nourishment – accomplished by dredging sand from offshore shoals – is needed to maintain the beach in its present configuration.

Figure 13 is a composite aerial photograph showing the southernmost shoreline of Delaware Bay from the Primehook area to Cape Henlopen to Rehoboth Beach. The thin white strandline of Delaware Bay is shown along the low-lying uplands and marsh of Sussex County. The inner harbor (Breakwater Harbor) is clearly defined by the piers and breakwater on the right of the figure. Through the development of a spit in the 1800s, a beach was formed by sand flowing around Cape Henlopen toward the northwest, creating the barrier island that is now occupied by the town of Broadkill Beach. The changes in sediment flow regimen caused by the building of the breakwaters in Lewes Harbor led to the cutoff of the supply of sand to the beach by the beginning of this century. Thus the Broadkill Beach strandline is undergoing severe erosion. As seen in Figure 14, a series of groins have been built to protect the village of Broadkill Beach. Without these groins, over half of the village would have disappeared through normal coastal erosion.

Coastal changes in the triangular area from Lewes to Cape Henlopen to Rehoboth Beach continue in a systematic manner similar to processes of coastal change that occurred over the past 3000 years. Originally, a southwestern Delaware Bay shoreline was present approximately along the Lewes-Rehoboth Canal. As ancestral Cape Henlopen began to move into the area, recurved spit tips formed and gradually built to the northwest. This was accompanied by sea level rise and ongoing erosion of the Atlantic coast of Delaware offshore from present-day Rehoboth Beach. Eventually, the recurved spit tips that now protrude into Lewes Creek Marsh enclosed a shallow body of water or lagoon in the present position of Lewes Creek Marsh. As coastal erosion continued and beach migration evolved ever forward farther to the northwest, the recurved spits joined with the mainland near the town of



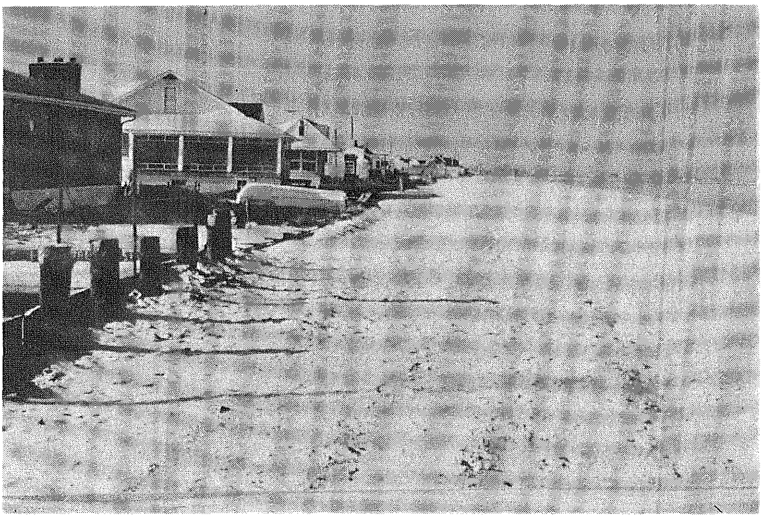


Figure 12. Slaughter Beach along the Delaware Bay shoreline. This coast has been bulkheaded as a protection against coastal erosion; a) after normal erosion; b) after beach nourishment by dredging sand from an offshore shoal.

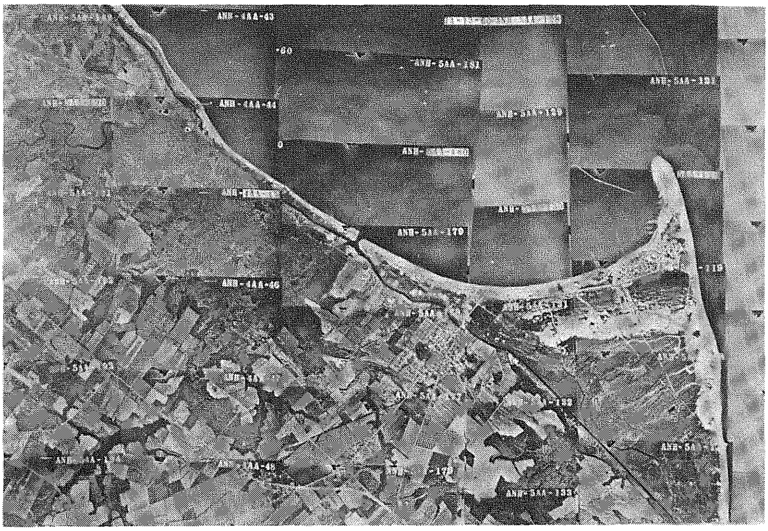


Figure 13. An aerial composite of the shoreline area of southern Delaware Bay from the Primehook region southward through Broadkill Beach to Lewes Beach, Cape Henlopen, and thence to Rehoboth Beach. Note the great difference between the Delaware Bay barrier widths and the Atlantic coastal barrier widths and the protrusion of the simple spit, Cape Henlopen into the Harbor of Refuge, tending to surround the inner breakwater and Breakwater Harbor.

Lewes. A cuspate foreland type of spit developed. With the construction of the inner breakwater, the sediment flow regimen was disrupted. A simple spit, the present Cape Henlopen, began to protrude northward around the inner breakwater. Eventually the outer breakwater was built to form the Harbor of Refuge. Presently, with continued coastal erosion of the Atlantic coast of Delaware, the simple spit, Cape Henlopen, is rapidly advancing to the northwest into the Harbor of Refuge. Eventually, the Harbor of Lewes will be destroyed. The spit, Cape Henlopen, should join the inner breakwater. At such time, the Harbor of Lewes will require extensive dredging should man desire to maintain it in its present position. If not, the harbor will eventually silt in and become a marsh and the shoreline will continue to build northward and westward. Details of the development of the Cape Henlopen area may be found in Demarest (1978), Kraft (1971b), and Kraft and Caulk (1972). When

Europeans first arrived in the area of the Delaware cape in 1629, Cape Henlopen was a broadly rounded cuspate foreland. Eventually, in the 1760s, a lighthouse was constructed on Cape Henlopen, approximately 400 m from the Atlantic shoreline. The lighthouse was built on top of a dune approximately 14 m above sea level. Coastal erosion in this area of Delaware's Atlantic coast is approximately 3 m per year. Thus, in 1926, the old Cape Henlopen lighthouse fell into the sea (Figure 15). Coastal change in the area of Cape Henlopen continues at a very rapid rate. Figure 16 shows paleogeographic reconstructions of the Delaware coastal zone over the past 3000 years. A continuing erosion of the Atlantic shoreline and deposition of the Delaware Bay shoreline may be observed for the last 300 years. This process will continue into the future.

From Cape Henlopen southward to Fenwick Island, coastal erosion continues at varied rates (Figure 5). In those areas where man has developed the coastal zone, frequent damage occurs as a result of in-

Figure 14. An aerial photograph of Broadkill Beach, southern Delaware Bay. Note that the small village of Broadkill Beach tends to protrude into the Bay. The groin field and repeated beach nourishment by pumping sand from offshore has prevented major coastal erosion. However, to the north and south erosion continues at a rapid rate.

tensive coastal storms and long-term gradual erosion of the shoreline. At Rehoboth Beach and Bethany Beach, a groin field has been devel-

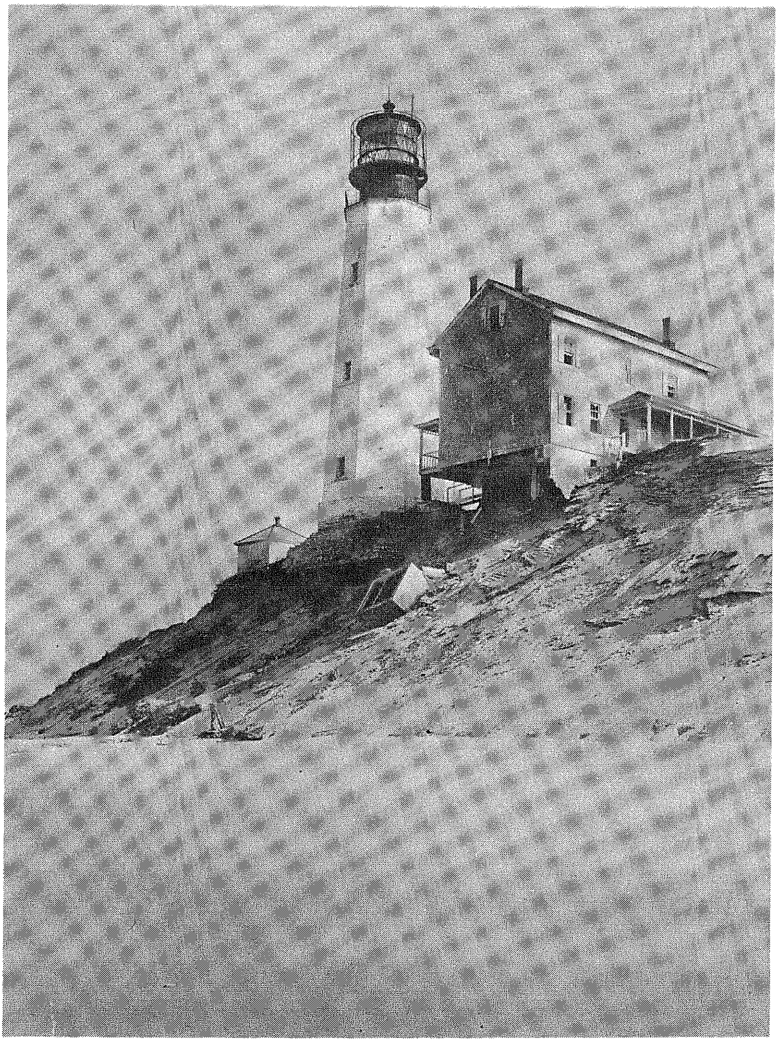


Figure 15. Coastal erosion along the Atlantic coast south of Cape Henlopen is at the highest rate along the Atlantic coast of Delaware. Cape Henlopen lighthouse constructed in 1760s and once 400 meters from the coast, fell into the sea in 1926. Photo by R. C. Wilson, 1926, used with permission of J. W. Beach.

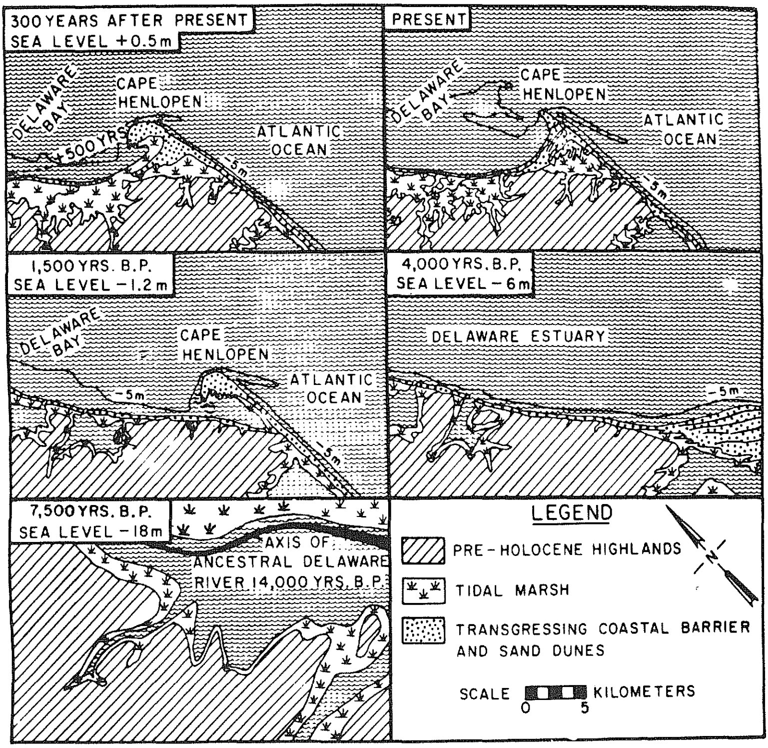


Figure 16. Coastal change in the area from Rehoboth Beach to Cape Henlopen continues at a rapid rate. Paleogeographic reconstructions shown are based on extensive geologic studies of this area. The Atlantic shoreline erodes while the bay shoreline infills Lewes Harbor. From Kraft et al. (1978).

oped to protect the coastal zone and entrap sand in front of the boardwalks. These measures slow down the rate of coastal erosion. However, elsewhere along the shoreline erosion continues at normal or even accelerated rates as a result of these groin fields. The towns of Rehoboth Beach and Bethany Beach tend to protrude slightly into the Atlantic Ocean. Accordingly, when massive coastal storm waves hit the shorelines of these developed areas, damage is heavy. Figures 17 and 18 show Rehoboth Beach after the early 1962 major "northeaster." Damage from the 1962 storm was exceptional because storm winds and waves stayed

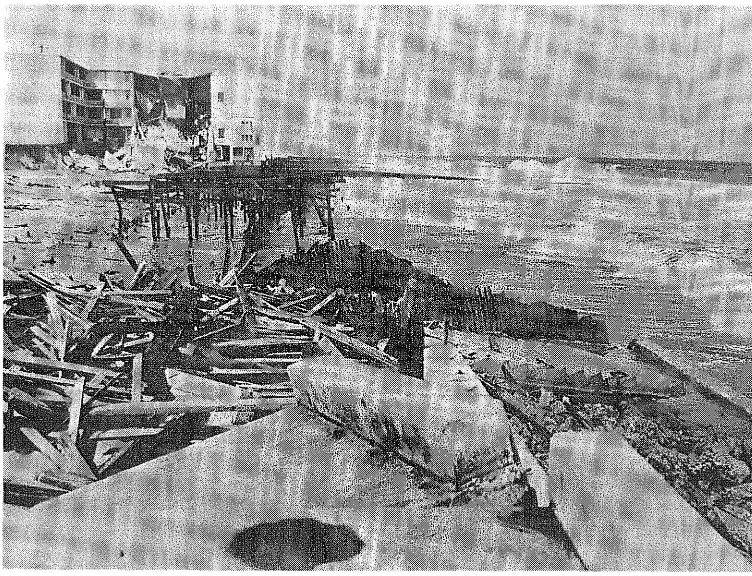


Figure 17. Rehoboth Beach, Delaware, March 1962. Courtesy of Delaware State Highway Department.

in position for a number of high tidal cycles. Normally, coastal storms move by the shoreline area at a relatively rapid rate, causing less damage. However, every coastal storm causes coastal erosion. Thus it may be anticipated that anyone who builds in the immediate shore zone area might anticipate damage to his structure. In some areas along the Delaware coast, people have placed buildings on the beach and berm in front of the coast-parallel dunes. Such practices ensure that the structures will be subjected to storm damage.

Evidence of Coastal Change

Continuous studies of the geology of Delaware's Atlantic coastal zone have been made over the past decade. From these studies it can be determined that the overall net movement of the barrier between the Atlantic Ocean and the coastal lagoon is landward and upward in space and time (Kraft, 1971a, b; Kraft et al., 1976; Kraft et al., 1973; Kraft and John, 1976; Kraft et al., 1974).

Intensive studies have been made of the coastal barrier south of Dewey Beach (Figure 19). This relatively narrow Atlantic washover barrier between the Atlantic Ocean and the lagoon, Rehoboth Bay, includes narrow linear barrier areas and broader areas of older tidal deltas. One tends to view barrier islands in terms of their surface expression. However, one should think of barriers as larger bodies, having three dimensions, and extending a short distance seaward and a longer distance landward along the adjacent lagoon. The barrier was formed by sands washing across the narrow strip during storms and depositing on the barrier-back and into the adjacent coastal lagoons. In the beach, berm, and foreshore area along the coast, major erosion occurs as Atlantic storm waves attack. We tend to think of erosion as occurring on the beach, but erosion actually occurs to a depth of approximately 10 m in the nearshore area. Figure 20 is a geologic cross section constructed

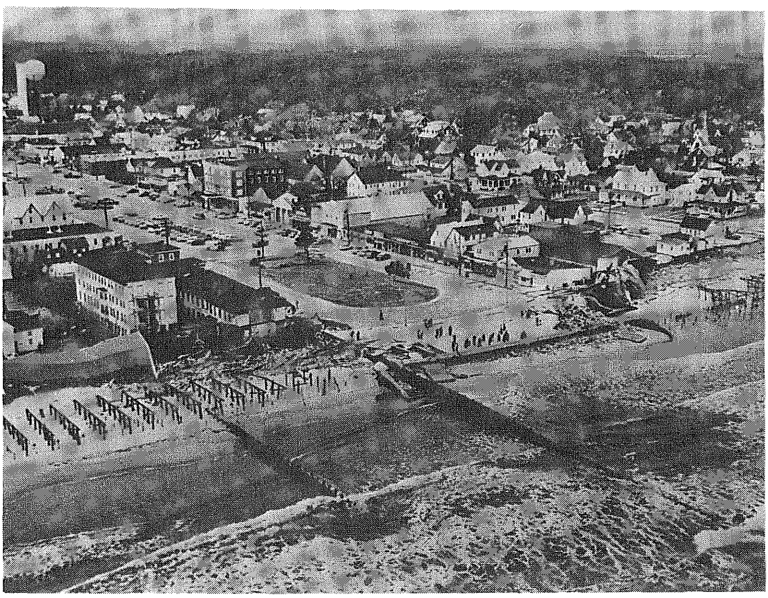


Figure 18. Rehoboth Beach, Delaware, March, 1962. Courtesy of the Delaware State Highway Department.

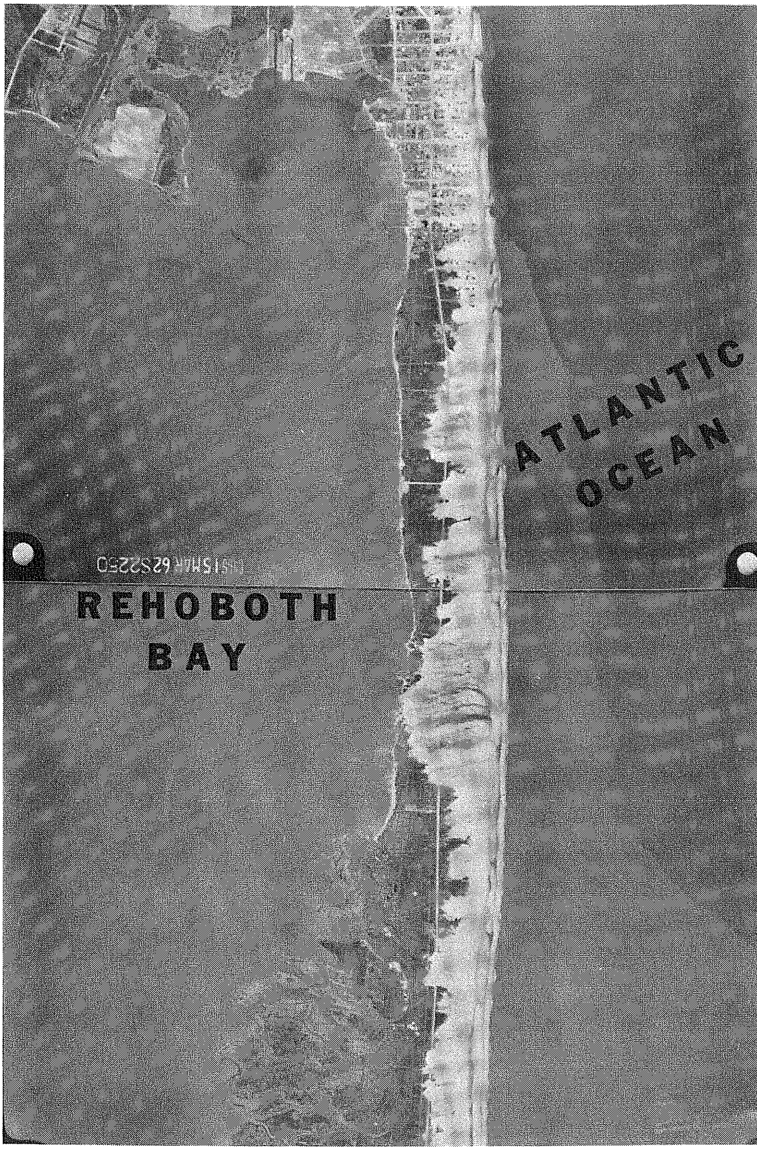


Figure 19. An aerial photograph of the coastal barrier between the Atlantic Ocean and Rehoboth Bay, south of Dewey Beach, Delaware. Much of the barrier is submerged under the waters of Rehoboth Bay to the left, and a few hundred yards under the Atlantic Ocean to the right.

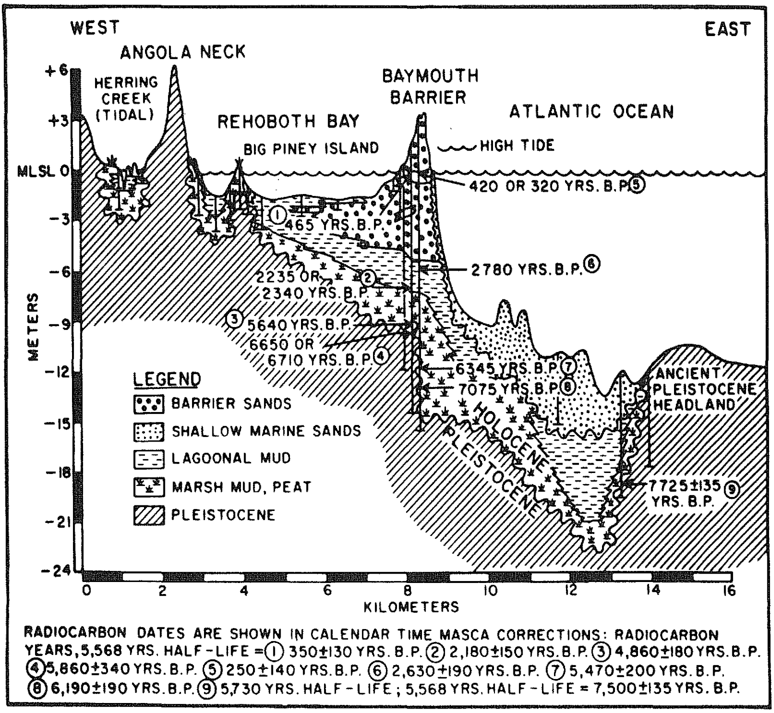


Figure 20. A geologic cross section across Rehoboth Bay, the Atlantic washover barrier into the inner shelf area under the Atlantic Ocean. Radiocarbon dates and drill-hole evidence show that present-day coastal environments were lower and farther eastward in this area 8 millennia ago.

from evidence gained from drill holes through the lagoonal sediments and the Atlantic barrier and nearshore submarine area. Information derived from the study of the sediments shows that the barrier overlies an ancient lagoon that is a continuation or extension of present-day Rehoboth lagoon. Furthermore, drill-hole information shows that lagoonal fringing marshes underlie the barrier and the nearshore marine area. Radiocarbon dates may be made of these salt marsh organic sediments; thus, we are able to determine that a lagoon barrier system existed in the region south of Bethany and eastward under the Atlantic shelf for

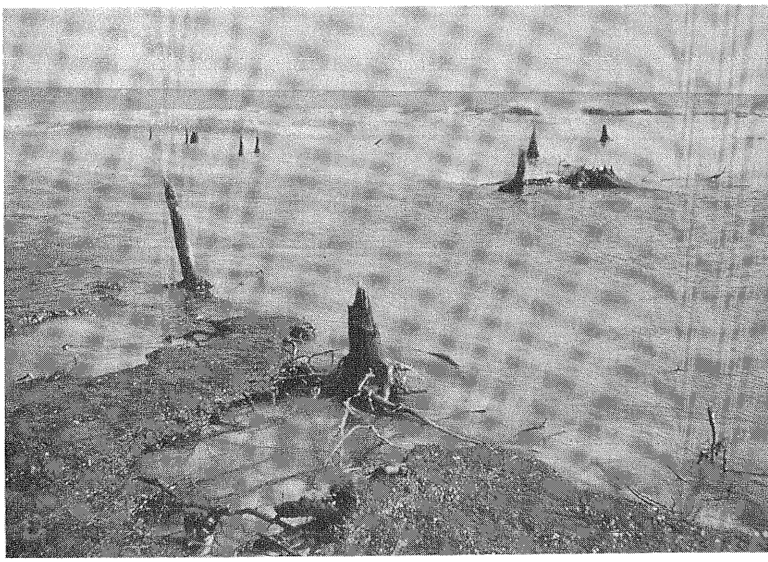


Figure 21. An ancient pine forest eroded in the surf after a moderate "northeaster" in the late 1960s. Normally a beach at least 2 m high covers the remnants of this old pine forest. However with every major coastal storm, the sands of the beach and berm are stripped away and this back-barrier pine forest of 300 years ago is exposed. This occurrence is an absolute indicator of relative sea level rise and major long-term coastal erosion.

at least the past 8000 years. Based on evidence found under the barrier at Indian River, we know that coastal lagoonal systems and salt marshes occurred in the region back to 11,000 years ago.

Observation of the barrier throughout a number of years shows many evidences of coastal change and erosion. For instance, it is fairly common for storms in the winter to erode away the beach and berm and form a nearby shallow offshore bar. During the summer, it is common for sands from this offshore bar to migrate back onto the beach and redevelop the berm. However, these storms can occur at any time during the year, although they are concentrated in the winter season. During some storms, sands are washed across the barrier and into the adjacent lagoons. At other times, sands from the beach and berm are blown by wind into the narrow dune field along the center of the barrier. Figure 21 shows the remnants of an ancient pine forest and its floor of pine needles and pine cones exposed in the surf after a northeaster that occurred in the 1960s. This pine forest is at present in a position of mean low sea level relative to the present ocean. When it was alive, approximately 250 to 350 years ago, the pine forest was on the back of a barrier island up to 1 m above sea level, above the level of tidal water intrusion. The coast of Delaware at that time lay a considerable distance seaward. Figure 21 is absolute proof of coastal erosion and relative rise of sea level versus land. This process has been ongoing at a relatively rapid rate for at least the past several hundred years.

Erosion along the Atlantic coast of Delaware continues. At present, some structures built in the coastal zone are being placed on the eroding beach-berm surface. Although one cannot predict with certainty the frequency of major Atlantic storms, the relatively minor northeasters that impinge upon our shoreline cause coastal erosion each year. Thus it is certain that structures that are built in front of the dune line along our coastal barriers are doomed to continual damage from storm erosion. Figure 22 shows an example of structures built in the eroding coastal zone. Should one desire to have a home built on a beach, one must anticipate continual maintenance problems and the possiblity of massive destruction.

Out of the Past and Into the Future

Fifteen thousand years ago sea level was over 100 m below present sea level and the coast lay over 50 km to the east of its present position. Since then, sea level has risen and the coast has eroded and transgressed across the coastal plain landward and upward in space and time to its present position. All indications are that this process will continue into the future. Man has been strongly affected in the past by this process. Many archaeological sites must have existed on this broad coastal plain and are now buried by the sea. Kraft (1977a, b); Kraft et al. (1976); and Kraft and Thomas (1976) indicate some of the relationships of archaeology and coastal change. Furthermore, the implications of man's present development of the coastal zone of Delaware are discussed in detail in Kraft et al. (1976). Our many present coastal sites will be strongly affected by ongoing coastal processes.

We do not know what the future holds. Our ability to project into the short-term future should be fairly precise. However, we are not out of the glacial age. Ice caps still exist in the world in Greenland and

Antarctica and sea level continues to rise. Should all of the world's ice melt, various projections have been made as to the elevation to which the sea would rise. These include possibilities from 60 m to 200 m above present sea level. Figure 23 is a schematic diagram, showing positions of Delaware's shoreline in the past, present, and predicted short-term (geologic time) future. Projections into the future in the longer term geologic sense are highly likely to be inaccurate. Sea level has risen to the point of an interglacial age, in which the world's ice has melted, over eight times in the past 1.5 million years. It might just as well be argued that we have recently undergone a high cycle of sea level rise and that the situation may reverse and go back into peak glacial time. The Wisconsin Epoch glaciation which occurred from approximately 80,000 to 10,000 years ago had at least four fluctuations or advances and retreats for the continental glaciers. We may be on the flank of one of these retreats. Thus the possibility exists that we are not out of true glacial times. Should glaciers again advance in the near future, sea level would lower and the coast would retreat and more coastal plain would become exposed. However, these are thoughts for the long-term geologic

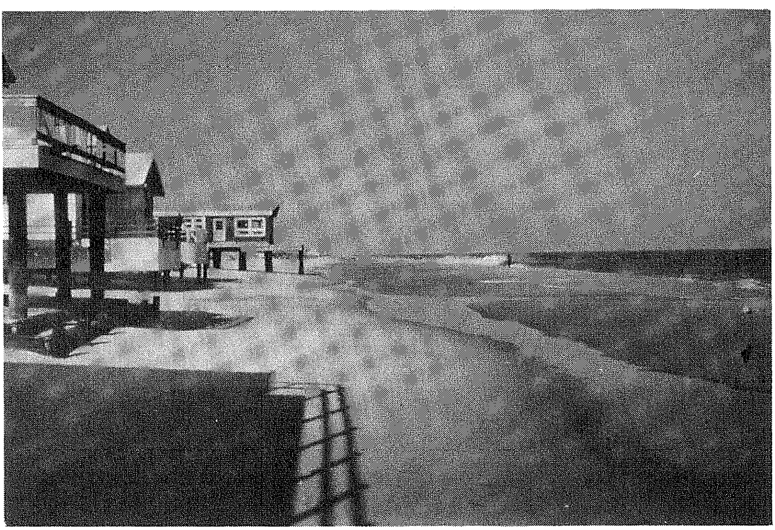


Figure 22. Coastal erosion continues. Some structures built in the coastal zone are placed on the eroding beach.

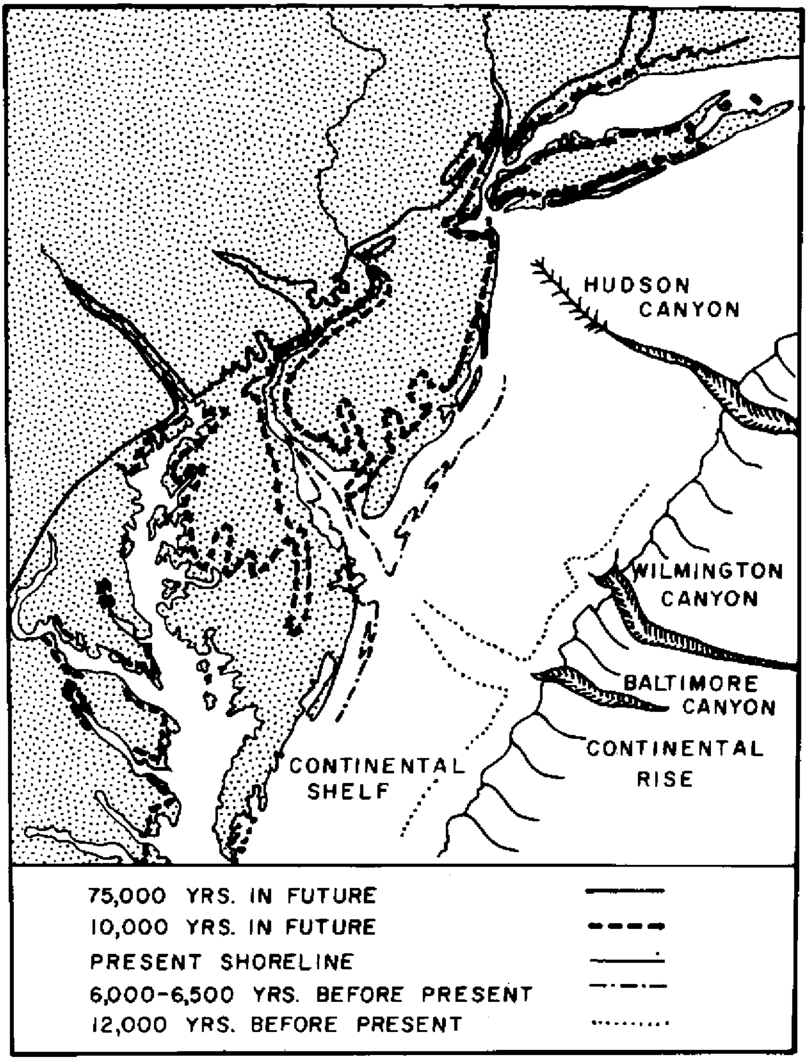


Figure 23. Delaware's shorelines, past, present, and future. Paleogeographic and predictive coastal positions are based on over 10 years of intensive geologic studies in the Delaware coastal zone.

future. We should concern ourselves more with the present and man's adaptability to the coast.

Man and the Coast

Man is inevitably attracted to the shoreline from the aesthetic point of view. The mere processes that are destroying the coast and ever causing it to change in shape and morphology are those that make it attractive to man and create the clean white sandy beaches that we all like. For the past several hundred years, man has adapted to occupying the coast by simply building as near to the strandline as he could. With the increased development of the coastal area, serious problems arise and much consideration must be given to the way in which we develop the coastal zone.

An example is Indian River Inlet, Delaware (Figure 7). In the earlier part of this century, many problems existed with Indian River Inlet constantly opening and closing with the natural littoral transport of sands and storm surge channel cutting. At times of high rainfall, the levels of the coastal bays would rise and flood adjacent farm land. In addition, access to the sea for fishermen was frequently restricted. Accordingly, the United States Army Corps of Engineers constructed the stone-walled jetties that are shown in Figure 7. This ensures that a deep inlet, with strong tidal currents, will scour and maintain an opening to the sea. On the other hand, the intrusion of the jetties into the Atlantic Ocean has caused an accumulation of sand on the updrift side and severe erosion on the down littoral transport side of the jetties. Wave refraction around the jetties plus the fact that sand is not bypassing the inlet effectively causes severe erosion. This erosion has extended to the footings of the highway across the bridge at Indian River Inlet. Many actions have been taken to stop this, including dumping of sand on the beach by trucking it to the place of erosion, dredging sand from shoals in the adjacent lagoons onto the beach, and building snow fences in an attempt to establish dunes on the beach-berm itself. Inevitably they must fail. Probably the best way to protect the shoreline under these conditions is to continually feed the beach the amount of sand that is eroded away or to build a massive sea wall.

The great storm of 1962 is well remembered by occupants of the coastal zone, although man's actions in the 1970s might belie this. Since 1962, Delaware's coastline has undergone continuous erosion and storm damage by "northeasters" as they pass along the Delaware coast. Fortunately, none of these storms has developed to the intensity and time length of the storm of 1962. Damage to the Delaware coastline in 1962 was valued at many millions of dollars. Statistical predictions suggest that a storm of 1962 proportions or worse could occur again. It is inevitable that all variants of northeasters, hurricanes, and average coastal erosion will occur. In view of this inevitability, man must learn to live with these storms and adapt. Presently, coastal zoning laws are being only partially applied. It is clearly recognized that the dunes are a potential protective device for structures in the coastal zone, yet many people destroy the dunes on their property. In addition, the berm of upper beach area is an area of washover at every spring tide or high tide and certainly an area of major erosion during even a minimal storm. In spite of this, people in Delaware are building houses on the dunes and berm-beach. Figures 17 and 18 show a post-storm coastal configuration in 1962. It would seem that the public has ignored history of coastal erosion.

To understand the nature of Delaware's coast, its zones and environments, its morphology, and its rates of change is not enough. The people of Delaware must discipline themselves to properly occupy the coastal zone. A major problem is that the frequency of storms and their magnitude is erratic. Statistically it can be told when a hurricane or northeaster will hit the Delaware coast and potentially cause major damage. Prediction by statistical chance is a highly developed science. However, the actuality is that one major "one in a hundred year" storm can be followed by another storm of similar magnitude within a period of a few days. The likelihood of this is extremely low; however, it is possible. Furthermore, in spite of the relatively long time between storms of major damage, even the storms with minor damage potential are such that they can destroy some of Delaware's present coastal structures.

Planners have discussed this problem for a long time. Many people have thought intensively about the problem. One school suggests that we should simply let everything be and allow the coast to erode. This would require that we step back from the beach a relatively short distance and allow the beach to wander and migrate landward at is present rate. This seems to be intolerable to many occupants of the coastal zone. Our major cities must of course be protected. However, the cost of protecting and holding a shoreline position for a long number of years greatly exceeds the value of land and property that is being protected.

Costs of protection of Delaware's coast over the next 50 years have been estimated from 100 million to 1.5 billion dollars. The question must be asked: "Is it worth it?"

Some say that we must develop the coasts for industrial reasons. The same problems of occupancy of the coastal zone will affect the industrial occupant. There are many alternatives and other approaches or solutions to problems of harbors in Delaware that must be explored. We should not simply say that Lewes and Wilmington are the only viable ports in Delaware. Alternatives may vary from reoccupying important harbors of the eighteenth and nineteenth centuries to creating new harbors to creating offshore harbors. The number of variants of actions that man may take in the coastal zone is infinite. The greatest danger lies in that man may take these actions without properly considering their cost-benefit ratios or without even bothering to consider the presently ongoing processes of coastal change in Delaware.

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4

Geology of the Atlantic Continental Margin Off Delaware

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SEISMIC exploration has identified eight distinct basin structures along the North American Atlantic continental margin forming a chain of elongate depocenters parallel to the continental slope and interrupted by transverse basement arches and impinging oceanic fracture zones (Figure 1). All the basins are characterized by great depths to basement filled with more than 7 km of possible Triassic, Jurassic, Cretaceous, and Tertiary sediments. Basement faulting apparently controls the basins' boundaries.

Two typical basins of the Atlantic margin geosyncline are the Baltimore Canyon Trough east of Delaware and Blake Plateau Basin east of Florida. Publicly available multichannel seismic reflection data and interpretations were used to construct the cross sections of these sedimentary basins off the United States (Figure 2). Sources include the

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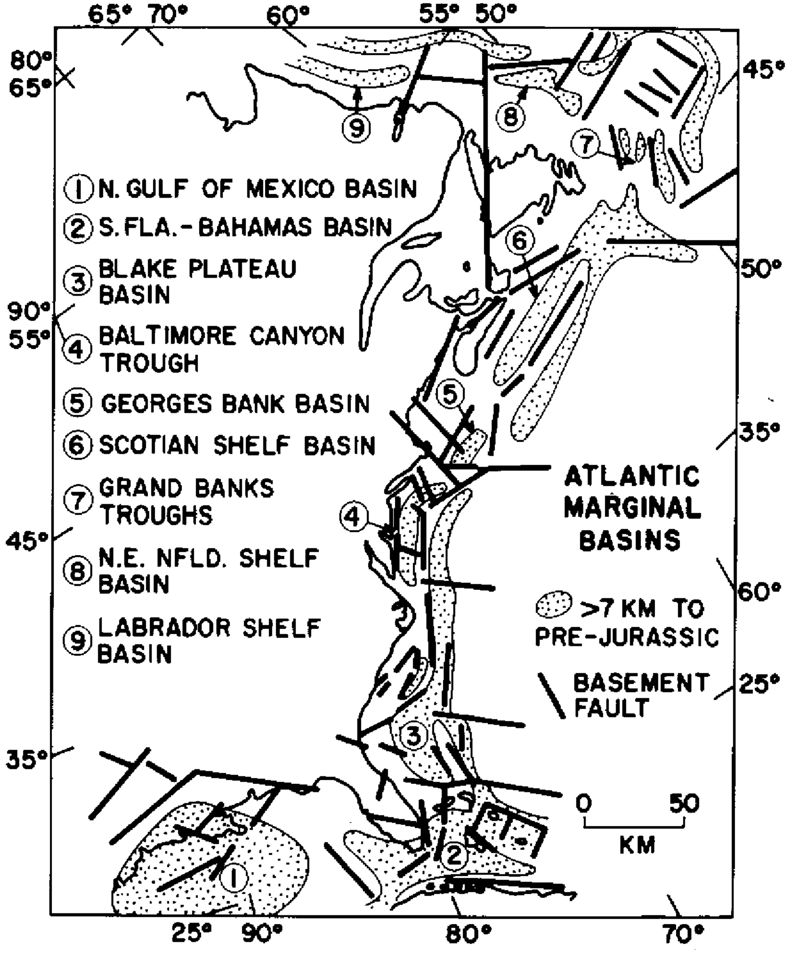


Figure 1. Major structural basins of the North American Atlantic continental margin geosyncline, showing interpreted basement faults (after Sheridan, 1974a). Note the Baltimore Canyon Trough (4) off Delaware.

petroleum industry (Schultz and Grover, 1974; Scott and Cole, 1975), government agencies such as the United States Geological Survey (Dillon et al., 1976; Grow et al., 1975; Mattick et al., 1974; Schlee et al., 1975), as well as the work of oceanographic institutions such as Lamont-Doherty

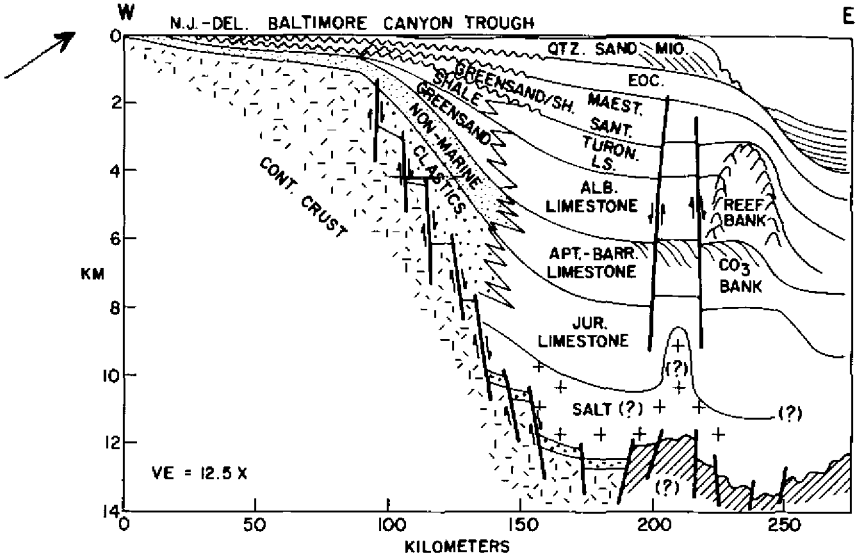
Geological Observatory (Windisch et al., 1976). In addition, information from University of Delaware single channel seismic data was incorporated into the cross sections (Figure 3).

This seismic information, when integrated with the available drilling information such as the Deep Sea Drilling Project data (Benson et al., 1976; Ewing and Hollister, 1972), existing D/V CALDRILL data (JOIDES, 1965, Weed et al., 1974), and the drilling information on the Atlantic coastal plain (Brown et al., 1972; Maher, 1965; Perry et al., 1975) yields a reasonably detailed picture of the Jurassic and younger stratigraphy in the Baltimore Canyon Trough off Delaware and Blake Plateau basin off Florida.

Essentially, the picture that emerges is one of basins having basement depths of from 4 to 14 km where depths can be measured. In some areas under the Baltimore Canyon Trough and the Blake Plateau Basin, high-velocity limestones and olomites mask the basement even on the most modern reflection profiles. Thus, in some cases, depth to the basement rocks of the continental shelf cannot be accurately measured. Where the basement is observed it is commonly faulted.

The basement faulting along the Atlantic margin is known to have been important during the Triassic and younger periods as well, such as the half-graben development on the Grand Banks which occurred more in the Jurassic (Amoco Canada Petroleum and Imperial Oil, 1974). Brown et al. (1972) attributed much of the change in sedimentary geometries in the Atlantic coastal plain of the Baltimore Canyon Trough to movements along these suspected basement faults, indicating that these faults were apparently active throughout the Mesozoic and Cenozoic eras. Recently, high resolution seismic reflection surveys have found Pleistocene and younger faults just below the sea floor, attesting to the possible continuing activity on these older subsurface faults (Sheridan and Knebel, 1976). While the major basement faults forming the boundaries to these basins very likely originated with the initial rifting along the North American margin in Jurassic or perhaps Triassic, there apparently has been some recurrent activity along these faults as the basins formed and sediments accumulated.

Sheridan (1974a) has mapped major basement faults by the location of prominent lineaments such as hinge zones and magnetic anomalies or magnetic discontinuities (Figure 1). Boundary faults parallel the trend of the Atlantic margin and are interrupted by the impingement of transverse oceanic facture zones. Arches and platforms in the continental basement often strike transverse to the basins' alignments.


W
N.J.-DEL. BALTIMORE CANYON TROUGH
E
QTZ. SAND
MIO.
EOC.
GREENSAND/SH.
SHALE
GREENSAND
MAEST.
SANT.
TURON. LS.
NON-MARINE
CLASTICS
CONT. CRUST
ALB. LIMESTONE
REEF BANK
APT.-BARR. LIMESTONE
CO_3 BANK
JUR. LIMESTONE
(?)
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VE = 12.5 X
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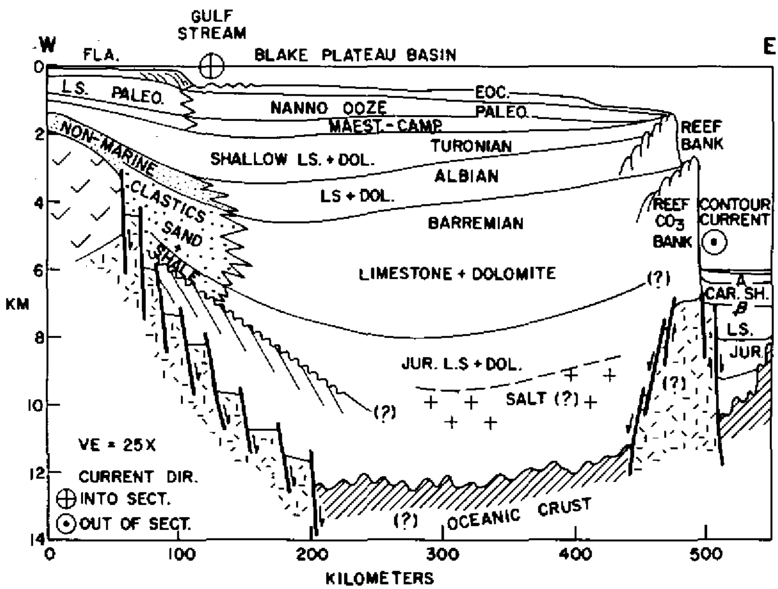
GULF STREAM
W
FLA.
BLAKE PLATEAU BASIN
E
L.S.
PALEO.
EOC.
NANNO OOZE
PALEO.
MAEST.-CAMP.
REEF BANK
NON-MARINE
TURONIAN
SHALLOW LS. + DOL.
ALBIAN
CLASTICS
LS + DOL.
SAND + SHALE
REEF CO_3 BANK
CONTOUR CURRENT
BARREMIAN
LIMESTONE + DOLOMITE
(?)
A
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B
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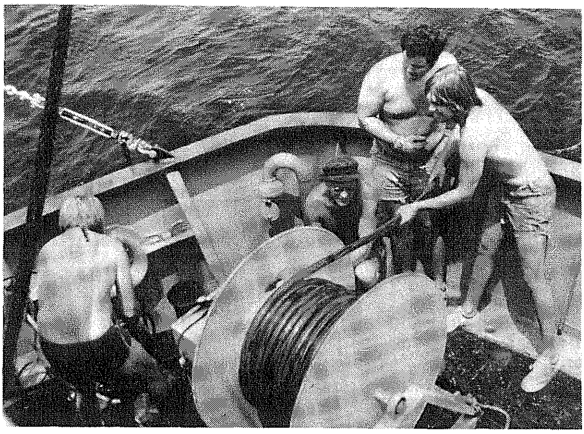


Figure 3. University of Delaware geology and geophysics students launching the single channel seismic reflection hydrophone in studies of Delaware continental margin.

These features form important boundaries. Interruptions by arches and fracture zones along the continental margin led to the isolated nature of the basins.

The Blake Plateau Basin east of Florida (Figure 2) is a north-south-striking structure bounded on the southwest by the Peninsular Arch of Florida and the impingement of Great Abaco fracture zone, and on the north by the southeast-trending Cape Fear Arch and the northwest-striking Blake Spur fracture zone. No deep drilling has been done in the basin proper, but shallow coring by the JOIDES Program and the Deep Sea Drilling Project have sampled the Tertiary and Cretaceous sequence in stair-step fashion on the Blake Plateau (Benson et al., 1976; JOIDES, 1965). Limestones as old as Barremian have been drilled on the Blake Nose, corresponding to reflectors as deep as 4 km (2.6 sec) under the plateau. Also, extensive rock dredging of the Blake Escarpment (Heezen and Sheridan, 1966; Sheridan et al., 1971) reveals that a thick section of Cretaceous limestones and dolomites, at least as old as Berriasian, underlies the plateau up to 5 km in depth. The drilling of Jurassic on

Figure 2. (opposite) Diagrammatic cross sections of Baltimore Canyon Trough east of Delaware and Blake Plateau Basin east of Florida based on interpretation of all available data (Sheridan, 1976).

the Bahamas to the south (Meyerhoff and Hatten, 1974) suggests that the deeper sediments under the Blake Plateau are of this age.

The Baltimore Canyon Trough (Figure 2) is a northeast-striking basin that appears to be segmented into smaller, separate basement depressions, one off Maryland, one off New Jersey-Delaware, and one south of Long Island (Sheridan, 1974b). The basin extends from Cape Hatteras in North Carolina to Long Island. On the northeast it is terminated by the Long Island Platform and the impingement of the Kelvin fracture zone. Seismic reflection data also reveal a large doming by an igneous body in the center of the Trough off New Jersey (Mattick et al., 1974).

Drilling has only been done on the western flank of the basin in the emerged Atlantic coastal plain, where Jurassic through Holocene sediments have been recovered (Brown et al., 1972). Only a few CALDRILL and DSDP shallow core holes recovering Eocene and younger sediments exist on the continental slope (Ewing and Hollister, 1972; Weed et al., 1974). A 4900-m off-structure stratigraphic test has been drilled in the basin proper by a consortium of petroleum companies. The drill information confirms the extrapolation of coastal plain stratigraphy to the outer continental shelf (Continental Offshore Stratigraphic Tests, COST). Extrapolations suggest Jurassic-Cretaceous carbonates are present offshore.

Mechanics of Basin Formation in the Baltimore Canyon Trough

Enough detailed information is available on the Baltimore Canyon Trough and the Blake Plateau Basin so that their development might now be examined in hopes of deriving a suitable model for the Delaware margin. The diagrammatic cross sections of these basins shown in Figure 2 are the author's interpretations based on all available information. At this stage of analysis, much of the interpretation is based on extrapolation and geologic reasoning. Much of what is shown is based on sufficient data to be widely accepted. Several features of these marginal basins should be noted (Figure 2):

1. Great subsidence of the basement to 12-14 km depths since Jurassic, perhaps Triassic
2. Clastic nonmarine sand and shale facies for the Jurassic-Early Cretaceous where drilled onshore along the flanks of the basins

3. Thick accumulation of carbonates and evaporites offshore in the Jurassic and Early Cretaceous
4. Development of Cretaceous reef and carbonate bank complexes along what is now the continental slope and Blake Escarpment
5. Clinoform bedding progradations of carbonate bank and reef bank buildup until Aptian/Barremian, when this phase of bank construction terminated with a regression
6. Continued reef-bank development farther south along the Blake Escarpment until termination in possibly the Coniacian
7. Overlap of the reef banks by Santonian/Campanion and younger nonreefal and nonbank facies
8. Major regressive hiatuses on the onshore coastal plain in Coniacian, Paleocene, and Oligocene, each overlying marine facies of major transgressions
9. Westward differential dip of Barremian through Maestrichtian beds
10. Planar bedding episodes of widespread reflectors in the Barremian through Eocene
11. Intrusive igneous doming after the Albian but before the Cenomainian
12. Faults and horst structures along the outer edges of the basins either from basement uplifts along this area or from possible salt movements
13. Fault activity along these outer marginal fault zones persisting through the Tertiary and into the Pleistocene or Holocene
14. Prograded bedding and shelf edge buildout in the Miocene, except where prevented by the Gulf Stream on the Blake Plateau

Any thesis for basin formation off Delaware will have to consider all of these observations; it is hoped an explanation can be provided.

Regional Subsidence

It is reasonable to assume that the broad drastic regional subsidence of the Delaware margin continuing since the Jurassic is probably caused by some deep crustal process such as cooling and densification of the lithosphere as it spread away from the heat source at the mid-Atlantic Ridge (Sleep, 1971). Clearly such a mechanism is required since the sediment loading by clastic input was low or nonexistent during deposition of much of the chemical carbonate and glauconitic greensand facies of the margin.

The fault-block nature of the basement and its interruption by fracture zone impingements can be explained by the faulting that occurred in the initial rifting of the Atlantic Margin in Jurassic or perhaps Triassic. As the North American and African crust fractured, faults aligned along old lines of weaknesses, with initial offsets in the fracture pattern perhaps connecting a series of triple rift junctions over individual hot spot welts. Once the continental crust of the margin was initially offset along an ancient transform, each part of the margin subsided as spreading proceeded according to its offset distance from the ridge axis; each part of the margin, being offset from the other across ancient transform faults, subsided relative to the others across what became transverse hinge-fault boundaries (King, 1974). Thus the individual basins became isolated along the strike of the margin and subsided somewhat independently.

Meanwhile, nonmarine clastic deposits from the eroding Appalachians in the Jurassic-Early Cretaceous gave way seaward to carbonate and evaporite facies forming in the isolated narrow marine seaway invading the juvenile Atlantic Ocean.

Although this scenario explains many of the observations of the Atlantic margin geology, namely, items one through four above, it does not explain the other items.

Differential Subsidence

Brown et al. (1972) studied the isopach and facies patterns of time-stratigraphic units of the Atlantic coastal plain on the flank of the Baltimore Canyon Trough. They determined that the area was controlled by basement hinge zones, one trending north-south and one N25°E, which acted independently in time throughout the Cretaceous and Tertiary. The motion of these hinge zones was such that there was a slight westward tilt and thickening when the north-south hinge zones were active, whereas there was a southeast tilt and thickening when the N25°E hinge zones were active. Brown et al. (1972) took these hinge zones to be basement faults whose movements would reflect east-west and northwest-southeast extensional stress axes which alternated in time. Associated with these north-south and N25°E extensional faults were complementary northwest-southeast-striking and north-south-striking right-lateral shear fractures, respectively.

On a regional scale, these same major basement fault trends can be seen to exist on the Atlantic continental margin (Figure 4; Sheridan, 1974b). If the boundary faults of the Blake Plateau define an east-west extensional axis, then the Atlantic Ocean fracture zones would act as right-lateral shear faults complementary to the east-west extension, and the White Mountain igneous trend would have a right lateral shear zone complementary to the northwest-southeast extension. These two distinct stress systems are therefore named the Atlantic Ocean stress sys-

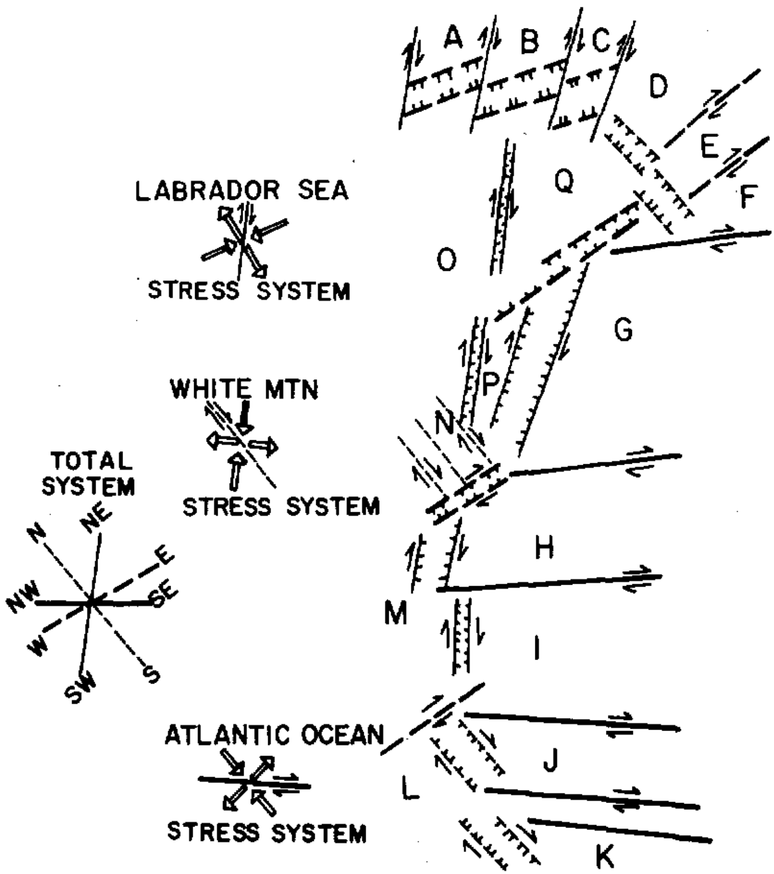


Figure 4. Fundamental basement fault and local stress systems of the Atlantic continental margin geosyncline (Sheridan, 1974b). Blocks A-K essentially on oceanic crust, L-O on continental crust. For location reference, L = Florida, M = mid-Atlantic states, N = New England, P = Nova Scotia, Q = Newfoundland-Grand Banks.

tem (referring to when the Atlantic fracture zones were active shears) and the White Mountain stress system (referring to when the White Mountain linear igneous trend was an active shear zone). Analogously, the Labrador Sea stress system can be defined by the extensional axis causing active shear on the northeast-trending fracture zones there. Thus with the existing Atlantic Margin fault system, three local stress systems can be deduced.

The findings of Brown et al. (1972) indicate that the Atlantic Ocean stress system (their first-order tectonics) and the White Mountain stress system (their second-order tectonics) were an alternating influence on the Baltimore Canyon Trough. These independent stress systems appear to be overlapping in space but acting independently in time.

On a first-order approximation scale, the Atlantic margin is actually on the North American plate interior and therefore it should be a torsionally rigid structure. However, the larger plate rotation caused stresses on the existing faults of the Atlantic margin, and slight intraplate shearing resulted from the larger rotational couple set up by the slight differential rotations of the North American plate.

To check this, the extension on the basin boundary faults and the shear on the transverse fracture zones were removed to restore the Atlantic margin to a hypothetical unit structural block (Figure 5). This model indicates that slight differential spreading in the Labrador Sea and Atlantic Ocean, producing a clockwise rotational couple on the unit structural block, would create the right-lateral shearing and extension as observed.

Brown et al. (1972) found that the White Mountain stress system dominated the Baltimore Canyon Trough during the earliest Cretaceous through Aptian, then the Atlantic Ocean stress sytem affect the basin for the Albian through early Eocene (Figure 6), with a return to the White Mountain stress sporadically throughout the Eocene through Holocene. These periods of stress direction can be correlated very well with the periods of various drift orientations of Africa/Europe away from North America (Pitman and Talwani, 1972). For example, during the Neocomian to Aptian, the White Mountain stress system would be compatible with extension to the southeast just as Africa was drifting away to the southeast. During the Albian to early Eocene, the Atlantic stress system with east-west extension occurred just as Africa together with Europe drifted east relative to North America. This major change in orientation in sea floor spreading roughly corresponds to the activation and opening of the Labrador Sea in Late Cretaceous.

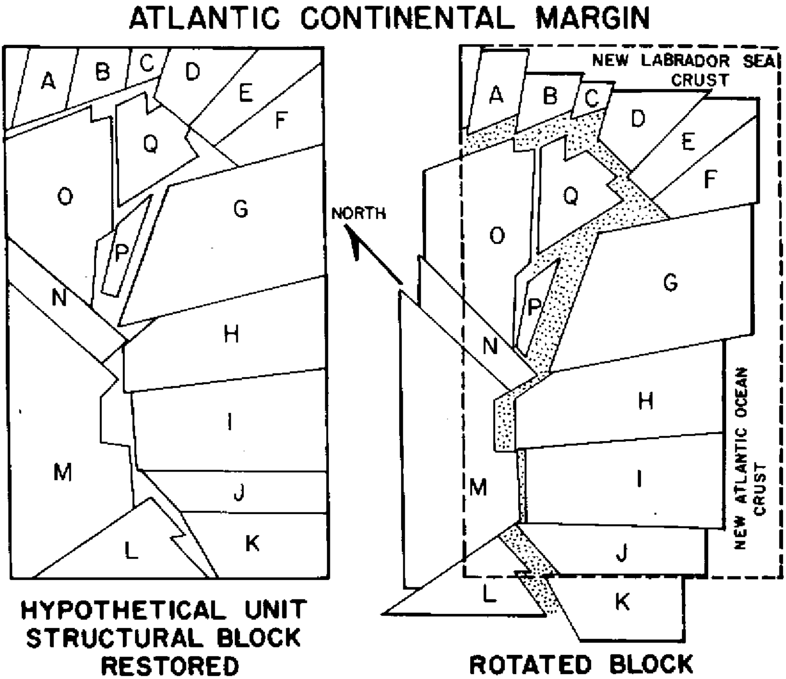


Figure 5. Reconstruction of hypothetical unit structural block of Atlantic continental margin geosyncline and clockwise plate rotation which produces the interpreted basement fault motions (Sheridan, 1974b). The speckled pattern represents the depositional graben of the geosyncline.

In the late Eocene, the return to the White Mountain stress system corresponds to a more southeast drift of Africa and Europe away from North America when the Norwegian Sea began to spread and the Labrador Sea became inactive.

Basically, it appears that the differential subsidence within individual basins, such as that causing the westward dip of the Barremian to Maestrichtian beds under the Blake Plateau, can be attributed to local stress systems produced by slight intraplate shearing and rotational couples causing local tilts of existing basement blocks. These cross-strike tilts occurred in sympathy with epochs of sea floor spreading orientations, and the tilts changed as sea floor spreading directions changed.

Some consequences of the westward tilt in the Baltimore Canyon Trough and Blake Plateau Basin were a subsidence of the source area enhancing the Cretaceous transgressions, and the creation of a broad flat shelf with a stable outer margin which caused widespread planar bedding.

A consequence of the clockwise rotational couple produced by slight differential rotations of the larger North American plate was the development of local shearing along older faults and fractures. When this occurred, igneous intrusions episodically invaded the shearing fractures. This resulted in the White Mountain Magma Series being intruded between Jurassic and Aptian, and the Kelvin Seamounts should have been intruded between Albian and Eocene. The intrusion under the New Jersey shelf in the Baltimore Canyon Trough apparently is related to the Kelvin Seamount intrusions, being Albian-pre-Cenomainian in age.

Termination of Reef Bank Development

The marginal carbonate bank and reef complexes identified in the Baltimore Canyon Trough and Blake Plateau are significant in their con-

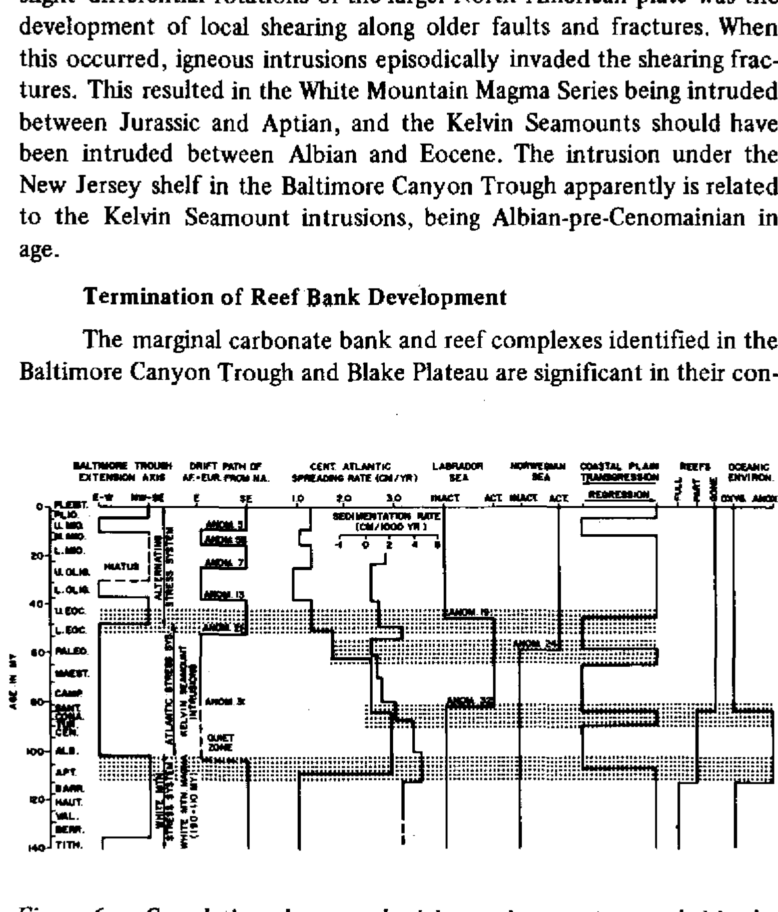


Figure 6. Correlation chart synthesizing major events recorded in the sedimentary buildup of the continental margin off Delaware, with major sea floor spreading events for the central Atlantic (Sheridan, 1976). Sea floor spreading rates and directions are from Pitman and Talwani (1972); sedimentation rate for the Cape Hatteras area of U.S. Atlantic coastal plain from Rona (1973) and Brown et al. (1972) data.

trol of the position of the shelf edge in the past. It is evident that carbonate outbuilding has changed the horizontal position of the continental slope some tens of kilometers through time (Figure 2).

The age of the carbonate banks and reef complex off Delaware are not known by drilling, but only by seismic correlation to the coastal wells. These correlations indicate a massive bank development up to possibly Aptian/Barremian time and a smaller marginal reef complex continuing to exist into the Aptian with termination by Albian.

On the Blake Plateau the age of the reef-bank development is better known from dredging the Blake Escarpment where contour currents have eroded back and exposed the reef rock (Heezen and Sheridan, 1966; Sheridan et al., 1971). Also, DSDP drilling has recently been completed on the Blake Nose where the deeper reef complex was definitely cored. A Barremian termination was documented in DSDP Site 392 where the reef complex apparently destroyed by exposure in a regression. Other reef banks persisted farther west to build the edge of the Blake Escarpment 1000 m shallower before final termination of the reef building by Campanian. These drilling studies also indicated that the Campanian overlies a marked hiatus, suggesting a change to strong bottom currents just before Campanian.

These correlations indicate that the reef and bank development phases and terminations in both the Baltimore Canyon Trough and Blake Plaeau Basin were nearly coeval and, therefore, that these events reflect major changes in the basins' sedimentary development.

The regression in Aptian/Barremian time would correlate with the change in local stress systems and differential tilts from southeast to west, which occurred because of the major change in sea floor spreading direction at about this time (Figure 6). Also, because of the boundaries of the just-forming Atlantic at that time, before the Labrador and Norwegian seaways existed, the deep Atlantic basin became anoxic and carbonaceous clays began to be deposited. Thus a change in environment might have impeded the recovery of the reef-bank complex after the local regression.

The termination in reef bank development in Santonian/Turonian might also be attributed to a regression and sympathetic oceanic circulation change. There is good evidence for a Coniacian regression in the New Jersey coastal plain followed by a Santonian/Campanian transgression (Petters, 1976). Such a regression correlates with a reduction in sea floor spreading rate at this time and with the opening of the Labrador Sea (Figure 6). Both these effects could have caused a eustatic drop in sea level by decreasing the world wide volume of the mid-ocean ridges and by the abrupt foundering of the Labrador seaway. Also, opening the Labrador seaway as a deep ocean body could have increased the cold bottom-current circulation and ended the stagnation of the deep Atlantic basin. These profound environmental changes impeded recovery of the reef-bank development after Campanian.

Transgressions and Regressions

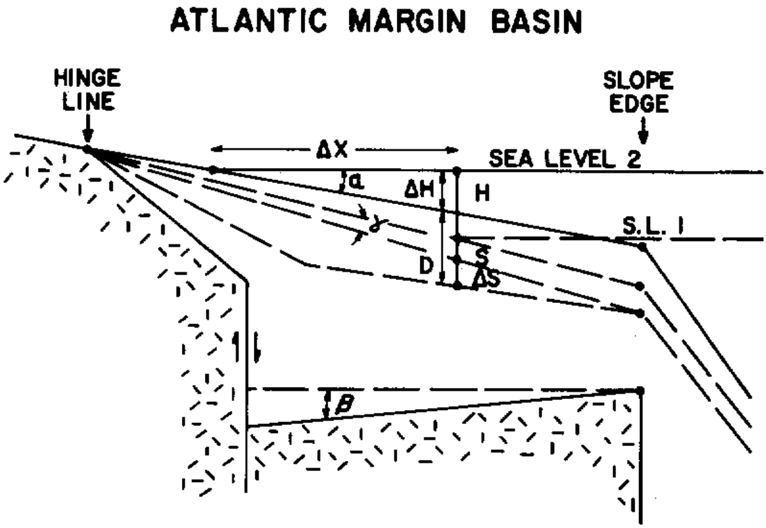
From the evidence available, it seems that the reef-bank terminations were related to regressions affecting the Atlantic Margin basins, but these regressions were sympathetic to changes in sea floor spreading, which triggered sympathetic oceanwide circulation changes.

To examine the influence of changes in sea floor spreading rates on transgressions and regressions at the Atlantic margin, a simplified model is useful (Figure 7). The essentials of this model are (W. Pitman, personal communication):

1. Transgressive and regressive excursions across a shelf of equilibrium profile depend on the relative sea level rise and fall, respectively.
2. Relative sea level changes can be larger or smaller than eustatic ridge-volume-related sea level changes depending on the amount of marginal, regional, and differential subsidence versus the amount of sediment deposition upbuilding the shelves.

Making some simplifying assumptions, a relationship can be ascertained between sea transgressions and the eustatic effect of sea level rise due to a worldwide increase in ridge spreading rates, and consequent decrease in volume of the ocean basins caused by the increased volume of the ridges. It is evident from the data on sedimentation and subsidence rates on the Atlantic Margin (Brown et al., 1972; Rona, 1973) that the subsidence and sedimentation rates increase as sea floor spreading velocities increase (Figure 6). Therefore, increased spreading rates, which cause a eustatic ridge-volume-related sea level rise, will be offset by increased sedimentation versus subsidence at the margins. For the Atlantic margin off the United States the subsidence and sedimentation rates are of the order of 2×10^{-3} times the sea floor spreading rates.

The increased subsidence and sedimentation rates with increased spreading rates are apparently due to the regional tilt of the margin, which would increase when the margin subsided along with the deeper basin in response to isostatic loading under the increased volume of water. This increased tilt also uplifted the continental source area more



$$\Delta X = \frac{1}{\tan \alpha} \qquad \Delta H = \frac{1}{\tan \alpha}(H + S + \Delta S - D)$$

ΔX = TRANSGRESSION DISTANCE

ΔH = RELATIVE RISE OF SEA LEVEL

H = EUSTATIC RIDGE VOLUME EFFECT

S = REGIONAL SUBSIDENCE

ΔS = DIFFERENTIAL SUBSIDENCE

D = DEPOSITION

α = SLOPE OF EQUILIBRIUM PROFILE

Figure 7. Simplified model of U.S. Atlantic Margin basin such as the Baltimore Canyon Trough off Delaware showing elements critical to transgressions and regressions across the continental shelf and coastal plain (Sheridan, 1976).

and allowed erosion of clastic deposits for increased deposition in the basin and buildup of the shelves.

Thus it is an interplay of marginal subsidence and sediment input versus eustatic ridge-related sea level rise that controls transgressions and regressions across the shelf. Because the sedimentation and subsidence rates are so much smaller than the sea floor spreading rates, the subsidence and sedimentation effects tend to lag behind and be more time-dependent than the eustatic ridge-related sea level changes (Figure 7). As a simplification, the eustatic ridge-related effects can be thought of as abrupt, more instantaneous changes compared to the more time-dependent subsidence and sedimentation effects.

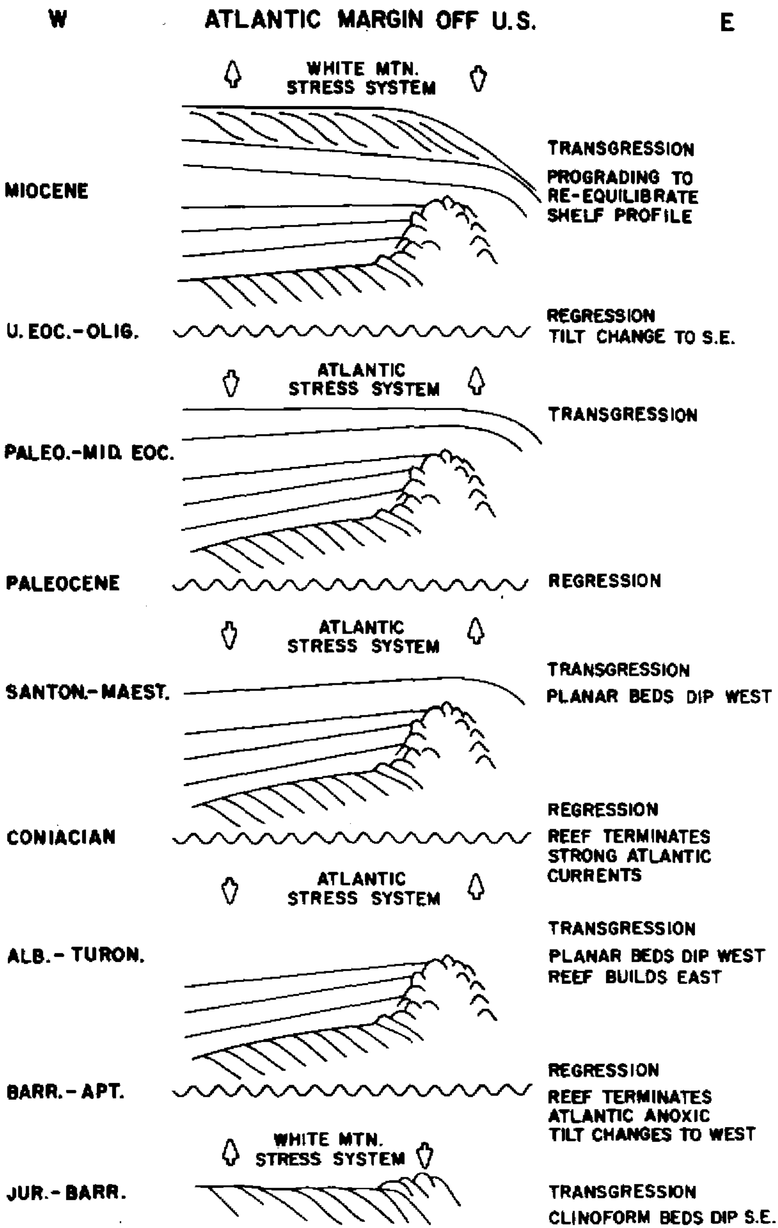
It is interesting to note that all the regressions and transgressions noted on the Atlantic coastal plain could be generated in this way (W. Pitman, personal communication). Also interesting is that even though the sea floor spreading rates decreased from a maximum in Albian to a minimum in Oligocene, which caused a drop in eustatic sea level throughout this time, the balance between regional and differential subsidence and deposition rates still caused transgression in the Santonian-Maestrichtian, Paleocene, and lower Eocene after major regressions.

How are these transgressions, even with dropping eustatic sea level, explained? Apparently, the more abrupt increase in the rate of eustatic sea level drop caused by sea floor spreading rate decreased, such as the Coniacian, resulted in abrupt regressions across the Atlantic coastal plain and shelf to a new point of equilibrium. Later, the decrease in sedimentation versus subsidence rate, which is more time-dependent, caused an apparent relative sea level rise as less and less sediment outbuilding took place with continued subsidence. Thus transgressions followed the abrupt regression as the marginal sedimentation regimen reequilibrated to the change in spreading and regional tilt rates.

Evolution of Atlantic Margin Off Delaware

Applying these correlations between sea floor spreading directions and differential subsidence of the Atlantic basins, between sea floor spreading rates and sedimentation rates, and between changes in spreading rates and transgressions and regressions, a simplified model can be developed to explain the buildup of the Delaware margin's sedimentary geometries (Figure 8):

Figure 8. (opposite) Time-sequential diagram illustrating the evolution of the U.S. Atlantic Margin basins such as the Baltimore Canyon Trough off Delaware through geologic time (Sheridan, 1976).


W
ATLANTIC MARGIN OFF U.S.
E
WHITE MTN. STRESS SYSTEM
MIOCENE
TRANSGRESSION
PROGRADING TO RE-EQUILIBRATE SHELF PROFILE
U. EOC.-OLIG.
REGRESSION
TILT CHANGE TO S.E.
ATLANTIC STRESS SYSTEM
TRANSGRESSION
PALEO.-MID. EOC.
PALEOCENE
REGRESSION
ATLANTIC STRESS SYSTEM
TRANSGRESSION
SANTON.-MAEST.
PLANAR BEDS DIP WEST
REGRESSION
CONIACIAN
REEF TERMINATES
STRONG ATLANTIC CURRENTS
ATLANTIC STRESS SYSTEM
TRANSGRESSION
ALB.-TURON.
PLANAR BEDS DIP WEST
REEF BUILDS EAST
REGRESSION
BARR.-APT.
REEF TERMINATES
ATLANTIC ANOXIC
TILT CHANGES TO WEST
WHITE MTN. STRESS SYSTEM
JUR.-BARR.
TRANSGRESSION
CLINOFORM BEDS DIP S.E.

1. Clinoform prograding bedding in the Jurassic reflects the southeast tilt of the margin at that time and the outbuilding of carbonate bank deposits to equilibrate an oversteepened shelf.
2. The regression in Aptian/Barremian might represent the culmination of this shelf outbuilding when the differential tilt of the basins changed to the west. This regression terminated the reef complex development, amplified by the Atlantic becoming anoxic.
3. Differential westward subsidence in the Albian enhanced the major transgression during this time. More platform-like reef complex facies grew on the eastern extremes of the shelf, which were positively maintained by the differential tilt. Planar, shelf-wide strata developed with a less detrital facies than in earlier Cretaceous.
4. A regression in the Coniacian was caused by the abrupt decrease in sea floor spreading rate and worldwide deep rift openings such as the Labrador Sea. This regression terminated reef bank development, which failed to recover as deep, cold bottom-water currents flowed into the Atlantic through the new Labrador Sea opening.
5. A transgression developed in the Santonian through Maestrichtian and was enhanced by decreased sedimentation rates and westward differential tilt.
6. A regression in the early Paleocene was due to decreases in sea floor spreading rate and the possible worldwide abrupt rift openings, such as the Norwegian Sea.
7. During the Paleocene-Early Eocene, a transgression ensued as westward differential tilt and decreased sedimentation rates aided the process.
8. A major regression in Oligocene occurred as sea floor spreading rates decreased to a minimum and the differential tilt changed to the southeast. Some of the uplift on the northwest may have enhanced erosion of the Atlantic coastal plain.
9. A transgression followed the Oligocene regression in the Miocene as the margin oversteepened to the southeast. This was caused by a slight increase in spreading rates and change in spreading direction. Sediment reequilibration caused prograding of Miocene sediments and building out of the oversteepened shelf. Uplift on the northwest renewed erosion of the continental source area to provide a new influx of clastic debris.

This sequence of events could explain the structural features observed in the Baltimore Canyon Trough of the Delaware Atlantic continental margin (Figure 2).

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5

The Geology of the Delaware Coastal Plain

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UPON entering Delaware from the north one first encounters the rolling hills of the Piedmont which generally do not exceed 400 feet in elevation. The Piedmont is composed of complex and old metamorphic and igneous rocks which are exposed in many road cuts. The stream valleys are relatively steep and the direction of streamflows is strongly controlled by the composition of the rocks and the underlying geologic structures. The Piedmont comprises about 20% of the area of Delaware (Figure 1).

The Piedmont abruptly ends at the Fall Line. After crossing the Fall Line the relatively steep gradient of the Piedmont streams becomes very

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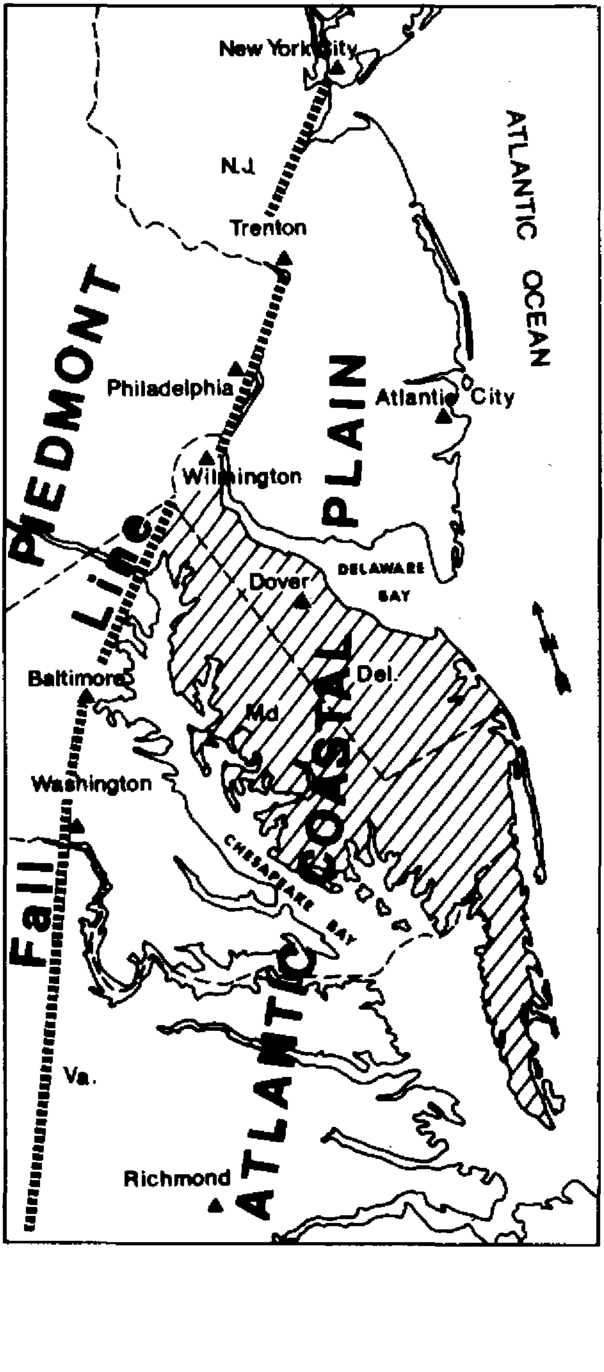


New York City
N.J.
Trenton
ATLANTIC OCEAN
PIEDMONT
Philadelphia
Atlantic City
PLAIN
Wilmington
Fall Line
DELAWARE BAY
Dover
Baltimore
Del.
Md.
COASTAL
Washington
CHESAPEAKE BAY
ATLANTIC
Va.
Richmond

gentle. The Coastal Plain area of the state is low and flat, and much of the coastal area is marshes. The streams draining into the Delaware River (Bay) are tidal for much of their length. However, hidden under this monotonous surface of the Coastal Plain is a complex and long geologic history.

Basement Rocks

Basement of the Coastal Plain sediments is composed of crystalline rocks similar to those that can be seen exposed in the Piedmont; they appear to be a subsurface extension of the Piedmont rocks. We do not know much about these basement rocks. The few samples obtained by drilling, particularly in the Delaware City area, suggest that they are primarily metamorphics. They are here overlain with their weathered products, which may locally exceed 100 feet in thickness. The age of these materials is controversial, but in a hole drilled just east of Iron Hill in northern Delaware, the weathered material was found to be interbedded with the Cretaceous fluvial sediments of the Potomac Formation. This relationship is interpreted as a slump of the weathered material into a depositional environment, possibly a stream channel, of the Potomac sediments (Spoljaric, 1972a). Thus it seems that the weathered material must have been formed before the onset of the Potomac deposition. In fact, if it is assumed that the age of the basement complex rocks is early Paleozoic, or even possibly Precambrian, the span of time until the depositions of the Cretaceous Potomac sediments would have been sufficiently long to allow the weathering of the crystalline rocks to proceed to the depths of 100 feet or more.

The surface of the basement complex appears to be broken by faults. These structural features have been discovered quite recently in the Delaware City area (Spoljaric, 1973) from the study of the well data. The findings have been confirmed by the detailed vibroseis survey (Figure 2). The main structural feature here is a graben trending approximately N25°E (Figure 3). The displacement along the border faults of the graben locally exceed 90 feet. Both the downdropped side of the graben and the bordering elevated blocks seem to be cut by a number of east-west trending faults. Several other basement faults have also

Figure 1. (opposite) Map showing the location of the study area (From Spoljaric et al., 1976.)

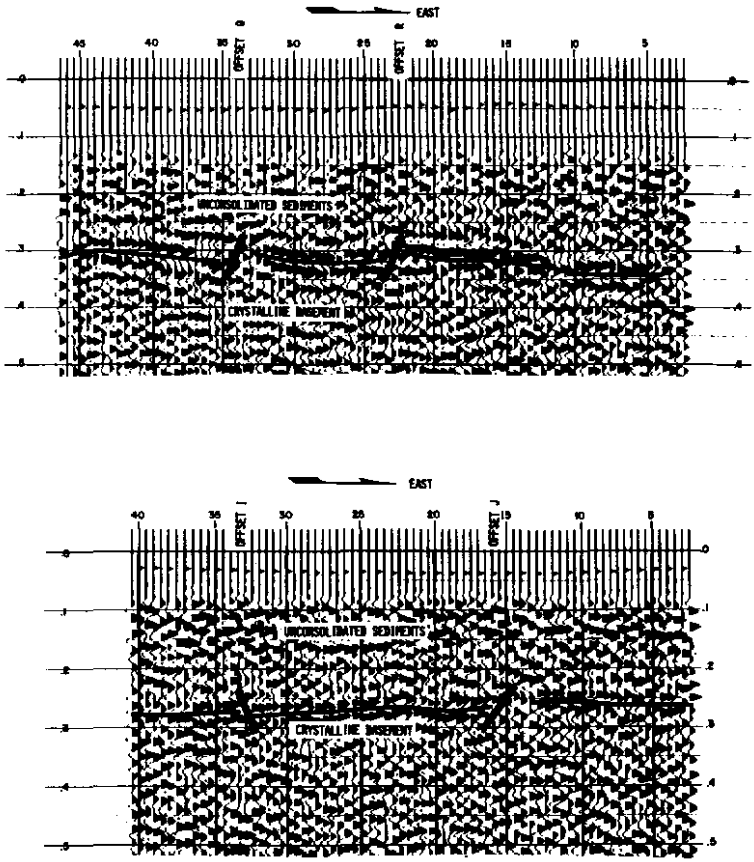


Figure 2. Seismic (vibroseis) profiles run in the area just west of Delaware City. Note several faults cutting through the crystalline basement complex.

been found along the Fall Line (Spoljaric, 1972a). The contact between the basement complex and overlying sediments of the Potomac Formation is the major unconformity. It spans the time between possibly early Paleozoic to early Cretaceous. We do not know what took place in this area during that time. The presence of thick overburden of weathered material over the fresh crystalline rocks suggests that these rocks were exposed most of that time.

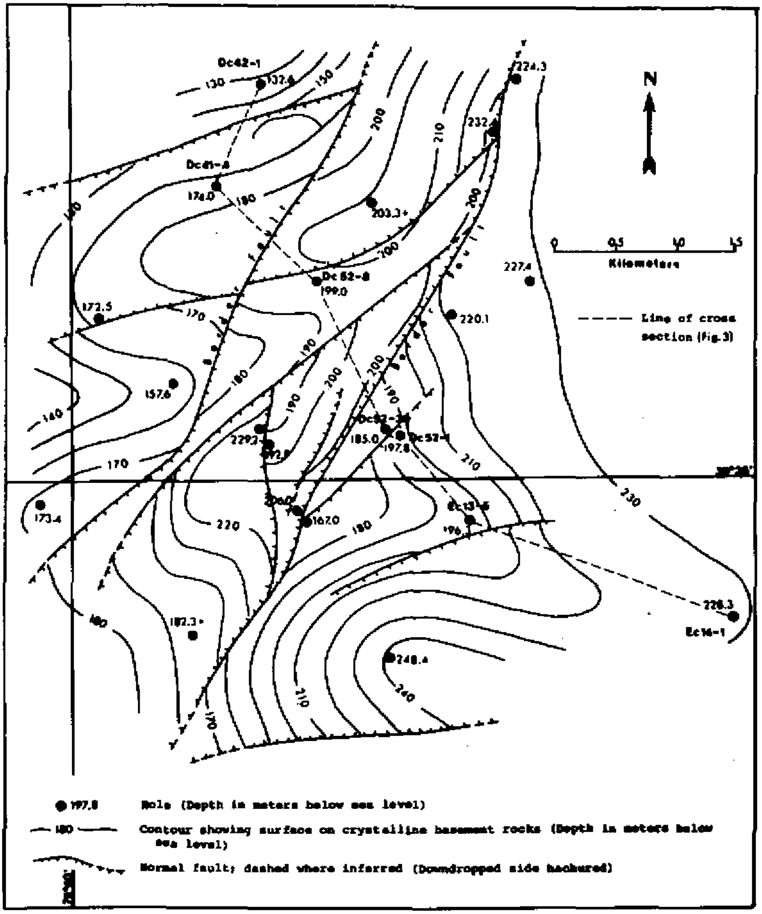


Figure 3. Structural map of the basement complex in the area west of Delaware City. The major structural features is the northeast-southwest trending graben bounded on the sides by the border faults. (Modified after Spoljaric, 1973.)

Sedimentary Rocks and Lithostratigraphy

The oldest Coastal Plain sediments in Delaware are the Lower Cretaceous deposits of the Potomac Formation. These sediments are composed mainly of clays, sands, and silts with locally found gravels. They are believed to have been laid down in a deltaic depositional environment (Groot, 1955; Spoljaric, 1967), similar to the Mississippi delta today. The Potomac sediments comprise more than 50% of the total sequence of the Coastal Plain seidments. Because they are of fluvial origin they generally lack fossils. In addition, the geometry of the sand bodies is characterized by shoestring form and thus they are extremely difficult to correlate laterally. In other words, distinct marker beds, which are so important for a proper subsurface correlation of sedimentary units, seem to be missing in the Potomac Formation. The Potomac Formation is overlain by the Magothy sediments; they are composed primarily of fine sands and dark silts and contain pieces of lignite. The Magothy is thought to have been deposited in near shore and small delta environments (Spoljaric, 1972b). The streams that deposited these sediments in the deltas are believed to have been short and for the main part located entirely in the Coastal Plain. This means that the importance of the Appalachian Mountain system as a potential source of the Coastal Plain sediments diminished; the importance of the Coastal Plain sediments of the Potomac Formation, as their source, increased. In fact, it is suggested (Spoljaric, 1972b) that the oldest part of the Potomac was indeed the source of the Magothy sediments. We have sufficient evidence to demonstrate that a considerable portion of the Potomac sediments was indeed eroded from the Coastal Plain. For example, a hole that was drilled in Chestnut Hill revealed the Potomac sediments at an elevation of about 300 feet. This is about 200 feet higher than the elevation of the Potomac in the surrounding Coastal Plain. A compaction test of the Potomac sediments from the Delaware City area conducted by Dames and Moore has indicated that they are overcompacted, and an additional 200 feet of the sediments would be needed to produce the compaction in the Potomac as determined by the test. These two independent pieces of evidence support the interpretations that at least 200 feet of the Potomac were eroded from the Coastal Plain.

The study of the heavy minerals in both the oldest part of the Potomac and the Magothy shows that the composition and the abundance of the heavy minerals in both formations are almost the same (Spoljaric, 1972b). This strongly suggests that indeed the oldest part of the Potomac was the source of the Magothy sediments. The upper part of the Potomac and the Magothy are believed to be of Late Cretaceous age. The first marine transgression occurred in the Late Cretaceous and is shown by the Merchantville sediments that overlie the Magothy. The Merchantville sediments are primarily composed of fine sands and silts containing large amounts of clay-like matrix. They also contain mineral glauconite. The Merchantville seems to have been deposited in a near-shore environment and in a shallow sea. A large variety of fossils was found in the Merchantville. During the remainder of the Cretaceous time the sediments reflect the fluctuating sea level.

The marine transgression was followed by Englishtown regression, which was followed by Marshalltown transgression and then by Mount Laurel regression (Figure 4). These transgressive and regressive events are evident in the nature of the sediments deposited during these different events and also by the interfingering relationships of the individual formations.

The last depositional event in the Cretaceous was another transgression that laid down part of the Hornerstown Formation. Great activity of animals during the Hornerstown deposition is evidenced by numerous burrowing marks. The Hornerstown deposition continued into the Tertiary (Paleocene and possibly Eocene) and was followed by a major regression, during which the Vincentown sediments were deposited. There are several important things that should be noted about the sedimentary formation, starting with the Magothy of Late Cretaceous age and ending with the Vincentown of the Middle Tertiary age. First, this continuous sequence of sedimentary units represents a number of transgressive and regressive sedimentary cycles; the individual units seem to interfinger with each other and the main sources of the sediments composing these formations seem to have been shifting to land areas north of the sea during the regressive cycles and to the sea to the south during the transgressive cycles.

Another important thing common to all these formations, with the exception of the Magothy Formation, is the presence of mineral glauconite in their composition. Glauconite is a green clay mineral rich in potassium and iron. However, a peculiar characteristic of glauconite is that it is most commonly found in pellets about 1 mm in size, contrary to other clay minerals, which form small plates. In some Coastal Plain formations this mineral may comprise more than 80% of the sediment. A notable example is the Vincentown Formation.

The origin of glauconite is not at all well known and therefore its abundance in the Coastal Plain sediments is not well understood. The differences in the composition that make it possible to recognize these various formations in the outcrop diminish as one follows them downdip into the subsurface. For example, Pamunkey, Piney Point, and Nanjemoy formations can be recognized only in the subsurface. Because

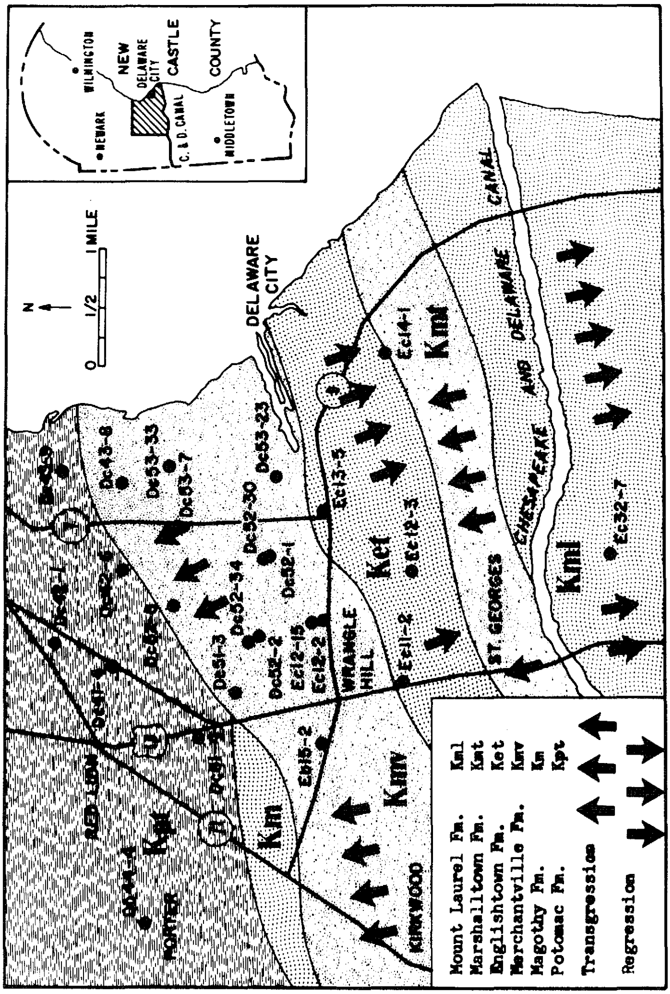


Figure 4. Transgressive and regressive sedimentary sequences in the general area of the Chesapeake and Delaware Canal.

they are not exposed at the surface, we know very little about them. It should be pointed out, however, that they are all glauconitic as well.

The Vincentown regression was followed by a major unconformity which separates it from the Middle Miocene sediments. Both the Oligocene and Early Miocene sediments seem to be missing from the Delaware Coastal Plain. We do not know what took place during these hiatuses, but we can speculate on some possible explanations. First, after the sea retreated from the area during the Vincentown time, the area remained exposed during Oligocene and Early Miocene. Second, the Vincentown regression was followed by an Oligocene transgression, but during the Early Miocene the sea retreated again and Oligocene sediments were eroded from the area. The Middle Miocene sediments that are found overlying the Vincentown deposits signify another marine transgression into the area. Starting with the Middle Miocene sediments and higher up in the stratigraphic column to the most recent deposits they are all characterized by the absence of glauconite. Thus here is another problem that needs explanation – why is glauconite so suddenly absent from the sediments? Both transgressive Middle Miocene sediments and overlying regressive Late Miocene deposits complete the Tertiary sedimentary sequence in the Delaware Coastal Plain. Some of the Miocene sediments are highly fossiliferous and they are grouped together under the name "Chesapeake Group."

The Tertiary sedimentary sequence ending with the Late Miocene sediments is separated from the overlying Pleistocene sediments of the Quaternary age by another unconformity; no Pliocene sediments have been found in the Delaware Coastal Plain. Some of the recent studies suggest that the Pliocene sediments may be present; however, this has not been proved. The Pleistocene sediments, better known as the Columbia Formation or the Columbia Group, form a relatively thin cover over most of the other older sediments in the Coastal Plain of Delaware. These sediments are the most accessible to study and their history and depositional environments are perhaps better known than those of the older deposits (Jordan, 1974; Spoljaric, 1970). The Columbia sediments seem to have been deposited in a braided stream system (Spoljaric, 1974). Most of the water for these streams seems to have been provided by the melting of Pleistocene continental ice, which at times may have approached Delaware to within 100 miles (Jordan, 1964). These sediments are generally much coarser than the deposits of older formations in the Coastal Plain and they contain considerable amounts of gravels.

Up to now the discussion of the geology of the Delaware Coastal

Plain has been centered basically on the lithologic composition of the sediments. The sedimentary rocks form a wedge that thickens southward or southeastward to a maximum thickness of about 8000 feet in the southeastern part of the State (Figure 5). With the exception of the major unconformities, there do not appear to be any significant irregularities in the distribution and thickness increases of the sediments. The fundamental characteristics of the marine part of this sedimentary sequence is its transgressive and regressive nature, which is reflected in the composition and texture of the sediments. The question is whether or not the interpretation of subsurface geology in the Coastal Plain is going to change if we look at the rocks not from the standpoint of their composition and textures (lithostratigraphic characteristics) but rather from the standpoint of their ages.

Sedimentary Rocks and Time Stratigraphy

Figure 6 shows the cross section showing the general relationship of the sedimentary units on the basis of their ages. There seem to be some significant differences in the subsurface interpretation when this cross section is viewed together with the one prepared on the lithostratigraphic criteria only (Figure 5). The names used in the cross sections are those used by the United States Geological Survey in their study of the Atlantic Coastal Plain (Brown et al., 1972). The major anomaly in the subsurface geology as seen in the cross section is the relationship of Claiborne and Jackson age sediments (Spoljaric et al., 1976).

Figure 7 shows the general relationships of these units and also the two major unconformities. The distinct feature of the Claiborne surface is the sudden change in its configuration along the southwest-northeast trend, accompanied by a sudden change in its thickness. This anomaly correlates with the southeastern margin of the depositional basin of the Claiborne sediments (Figure 8). It is interesting to note that the depositional basin trends northeast-southwest and the sediments thin both to the northwest and southeast. At the same time the sediments of the Jackson age (Figure 9), which overlie the Claiborne deposits, have a limited extent westward. It seems that an anomalous feature observed in the Claiborne age sediments had somehow limited the westward extent of the Jackson sediments. The contact of the Claiborne-Jackson sediments with the overlying Middle Miocene deposits is one of the major unconformities (Figure 7). There is also a minor unconformity separating the Claiborne from the Jackson. Nevertheless, in view of the

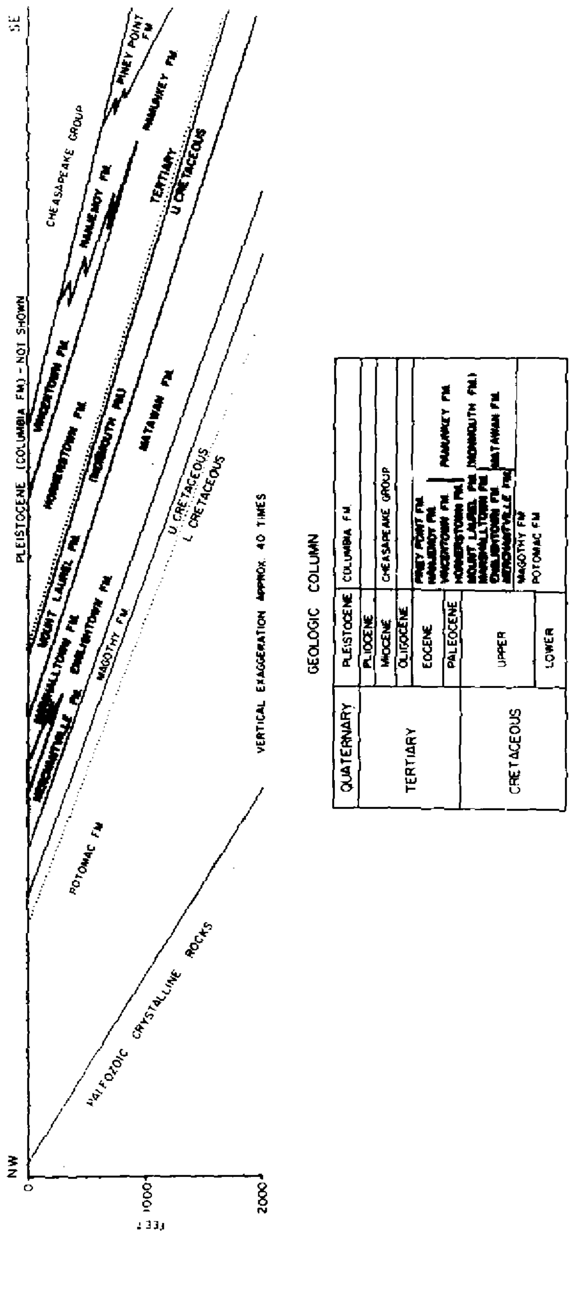


Figure 5. Cross section showing the relationships of sedimentary formations in the subsurface based on their lithologic composition.

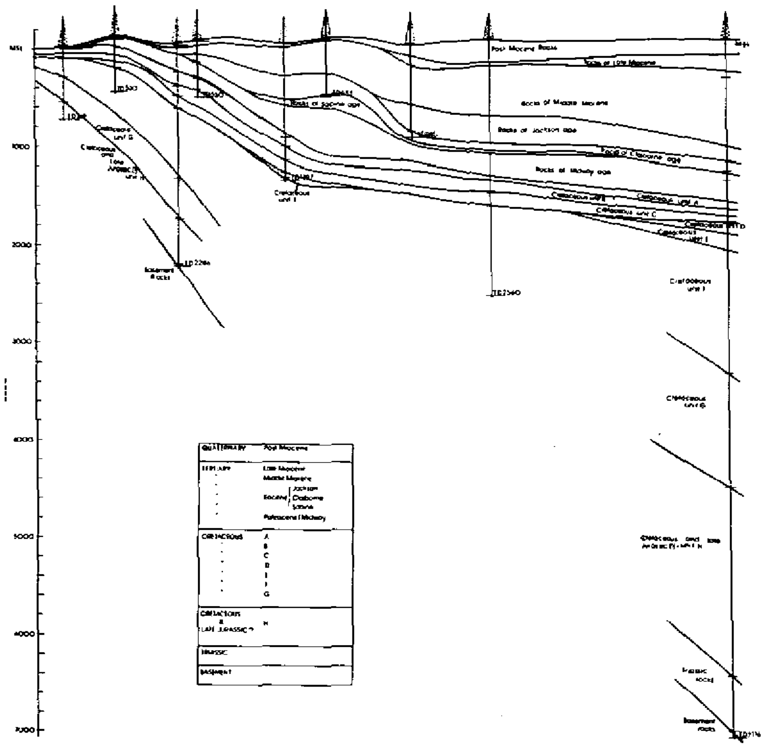


Figure 6. The same cross section as that shown in Figure 5, but showing the relationships of sedimentary units based on their ages. (Modified after Brown et al., 1972.)

fact that both are time-stratigraphic units, the relationship between the Jackson and laterally adjacent Claiborne is anomalous and two possible interpretations of it are offered.

The first possible explanation is that this feature is a fault. The problem with this interpretation is that the difference in the Claiborne thickness on the opposite sides of the postulated fault cannot be explained without invoking the reversal in the sense of movement along the fault. During the initial activation the northwestern block should have moved downward and the southeastern block upward. In the reactivation, the reversal in the sense of movement should have taken place.

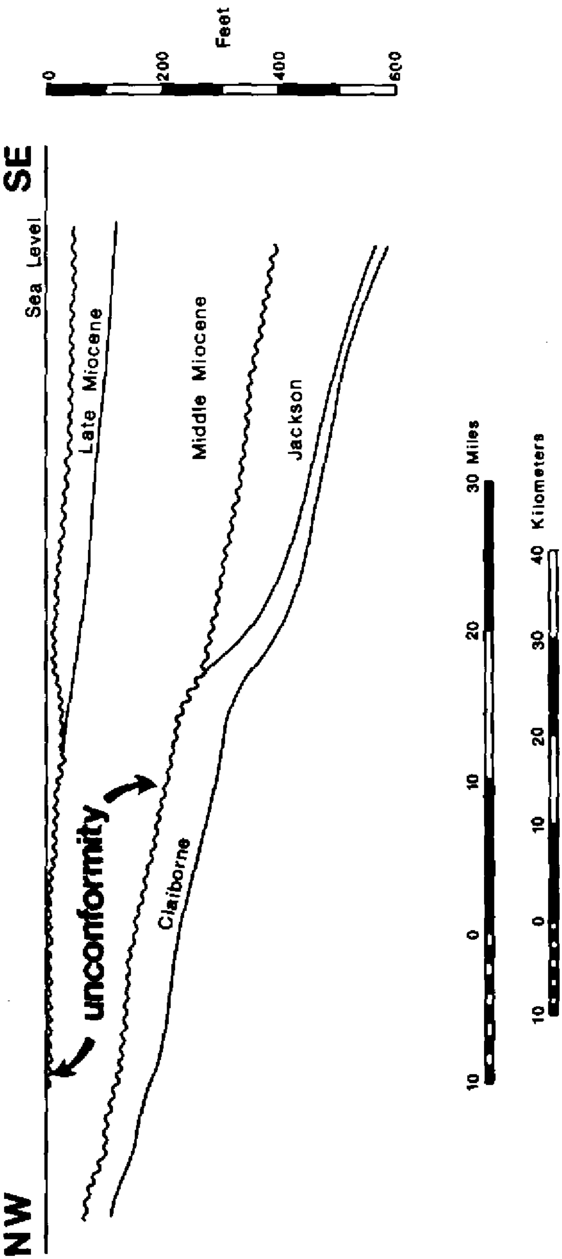


Figure 7. Schematic cross section of several Tertiary units discussed in detail in the text. (From Spoljaric et al., 1976.)

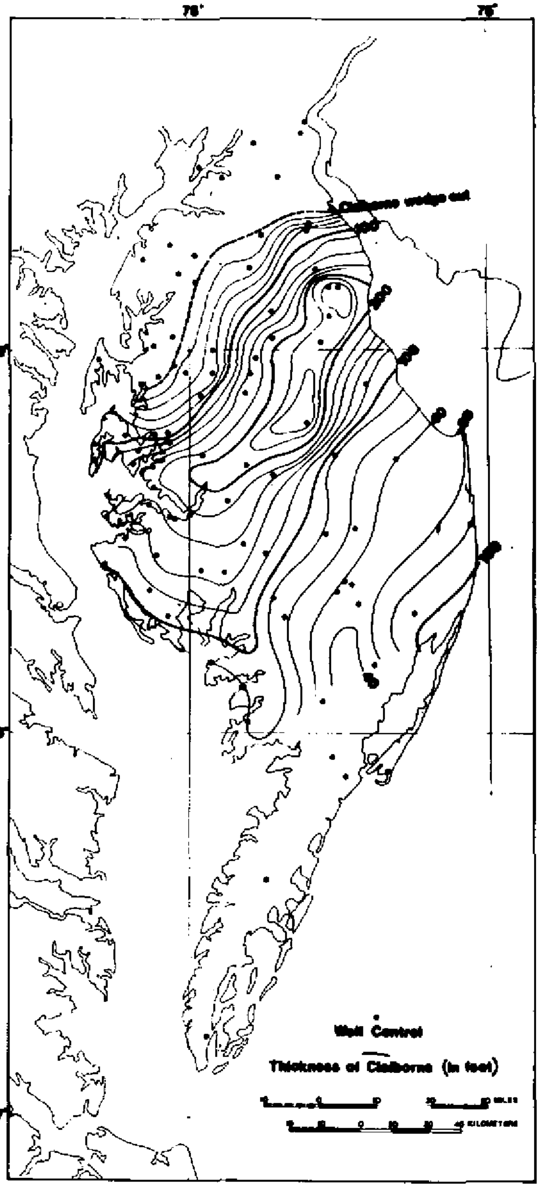
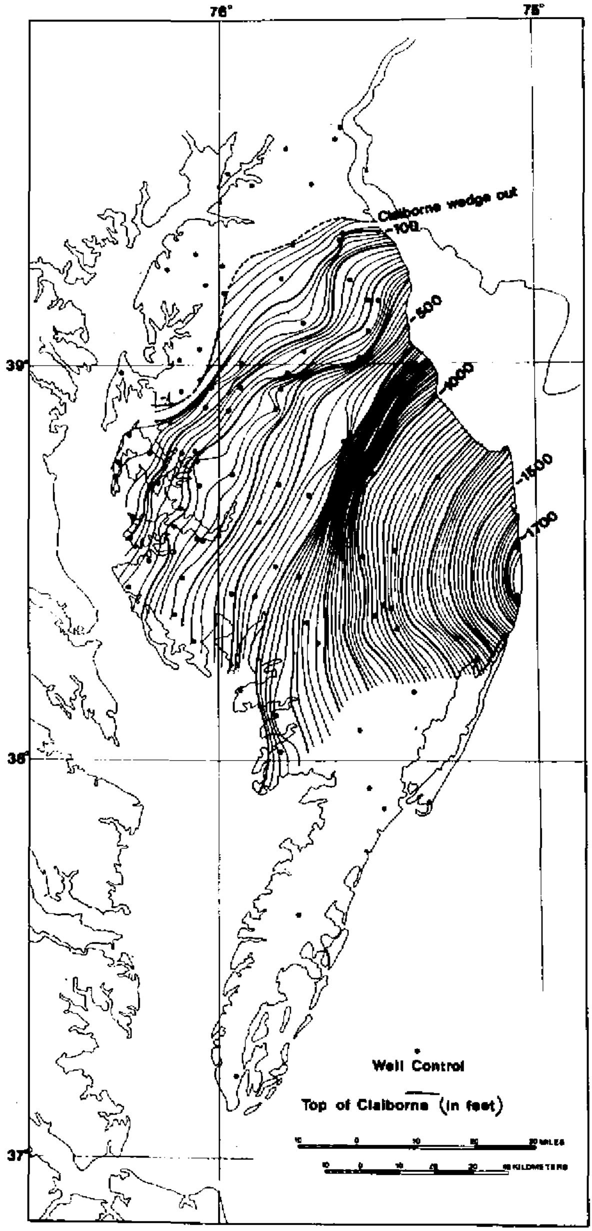


Figure 8. Maps showing the thickness (a) and surface (b) of the Claiborne age sediments. (From Spoljaric et al., 1976.)


76°
75°
39°
38°
37°
Claiborne wedge out
-100
-500
-1000
-1500
-1700
Well Control
Top of Claiborne (in feet)
MILES
KILOMETERS

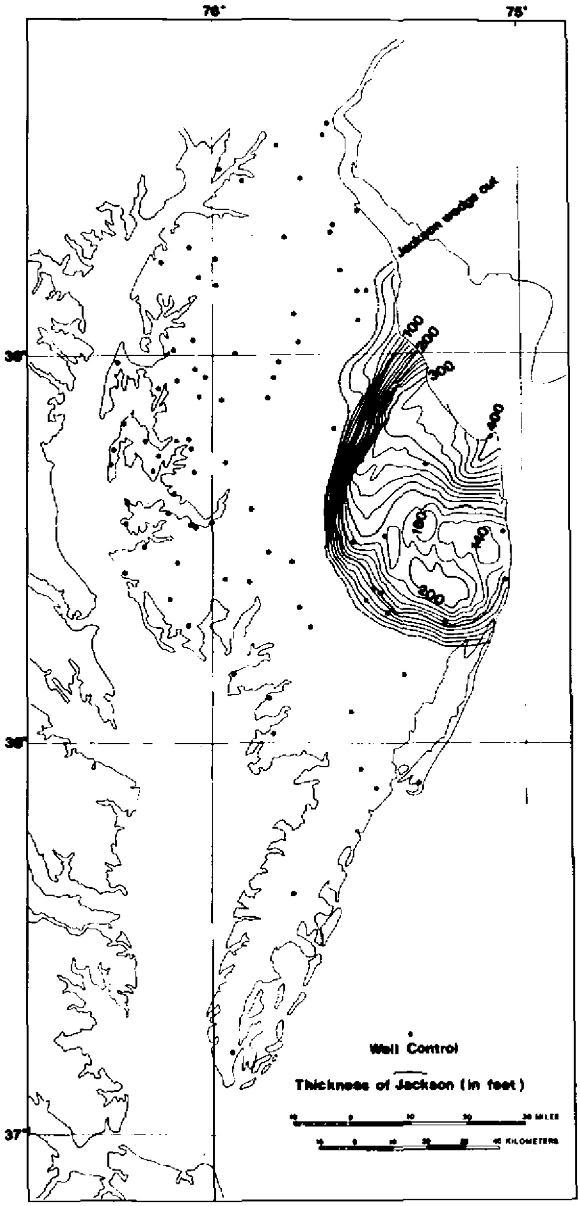
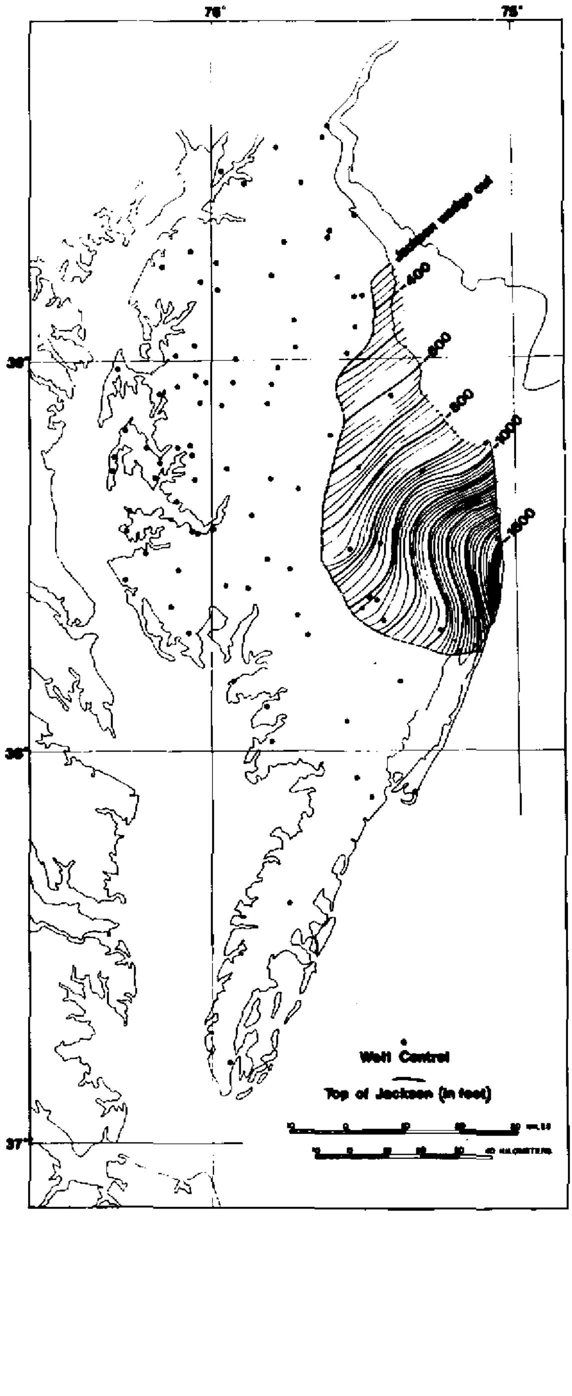


Figure 9. Maps showing the thickness (a) and surface (b) of the Jackson age sediments. (From Spoljaric et al., 1976.)



400
600
800
1000
1600
Well Control
Top of Jackson (in feet)

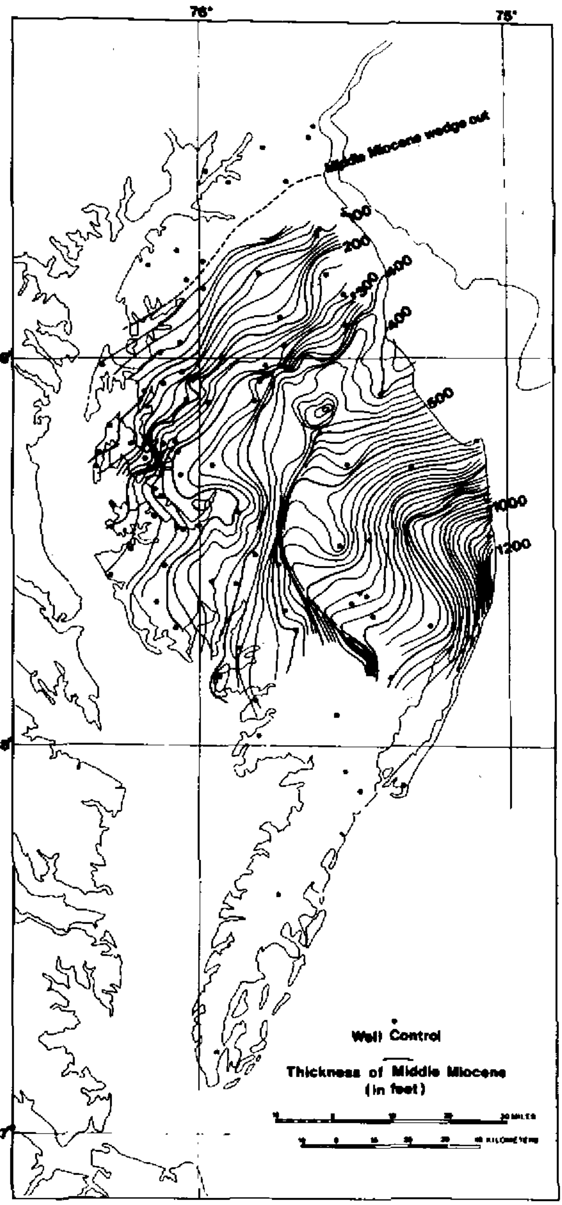
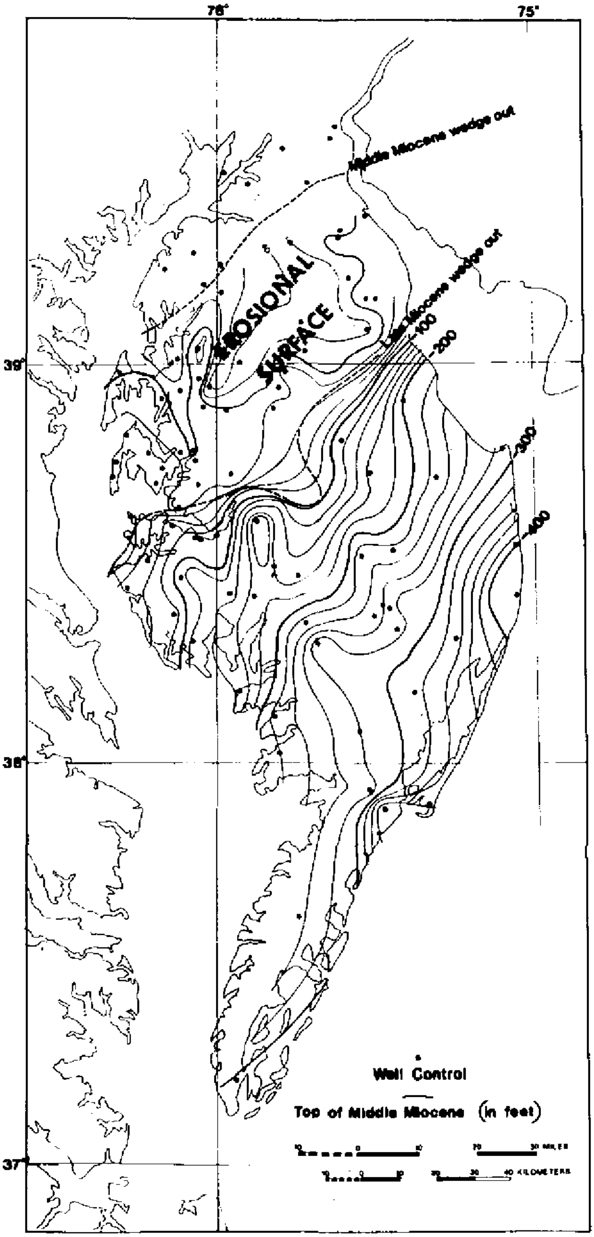


Figure 10. Maps showing the thickness (a) and surface (b) of the Middle Miocene sediments. (From Spoljaric et al., 1976.)


76°
75°
39°
38°
37°
Middle Miocene wedge out
Late Miocene wedge out
EROSIONAL
SURFACE
100
200
300
400
Well Control
Top of Middle Miocene (in feet)

The second possible explanation of this anomalous feature is a slump. The slump could account for the differences in the Claiborne thickness on the opposite sides of the feature but this would be very difficult to prove. The same feature is also quite apparent in the thickness map of the Middle Miocene sediments (Figure 10). The same map (Figure 10) clearly shows several other anomalies as well. Most of these, however, are not apparent in the map showing the surface of the Middle Miocene sediments, possibly indicating that whatever the cause of those features, they were probably formed before the deposition of the Middle Miocene deposits.

Thus, there seems to be little doubt that the sedimentary sequence in the Coastal Plain is not quite as monotonous and uniform as thought several years ago. There seem to be some distinct structural features present in the subsurface that were previously unknown. These structural features must have been formed as a result of some tectonic disturbance. The question is: Are these disturbances still active, and is the development of the Coastal Plain in Delaware still in progress?

Before attempting to answer these questions, perhaps we should look at the Coastal Plain from yet another viewpoint.

Interpretation of LANDSAT-1 Lineaments

The satellite photograph (LANDSAT-1, Figure 11) shows a number of distinct linear features that cannot be observed by any other means.

These linear features or lineamounts trend N-S, NW-SE, and NE-SW. The interpretation of these lineaments is very difficult because they are extremely hard to find on land and because in many causes they reflect some subsurface features rather than features of the land surface. We know, for example, that lineaments marked 1 and 5 can be related to the known faults in the basement complex. Lineament 1 corresponds to a fault originally found by drilling just south of the Fall Line (Spoljaric, 1972a). The northeastern side of this fault is down dropped with the maximum known vertical displacement of about 50 feet. The northwestward extension of this fault was later found in the Piedmont, and its southeastward extension is indicated by the lineament. Lineament 5 appears to be a surface expression of a graben fault system, discussed previously, which trends in the same direction as the lineament (Spoljaric, 1973). Although the lineament suggests that the fault system extends both to the northeast and the southwest for several miles,

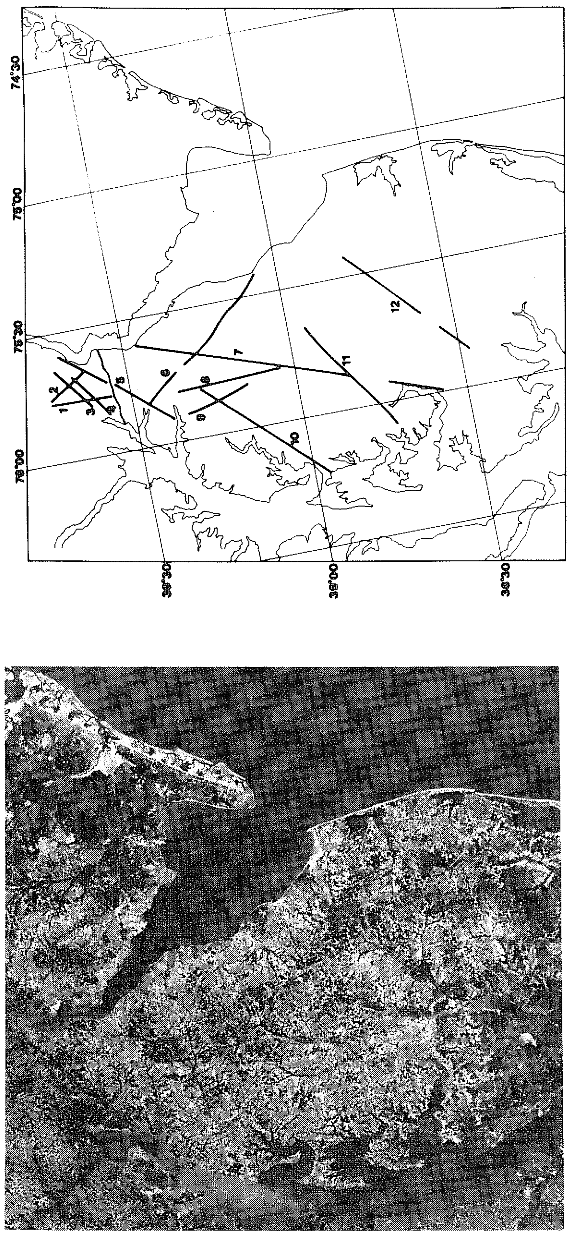


Figure 11. LANDSAT-1 (a) imagery of the study area with the map (b) showing the lineaments seen on the imagery. (From Spoljaric et al., 1976.)

this has not been conclusively confirmed. The vibroseis survey carried out by Dames and Moore along the lineament just south of the graben fault system was inconclusive. However, several faults trending in the same direction as the lineament have been found in proximity to the lineament. A detailed study of one of these faults suggests that the sediments of Early and lower part of Late Cretaceous age have been affected by faulting. If this is correct it means that the faulting occurred in the early Late Cretaceous time.

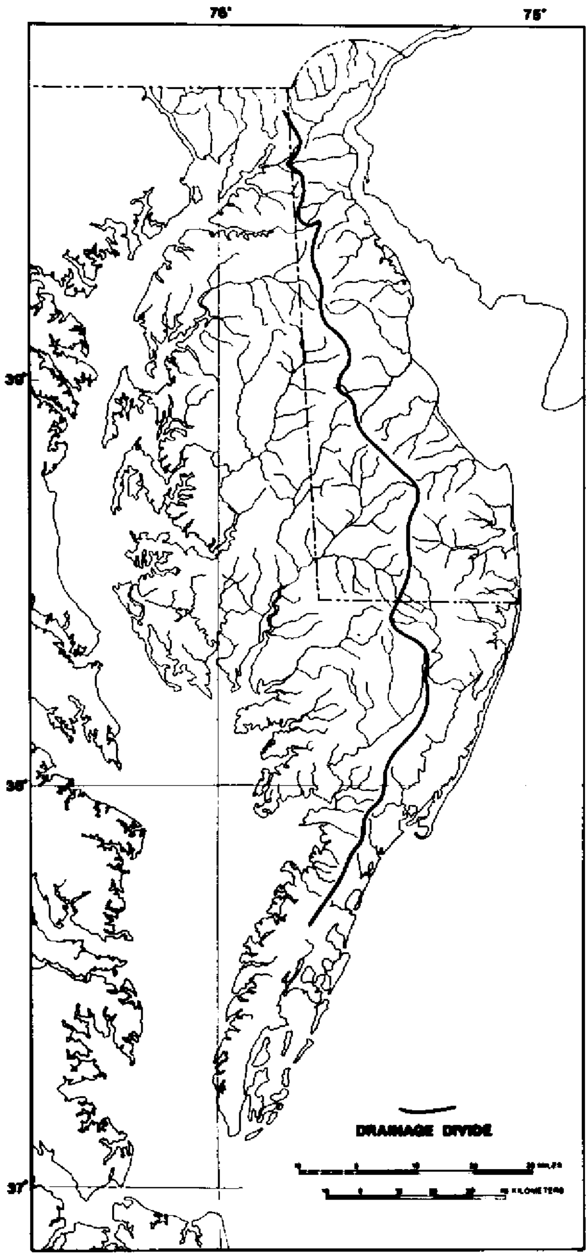
The lineaments marked 3 and 4 correlate with a postulated fault proposed by Higgins et al. (1974). The evidence for the presence of the fault is inconclusive, and therefore the significance of this lineament is uncertain. Lineaments 6, 7, 8, 9, 11, and 12 correspond to stream valleys. Whether or not some of these stream valleys are in fact structurally controlled is not known at present. Lineaments 5 and 10 do not seem to be related to any known surface or subsurface features in the Coastal Plain. Most of the tectonic structures discussed so far have only local significance, have a limited extent, and appear to have been of limited duration.

Major Unconformities

Regional vertical movements that affected other parts of the Atlantic Coastal Plain as well are also important for the understanding of the evolution of the Coastal Plain in Delaware. These are clearly indicated by at least two major unconformities in the Tertiary sedimentary sequence.

One is found between the Eocene sediments of the Claiborne and Jackson ages and the Middle Miocene deposits, and the other between the Middle and Late Miocene and the Pleistocene sediments (Figure 7). In the northern part of the Peninsula these two unconformities merge, thus increasing the hiatus from the Eocene to the Pleistocene; about 40 million years of geologic time. We do not know what events took place during that period. However, the area must have been emergent for a sufficiently long time to account for the unconformities. We do not know whether the sediments of Oligocene, Early Miocene, and Pliocene age, which seem to be missing from the Peninsula area, were first de-

Figure 12. (opposite) Drainage map of the Delmarva Peninsula. (From Spoljaric, et al., 1976.)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posited here and later eroded or not deposited at all. Perhaps the studies now in progress or those carried out in the future will help to answer these questions.

Geomorphology and Tilt of the Peninsula

In addition to the regional vertical movements indicated by the two major unconformities, there also seems to be evidence for the tilt of the Peninsula area (Spoljaric et al., 1976). The evidence for the eastward to southwestward tilt is provided by the subsurface geology and the drainage patterns. The surface of the individual formations and unconformities dips to the east and southeast. The drainage map provides more apparent evidence for the postulated tilt (Figure 12).

The coastal area along the Delaware Bay is rather monotonous, low, flat, and characterized by abundant marshes. Streams draining into the Delaware Bay are short and tidal for the greater part of their length. On the other hand, the coastal area of the Peninsula along the Chesapeake Bay is characterized by numerous bays, is higher than the Delaware Bay coast, and has small cliffs. The streams draining into the Chesapeake Bay are relatively long and their valleys are generally deeper than those of the streams draining into the Delaware Bay. The coastal geomorphology of the Delaware Bay and the Chesapeake Bay sides of the Peninsula are indeed quite different, although they developed on the same kinds of sediments. It is important to note that the drainage divide of the Peninsula is considerably closer to the Delaware Bay than the Chesapeake Bay. The difference in the coastal geomorphology and the "eastward shift" of the regional divide are to be expected if the Peninsula is tilting eastward or southeastward.

Now the question is whether the tectonic evolution of the Coastal Plain is still in progress, or whether it ceased sometime in the geologic past. Recent earthquakes that occurred in Delaware and adjacent parts of the Delmarva Peninsula suggest that the tectonic evolution is indeed still in progress (Woodruff et al., 1973).

Evidence for Recent Tectonics of the Peninsula

The first known damaging earthquake occurred on October 9, 1871, near Wilmington at the northern margin of the Peninsula. The intensity of the Mercalli Scale was estimated to be about VII. An earthquake with an estimated intensity of V took place in March of 1879 near Dover in the northern part of the Peninsula. Not much is known about this event except that it was felt strongly. The May 8, 1906, earthquake, with an estimated intensity of V, occurred in the central part of the Peninsula and it was also described as strong. Between July, 1971, and March of 1975, more than 20 earthquakes were felt or instrumentally recorded. Most of them occurred in southwestern Wilmington or close to the Fall Line. The majority of these events had estimated intensities of less than II with the exception of the November 10, 1972, event with an estimated intensity of III; the June 1, October 10, and November 27 of 1972 and July 10 of 1974 earthquakes with estimated intensities of IV; and the February 28, 1973, earthquake with an estimated intensity of VI and a magnitude of 3.8 on the Richter Scale. The fault-plane solution for the February 28, 1973, earthquake computed by Sbar et al. (1975) indicates a dip-slip motion on a nearly vertical plane with the southeastern side downdropped. The strike of the fault-plane was determined to be about N28°E. It lies along the possible northeastward extension of the basement graben fault-system (Spoljaric, 1973) and the lineament, observed on the LANDSAT-1 photograph (Figure 11).

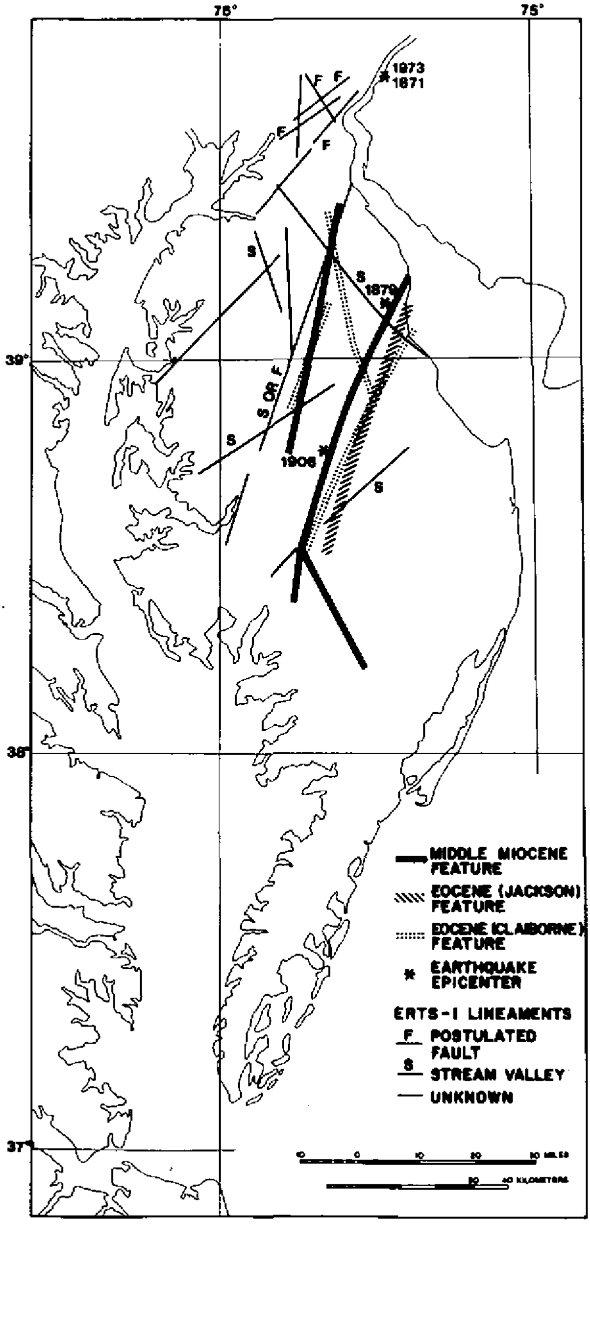
Two other earthquakes have been noted on the Peninsula, one in 1774 and the other in 1937. The 1774 event occurred somewhere in the southernmost part of the Peninsula, and the 1937 earthquake took place in the central part of the Peninsula, in southern Delaware; very little is known about them.

The approximate locations of the epicenters of the 1879 and 1906 earthquakes closely correspond to the location of the Tertiary subsurface anomalous feature (Figure 13). If this feature and the earthquakes are related, then it is quite possible that the feature developed as a result of some tectonic disturbance, and its interpretation as a fault becomes quite probable.

The map shown in Figure 13 summarizes our present interpretation of various structural features recognized in the Coastal Plain.

Conclusions

The geology of the Coastal Plain in Delaware is much more complex than it was thought to be several years ago. Numerous faults in the Coastal Plain have been found in recent years, some of which extend northward into the Piedmont. These faults appear to be associated with both compressional and tensional shear zones. Tectonic activity along


76°
75°
39°
38°
37°
1973
1871
F
F
F
F
S
S
1879
S OR F
S
1906
S
MIDDLE MIOCENE FEATURE
EOCENE (JACKSON) FEATURE
EOCENE (CLAIBORNE) FEATURE
EARTHQUAKE EPICENTER
ERTS-I LINEAMENTS
POSTULATED FAULT
STREAM VALLEY
UNKNOWN

these shear zones has been going on at least since the Tertiary time. Recent earthquakes demonstrate that this activity is still in progress.

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Figure 13. (opposite) Map showing the summary of the interpretation of various structural features on the Delmarva Peninsula, including the epicenters of the known earthquakes. (From Spoljaric et al., 1976.)

12. Spoljaric, N. 1974. Subsurface geological investigation of a Pleistocene braided stream in the northern Coastal Plain, Delaware (U.S.A.). *Sedimentology 21:*451-461.

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6

A Summary of the Geology of The Piedmont in Delaware

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DELAWARE contains two major eastern physiographic provinces. Most of the state lies within the Atlantic Coastal Plain province; only 4% lies within the Piedmont province. The Piedmont comprises 82 square miles of gently undulating, wooded, and open uplands, averaging perhaps 250 feet in elevation with as much as 300 feet of local relief. The Piedmont uplands lie in northern New Castle County, mainly north and northwest of a line drawn from Newark through Elsmere and southern Wilmington to the Delaware River (Figure 1), although Iron and Chestnut Hills near Newark properly belong to the Piedmont province.

Geologically the Piedmont uplands are underlain by high-grade metamorphic and igneous rocks, which are part of the ancient Appalachian mountain system. Many of the metamorphic rocks represent former

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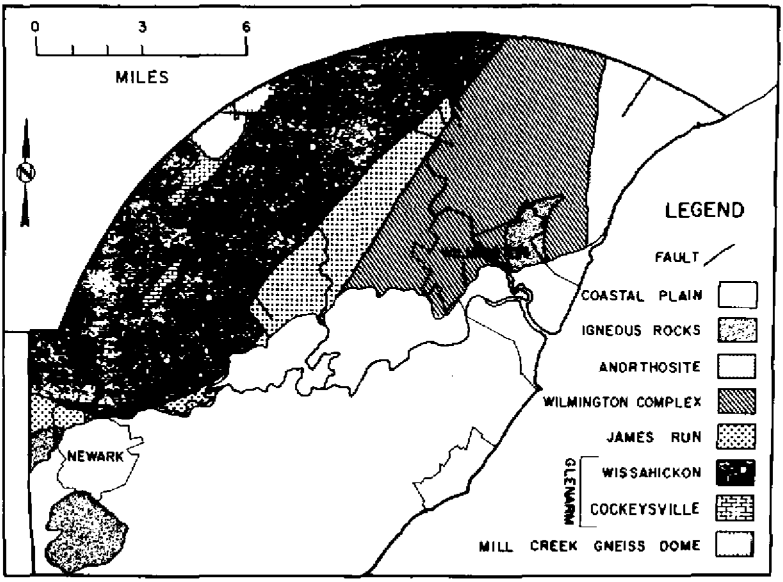


Figure 1. Generalized geologic map of the Delaware Piedmont showing major terranes and igneous rocks. Heavy black lines indicate known faults.

sediments, and attest to the former presence of ocean water and oceanic depths in this region. Although a relatively minor portion of the total Appalachian extent, the rocks in Delaware hold important clues and information on the evolution of the entire southern Appalachian mountain system.

Major Terranes in Delaware

Although a great number of individual rock types occur in the Piedmont of Delaware, there are several constraints on their distribution, and a relatively small number of rock associations may be recognized. Each association is limited geographically, so that four distinct terranes may be identified (Figure 1), each characterized by a suite of (mainly metamorphic) lithologies. Each terrane shows evidence of distinctive lithologic, metamorphic, and structural evolution, and the Piedmont in Delaware may be considered a composite of several blocks of distinct and possibly unrelated origin.

Mill Creek Gneiss Dome Terrane

Lying northwest of the Hockessin-Yorklyn valley (Figure 1) are metasedimentary schists and gneisses which may constitute the oldest rocks in Delaware. These rocks occupy the central, core zone of a probable anticlinal uplift termed the Mill Creek Gneiss Dome by Higgins et al. (1973). The rocks are mostly quartz-feldspar gneisses, amphibolites, and biotite-quartz-feldspar schists, and occur in discrete layers 1 to 3 feet thick. This terrane is polymetamorphic, with retrogression of orthopyroxenes to amphiboles characteristic of the amphibolite facies. These rocks have been termed the Baltimore Gneiss by Higgins et al. (1973), and although the rocks are not similar lithologically to the Baltimore Gneiss in its type section, stratigraphic and structural data (given below) support their designation as Baltimore Gneiss. If this correlation is correct, the rocks are of Precambrian age, and represent the southeasternmost occurrence of American continental basement anywhere in the central Appalachians.

Glenarm Terrane

Surrounding the Mill Creek Gneiss Dome terrane is an extensive area of metasedimentary schists, gneisses, marble, and minor amphibolite showing a consistent internal stratigraphy. This sequence is widely known as the Glenarm Group, and this region is thus termed the *Glenarm terrane* (Figure 1).

Lower Glenarm: The lowest unit of the Glenarm Group, the Setters Formation, is probably present as very thin lenses of quartz-rich mica schist on the immediate southern flank of the Mill Creek Gneiss Dome. Only one exposure has so far been found in Delaware. It is succeeded by the Cockeysville Marble, a sequence of dolomite and calcite marbles of thickness probably not exceeding 1000 feet. The Cockeysville underlies both the Hockessin-Yorklyn Valley and Pleasant Valley near Newark, and is a major groundwater aquifer in the Hockessin region. Together the Setters and Cockeysville make up less than 5% of the exposed Glenarm Group in Delaware.

Wissahickon Formation: Underlying the remainder of the Glenarm terrane in Delaware are rocks of the Wissahickon Formation. The Wissahickon is of unknown but great thickness; although some has probably been repeated by folding and faulting, probably more than 8000 feet of rocks are present within the Wissahickon in Delaware. The unit contains thin to very thick layers of mica schist, mica-quartz gneiss, and amphibolite. Mica schists generally carry almandine garnet and sillimanite and lack potash feldspar; biotite dominates over muscovite. Gneisses are quartz-rich and usually lack sillimanite and almandine, but show all gradations from quartz-rich gneisses through quartz-mica gneiss to mica schist. Assignment of specific rocks to one lithology or the other is often difficult. Amphibolites commonly show fine layering and elongate grains, and contain subequal amounts of plagioclase and hornblende, with considerable iron oxide. While the parent rock types of the amphibolites are often in doubt, clear evidence of an igneous origin is visible, in a few instances and a similar origin may be suspected for many others.

These lithologies may be mapped within the Wissahickon area throughout the northwestern Piedmont. They are best displayed along the valley of Red Clay Creek. Amphibolites and quartz gneisses support ridges, such as Horseshoe Hill and Mt. Cuba, while the less resistant mica schists have been eroded into valleys. The localized areas of meandering course of Red Clay Creek, for instance at Ashland and Wooddale, coincide with outcrop belts of mica schist.

The schists and quartz gneisses occasionally contain direct evidence of sedimentary parentage. Thinly interbedded gneisses and schists

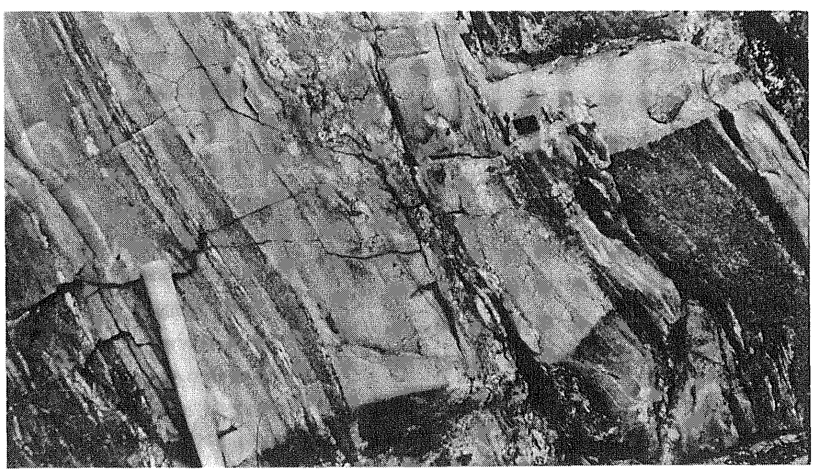


Figure 2. Typical biotite feldspar quartz gneiss of the Wissahickon Formation. Layering is compositional, and probably represents original sedimentary bedding. Barley Mill Road at Hoopes Reservoir.

show relict graded bedding, with quartz gneiss passing continuously upward into micaceous schist (Figure 2). The relations strongly suggest premetamorphic sandstone-to-shale grading, and imply origin in a deep-water, basinal environment, probably an open oceanic environment. This interpretation contrasts with the assumed shallow-water, platform environment for the underlying Cockeysville marbles, and implies a progressive deepening of the depositional basin through time.

The frequency and style of lithology change vary within the Wissahickon. In the interval just above the Cockeysville, schists and gneisses are thinly interbedded (inches to feet), sharply defined, and often discontinuous along strike; relict graded bedding occurs mainly in these zones. Farther southeast, individual lithologies are hundreds to thousands of feet thick, are much less variable, and are more continuous as mapping units. Relict sedimentary features are absent here, and the rocks contain more amphibolite and quartz gneiss. These differences suggest that the Wissahickon may actually contain two distinct rock associations, which reflect differing conditions of sediment supply and accumulation. Their present close association is a major puzzle.

Included within the Wissahickon are two types of igneous and/or metaigneous rocks. The first, serpentinite, crops out in two small areas near Hoopes Reservoir. These rocks represent altered dunite or pyroxenite, and must have been derived from ultrabasic parent rocks. The serpentinites lie along fault traces, and may represent transported fragments of former ocean floor ultrabasic rocks.

The second igneous rock comprises quartz-microcline-muscovite pegmatite masses. These bodies are generally small and numerous, and occur most frequently in mica schist lithologies. The largest such pegmatite occurs in the Yorklyn valley, and was mined for kaolin in former years. In many cases these pegmatites are truly igneous, but in many other cases they show no clear evidence for igneous origin, and may be metamorphic.

The Wissahickon Formation contains stable mineral assemblages indicating metamorphism in the amphibolite facies. The presence of sillimanite in stable contact with quartz and muscovite, and the notable rarity of microcline, indicate that metamorphism was less intense than the point of breakdown of muscovite, and was thus confined to the first sillimanite zone. Only in one fault slice near Wooddale does sillimanite occur with microcline.

James Run (?) Terrane

Lying in an elongate, northeast-trending belt adjacent to the Glenarm terrane are poorly known metamorphic rocks of the James Run (?) Formation (Figure 1). The James Run (?) contains mixed quartz-feldspar-pyroxene gneisses, mica-garnet schists, amphibolites, and associated igneous rocks. In addition, several distinctive rocks are apparently limited to the James Run (?), and serve to distinguish it from the Wissahickon. Thin-layered quartz-feldspar gneiss and amphibolites are most common (Figure 3). Most unusual is a mafic, hornblende-plagioclase-quartz gneiss containing large prophyroblasts of magnetite, "armored" by rims of plagioclase (Figure 4). The origin and significance of these "eyes" is uncertain; they may represent amygdaloidal fillings in former volcanic flows, or they may represent genuine porphyroblasts formed by breakdown of hornblende.

Most mica schists and gneisses, and many quartz-plagioclase gneisses, are probably metasedimentary. Although no graded bedding has so far been observed, the thin and irregular interbedding of different lithologies suggests original compositional differences. The assemblage biotite-almandine-sillimanite, common in the schists, generally indicates aluminum-rich sedimentary parent rocks such as shales. However, the James Run (?) contains many amphibolite and hornblende gneisses of probable igneous, volcanic origin. Prismatic hornblende textures, clotted fabrics, and streaky structures all resemble features of modern volcanic and volcaniclastic rocks. The James Run (?) contains major volcanic contributions, and implies proximity to an ancient volcanic source.

While broadly similar to the Wissahickon in field appearance, the James Run (?) differs from it in several important respects. First, metamorphic grade is consistently higher in the James Run (?). The gneisses and many schists carry hypersthene, and the James Run (?) is of granulite-facies grade. Second, the amphibolites of the James Run (?) are massive, coarse-grained, and poor in felsic minerals. Third, the James Run (?) contains many more volcanic rocks. Finally, structural features and attitudes of James Run (?) rocks differ significantly from those of the Wissahickon, and indicate a different deformational history.

Wilmington Complex Terrane

Lying east of the James Run (?) terrane, and underlying most of Wilmington and its northern suburbs, are high-grade metamorphic granulites and gneisses and associated igneous rocks of the Wilmington Complex (Figure 1; Ward, 1959). The complex is characterized by the general absence of potassium-bearing phases, absence of schists, rarity of amphib-

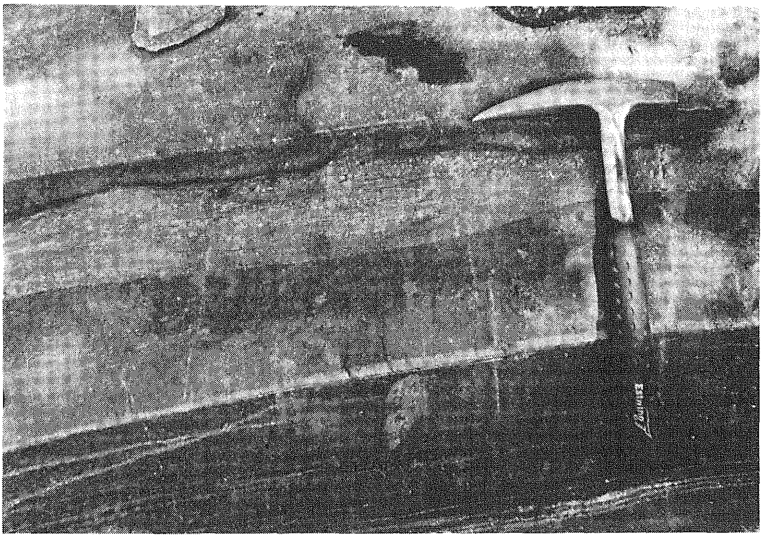


Figure 3. Typical thin-layered quartz-feldspar gneiss and amphibolite of the James Run (?) Formation. Note possible graded bedding. Kirkwood Highway bridge over White Clay Creek.

olites, ubiquity of orthopyroxenes, and a maddening lack of features of obvious genetic significance.

Two lithologies dominate the Wilmington Complex. Most abundant is pyroxene-quartz-plagioclase gneiss, which weathers light gray but is dark gray-blue on fresh surface; this rock is the famous Brandywine Blue Granite which was extensively quarried along the Brandywine. The gneiss is generally massive, with only very widely spaced, thin layers of pyroxene gneiss (Figure 5). Foliation is generally weak to absent; however, these gneisses usually show strong lineation, defined by streaks of up to 2 cm long of pyroxene, magnetite, and occasionally plagioclase. The gneisses occasionally contain inclusions of other gneisses, but they may well be tectonic rather than igneous inclusions. The lineated fabrics often show cataclastic effects, and the lineation may thus be due to regional cataclasis of an originally igneous rock. However, the presence of layering, even if widely spaced, places severe constraints on interpretations of igneous origin.

The second major lithology in the Wilmington Complex comprises thin-layered gneisses of several different compositions (Figure 6). Most gneiss compositions may be expressed as variations in proportions of quartz, plagioclase, orthopyroxene, magnetite, and occasionally almandine and grossularite garnet. Individual layers vary from 2 to 3 feet in thickness, and probably much more. Contacts between layers are sharp, and suggest sedimentary and/or volcanic parent rocks. Many layers show mineral lineations lying in the foliations, and also boudinage of the more competent (generally felsic) lithologies (Figure 7). The regional extent of this lithology is poorly known.

The grade of metamorphism in both lithologies is uniformly high, in the granulite facies. Coexisting lamellae of hornblende and hypersthene, with grains in stable contact, suggest the hornblende granulite subfacies.

Igneous Rocks

The Delaware Piedmont contains an assortment of igneous rocks. Most, however, are concentrated in the James Run (?) and Wilmington

Figure 4. "Armored" magnetite crystals, surrounded by rims of plagioclase feldspar in James Run (?) Formation. Coin for scale is a quarter. Limestone and Milltown Roads.

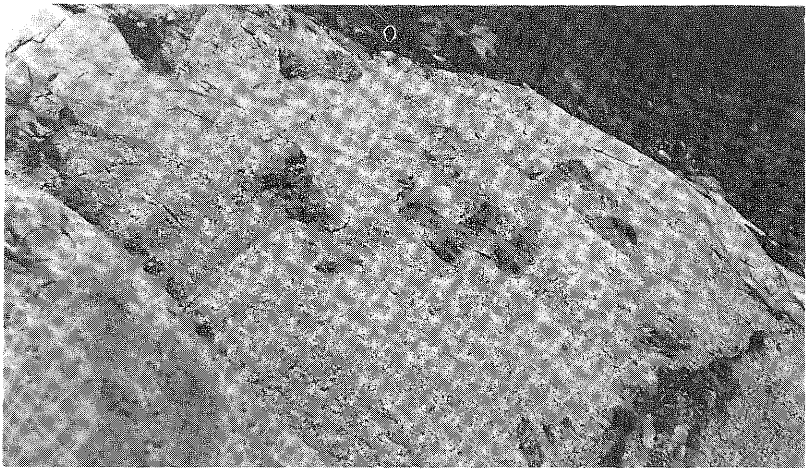


Figure 5. Poorly layered to massive pyroxene-quartz-plagioclase gneiss of the Wilmington Complex. Single thin layer of dark pyroxene gneiss is tightly folded by later, second folding event. Looking down plunge. Hagley Museum property.

Complex terranes. The compositions range from serpentinite to gabbro, quartz diorite, and granodiorite. Both volcanic and plutonic rocks occur; this discussion concentrates on plutonic rocks.

The largest and most distinctive plutonic igneous rock is a complex of anorthosite and gabbroic anorthosite which underlies Arden, Holly Oak, and Claymont (Figure 1). The anorthosite complex shows a range of compositions, from true anorthosite to gabbroic anorthosite, norite, rare mangerite, and very rare charnockite. The anorthosite contains megacrysts of clear gray andesine (Figure 8) which reach 3 inches in length; they are often granulated and rounded, and most of the anorthosite shows some cataclasis. Anorthosite of massive type has not been reported to date from Phanerozoic rocks, and the Delaware anorthosite thus is either the first Phanerozoic anorthosite reported, or is of Precambrian age. The details and significance of the Delaware anorthosite are of considerable debate at present.

Several small areas in the Piedmont, most notably in Bringhurst Woods Park, northern Greenville, and Iron and Chestnut Hills (Figure 1), contain small intrusions of olivine-bearing gabbro. These rocks are com-

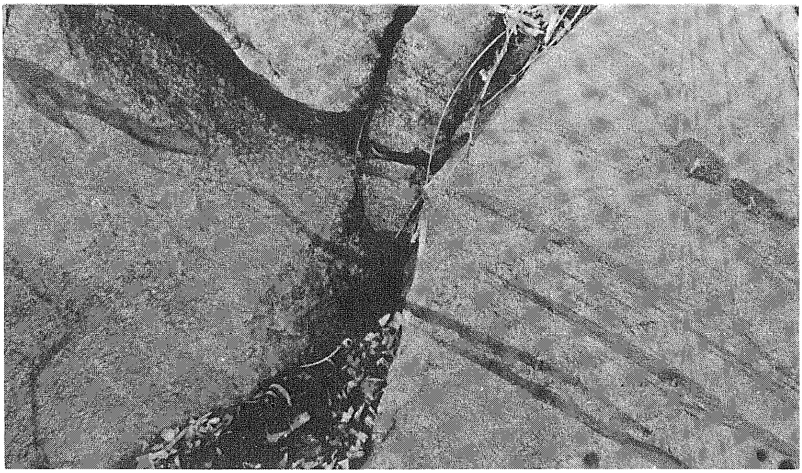


Figure 6. Typical thin-banded pyroxene-quartz-plagioclase gneiss of the Wilmington Complex. Dark bands are tightly folded and stretched out by early, first folding event; note fold noses and continuity of dark bands. Width shown in photo is 5 feet. I-95 at US 202 offramp.

monly very coarse-grained, and show classic ophitic and other igneous textures. Near the margins flow layering, grain-size variations; cognate inclusions and slight chilling are common. Metamorphism and deformation are absent, and the intrusions postdate the major deformational events.

Although not shown in Figure 1, the James Run (?) terrane contains irregularly distributed masses of quartz diorite. These rocks are best exposed along Barley Mill Road near Tatnall School. Pyroxene is absent from these rocks; the mafic phases are instead hornblende and biotite. Inclusions of many James Run (?) lithologies characterize this rock. Broadly similar rocks are suspected to occur in western Wilmington Complex near Rockland, but cannot be correlated with certainty.

Near Newark several poor outcrops indicate the presence of a large mass of quartz diorite to granodiorite (Figure 1). This rock contains appreciable potash feldspar, and small amounts of biotite; pyroxene again is absent. The rocks are probably continuous with those of eastern Cecil County, Maryland, and appear to terminate in Newark.

Near Mermaid there occurs a thin, elongate mass of fine-grained

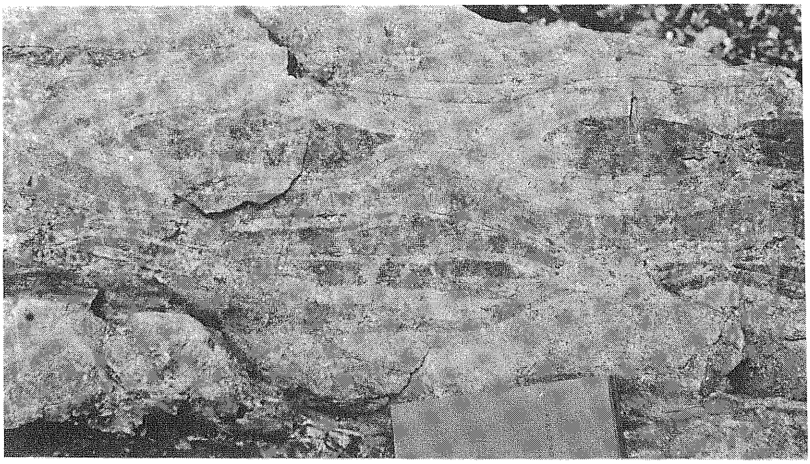


Figure 7. Boudinage in thin-banded gneisses of Wilmington Complex. Rockford Park.

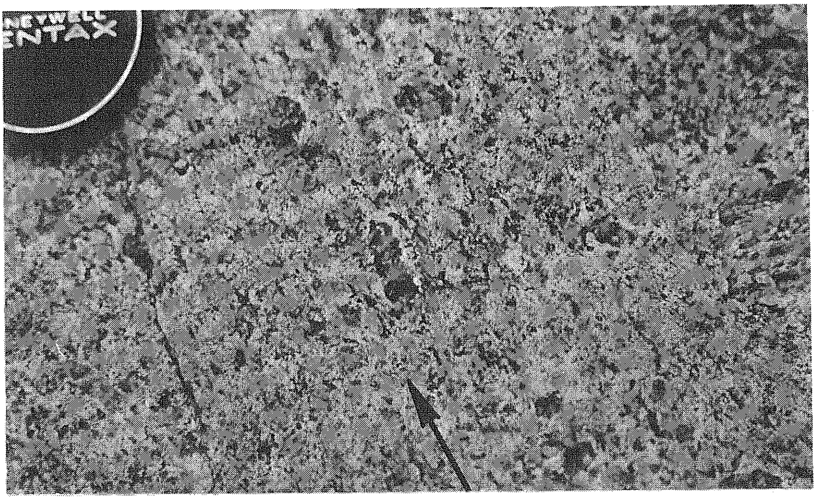


Figure 8. Typical appearance of anorthosite. Large crystals of plagioclase feldspar are surrounded by white rims of fine-grained, granulated plagioclase. Other minerals include pyroxene and minor quartz and potassium feldspar. Note faint foliation parallel to arrow. Afton-Timbers Park.

diabase. It is probably a dike, trending northeast, and is texturally similar to the diabase dikes common in the Triassic basing of southern and eastern Pennsylvania.

Structural Geology

The rock units discussed above, regardless of terrane, are highly deformed and metamorphosed. Both brittle structures, including faults, and joints, and ductile structures (folds) are extensively developed. The ductile structures are confined to and are characteristic of Piedmont rocks; many of the brittle structures cut across both Piedmont and Coastal Plain rocks. The Piedmont is structurally complex, and may be divided into several domains, each characterized by a distinct style and orientation of fold structures. These domains coincide with the terranes defined above on lithologic bases, and probably reflect differing conditions of origin and deformation. Thus each terrane evolved as a distinct structural and geologic unit; this evolution, and the positioning of the units into their present locations, is the major problem of synthesis in Delaware Piedmont geology.

The Mill Creek Gneiss dome terrane is characterized by small-scale, tight to isoclinal folds, whose orientations are diverse and are not consistent. These small folds have been arched over the axis of the gneiss dome, which is itself an anticline. The observed small-fold orientations do not correspond to any known orientation of deformation in the east-central Appalachians, and are thus of considerable significance.

Rocks in the Glenarm terrane are essentially vertical, and strike consistently N35E-N40E. These rocks are on the limbs of isoclinal, upright folds, whose axes plunge gently at S60W in all areas but one small fault slice (which contains Wooddale Quarry). There appears to be only one orientation of folds in this terrane. Near Newark the structural trend turns more westerly as it continues into Maryland. Isoclinal folding in the Glenarm is well exposed in the west wall of Wooddale Quarry (Figure 9).

The James Run (?) terrane, lying abruptly southeast of the Glenarm, has been strongly deformed into tight to isoclinal upright folds and other structures which plunge N15W at 15° to 30°. These folds are seldom well developed, and details of their geometry are lacking. Near the western margin of the James Run (?) terrane the northwest-trending folds contain a weakly overprinted mineral elongation direction of N35E. Folds of this style are best displayed in exposures behind Alexis

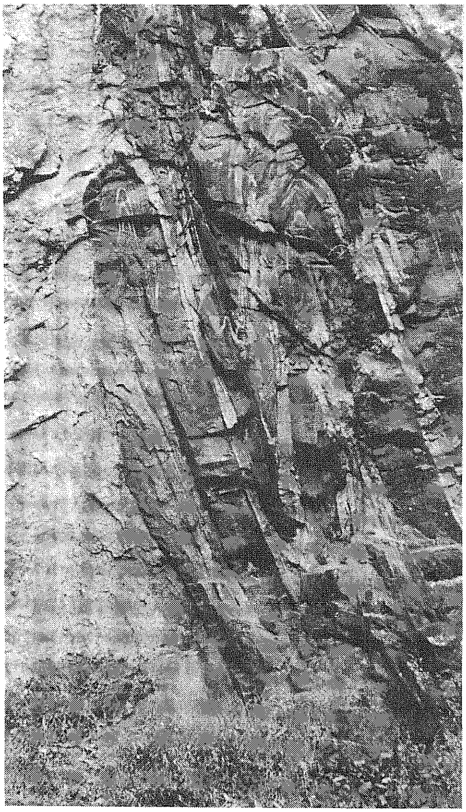


Figure 9. Tight to isoclinal, similar folding and partial melting in Wissahickon Formation. Light-colored rocks to left are granites formed by partial melting of metamorphic rocks at high temperatures; note intrusive contacts. Wooddale quarry.

I. Dupont High School in Greenville.

Rocks of the Wilmington Complex have been intensely deformed into isoclinal to open folds, which generally plunge N to N15E at 20° to 25°. Two generations of folds are apparent. Early folds are isoclinal and intense, and have resulted in much of the layering seen in the rocks; Figure 6 shows well the origin of this thin banding. These early folds are defined by compositional layering, which can be inferred to be original. They are overprinted by a second preferred orientation, plunging

N15W at 20° to 30°. These later folds are upright and less intense than the early folds (Figure 5). Parallel to the axes of later folds are many linear elements, including boudinage axes (Figure 7) and strong mineral lineations comprised of elongate grains of pyroxenes and magnetite.

Of the igneous rocks, only the anorthosite contains any regionally consistent structures, and many of these may be brittle rather than ductile. Structures in the anorthosite are weak, vertically oriented, planar and linear grain elongations or parallelism (Figure 8), which coincide in direction with the two orientations shown by the metamorphic rocks of the surrounding Wilmington Complex.

Brittle Structures

The Piedmont contains many structures that have involved brittle behavior of rocks and have involved rock breakage. Many faults are present in the Piedmont, and more are being discovered each year. Two types of faults are recognized. The first comprises breaks in rocks that parallel the N35E orientation of fold structures in the Glenarm terrane, and that probably originated during deformation of the Glenarm rocks (Figure 1). These faults are common in the Glenarm terrane, and are not well exposed. They show significant post-faulting healing and recrystallization, and are not well etched in the topography.

The most important of these organic faults separate the James Run (?) from other terranes (Figure 1). The northwest boundary fault is partly exposed in Wooddale railroad cut, and appears to die out to the southwest near Newark. The southeast boundary fault, exposed in Marshallton, is considered the master fault, and lies astride a faint lineament traceable in satellite photographs from Stanton toward Philadelphia. Significant and abrupt changes in lithology and metamorphic grade take place across these faults.

Faults of the second type cut across all previous structures in all four terranes and the Coastal Plain, and have not been healed or recrystallized (Figure 1). These faults parallel sets of fractures, or joints, along which there has been no movement, and probably resulted from the same stress systems as the joints. These faults are recognizable by gouge and crushed zones, linear topography, straight stream courses, and offset rock units. Strong northwest and northeast orientations characterize these fracture sets; an example of control by fractures is given by the alternating northeast and northwest, straight stretches of Brandywine Creek (Figure 1).

The Piedmont is fractured by at least four approximately orthogonal sets of joints and related faults. Nearly all sets are vertical and appear to have resulted from horizontally directed shear-stress systems in relatively cold, stable rocks.

Ages of Rocks

No fossils have ever been recovered from rocks of the Delaware Piedmont; this is probably due to their general rarity in the original rocks and to their destruction by metamorphism and deformation. Thus rocks are not datable paleontologically, and must be dated by other means. Lithologic correlations with rocks elsewhere in the Piedmont suggest lower Paleozoic, probably Cambrian, ages for Glenarm and James Run (?) rocks. These lithologic correlations are supported by radiometric ages of approximately 500 million years on igneous rocks intruding James Run and Glenarm metamorphic rocks in Maryland (Higgins, 1972). Similar dating of the Baltimore Gneiss in Maryland gives ages of approximately 1 billion years (Tilton et al., 1958); if the lithologic correlations of rocks in the core of the Mill Creek Gneiss Dome with Baltimore Gneiss are correct, then those core rocks are Precambrian and genetically distinct from adjacent rocks.

The Wilmington Complex is distinct, and cannot be correlated lithologically with any rocks in nearby regions. Two radiometric dates have been obtained for Delaware rocks, both related to the Wilmington Complex. One, a Rb/Sr whole-rock age on anorthosite, gives 510 million years as the age of anorthosite crystallization (Muessig and Foland, 1975). This suggests that the anorthosite, and the Wilmington Complex which it intrudes, are of Cambrian age. The other date, a U/Pb Concordia date on gneisses of the Wilmington Complex, gives 440 million years (Ordovician) as the time of peak metamorphism (Grauert and Wagner, 1975). This is in accord with other estimates of tectonic and metamorphic timing in the central Appalachians. Thus, the majority of Piedmont rocks in Delaware may be regarded as lowermost Paleozoic, Cambrian, or slightly older, affected by a (perhaps not the only) major deformation and metamorphism in Ordovician time.

Geologic Evolution of the Piedmont

This section presents only one of the several possible reasonable models for the origin of the present geologic relations in the Piedmont. However, this model is consistent with present data and observations in

Delaware. It draws on previous works of, among others, Higgins (1972), Bird and Dewey (1970), and Crowley (1976).

A primary assumption underlying the model is this: the different terranes originated in the same relative positions as they show today, but not in the same absolute geographic positions; the original distances between them have been considerably foreshortened by folding and faulting. The Precambrian gneisses in the Mill Creek Gneiss Dome terrane probably represent the edge of the pre-Paleozoic American continental crust, alongside which the Appalachian orogenic belt developed. The clastic rocks of the Glenarm terrane originated on the edge of, and largely next to, the continental margin (Dietz, 1963). The facies of Glenarm rocks are considerably different north and south of the gneiss dome, and may represent genetically different associations; however, this still does not alter the position of the Delaware Glenarm rocks relative to the continental crust. The James Run (?) terrane lay southeast of the Glenarm, although its position has probably been altered by faulting. The Wilmington Complex lay next southeast, and extending southeast of its present outcrop limit for an unknown distance. The geographic relationships were maintained despite northwestward displacement of James Run (?) and Wilmington Complex terranes along faults. The abrupt and discontinuous changes in metamorphic grade and structural style across present terrane boundaries support the interference of considerable tectonic modification of original geography.

A pre-deformation, paleogeographic model for the Paleozoic rocks of the Piedmont (Figure 10, top) can be constructed if we consider the implications of rock type for environment of formation. The Glenarm rocks are clearly metasedimentary and are largely clastic. The basal Setters and Cockeysville Formations probably represent shallow-water, shelf-type deposits laid atop the continental crust margin. The Wissahickon probably represents very thick sandstone and sandy shale deposited on an ocean rise and floor developed at the edge of the continent. This ocean basin lay southeast of the continental margin and accumulated muds and minor sands near the toe of the rise.

The James Run (?) contains metavolcanic rocks in addition to pelitic, garnet-, and sillimanite-bearing schists which represent metamorphosed shales. These rocks accumulated southeast of the oceanic rise, and probably signify a volcanic source to the southeast. The volcanic rocks in the James Run (?) probably represent ash flows, tuffs, and genuine lava flows interbedded with marine sediments.

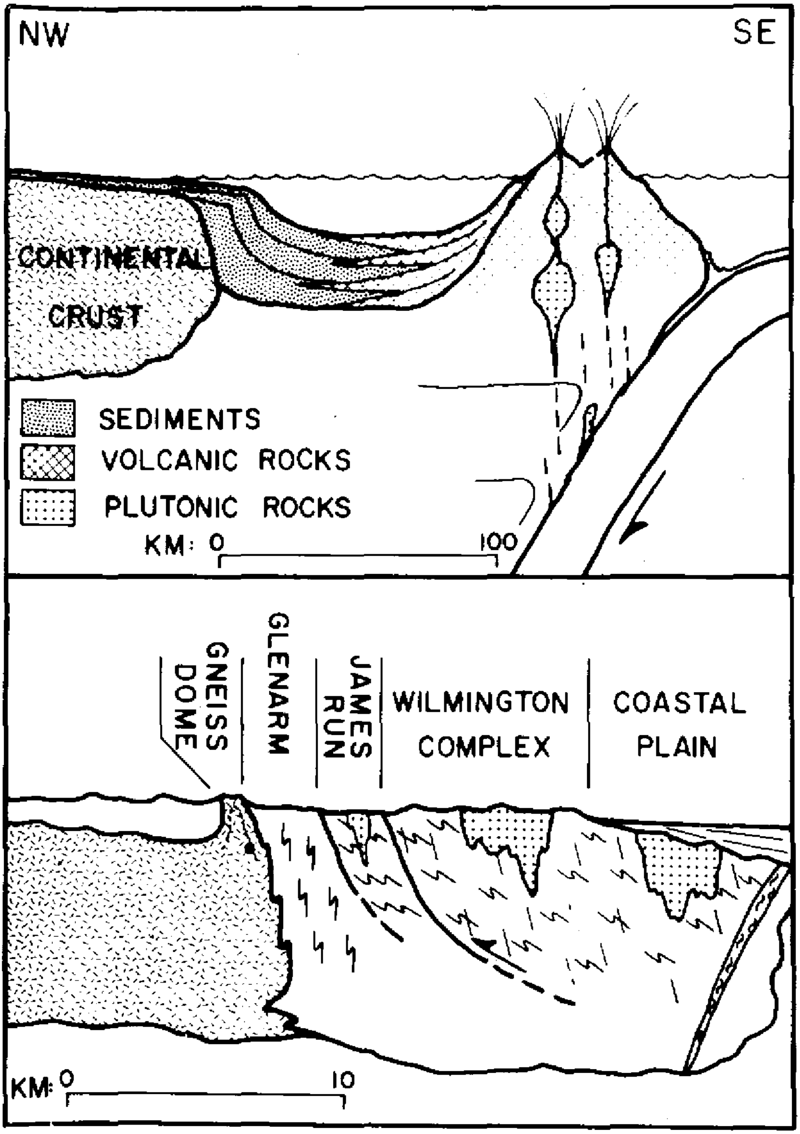
The Wilmington Complex, with its abundance of igneous rocks and very high grades of metamorphism, may well represent the deeply eroded core of a volcanic-plutonic complex developed some distance off the American continental margin. Plutonic rocks, possibly including anorthosite, were intruded into the complex, and fed magma to the surface in the form of volcanic flows and tuffs.

These inferred relations between continental margin, continental rise, oceanic basin, and offshore volcanic-plutonic complex are similar to those documented today in many oceanic island-arc complexes and certain continental margins. Island arcs are developed above subduction zones, and receive magma from melting of rocks by heat generated along those zones. The James Run (?) terrane and Wilmington Complex, then, record the existence of a former island arc, and imply the presence of an early Paleozoic subduction zone and related deformation beneath the eastern margin of middle North America.

Tectonic History

Initiation of subduction probably took place in the very early Cambrian, as suggested by radiometric data. Volcanism and plutonism occurred seaward of coeval clastic deposition adjacent to the continental margin (Figure 10). Continued subduction through Cambrian and much of Ordovician time generated continued volcanism, and also generated continuing compressive and ductile deformation of the back-arc ocean basin and continental margin sediments (Figure 10, bottom). Early deformation was ductile flow folding; later folding was more flexural, in largely dehydrated rocks, although extensive recrystallization took place along cleavage intersections. Deformation was probably earlier on the eastern side, near the origin of compressive stress, and slightly later farther west; this is supported by the multiple metamorphism in eastern-arc rocks and single metamorphism in western continental margin rocks. Metamorphism reached its highest levels in mid-Ordovician time in all terranes but was probably stronger in eastern zones, closer to the thermal sources. Westward emplacement of James Run (?) and Wilmington Complex terranes against the continental-margin metasedimentary pile probably occurred relatively late in the deformational history, but before cessation of metamorphism.

The closing of the proto-Atlantic ocean, which gave rise to the subduction, took longer times in different areas, and the tectonic effects were not finally terminated until the Late Paleozoic. The resulting supercontinent, Pangaea, endured as a single land mass for about 150 million years, or into the early Mesozoic. At that time it was distended


NW
SE
CONTINENTAL
CRUST
SEDIMENTS
VOLCANIC ROCKS
PLUTONIC ROCKS
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100
GNEISS DOME
GLENARM
JAMES RUN
WILMINGTON COMPLEX
COASTAL PLAIN
KM: 0
10

and rifted apart as the present Atlantic Ocean began to form. The bulk of the brittle structures probably resulted from stress systems associated with this opening. The Atlantic opened, and is opening today, along west-north-west-trending transform faults from a spreading pole located near Iceland. These relationships generated simple shear couples in each coherent spreading block. These shear stresses, generated near the ocean ridges, were transmitted through the rigid spreading blocks, and led to northwest- and northeast-oriented fracture sets within the blocks. The fractures affected both oceanic crust and continental crust, and were only coincidentally related to Paleozoic tectonic directions. Fault movement occurred along some of the more fundamental fractures; both strike-slip and normal faulting probably took place. The joint and fault systems in the Piedmont date from Cretaceous, and probably from Triassic, time. The abundance of distinct sets can be related to differing episodes and rates of sea floor spreading since the Triassic.

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Figure 10. (opposite) One possible evolutionary model for the Delaware Piedmont. Vertical scale is not consistent. Top: Paleogeography of Atlantic margin in the Delaware area at beginning of Cambrian time. Continent-derived sediments of Wissahickon Formation pass laterally into volcanic-dominated rocks of James Run (?) Formation, which flanks an active volcanic island arc atop a west-dipping subduction zone. Bottom: The Delaware Piedmont today. Westward compression and tectonic transport in Ordovician time generated new continental crust from former sedimentary and igneous rocks in forming the original Appalachian mountains, since eroded away. Delaware Piedmont rocks represent the deep, core zone of those original Appalachians. Note change in horizontal scale from top to bottom diagrams.

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7

Geohydrology of Delaware

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The Water Budget

WE are accustomed to thinking of water as occurring naturally in two distinct ways – either as surface water in streams and lakes or as groundwater that is hidden beneath the surface of the earth in rock reservoirs. This arbitrary division has usually been convenient for administering water laws and for classifying water studies. However, consideration of what hydrologists call the water budget will show that such a division is indeed an artificial one. Rainfall is the source of the renewable water resources and the total amount of renewable water available from both surface and underground sources cannot exceed the amount of rainfall remaining after evapotranspiration occurs. In simplest form this can be expressed as:

$$P = E + R + \Delta S$$

where P = rainfall, E = evapotranspiration, R = runoff (surface and

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groundwater), and ΔS = any change in groundwater storage.

Note that runoff includes both short duration overland runoff from storms and groundwater runoff. During periods of no rainfall the flow in surface streams is sustained entirely by discharge of groundwater to stream channels (neglecting any bank storage). If, during this time, the demands on groundwater storage are excessive, then the groundwater discharge to streams must decrease in accordance with the equation above (assuming relatively constant evapotranspiration). In Delaware, the water table groundwater reservoir, or aquifer, is usually full and discharging to surface streams. In more arid states groundwater mining commonly occurs, which means that more groundwater is withdrawn than can be replenished. In this case there is often no streamflow during dry periods. The recognition that ground and surface waters are derived from the same source is part of the key to successful total water management.

Estimates are available on the magnitude of the various elements of the hydrologic budget in Delaware. Rainfall is the easiest factor measured and rainfall data are available for many locations. Some total yearly precipitation figures averaged for selected locations are listed in Table 1.

Rainfall in any given year may vary widely from the northern to the southern part of Delaware. Figures 1a, 1b and 1c show rainfall variations across the state for the water year 1975. Note particularly the differences in rainfall for the month of July, 1975.

Losses due to evapotranspiration (E) may be considerable during summer months and probably range between 60% and 75% of a given rainfall. During winter months these losses are much smaller and may be negligible depending on exact climatic conditions. Evapotranspiration can occur directly from surface water bodies and also from the groundwater table when the latter is within a few feet of the surface of the ground. In some cases it is possible that a lowering of the water table will actually reduce losses due to evapotranspiration. Evapotranspiration is usually best calculated indirectly by measuring the other elements of the budget, although it can be measured directly if necessary.

Changes in the amount of water stored in the ground (ΔS) can be estimated by periodically measuring the depth to the water table in observation wells. Figure 2 shows water levels averaged for 13 selected shallow observation wells for the period 1950-1961. Note that there is a seasonal variation of levels with a general downward trend of levels during the summer months and a rise in levels during the winter months.

TABLE 1

Yearly Precipitation in Delaware[1]

Year	Rainfall (inches)
1950	40.49
1951	45.26
1952	48.95
1953	45.15
1954	33.72
1955	37.14
1956	47.85
1957	39.09
1958	51.87
1959	38.19
1960	46.03
1961	40.44
1962	34.41
1963	32.10
1964	32.82
1965	24.90
1966	39.51
1967	44.65
1968	31.75
1969	40.38
1970	38.31
1971	52.24
1972	52.92
1973	47.48

Condensed from Delaware Statistical Abstract, 1974.

[1] *Average statewide precipitation from 1894 through 1973 = 43.50".*

Throughout most of Delaware, over periods of years, the average levels remain about the same so that there is little change in net groundwater storage. During drought periods, such as occurred in the 1960s, levels may be below average for as much as several years but usually recover again when consistent normal rainfall returns.

Occasionally, combinations of factors occur to suppress groundwater levels. During the fall and winter of 1976-1977 levels in shallow wells did not show a normal upward trend because of: 1) the lack of precipitation and 2) an unusually cold winter with frozen soil conditions

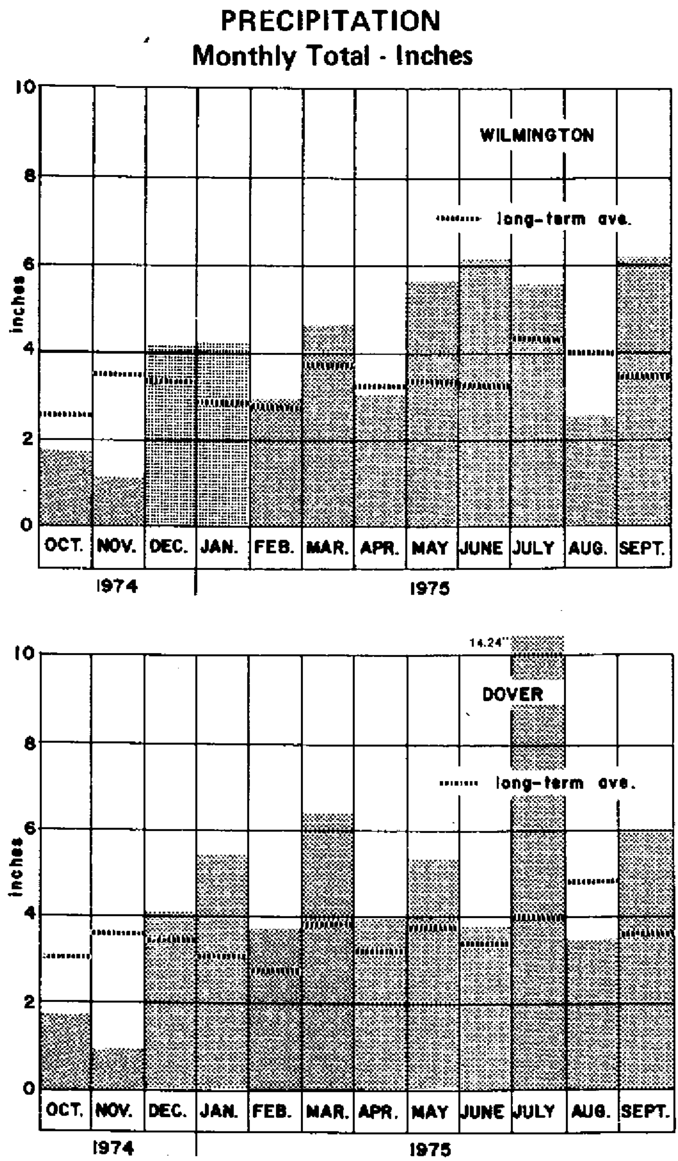


Figure 1a and 1b.

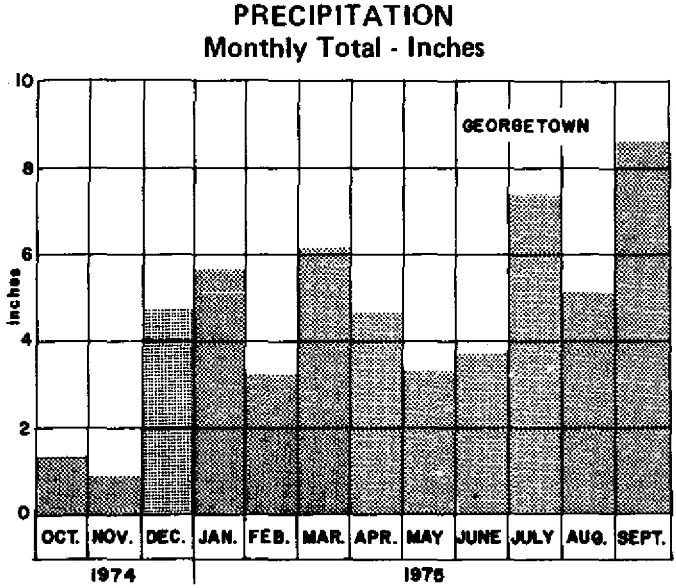
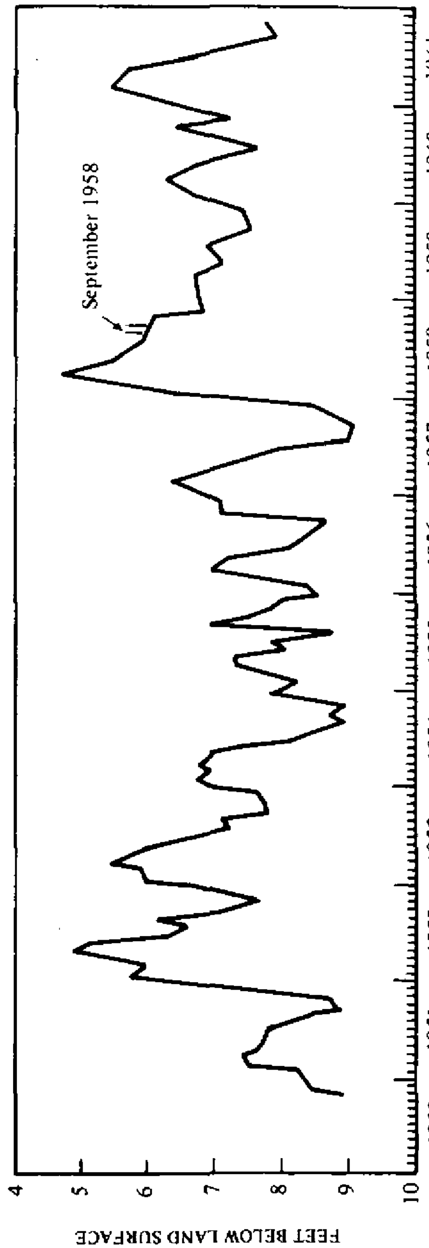


Figure 1a and 1b (opposite), and 1c (above). Precipitation at selected locations in Delaware. (From Talley, 1975.)

throughout most of the period. Thus what precipitation did occur was not able to recharge the water table. Groundwater levels (and groundwater storage) were therefore below normal in the spring of 1977 and continued to decline seasonally. Figure 3 shows levels as measured in observation well Db24-10 near Newark during this time. The lack of seasonal recharge during the winter months can be clearly seen.

Runoff (R) is measured by means of stream gauging stations located on all major streams in the State. A fairly comprehensive record of continuous streamflow is thus available and many spot flow measurements have been made for smaller tributaries. Analytical techniques exist that make it possible to separate the overland and groundwater flow components by study of the flow records. Johnston (1973) applied such a technique in a study of six streams located in Kent and Sussex Counties and showed that the groundwater runoff to streams appeared to be about 14 inches of rainfall per year. This is equivalent to about 650,000 gallons per day per square mile. Sundstrom and Pickett (1970)


September 1958
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AVERAGE DEPTH TO WATER IN
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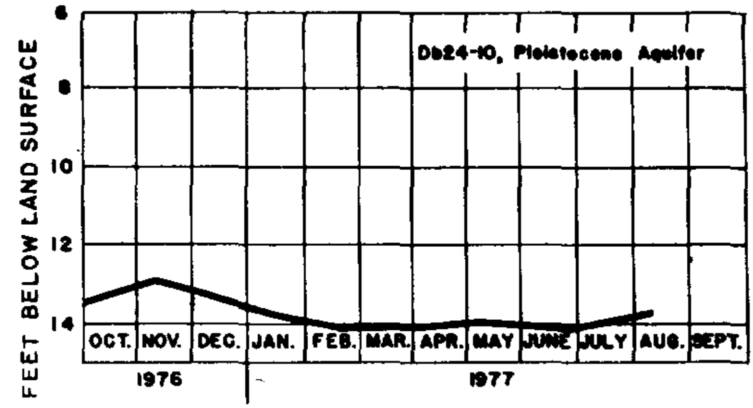


Figure 3. Levels in observation well Db24-10 near Newark. (From Talley, 1975.)

indicated that in Western Sussex County about 21 inches of rainfall per year were available as recharge. On an area basis this is about 1 million gallons per day per square mile. These estimates probably bracket a reasonable range of the amount of groundwater recharge available in the state. Theoretically, the average groundwater recharge could be withdrawn without affecting groundwater storage. If this amount is withdrawn, however, streamflow will decline sharply for the reasons already discussed. If withdrawals should exceed the recharge, then groundwater storage will decrease with an accompanying lowering of the water table.

Regional Occurrence of Groundwater

Chapters 5 and 6 outline the geologic framework of the state and indicate the presence of two major physiographic provinces – the Atlantic Coastal Plain and the Appalachian Piedmont (see Figure 1, page 88). These two physiographic divisions also correspond to the two major groundwater provinces of Delaware. The different rock types underlying each province largely determine how groundwater occurs, how it behaves, and how it is located.

Figure 2. (opposite) Average depth to water in 13 water table wells in Delaware. (From Boggess and Adams, 1963.)

Coastal Plain Aquifers

Rocks underlying the Coastal Plain are unconsolidated sediments and water is stored in the void space between sediment grains. The porosity of a rock is a measure of the void space and thus is an indication of the amount of water a material will hold. However, for a material to function as an aquifer it must also transmit water readily; that is, it must have a relatively high permeability. Coarse sediments (sands) have both relatively high porosity and permeability and therefore function as aquifers when saturated with water. Finer grained sediments (silts and clays) may have appreciable porosity but no permeability, and therefore do not transmit water with sufficient velocity to sustain a pumping well. Water moves slowly through an aquifer in response to either natural or man-made hydraulic gradients. Stream channels are natural points of discharge, while pumping wells are discharge points created by man.

Confusion occasionally arises over the terminology applied to local aquifers and the relationship of an aquifer to a formally named geologic unit, such as a formation. A formation may be comprised of a range of lithologies, but only the sandy portions, which store and transmit water, function as an aquifer. In some cases an aquifer comprising part of a formation may take on the formation name. For example, the Piney Point Formation beneath the northern half of Kent County contains a major sandy unit informally called the Piney Point Aquifer. In other instances the aquifer may be designated by a separate name often an informal one, originating through local usage. Other examples become evident in the discussions that follow.

The Water Table Aquifer

In Delaware a blanket of sediment known as the Columbia Formation (or Columbia Group in southern Delaware) covers most of the Coastal Plain and rests unconformably on older sediments (see Figure 4). The Columbia is composed primarily of coarse-grained materials, is nearly entirely saturated with water, and is one of Delaware's most important aquifers. Most shallow dug wells in the state are located in the Columbia. The water in the Columbia, because of the stratigraphic position of the formation at the top of the geologic column, is not under confining pressure but is under atmospheric pressure only. The water table, referred to in the discussion on the water budget, is the point below the surface of the ground at which the sediments are entirely saturated. The Columbia Formation is thus often termed the "water table aquifer." Where present, the formation varies in thickness from a few feet to over 100 feet. In New Castle County, sands are thickest in channel-like deposits, but in the southern part of Delaware the Columbia is more of a sheet-like deposit. Figure 5 indicates the saturated thickness of the Columbia Formation across the state.

Water in the Columbia moves naturally from topographically high areas to discharge points along stream valleys. This pattern may be altered locally by groundwater withdrawals in either the Columbia or underlying formations. Natural heads or water levels in the water table aquifer generally range from about 5 feet to as much as 35 feet below ground surface. Generally, levels are highest in the southern part of the state and lowest in New Castle County.

In an area where the Columbia rests upon older sands, both the Columbia Formation (or Group) and the underlying sands will act as a single aquifer. The Columbia thus also serves as the "sponge" through which recharge passes to underlying aquifers (except for a few areas in New Castle County where the Columbia is thin or absent.) The management and protection of this water table aquifer is therefore particularly important in any overall groundwater management scheme.

The water table aquifer along coastal areas is in direct contact with the brackish water of the ocean, Delaware Bay, or tidal streams. Local pumping can reverse the natural flow of groundwater into these surface waters and induce saltwater intrusion. This occurred in the initial shallow well fields at Lewes and Rehoboth Beach. Pumping wells were located too close to the ocean and eventually saltwater intrusion occurred. Moving the well fields inland 1 or 2 miles solved the problem in both cases. There are other reported instances of saltwater intrusion in shallow domestic wells around Indian River Bay and in small communities located up and down the coast. The possibility of saltwater intrusion must be considered in planning any groundwater withdrawals from the water table aquifer in coastal areas. The aquifer is also particularly susceptible to other sources of contamination, such as landfills, chemical spills, dredging spoils, and septic tank concentrations. In most cases, proper engineering and construction techniques will minimize the impact of these potential hazards.

The Artesian Systems

Beneath the Columbia Formation is a wedge-shaped mass of older sediments that varies widely in composition. The entire mass tilts or dips

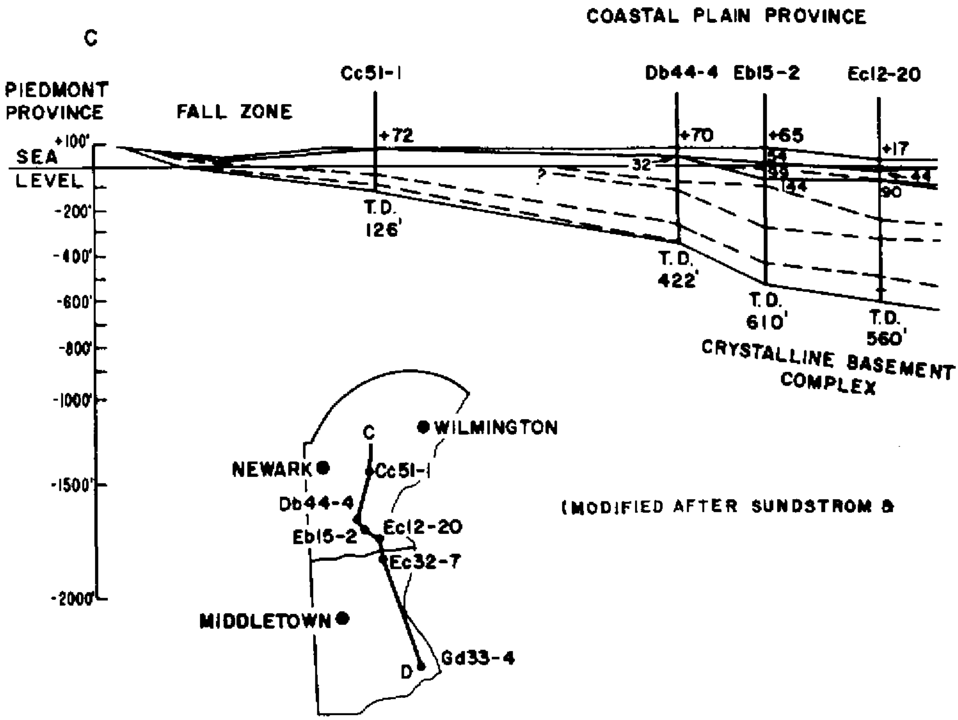
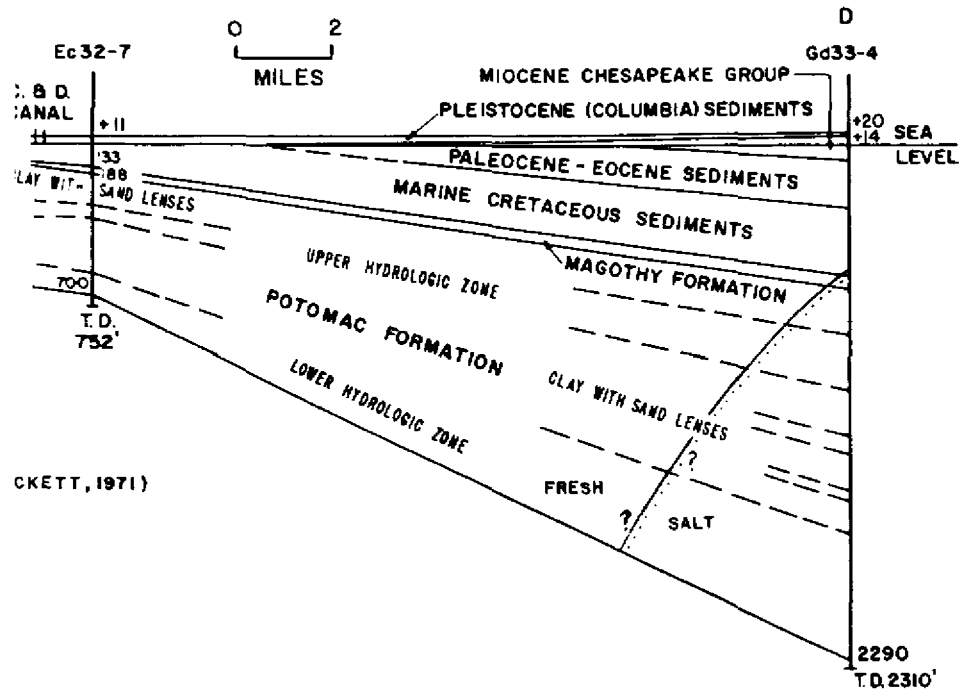


Figure 4. Geologic cross section of New Castle County.

gently in a southerly direction and ranges in thickness from a thin edge at the Fall Zone in northern Delaware to over 8000 feet in Sussex Country (Rasmussen et al., 1960). The geologic nomenclature and ages for the individual Coastal Plain units are shown in Figure 6. Most of these units subcrop or are exposed beneath the Columbia cover in narrow bands striking northeast-southeast across the state. These subcrop areas are usually the recharge areas for those sandy units that function as aquifers. Downdip from the subcrop areas the various aquifers within the sediment mass are under the pressure of the sediment load or lithostatic pressure. Heads, or water levels, measured in these aquifers will reflect both the lithostatic pressure and the higher elevations of the intake areas. The water level in an observation well tapping on of these aquifers will thus rise to a point above the top of the aquifer. Such an aquifer is known as an artesian aquifer. The most vivid example of this



is a flowing artesian well which results when the water level or piezometric surface is above the top of the ground. Pressures in most artesian aquifers in the Delaware Coastal Plain have been lowered below ground surface by pumping and few flowing artesian wells are found today. In the following discussion the major artesian aquifers or aquifer systems are briefly described, beginning in New Castle County and generally proceeding southward.

The Potomac Formation: Figure 4 shows the aquifers underlying the Coastal Plain from the Fall Zone south to approximately the New Castle-Kent County Line. The sands of the Potomac Formation and those of the overlying Columbia provide most of the groundwater in the area north of the Canal. The Potomac Formation, an ancient delta complex, is the oldest of the Coastal Plain units in Delaware and rests

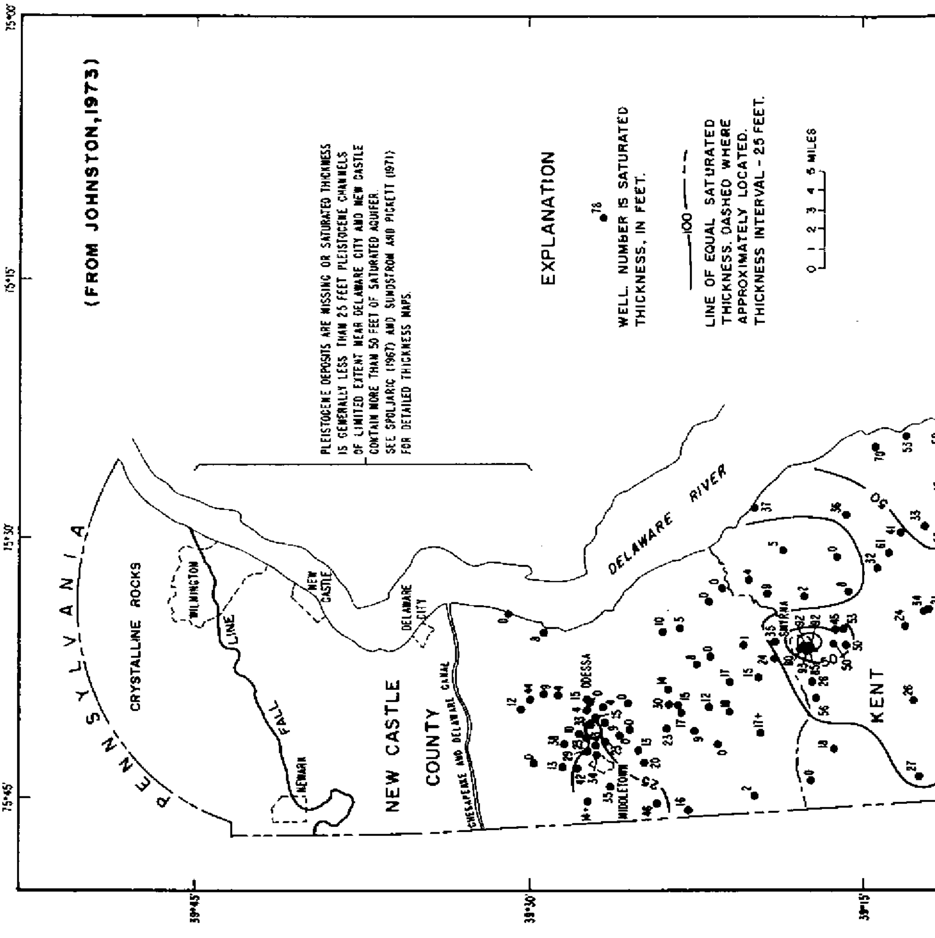
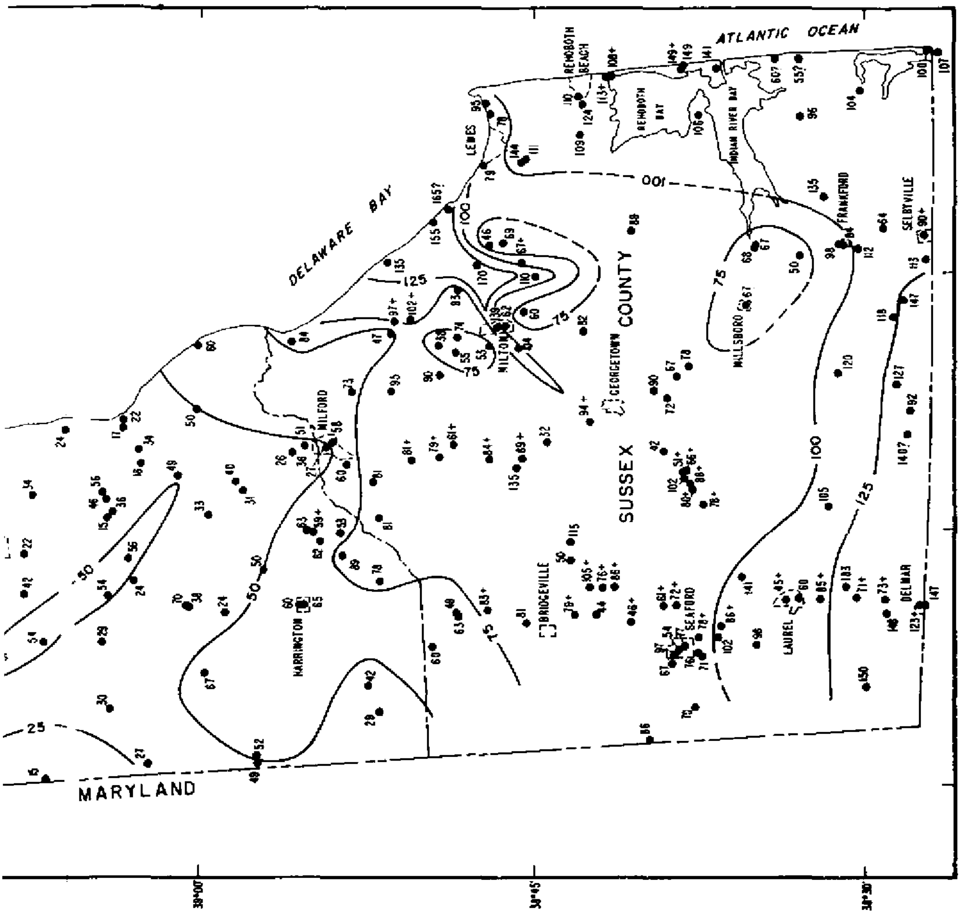


Figure 5. Saturated thickness map of the Columbia (Pleistocene) deposits in Delaware.

directly upon crystalline basement rocks. The thickness of the Potomac varies from a few feet at the Fall Zone to about 2300 feet in the southern part of New Castle County. In the northern part of the County, Potomac sands are generally thin and occur mainly as channel sands or stringers randomly distributed within a mass of finer grained sediments. Because of this, groundwater exploration in the Potomac in northern



New Castle County is especially difficult. Farther to the south, near the canal, Potomac sands seem to occur with more certainty within general depth zones, particularly in a zone just above crystalline basement. Sundstrom et al. (1967) recognized two such general zones (including the zone just above basement) and informally referred to them as the upper and lower hydrologic zones of the Potomac (see Figure 4). Sundstrom et al. (1967) also determined that in short-term pumping tests (up to a few days) there does not seem to be any leakage of water from one zone to the other through the intervening fine-grained sediments.

AGE		UNIT
Quaternary	Pleistocene	Columbia Fm. Omar Fm. Beaver-dam Fm. Columbia Grp.
Tertiary	Pliocene (?)	
	Miocene	Chesapeake Group Pocomoke Manokin Frederica Cheswold Aquifers
	Oligocene	
	Eocene	Piney Point Fm. Nanjemoy Fm. Vincentown Fm.
	?	
	Paleocene	Hornerstown Fm. Rancocas Grp. Pamunkey Fm. (downdip)
Cretaceous	Upper Cretaceous	Mt. Laurel Fm. Monmouth Fm. (downdip) Marshalltown Fm. Englishtown Fm. Merchantville Fm. Matawan Grp. Matawan Fm. (downdip) Magothy Fm.
	Lower Cretaceous	Potomac Fm.

Figure 6. Stratigraphic units underlying the Coastal Plain of Delaware. (Modified after Pickett, 1972.)

Very probably, however, the entire system functions as a leaky aquifer over long periods of time.

Major centers of pumping from the Potomac are located in the industrial complex near Delaware City and in well fields of the Artesian Water Company located throughout northern New Castle County. The City of Newark also draws some water from the Potomac through wells located south of the city. Relatively large withdrawals from the Potomac began in about 1955, and since that time heads or artesian pressures in most Potomac sands have dropped several tens of feet.

Yields from the Potomac are extremely variable and range from a few gallons per minute to several hundred gallons per minute. There is brackish water in the Potomac in the southern part of New Castle County below depths of about 600 feet. There are a few reported cases of salt-water intrusion into wells tapping the Potomac near Delaware Bay in the Wilmington-New Castle area. High iron is common in waters from the Potomac Formation, but otherwise quality is generally good.

The Magothy Formation: Figure 4 indicates that the Magothy Formation overlies the Potomac Formation across most of the state. Both sandy and silty units comprise the Magothy Formation. The Magothy sand, a laterally persistent unit, about 40 to 45 feet thick in most places, is capable of sustaining yields of up to about 250 gallons per min. The Magothy is presently used in and near Delaware City and at Middletown, where the formation is about 150 feet below sea level. Wells have also been drilled through the Magothy near Cheswold and at the Dover Air Force Base. However, south of about Smyrna, the Magothy contains brackish water (chlorides in excess of 250 mg per liter) and is thus not suitable for public supply without treatment. One industrial plant near Cheswold, where the Magothy is about 1100 feet below sea level, uses the brackish water from the Magothy in a chemical manufacturing operation.

Other Aquifers – New Castle County Area: Several "minor" aquifers are present above the Magothy from about the canal area south to about Middletown. On Figure 4 these aquifers are found as sands within the unit marked as "marine Cretaceous sediments." They do not yield large amounts of water and thus are generally tapped only by domestic wells. The Town of Middletown has a well in one of these sands, the Monmouth Formation, which initially yielded about 70 gallongs per min.

The Rancocas Group: Much of the water in the area just north

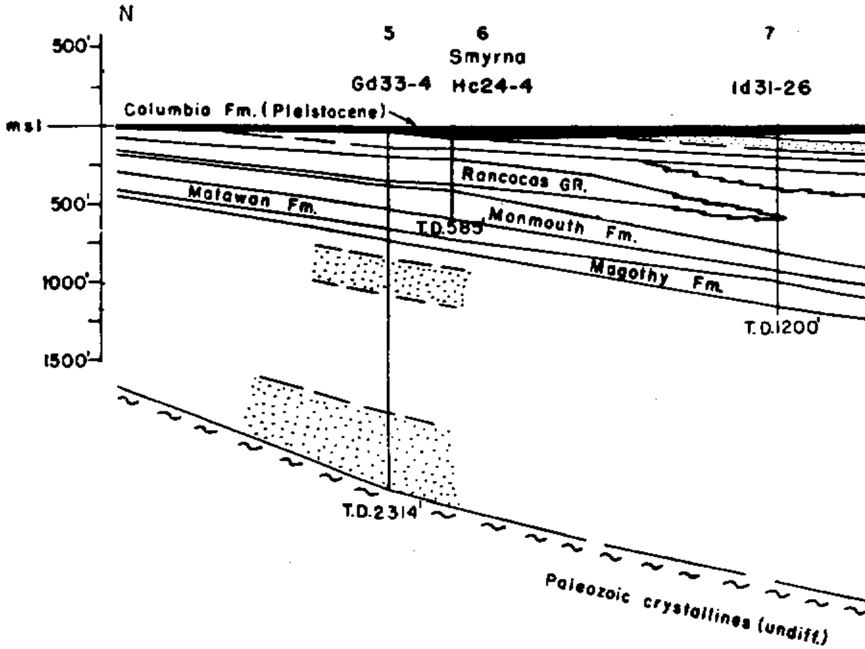
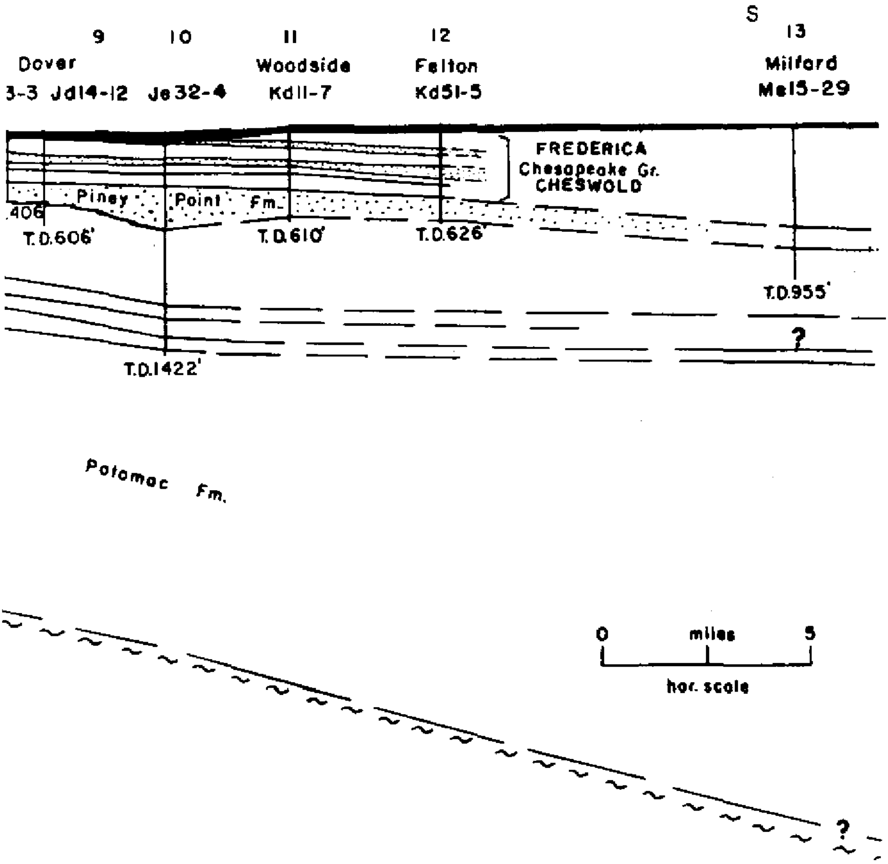


Figure 7. Geologic cross section through Kent County, Delaware. (Modified after Woodruff, 1969.)

of Middletown and south to about Smyrna is supplied from sands belonging to the Rancocas Group (comprised of the Vincentown and Hornerstown Formations). Drillers often refer to these sands as "greensands" because of their characteristic greenish-black color imparted to the sediments by glauconite. The Rancocas subcrops in the Middletown area, where it may act as part of the water table aquifer with the overlying Columbia sediments. To the south, the Rancocas Group becomes deeper and behaves as an artesian aquifer. Aquifer characteristics of the



Rancocas are not particularly outstanding, and it might be described as having fair water-yielding properties. In the Smyrna-Clayton area the best sands are located about 250 feet below land surface and pumping rates of several hundred gallons per min are not uncommon because of the large amount of drawdown available. Drawdown refers to the total column of water in a well above a fixed point, usually the top of a well screen. The Rancocas is tapped by wells at the Delaware State Correctional Institute near Smyrna and is used as a source of public supply at Clayton and Townsend.

There is some evidence from analyses of Rancocas water that bicarbonate concentrations are higher than for most Delaware groundwaters. This may cause screen incrustations, and there are indications that yields of some larger wells in the Rancocas have dropped off with time (A.C. Schultes and Sons, personal communication). Acid treatment may restore at least part of the initial well yield.

South of about Smyrna, the Rancocas becomes finer grained and apparently grades laterally into the Pamunkey Formation (Pickett, 1972), an aquiclude or nonwater-yielding formation.

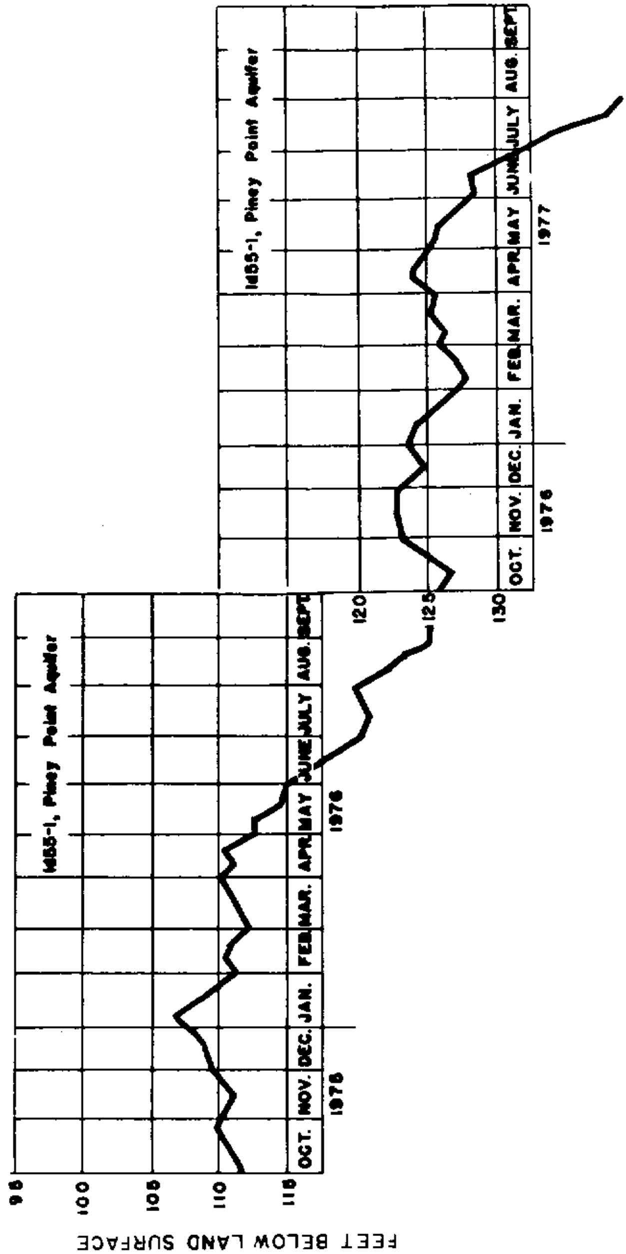
The Piney Point, Cheswold, and Frederica Aquifer System: The area just north of Dover south to about Milford is underlain by three freshwater artesian aquifers – the Frederica and Cheswold aquifers of the Chesapeake Group and the Piney Point Formation (see Figure 7). All three are extensively pumped. At least the lower two of these aquifers, the Cheswold and the Piney Point, seem to be somewhat interdependent as shown by recent studies (Leahy, 1976). The Piney Point Formation, the deepest of the three, is heavily used by the City of Dover, which pumped about 2.5 million gallons per day (mgd) from it in 1975 (Leahy, in press). The Piney Point extends into New Jersey to the northeast and as far southwest as Virginia. This formation has no outcrop area and thus must receive all of its recharge by vertical leakage through overlying formations. In the Dover area the top of the Piney Point is at an altitude of about 250 feet below sea level and may reach a thickness of over 150 feet. Relatively high yields have usually been obtained from individual wells because of the large amount of drawdown available in the aquifer. Pumping rates in the best portions of the aquifer have been as high as 600 gallons per min in single wells. However, over the past 2 to 3 years, artesian pressures in the Piney Point have declined sharply (see Figure 8) because of increased pumping and the lack of a direct recharge area. A computer (digital) model of the Piney Point has been constructed by the United States Geological Survey under a cooperative program with the Delaware Geological Survey, Kent County, the City of Dover, and the Delaware Department of Natural Resources and Environmental Control. The model provides predictions of drawdown due to given pumping rates and is expected to serve as a management tool. Various development schemes for the Piney Point have been initially tested and preliminary drawdown maps prepared. The model study has shown that under present total withdrawals (2.7 mdg) levels would stabilize at about 150 feet below sea level in the Dover area. This would leave about 100 feet of drawdown still available above the top of the well screens (Leahy, in press). Maximum pumpage in the Dover area should not exceed about 5.5 mgd or water levels will fall into the screens in most Piney Point wells.

The Piney Point aquifer extends about as far south as Milford where the top of the formation is approximately 650 feet below sea level. Here the formation becomes much finer grained and aquifer properties are poor. In addition, the chloride content of the Piney Point waters is about 500 mg per liter as determined from a test well drilled in 1968. The Piney Point Formation can be identified in the subsurface as far north as Cheswold, where it is much finer grained than in the Dover area and not usable as an aquifer. For all practical purposes the Piney Point as an aquifer is not found farther north than about 3 to 4 miles from the center of Dover.

The Chesapeake Group (Miocene age) overlies the Piney Point (Figure 7) and includes a number of distinctive sandy units. In the Dover area the principal sand of the Chesapeake Group is the Cheswold aquifer, which lies above the Piney Point and is separated from it by a silty to clayey confining bed. The top of the Cheswold occurs in the Dover area at about 135 to 150 feet below sea level and averages about 60 feet in thickness. The Cheswold is the major water source for the Dover area and total Cheswold pumpage in 1975 averaged about 6.5 mgd. The Cheswold can be mapped in the subsurface as far north as the New Castle-Kent County line and south well into Sussex County. Aquifer properties are poor, however, outside of the Dover area.

Water probably moves vertically through the Cheswold aquifer and underlying confining bed into the Piney Point aquifer in response to the head differences between the two aquifers. Groundwater management schemes should take into account this interdependence. The Cheswold is probably nearly fully developed in central Kent County and most future development should probably occur outside of the Dover area to the south and west.

The Frederica is the uppermost sand of the Chesapeake Group in central Kent County and is separated from the underlying Cheswold by a silty confining layer. The aquifer subcrops in a northeast-southwest trending belt which passes through Dover and dips gently to the southeast. At Milford, about 18 miles south of the subcrop area, the top of the Frederica is approximately 200 feet below sea level. The maximum thickness of the aquifer is approximately 50 feet and occurs a few miles south of Dover. The Frederica is used extensively in central Kent County


Id55-1, Piney Point Aquifer
OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT.
1975
1976
95
100
105
110
115
FEET BELOW LAND SURFACE
Id55-1, Piney Point Aquifer
OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT.
1976
1977
120
125
130

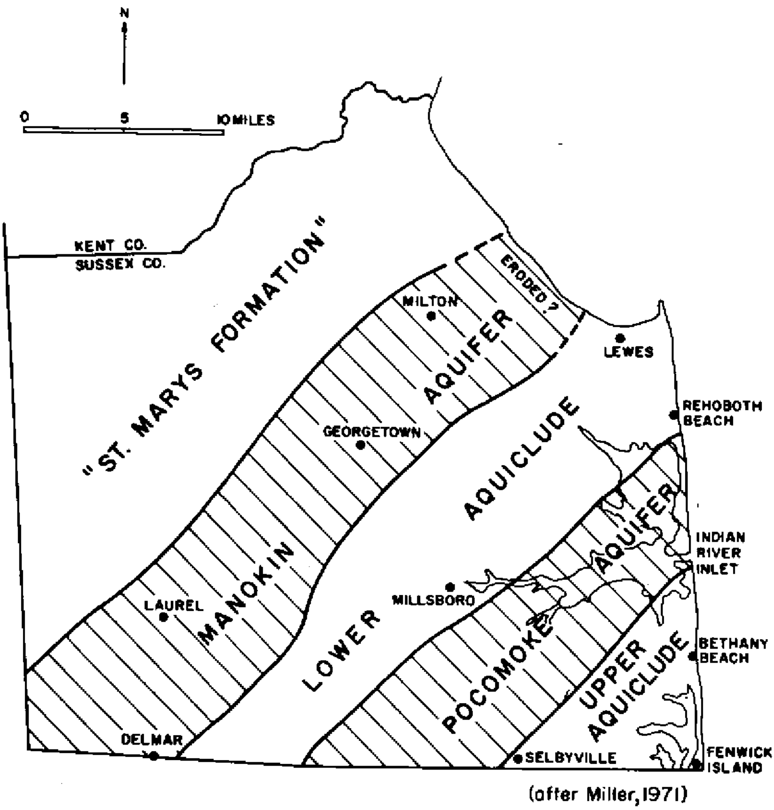


Figure 9. Subcrop distribution of the Manokin and Pocomoke aquifers.

south to about Milford and total average daily pumpage in the 1970s is estimated at slightly under 3 mgd. South into central Sussex County the aquifer becomes finer grained and maximum yields from individual wells are only a few tens of gallons per min. Additional development from the aquifer is probably possible, particularly in southern Kent County and Northern Sussex County. However, in some places it would

Figure 8. (opposite) Water levels in observation well Id55-1, near Dover. (Modified after Talley, 1976, 1977.)

be more economical to tap other overlying sands of the Chesapeake Group or the sands of the Columbia.

In some areas of central Kent County and northern Sussex County a sand occurs between the Frederica and Cheswold aquifers. Cushing et al. (1973) referred to the sand as the Federalsburg aquifer because of its correlation with a similar sand in the Federalsburg, Maryland, area. Before Cushing's work the Federalsburg had usually been considered as part of either the Frederica or the Cheswold aquifers. The Federalsburg has been tapped by wells in the Dover area and at Milford according to Sundstrom et al. (1976). The water-yielding properties appear to be only fair and the aquifer does not seem to be suitable for extensive development.

The Manokin and Pocomoke Aquifers: Two other distinctive aquifers of the Chesapeake Group can be recognized in Sussex County. These are slightly younger in age than the Cheswold and Frederica aquifers and thus, where they occur, are higher in the geologic column. The Manokin aquifer, the oldest of these two younger sands, has been shown by Miller (1971) to subcrop in a northeast-southwest trending belt across central Sussex County passing through Laurel and Milton (see Figure 9). Sundstrom et al. (1976) place the occurrence of the Manokin as far north as Bowers Beach to the northeast and Harrington to the southwest. The water-yielding properties of the aquifer appear to be best in eastern Sussex County, although there are little data on the aquifer in the western part of the County. At Fenwick Island the top of the Manokin is about 300 feet below sea level (see Figure 10). Drilling results indicate that in the area from Dewey Beach south to Indian River Inlet, the Manokin becomes quite silty and produces only small amounts of water. At other places in eastern Sussex County the Manokin is capable of sustaining average yields of several hundred gallons per min. Higher than average well yields can usually be obtained in those areas where the Manokin subcrops directly beneath Columbia sands because of the great amount of total saturated sand.

The position of the freshwater-saltwater interface in the Manokin is not known with any certainty, but offshore to the east the aquifer probably contains saltwater. At Fenwick Island brackish water occurs at the base of the Manokin, about 450 feet below sea level, and Weigel (1974) reports a similar situation near Ocean City, Maryland. It is not known if this brackish water is due to upward leakage from underlying sediments or represents the toe of the interface to the east.

The uppermost sand of the Chesapeake Group in Delaware is called the Pocomoke Aquifer (Miller, 1971). It is separated from the underlying Manokin by a silty confining layer or aquiclude. The distinction between the two aquifers is often arbitrary since in some places the Pocomoke-Manokin system is represented by a series of sands separated from each other by confining layers of variable thickness. The Pocomoke subcrops beneath Columbia sediments in the southeastern part of Sussex County (Miller, 1971) and in the subcrop area behaves as a watertable aquifer.

Aquifer properties of the Pocomoke are generally good, but saltwater intrusion may be more of a potential problem than in the underlying Manokin. In some locations, particularly near Rehoboth Beach, the Pocomoke is in direct contact with thick Columbia sands, which in turn are in direct contact with the ocean. Thus, high-yielding wells in the Pocomoke must be located with a great deal of caution. The Pocomoke is extensively tapped in the Fenwick Island area by domestic wells averaging between 200 and 300 feet deep. There is considerable undeveloped potential remaining for both the Pocomoke and Manokin aquifers, especially inland from beach areas. Miller (1971) indicated that an additional 10 mgd could be developed from the Pocomoke and about 8 mgd from the Manokin aquifer.

Potential of Other Coastal Plain Aquifers

The aquifer systems discussed above comprise the upper 400 to 600 feet of the entire sediment column in Kent County and only about the upper 400 feet in Sussex County. In Sussex County, the maximum thickness of Coastal Plain material resting on crystalline basement is probably in excess of 8000 feet. The bulk of these sediments is part of the Potomac Formation, which is extensively used for groundwater supplies in New Castle County. In southern Delaware two main factors have precluded development of these deeper aquifers: 1) The Columbia sediments and underlying Tertiary age aquifers (Piney Point Formation and Chesapeake Group aquifers) have been capable of supplying most water needs up to the present time. Inland, the Columbia Formation will continue to provide most of the freshwater needs. Particularly in Kent County, emphasis will probably shift from development of deeper aquifers to development of thick sections of the Columbia Formation. 2) Brackish water exists in most aquifers at depths greater than about 500 feet below sea level. These brackish water aquifers may be a potential resource. Possible future development may include the extraction

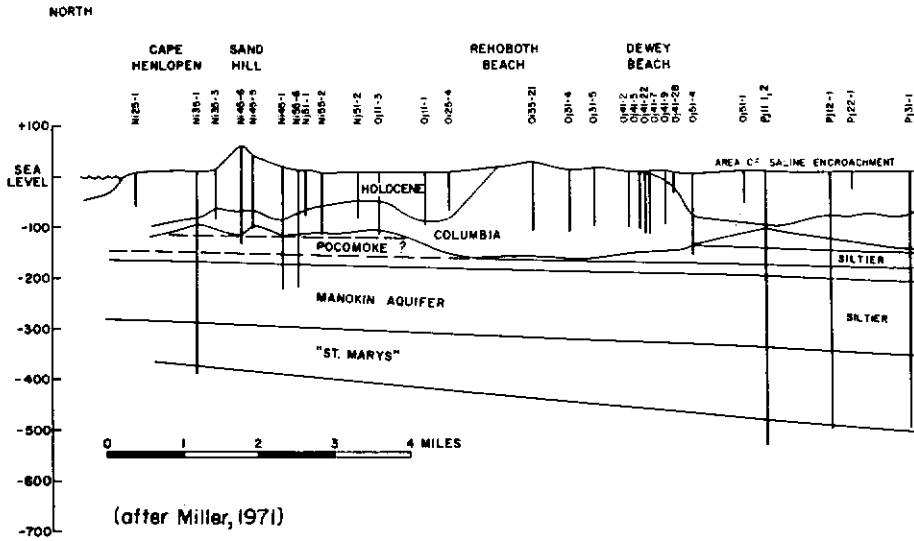
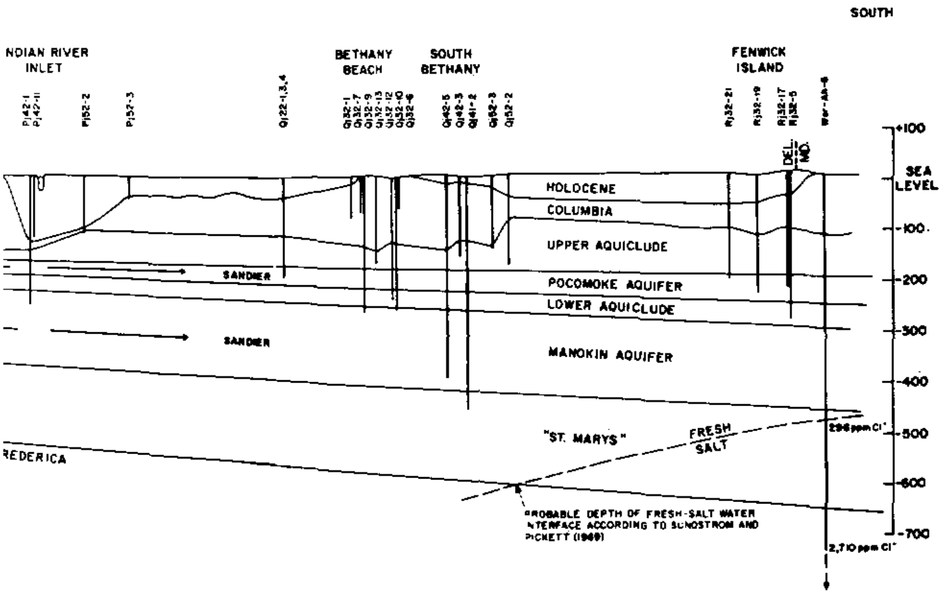


Figure 10. Geologic cross section of the Delaware-Atlantic seashore area.

of minerals and use as a source of low, constant temperature heating or cooling water. Development of the deeper aquifers will initially be expensive compared to development of shallow sources of groundwater.

Water Problem Areas in the Coastal Plain

An area 7 to 8 miles wide between the New Castle County-Kent County line on the north and south to about 3 miles north of the center of Dover is somewhat unique in terms of available groundwater supplies (see Figure 11). No high yielding, freshwater aquifers are known to underlie this area in which some future growth is planned. The Columbia Formation is thin and the formations between the Columbia and the Magothy are represented by fine-grained sediments which yield little water to wells. Water in the Magothy and older formations is brackish and thus not suitable for direct consumption or for many industrial uses. The Cheswold aquifer, discussed above, does subcrop in this area

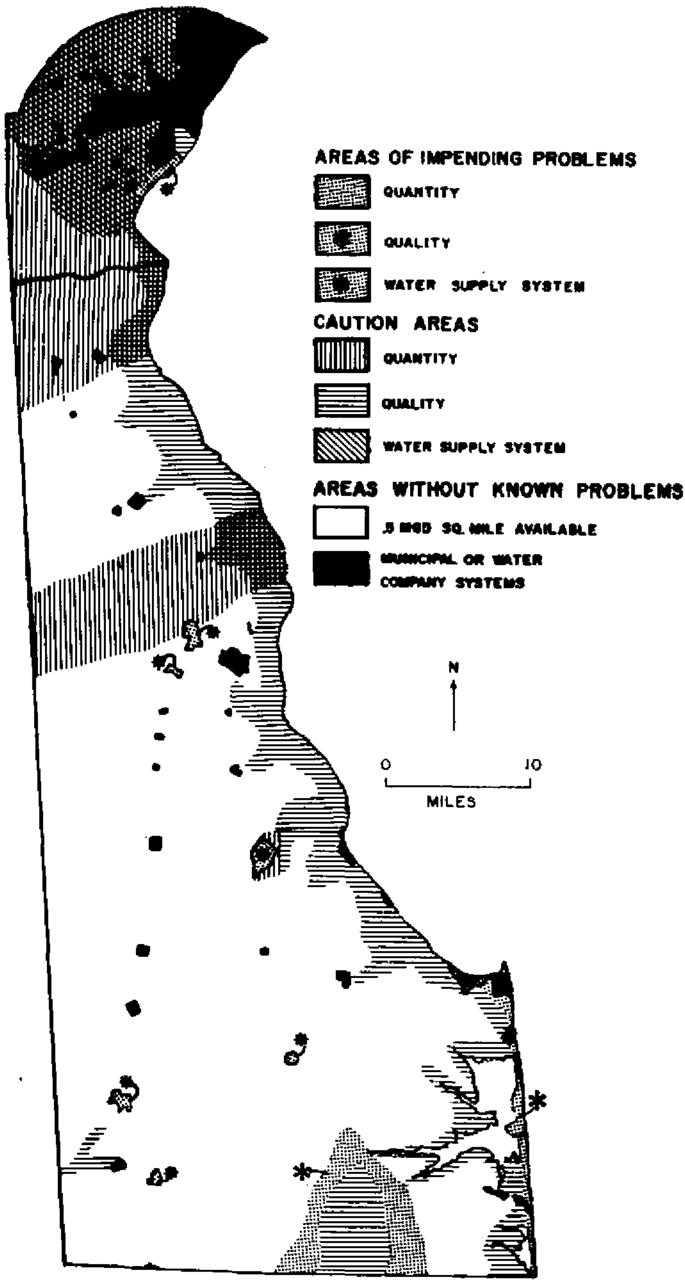


but it is neither thick enough nor sandy enough to yield large amounts of groundwater.

In New Castle County north of the canal there appears to be little or no potential left for groundwater development in the Potomac except possibly in the western half of the county (Sundstrom et al., 1976). The Columbia sediments may provide some additional yield in selected locations.

Additional development of high-yielding wells in the artesian aquifers beneath the Dover area must be limited. It has been shown that lowering of heads in the Cheswold aquifer has significantly reduced streamflow in a tributary of the St. Jones River (Johnston and Leahy, 1977). In addition, observation wells in the area have indicated record low levels in the last year (Delaware Geological Survey, unpublished data). A considerable amount of drawdown remains in the Piney Point aquifer, but management schemes should be worked out now to ensure the best utilization of the remaining water.

The possibilities of saltwater intrusion have been indicated in the previous discussions on the individual aquifers. Saltwater intrusion is always a potential problem along the coast, particularly in the water-


AREAS OF IMPENDING PROBLEMS
QUANTITY
QUALITY
WATER SUPPLY SYSTEM
CAUTION AREAS
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QUALITY
WATER SUPPLY SYSTEM
AREAS WITHOUT KNOWN PROBLEMS
.5 MGD SQ. MILE AVAILABLE
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table aquifer (see Figure 11). Also, proper well construction standards must be followed to ensure that individual wells into deeper aquifers do not become leakage pathways for brackish water from overlying shallow sediments.

Crystalline Rocks as Aquifers

The crystalline rocks of the Piedmont have much less permeability and porosity than do the unconsolidated sands of the Coastal Plain. Most of the permeability is imparted to crystalline rocks by fractures or openings. It is in such openings that water is stored and moves in response to pumping. The rock mass itself has little ability to transmit water, and the yields from poorly fractured rocks may be only a few gallons per min. Thus, obtaining groundwater of any quantity in the Piedmont rocks depends on locating fairly extensive water-filled fracture systems (see Figure 12). Some water is usually found in the overburden or weathered portion of the crystalline rocks, especially if the overburden is of a sandy nature. The quality of this "surface water," as it is often called by drillers, may be questionable at times. Delaware well construction regulations require that pipe or casing be set to the base of the overburden or driven into hard rock in order to seal off this source of water. There is some evidence that the overburden acts as a storage reservoir (Poth, 1968) and feeds water to fracture systems in the underlying unweathered rock in response to pumping.

Rocks in the Delaware Piedmont can be grouped for the purposes of their water-yielding abilities into three broad types: 1) marble, which underlies the Hockessin-Yorklyn valleys and the valley just to the south of Pleasant Hill, 2) schists and gneisses, which underlie much of the weathered portion of the Piedmont, and 3) igneous (?) rocks of the Wilmington Complex, which include those rocks in the eastern portion of the Piedmont. Yields in all three rock types are highly variable and dependent on the development of secondary openings, joint patterns, or other fracture systems. The Cockeysville marble is capable of giving initially high yields of up to several hundred gallons per min, where wells intercept solution channels or are finished in the weathered portion of the rock. However, long-term yields are still limited by the amount of recharge occurring within or near the immediate outcrop area. Yields

Figure 11. (opposite) Water resources evaluation map of Delaware. (Modified after Sundstrom et al., 1976.)

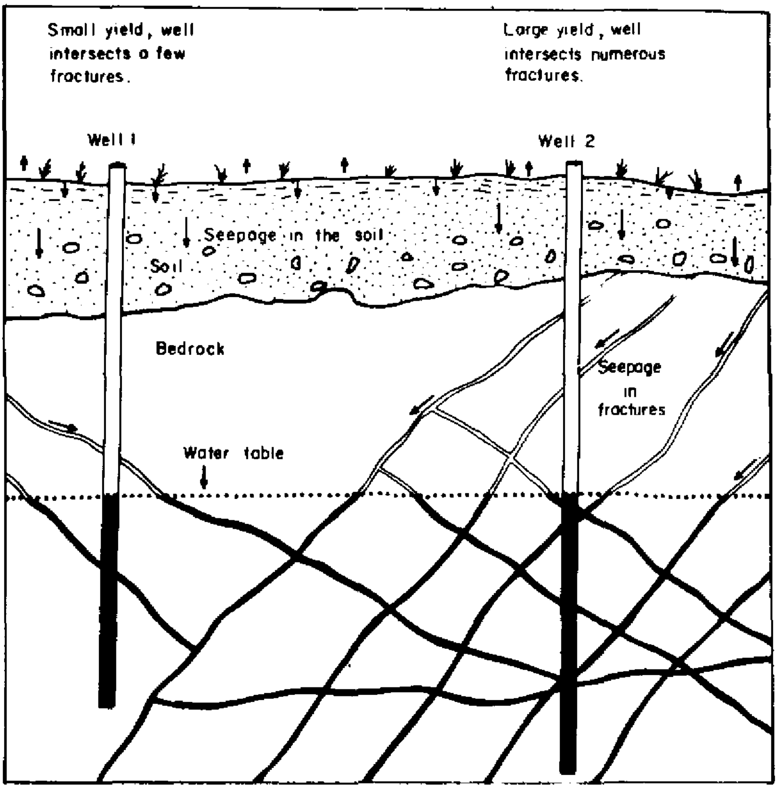

Figure 12. Occurrence of groundwater in fractured rock. (After Newport, 1971.)

in fresh, unaltered marble usually average only a few gallons per min.

The schists of the Wissahickon Formation and the rocks of the Wilmington Complex are generally poor water producers, except when fracture systems are encountered. In such a case, high short-term yields can often be obtained. These fracture systems probably have limited recharge areas, and once the initial storage is depleted yields usually start to decline. Nevertheless, groundwater exploration for high-yielding wells in Piedmont rocks is usually directed toward locating such fracture systems by detecting their surface expression. Locally, conventional aerial photographs, satellite imagery, and topographic maps have all proved useful in locating surface traces of apparent fracture systems. Figure 13 shows postulated fracture traces in an area just north of Newark and the well sites that were selected by study of the traces.

Groundwater in Piedmont fracture systems usually behaves like it does under artesian conditions. Flowing artesian wells are not uncommon, but pressures usually decline rapidly once pumping is initiated. It is difficult to apply standard pumping test techniques to the hydrologic analyses of fractured rock systems. The aquifer characteristics derived

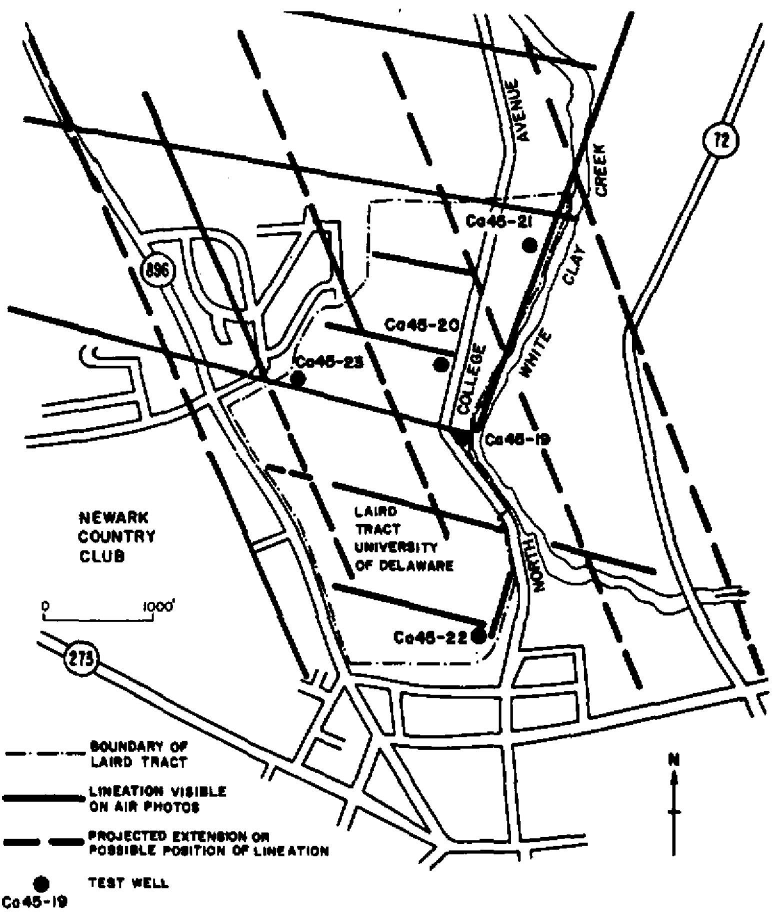

Figure 13. Aerial photograph lineations interpreted as possible fracture zones. (After Woodruff et al., 1972.)

from such tests, and upon which well performance is based, are usually too optimistic. However, if this is recognized at the start, reasonable predictions of well yield can usually be made.

Water Use

Total water use in Delaware during 1974 was estimated at about 138 mgd (Sundstrom et al., 1976). Of this amount, about 58 mgd was from surface sources and 81 mgd was from groundwater sources. Nearly all of the surface water used was in New Castle County; Kent and Sussex Counties were dependent on groundwater, except for a small amount of irrigation from surface sources (about 0.5 mgd). Table 2 shows the amount of groundwater used in each county during 1974.

TABLE 2

Average Daily Groundwater Use in Delaware, 1974

New Castle County	28.0 mgd (33%)
Kent County	22.3 mgd (100%)
Sussex County	30.5 mgd (98%)

Condensed from Sundstrom et al., 1976.

The use of groundwater for irrigation has increased greatly in the last decade. The uncertainties of rainfall have prompted the installation of irrigation wells in most large agricultural operations in the state. During the past few years, systems of multiple, small-diameter wells for irrigation purposes have become fairly common as have shallow, large-diameter, reverse-rotary drilled wells. Industrial use of groundwater has slightly more than doubled from 1954 to 1974 in New Castle County and increased somewhat less than this in the other two counties. Municipal use of water has about tripled during the same time period in New Castle and Kent Counties and about doubled in Sussex County (Sundtrom et al., 1976).

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8

Water, People, and Pollution

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DELMARVA peninsula is blessed with water. Residents and visitors alike enjoy the aesthetics of water that characterize almost the whole area: to be on the water can be both peaceful and exhilarating; water – salt or fresh – enhances the beauty of the adjacent land; and the recreational opportunities are varied and vital to the area's well-being. The commerce and industry that water has brought are an essential part of the overall economy.

Water has very important functions in addition to aesthetics, recreation, commerce, and industry. Of prime importance is the water supply. Although the Peninsula has an abundance of water, there are localized water problems. Also, water transports all of our wastes and nature's wastes. A first consideration is that water transports the Delmarva population's wastes: that is a vital function.

Transactions of the Delaware Academy of Science – 1976, Delaware Academy of Science, Newark, Delaware 1979.

Until recently, dilution was the solution to pollution. There was a lot of water and there were not many people. The Peninsula is very fortunate: it still does not have many people, but it does have enough to have a few pollution problems. When population increases even as little as it has, the wastes increase and create problems that have to be faced. Some are very minor, others are moderate, and one is horrendous. Fortunately, the indications are that the awareness is here, reaction is underway and the problems are being attacked. They are likely to be solved, and the Peninsula may well be ahead of many other areas.

Delaware, particularly the northern part, can benefit from the experiences of more urbanized areas. For example, Long Island's urbanization is 20 years ahead of northern Delaware's, and it should be possible to avoid doing what Long Island did. Detergent-contaminated water from septic tanks got into wells, and Nassau County residents drew a fine head of foam on their faucet water. The foam problem was solved by using nonfoaming detergents, but some areas still have detergent-contaminated wells. Delaware should be able to avoid the mistakes or the wrong decisions that were made in Nassau County.

Before looking at specifics, Barry Commoner's four basic rules of ecology should be examined:

1. *Everything is connected to everything else.* This was expressed in different words about a century ago by John Muir: "When we try to pick out everything by itself, we find it hitched to everything else in the universe."
2. *Everything must go somewhere.* Almost everything from the Peninsula goes eventually to the Atlantic Ocean or the Chesapeake Bay.
3. *Nature knows best.* The streams are where they are for the best reasons; so is everything "unimproved"; everything nature does is done in the best way for the long haul. Anything that man does, even for beneficial purposes, should try to be as compatible as possible with nature.
4. *There is no such thing as a free lunch.*

These four rules of ecology (or life) are going to have to be respected so that any actions proposed or taken will not violate them or, at least, will conform to them as much as possible.

Water

To guide thinking about water, there is a comprehensive view of its ecology called the hydrologic cycle. Everything in the four "rules of ecology" is embodied in this concept. It is the basis for this chapter on water, people, and pollution of the Delmarva Peninsula.

The hydrologic cycle (Figure 1) is one of nature's grand designs, and any proposed solutions to any of the water problems that arise must be consistent with it. The hydrologic cycle is the interchange of water between the atmosphere, the land, and the ocean. There is precipitation onto the ocean and evaporation off of the ocean into the atmosphere, and, likewise, there is precipitation from the atmosphere onto the land, and evaporation off of the land back into the atmosphere. It is a moving picture. Most of us living on the solid part of the earth are concerned about: a) the amount of precipitation onto the land, b) what happens to the water when it falls onto the land, and c) what happens as the water goes to the ocean. This part of the hydrologic cycle is of prime importance to people. It must be remembered that since most of the earth's surface is ocean, most of the precipitation falls on the ocean. Note also that most of the water falling on the land runs off into the ocean. There are two components transported by that water which are of prime importance. First, the water running off or through the land to the ocean has always carried two things: salts and sediments. Thus, there have always been "polluted" streams. Some streams were filled with mud after heavy rains, and other were filled with salts almost continuously. It is misleading to talk about trying to get streams back to the crystal clear conditions of 150 or 200 or 300 years ago: most were never crystal clear. Great care is needed in deciding how far to go in upsetting nature. There is no way to stop the streams or groundwater from carrying some salts and some sediment. Man cannot revoke the hydrologic cycle.

The second important point about the hydrologic cycle is that no matter what is put onto the land, most of it is going to end up in the ocean. That is what nature does and there is no way to change it. There may be some minor variations in the hydrologic cycle as it is described here, but this is basically the way water behaves in this world.

Table 1 shows the total distribution of water on earth related to the natural hydrologic cycle. Note the columns for fresh and salt water and the relative size of the numbers of the columns. There are three important facts revealed in this table. First, the total fresh surface water on the earth is about 30,000 cubic miles, and the total underground water (or groundwater) is 2 million cubic miles. There is approximately 60 times more underground water than there is surface water. That ratio is even higher for the Delmarva Peninsula. Basically, there are

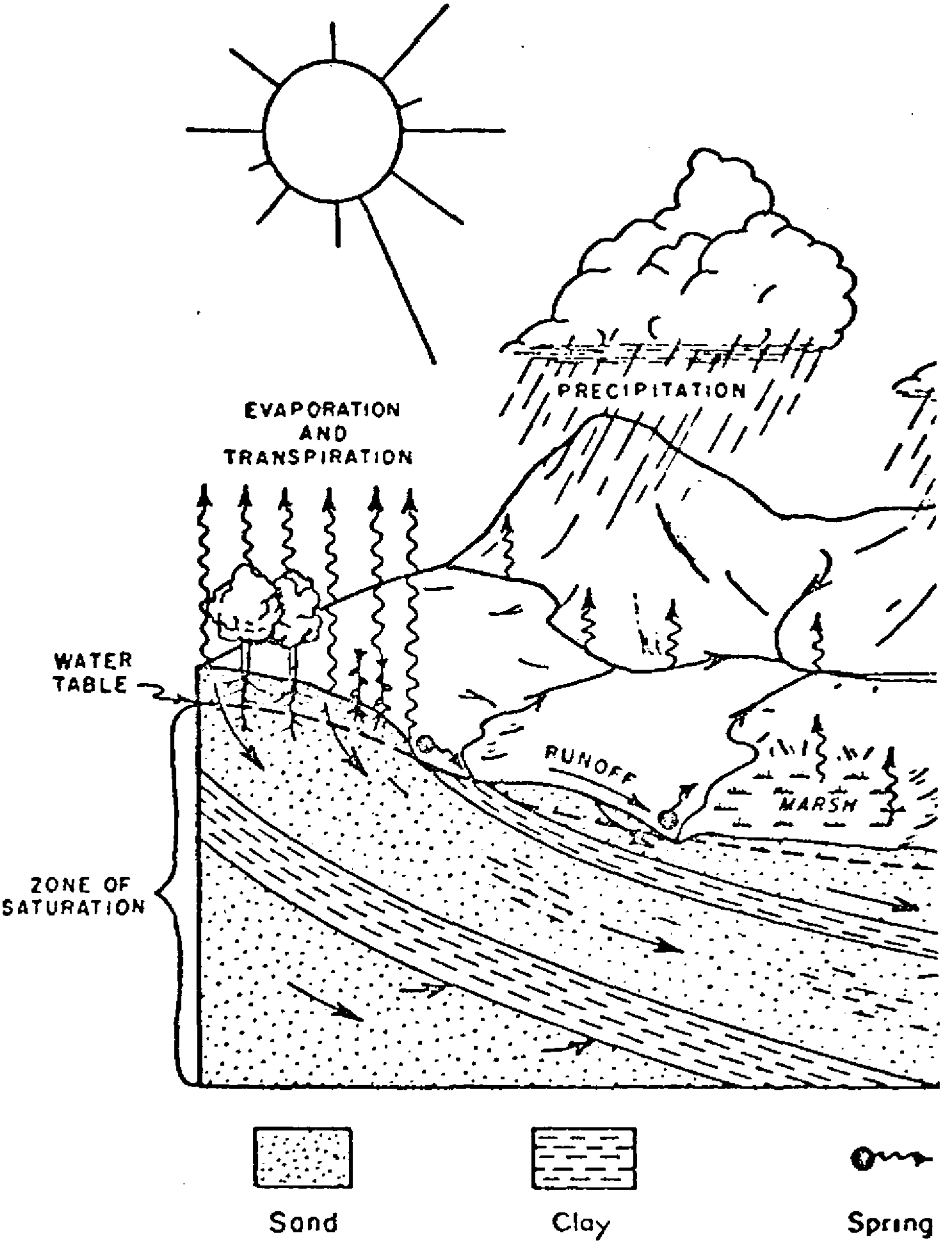
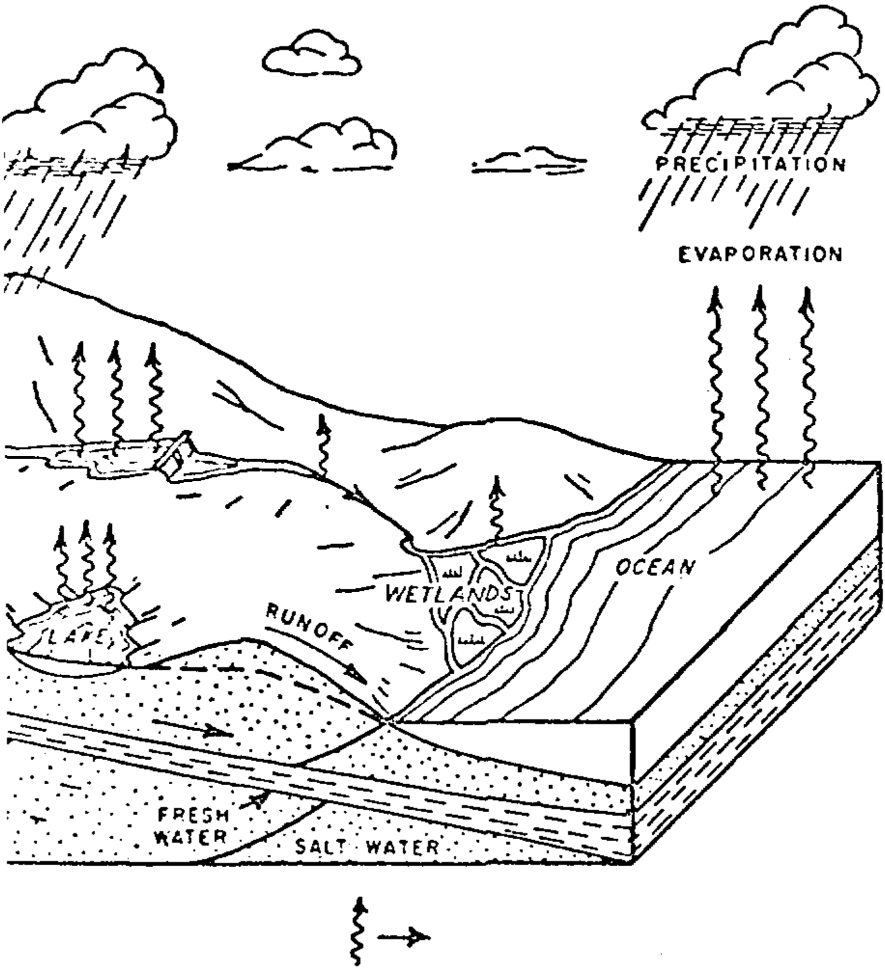


Figure 1. The hydrologic cycle.



Direction of water movement

TABLE 1

Estimated Distribution on World Water Supply
(Thousands of cubic miles)

Distribution	Fresh	Salt	Total
Rivers and streams	0.3		
Fresh water lakes	30		
Salt lakes and inland seas		25	
Total surface water	**30.3**	**25**	**55.3**
Soil moisture and seepage	16		
Underground water to 1/2 mile depth	1,000		
Underground water below 1/2 mile depth	1,000		
Total ground water	**2,016**		**2,016**
Glaciers and ice caps	7,000		
Oceans		317,000	
Total world water supply	**9,046.3**	**317,025**	**326,071.3**

hundreds of years worth of water beneath the ground and only a small fraction of fresh water on the surface of the ground. The other two facts are that most of the fresh water is in solid form, at the polar extremities, and there is very little access to it. The first International Conference on Iceberg Utilization took place recently at Iowa State University in Ames, Iowa. Co-sponsored by Prince Faisal of Saudi Arabia and the National Science Foundation, the conference explored the possibility of transporting icebergs to Saudi Arabia and other water-short areas.

Where is all the water? Almost all of the water is in the ocean, 317 million cubic miles of it. Of all of the water on earth, 97.2% of it is in the ocean and another 2.2% is not: 99.44% of all the water is either salty or solid, leaving about 0.6% that is fresh and can be used. Much of the usable water is stored underground. For every person in the world today there are thousands of gallons of underground water available per day, but it is not always accessible to man. In general, the world has plenty of water, and there is very little to worry about if that water is kept clean.

What happens to the water on the Delmarva Peninsula? The average annual precipitation is about 40 to 44 inches or 100% in Table 2. About

40% of that precipitation is evapotranspired up into the atmosphere, usually within a few hours or a day. This is the water that falls on vegetation and the earth's surface and that quickly evapotranspires back up into the atmosphere (less quickly in the winter), leaving 60% of the precipitation to do something else. About 10% stays on the surface and runs down the hillsides into creeks and larger streams, and ultimately into the ocean. This 10% is called surface runoff. The remaining 50% of the precipitation goes into the ground.

The Delmarva Peninsula, except for its extreme northern part, is largely composed of sand. The water constantly moves through the sandy ground, toward the ocean/bay. It also moves toward some of the streams, reappears as water in those streams, and then goes back to the ocean/bay. Specifically, of the 50% of the water that goes into the ground, about half of that water, or 25% of the total precipitation, finds its way back to the surface, and, months later, is also evapotranspired into the atmosphere. Thus, two-thirds (65%) of our rain and snow is evapotranspired into the atmosphere, leaving only one-third to drink or otherwise use. The other half of what goes into the ground moves directly into the ocean/bay. The rest replenishes the great bank of our underground fresh water. There is a 200-year supply of fresh water under the Peninsula moving toward the streams and toward the ocean/bay.

This underground water also provides the fair weather flow for our streams. If it does not rain for the next month on the Peninsula, most of the streams are still going to flow because most of the water in the streams has come out of the ground. In fact, again using very rough estimates, 25 and 10 is roughly a 2 to 1 ratio, so about two-thirds (65%) of the water in every one of our streams has come out of the ground. Only one-third (10%) of the precipitation is water that stayed on the surface. This shows the importance of groundwater and also shows that

TABLE 2

Where Does the Rainfall Go?

Distribution	Percent
Total rainfall	100
Evapotranspired directly from earth's surface	40
Runoff	50
Infiltration	50
To ground water (25%)	
Returned to surface and evapotranspired (25%)	

if we start sealing this surface with concrete and asphalt, it will have tremendous implications, as is the case already in northern Delaware.

This is what nature does when man has not affected the situation. This is the way it was 200, 300, 400, 1000 years ago. Of course, there were salts and sediments transported in the runoff water. This is what nature has blessed us with, and for the Peninsula, it is quite a bit. Calculating the total amount of fresh water in the sands and aquifers below the Peninsula reveals about 200 years worth of precipitation. The national average is about half that amount. The Delmarva Peninsula is lucky because of the nature of its subsurface and the high amount of precipitation it receives. Certainly, if there were only 10 inches of rainfall there would not be that much water in storage, because the evapotranspiration would be much higher. The Peninsula is actually a water-rich area.

People and Pollution

People use the water in three basically different ways:

1. They can use it and put it back in undiminished quantity and quality (springhouses are an example), but that very rarely happens. It used to happen to some extent, but seldom do we use the water and put back into the natural hydrologic cycle the same amount and same quality. Thus, one of the three ways in which water can be used is negligible.

2. Some of the water is evaporated as we use it, as, for example, when washing clothes. The water used in washing is taken out of a well, or out of a stream, or from other freshwater sources. When the clothes are hung on a line or put through a dryer, water evaporates. For a long time, the principal use of water that caused evaporation was irrigation. It was a good use of water, and only about 5% of the water supply was used for irrigation. Ten to 20 years ago, it could have been said that most of the water that man caused to evaporate came about through irrigation and was not a significant loss.

   There is a new and serious problem associated with man's use of water that causes evaporation. Water-cooled power plants consume major amounts of water, and although irrigation was not much of a villain in terms of dissipating water, power plant cooling is. This may well be the number one water issue in the next 10 years: the use of water to cool power plants which causes that water to evaporate.

3. In using water we inflict on it a Pandora's box of contaminants (of

which soap may be the mildest) and then discard it. The traditional way of handling water after it has been used is to put it into some sort of a system which carries it to a treatment plant. At this point, one has to be critical. "Treatment plant" is a misnomer (rather like false advertising) because most treatment plants are not doing the job: there are three major deficiencies. First, some waste gas goes into the atmosphere from the treatment plant, and that problem has not been tackled yet. Second, these treatment plants frequently do not clean the water very well. Someone waves a wand over the water and does nothing else, and back it goes, polluted, into the natural hydrologic cycle. The ample supply of freshwater we have (Table 1) does not mean anything if it becomes so degraded in quality that we cannot use it. The problem is not one of quantity, because there is plenty of water that can be used. The problem is contaminating the water and putting it back into the system where it spoils the water that is already there. Third, the "solids" from the treatment plant have to go somewhere. Very often an "out of sight, out of mind" solution is used, euphemistially called a "sanitary landfill." Remember those rules of ecology? Everything is connected, and everything must go somewhere. Because it is "out of sight, out of mind," and sometimes thinly covered, does not mean that it is an end of it. What happens to the material – the sludge in the landfill? It is in the hydrologic cycle, moving into the groundwater, the streams, and into the ocean/bay. (Water percolating through a "sanitary landfill" in Delaware's New Castle County is polluting a major underground freshwater source, and no cure has yet been found.)

The natural hydrologic cycle is disturbed in other ways. Recall the hydrologic budget – nature's budget (Table 2). Of the 100% precipitation, half went into the ground: that is what nature did. When man comes along he affects the surface by urbanization, cutting off this ground infiltration and increasing the runoff. A typical problem in an urbanized area is flash flooding. The reason for flash flooding is that nature had the right-size streams for a 10% runoff, but they are too small to carry the extra load caused by decreased ground infiltration. The Delmarva Peninsula is plagued with drainage problems. They are multimillion dollar problems because so much of the land has been blacktopped and concreted. In addition, when infiltration is cut off, so is our principal source of water, because groundwater should be the main source of water in this Peninsula. If urbanization continues to the point of making the Peninsula one big parking lot, water is not going to be able to get into the ground to replenish a vital supply source.

The natural hydrologic cycle can also be disturbed by pumping too much groundwater. Eventually, the groundwater will no longer move back to the ocean/bay, but will be replaced by salt water from the ocean/bay. Overpumping is not yet a problem, but it could be if urbanization continues indiscriminately. The Atlantic coast and Eastern Shore areas are particularly vulnerable to saltwater infiltration. We must constantly be aware of this natural process and work in harmony with it.

Be it in the Delmarva Peninsula, or in the eastern United States, the problem is not one of quantity of water, the problem is quality. "Water, people, and pollution" go hand in hand: the pollution is what creates the quality problems.

What are the options? What is the practical solution? The solution to quality problems, pollution problems, and water problems in Delaware and in the eastern United States lies in some form of water reclamation and reuse.

The natural hydrologic cycle (Figure 1) must be the guide. Man takes water out of this natural hydrologic cycle; he uses it, either evaporates it, or puts something into it. After he puts something into it, it should go into a reclamation plant. A reclamation plant is nothing more than a treatment plant that really works. This is badly needed because we do not want anything going back into the natural hydrologic cycle, be it streams, the ground, or the ocean/bay, that is not good water. This reclamation plant should not allow water to return to the natural hydrologic cycle unless it is as good, or better, as what originally came from the natural cycle.

The other problem is what to do with what is left over after the water has been cleaned so well that we could amost drink it; the dregs have to go somewhere. These "concentrated wastes" still have to go through some sort of an effluent treatment plant. After they go through this treatment plant, they have to go somewhere.

There are basically two choices; to put them directly into the ocean/bay, or to put them onto the land as an intermediate step to having them go into the ocean/bay. If they are put onto the land, they still will go eventually into the ocean/bay. What are the pros and cons of putting something directly into the ocean/bay or putting something onto the land?

Keep in mind that the ocean/bay is the ultimate receptacle of the waste regardless of what we do. Put it in a landfill and it will eventually get into the ocean/bay. Put it on the land, spread it on the land, and it will get to the ocean/bay. The question is: How do we want to do it?

What are the pros and cons of land application of waste water? The principal advantage is that waste water can be a valuable resource if it is cleaned up to the point that we could almost drink it. It is "fresh" water that could be used for irrigating crops, or it could be put on the land and eventually recharge the groundwater. It could go into the ground again and be recovered miles away through wells, or be used just to keep the salt water from coming in when there is a danger of that happening. In Delaware it may be more economical to put it on the land. Sussex County, Delaware's southernmost county, is probably going to put their next treatment plant into operation with land disposal. The other advantage is that the land may provide better treatment for the water.

One of the disadvantages of land application versus ocean/bay disposal is that the land requirements are significant. Thousands of acres would have to be devoted to waste disposal. There is still some doubt about the complete safety, healthwise, of land application. This is something that is being debated all over the United States. There is space in the Peninsula for land application systems, but the sites would have to be where there would not be many problems if things went wrong. In other words, it would be imprudent to put things on the land near large water supply wells. Places would have to be found so that if things did not quite work out, the waste water would go to the streams and to the ocean/bay and people would not be affected by it.

The title "Water, People, and Pollution" reflects a logical progression: the water was here first, then the people, and then the pollution. Actually, people should be first. The decision to spend money, to not spend money, use the water this way, use the water that way, rests (or should rest) with the citizens.

> The Army Corps of Engineers
> Insists on building dams and weirs,
> The Reclamation men assume
> That *every* desert ought to bloom.
> The wildlife people often wish
> That all the world were game and fish.
> The conservationist's a whiz
> At keeping nature as she is.
> The Church is measured by its steeple –
> And no one gives a damn for people!

It *is* the people's decision, however, and time is running out.

Until recently it was reasonable and proper to be optimistic about solving the world's water supply, conservation, and quality protection problems through technology, but technology is on a collision course with economics, ecology, and the American dream. Former Secretary of the Interior, Stewart Udall, summed it up in "The Last Word":

> Frankly, when I was Secretary of the Interior, I was a technological optimist, but I was wrong. There is no magic wand to replace our diminishing resources. . . We have to live lean, tighten our belts, and put an end to present wastefulness. Many people already are turning away from growth for the sake of growth and bigness for the sake of bigness. We must reconstruct American cities. We have to begin a complete change in our transportation system – rehabilitate the railroads and strengthen public transit. We can no longer tolerate sprawl, but must make our communities more compact. For ethical reasons, to meet our responsibilities to future generations, conservation must become our way of life.

9

The Minerals of Delaware

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The Author: Peter B. Leavens received his B.A. in mathematics at Yale University in 1961 and his Ph.D. in mineralogy from Harvard in 1966. After postdoctoral work at the Smithsonian Institution, he joined the Department of Geology at the University of Delaware in 1967, where is now Associate Professor and Curator of Minerals. His chief research interests are the mineralogy and geochemistry of megmatites and of metamorphosed marbles, and he has published over a dozen papers in technical journals, including descriptions of five new minerals.

Historical Background

MINERALOGY in Delaware dates from the first quarter of the nineteenth century. The investigations of Lea (1818) and Carpenter (1828) concentrated on the mineralogy of southeastern Pennsylvania but included northern Delaware as well. In 1831 Henry duPont, then a student at Mt. Airy College, prepared a paper entitled "Remarks on the Mineralogy, State of Delaware," which is preserved in manuscript at Winterthur Museum (duPont, 1831). Booth's *Geology of Delaware* (1841) included observations on minerals and mineral deposits.

More modern works on Delaware's mineralogy are rare. Larson and Shannon's (1921) paper on the proposed new mineral species canbyite stands out among these. However, amateurs have been interested in Delaware's minerals and have assembled collections which are of scientific interest. The collection of W. W. Jeffers, of West Chester, Penn-

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sylvania, assembled in the second half of the nineteenth century and now at the Carnegie Institute of Pittsburgh, is one of these; another is the collection of Fred J. Hillbiber. Mr. Hillbiber was a resident of Wilmington in the early 1900s and collected at a time when many quarries and other localities now worked out or closed were accessible. Being of German extraction, he was subjected to persecution during the period of anti-German feeling in World War I; being a convivial man, he was much upset by this treatment. He retired to Schwenksville, Pennsylvania, and his collection ultimately passed to his family. However, he wrapped many of his Delaware specimens in newspaper, put them in a barrel, and left the barrel on the front porch of the president of the Delaware Natural Historical Society. This material was incorporated into the Society's collections, and finally came to the University of Delaware. However, many of the labels were lost or misplaced. Poor labeling poses a problem for students of Delaware minerals, because many localities open in the past are obliterated or worked out now. This is also true of localities in Pennsylvania, Maryland, and New Jersey. Modern studies of the minerals of these states depend to some degree on preserved and properly labeled specimens, and wrongly labeled specimens are worse than no specimens at all, because they may deceive the modern investigator.

Types of Occurrences

This chapter is concerned with localities for distinctive and interesting minerals in the state. Of course, all rocks are made of aggregates of mineral grains, but the study of the character and formation of rocks is considered a separate discipline, petrology. The petrology of the Delaware Piedmont, the location of most of the mineral occurrences of the state, is covered in Thompson and Branca (1978).

The oldest rocks of the Piedmont are the mafic gneisses, amphibolites, and gabbros of the Wilmington Complex. Veins in these rocks have been among the most prolific localities in the state, and are quite different in their mineralogy from the rocks themselves. The northwestern part of the state is underlain by rocks of the Glenarm series: the Cockeysville marble, formerly mined for lime around Limestone Road and in the Hockessin valley, and the amphibolites, gneisses, and schists of the Wissahickon formation. Pegmatites, small bodies of coarse grained, granite-like rock, cut the Wissahickon and produce a number of interesting minerals. At the northern edge of Hoopes Reservoir, a mass of serpentine lies within the schists; it formerly was an important mineral locality.

In southern Delaware, the 80% of the state below the Fall Line, there are relatively few mineral localities. Chemically, these occurrences in sediments can be divided into two kinds: those of oxidizing environments or oxygen-rich sediments, and those for which the environment is reducing or oxygen poor. In the first class are various iron oxide deposits, which supported an extensive although small smelting industry in the state until the 1850s. In the second class are occurrences of iron sulfides, phosphates, and carbonates in greensands and organic muds.

The Appendix contains an alphabetical list of the more common or more interesting minerals found in Delaware, with notes on their occurrence and abundance. Some species occurring as small grains in Piedmont rocks, or found as detrital grains in sands of the Coastal Plain, are not included, and others may have been left out through oversight, but the list should be reasonably complete.

Mineral Deposits of the Wilmington Complex

The mafic gneisses and amphibolites of the Wilmington Complex, although widely exposed throughout the Wilmington area, offer only a few notable mineral occurrences. Large anhedral crystals of hypersthene occur in the Brynhurst Woods gabbros (Thompson and Branca, 1978), and apparently were known in the 1830s (duPont, 1831). DuPont (1831) noted that at that time it was a rare mineral, although it has since proved to be a common and important species in many mafic igneous rocks. Hypersthene was noted at Brynhurst Woods because of the very large size of the crystals, up to 7 cm (3 inches) across.

In the steep cliffs along Brandywine Creek are a number of quarries, excavated in the nineteenth and early twentieth centuries for building stone. The cliffs provided an ideal place to open a quarry, with good exposure of rock and without drainage problems. The rock, a tough hypersthene-quartz-andesine gneiss (Woodruff and Thompson, 1975), was called the Brandywine Blue Granite and was cut into dimension stone for use in foundations, bridge piers, and other construction. In the collections of the Delaware Natural Historical Society are numerous interesting mineral specimens, many collected by Mr. Hillbiber, labeled "Brandywine Quarry." This name may refer to all the quarries along the Brandywine, or specifically to the largest, which is situated about 300 yards south of the confluence of Alapocas Run with the Brandywine. The specimens are predominately from small hydrothermal veins, formed by the action of hot water seeping through fissures in the rock. Among the minerals of the veins are a number of sulfides; these minerals are important metal ores, but only a few kilograms, at most, have been found in Delaware. The sulfides include pyrite, galena, chalcopyrite, bornite, and chalcocite. On top of the sulfide minerals, deposited in openings at lower temperatures, are small crystals of quartz and calcite and a number of sodium and calcium zeolites – framework silicates containing abundant water, very common in lower temperature veins. The zeolites include chabazite, laumontite, stilbite, and natrolite. Although they do not compare with the spectacular groups of zeolite crystals from the trap rocks of northern New Jersey, a number of attractive specimens were collected by Mr. Hillbiber and others around the turn of the century.

There is one mineral in these veins that is far from ordinary. This is the species that has been given the name canbyite, after Canby, who was president of the Delaware Natural Historical Society in the early 1900s. It is uncertain whether canbyite can be considered a valid mineral species by the modern criteria of crystallinity and uniqueness. Canbyite is a ferric iron silicate. It appears to be crystalline, but the paper defining canbyite, written by Larson and Shannon in 1921, does not include x-ray diffraction data, which proves crystallinity and which is central to the study of any new mineral species today. Larson and Shannon's paper did include a chemical analysis, optical data, and a detailed description of the textures and mineral associations shown by the specimens. The authors concluded that canbyite is a crystalline form of a rather curious family of minerals called the hisingerites. Hisingerites are ferric iron silicates that generally form at low temperatures from the oxidation and alteration of other iron silicates. Most hisingerites are poorly crystallized and give diffuse, weak x-ray powder diffraction patterns, indicating that they have little internal atomic order. Such hydrated, amorphous mineral materials are called *gels.* From its optical properties, canbyite appears to be a crystallized equivalent of the gel-like hisingerites. If so, it should give a distinct x-ray diffraction pattern. There is a published x-ray diffraction pattern of canbyite, made long after Larson and Shannon's paper. Unfortunately, Larson and Shannon did not indicate where specimens of canbyite for further study were going to be deposited, and it is uncertain whether the material x-rayed is the same as the original canbyite. However, the collections of the Delaware Natural

Historical Society do include several pieces labeled canbyite that correspond to Larson and Shannon's detailed textural description. X-ray study of this material promises to resolve the problem of canbyite's character and will show whether canbyite is indeed a crystalline hisingerite, and so may help characterize this difficult and obscure group of minerals.

To a mineralogist canbyite is a most interesting species, but specimens are drab, composed of thin, dark brown crusts of canbyite associated with pyrite and quartz.

Minerals of the Marble

The Cockeysville Marble underlies the Hockessin-Yorklyn Valley and Pleasant Valley near Newark. Small lime quarries have been excavated in the marble at several places, but none has been active for many years. The marble is composed chiefly of the carbonates calcite and dolomite, with minor tremolite, a metamorphic mineral formed by reaction of sand in the original limestone with the dolomite. Booth (1841) does not report other minerals from the marble in Delaware. However, in the small lime quarries in Landenberg, just across the Pennsylvania line, there occur additional minerals, including phlogopite, diopside, and serpentine. These may occur in Delaware as well, but not have been noted. The mineralogy of the marbles in this region deserves further investigation.

Minerals of the Wissahickon

The Wissahickon Formation, which underlies most of the western Piedmont of Delaware, is composed of mica schists, mica gneisses, and amphibolites. A few minerals are found therein in masses large enough to be of special note. Outstanding among these is sillimanite, Al_2SiO_5, or, as it used to be called, fibrolite. It is named after Benjamin Silliman, a famous nineteenth-century American geologist, founder of *Silliman's Journal*, now the *American Journal of Science*. Sillimanite occurs as masses of tight, densely aggregated fibers, with a texture somewhat like that of petrified wood (Figure 1). It is characteristic of aluminum-rich rocks which have been metamorphosed at temperatures in excess of 500°C. It is widespread throughout the Wissahickon in Delaware, and is especially common in the rocks around Hoopes Reservoir and in

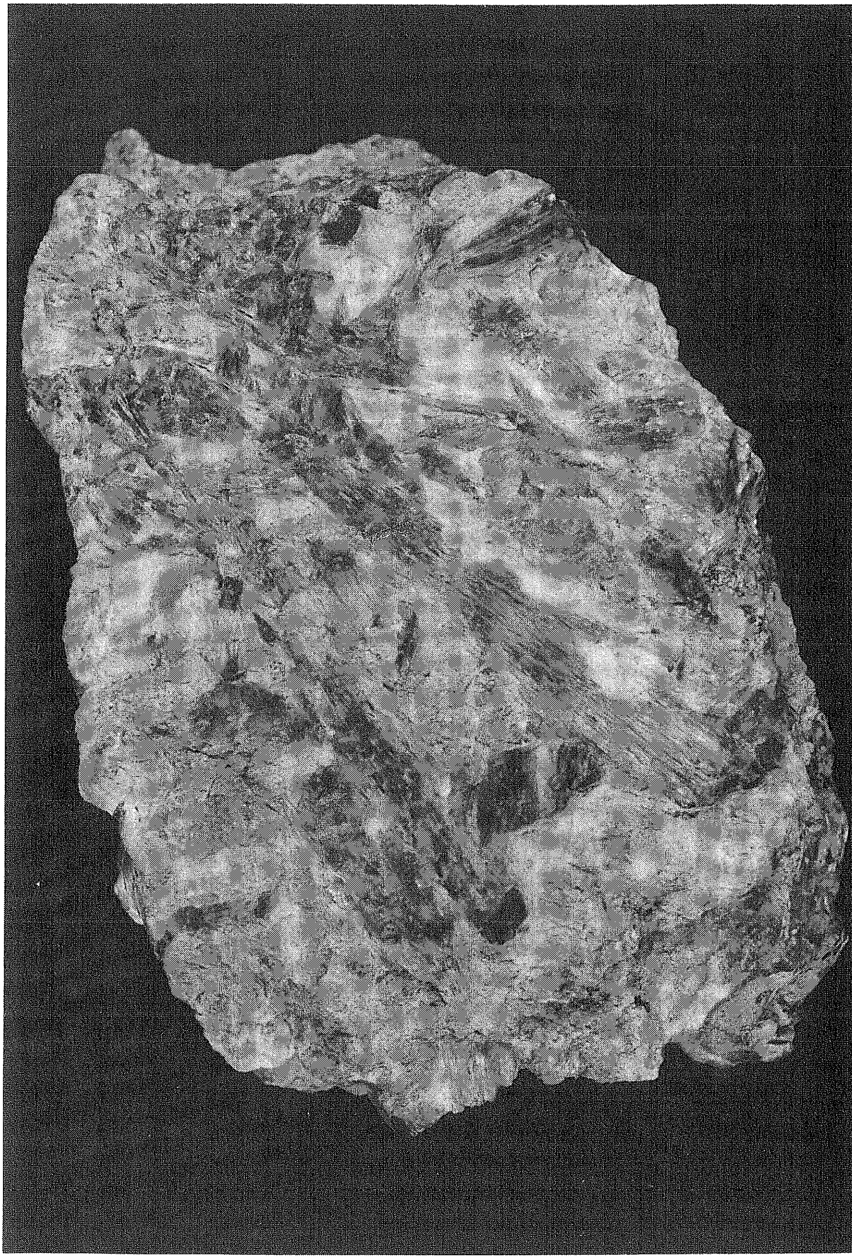

Figure 1.

Brandywine Springs State Park. Brandywine Springs used to be a resort; duPont (1831) refers to it as the Chalybeate Springs. In the stream bed are boulders of sillimanite eroded out of the surrounding schists. A mass of sillimanite in excess of 100 kg (220 pounds) is on display at the Iron Hill School Museum. Masses of sillimanite of this size are very rare, although the mineral has been found in fist-sized chunks at many localities worldwide. The occurrence at Brandywine Springs may be a metamorphosed lens of sedimentary clay; at any rate, the original sediment from which the schists were derived must have been high in aluminum to produce so much sillimanite.

On March 24, 1977, Governor duPont signed a bill declaring sillimanite the state mineral of Delaware. The occurrence of sillimanite in Delaware is geologically interesting, and specimens of Delaware sillimanite are suitable for cutting into cabachons showing chatoyance, the cat's eye effect.

Crystals of almandine, or iron garnet, have been found at a number of localities in Delaware, particularly in the vicinity of Hoopes Reservoir, weathering out the schist. Occasionally crystals of up to 10 cm (4 inches) have been reported, but none can be accepted as genuine. There are a number of well-known localities for large garnet crystals just across the border in Pennsylvania. Perhaps state pride has caused certain collectors to attribute a few of these crystals to localities in Delaware. However, there is no reason large garnets should not be found in Delaware, although they cannot be confirmed from present knowledge.

Amphibolite is exposed in one of the cuts of the Wilmington and Western Railroad near Woodale. A small vein in this amphibolite contains biotite, plagioclase, and well-formed crystals of apatite up to 4 mm in diameter and 1 cm in length. The locality was discovered by Eric Koch, a former junior member of the Delaware Mineralogical Society, in 1977. Not more than a kilogram or two of apatite has been recovered.

Along the Brandywine, between Montchannin and Rockland, the feldspar-quartz gneiss of the James Run (?) Formation (Thompson and Branca, 1978) contains crystals of cordierite up to a centimeter long. Cordierite is a mineral characteristic of rocks formed at lower pressures than those believed to have prevailed during metamorphism of the Delaware Piedmont. However, the cordierite occurrence lies on a major linear trend, which may mark a fault and be a locus of late, low pressure metamorphic activity in the Piedmont. The discovery of cordierite was made only recently by Dr. Thompson, and the occurrence is still under investigation.

Minerals of Pegmatites

Pegmatites are small bodies of coarse-grained, granite-like rock composed primarily of alkali feldspar and quartz, but with many other minerals sometimes present as minor or accessory constituents. Pegmatites occur as veins or lenses conformable with our cutting across the foliation of the schists and gneisses of the western Delaware Piedmont. Small deposits, a few meters in maximum dimension, are common throughout this region, and a few deserve particular mention. A pegmatite with 12 cm (5 inches) books of muscovite was observed by the author weathering out of the banks of the ravine at Brandywine Springs State Park. On the property of the trustees of the Woodlawn Estate is a pegmatite containing quartz, alkali feldspar, muscovite, schorl tourmaline, and almandine/spessartine garnet. About 4 km north of Newark, on McCllendville Road, is a small pit in a coarse, microcline-rich pegmatite, probably opened to recover the microcline feldspar, which is used in the manufacture of porcelain.

The best-known pegmatite deposit in Delaware was mined for feldspar in Dixon's Quarry, which is now under water near the northern end of Hoopes Reservoir. DuPont (1831) reports feldspar in large, white "tables" (cleavage blocks), quartz, graphic granite (an oriented intergrowth of quartz crystals in feldspar, with an appearance reminiscent of Hebrew characters), and garnets up to the size of a small walnut. He observed that "formerly many very fine specimens were obtained at this locality but have of late become more scarce." Apatite crystals of a deep green color several centimeters long were also found at Dixon's; a prism of apatite on white feldspar in the Delaware Natural Historical Society collection is attributed to this locality. Beryl has been reported in similar but paler green crystals.

Schorl tourmaline, the common black species, is found in crystals of up to 4 cm in diameter in several pegmatites in the region, but duPont (1831) tells of a particularly notable occurrence:

> Many years ago, the proprietor of Dixon's farm, while plowing turned up several crystals a foot in length and some inches in diameter – thinking he had discovered a coal mine on his otherwise barren farm, he was so foolish as to endeavor to burn them – only one was saved.

Minerals of Serpentine

Near the pegmatite deposits of Dixon's farm is a small body of serpentine, an outlier of the belt of serpentine deposits that cuts across the Piedmont a few miles north in Pennsylvania. The body is composed almost entirely of the mineral serpentine, but it includes a number of other minerals: masses of talc and chlorite a few centimeters across, and small amounts of chrysoltile (serpentine asbestos). A little chromite has been found; duPont (1831) reports octalhedral crystals, probably like the small, brilliant crystals less than 3 mm (1/8") across that can be panned out of Crum Creek in Media, Pennsylvania. Magnesite, magnesium carbonate, occurs as chalky masses formed by the weathering of the magnesium silicate, serpentine.

The soil over serpentine bodies is a mixture of ocherous iron oxides and masses of fine-grained quartz, commonly in "boxwork" veins lined with minute crystals. This soil is particularly poor and gives rise to such sparse vegetation that areas underlain by serpentine are called *barrens*. Note that the quote from duPont (1831) cited above refers to Dixon's farm as "barren"; it is underlain by serpentine.

Minerals of the Coastal Plain

The Cenozoic sands and gravels that underlie most of Delaware below the Fall Line are important aquifers and are dug at many places for sand and gravel, but they are devoid of significant mineral occurrences. However, the southern part of the state is not without mineral localities of historic and scientific interest. The residual iron deposits of Iron and Chestnut Hills, south of Newark, and bog iron ores in swamps in the two lower counties were mined during the eighteenth and nineteenth centuries. Cretaceous and Miocene greensands and clays contain a variety of minerals at various places.

Iron Hill and its neighbor Chestnut Hill are outliers of the Piedmont, knobs of mafic rock rising about 75 m (220 feet) above the coastal plain about 3 km (2 miles) south of Newark. Weathering has broken down the rock and leached away much of its substance, leaving a layer of iron oxides – essentially rust – mixed with ferruginous jasper. The jasper is yellow-brown, turning brick red when heated, and contains thin seams lined with tiny crystals of drusy quartz. A few pseudomorphs of limonite after pyrite crystals have been found in pockets in the jasper. This jasper, or material similar to it, from outcrops in Maryland was used by the local Indians in making artifacts.

The iron oxides include amorphous, or poorly crystalline, limonite, and the crystalline minerals goethite and hematite. Limonite forms compact brown masses, or a loose yellow earth called *ochre*. Goethite occurs as compact-fibrous veins and geodes, with the fibers oriented perpendicular to the surface. This texture serves to distinguish goethite from limonite. Hematite is red when fine grained, and is the red coloring agent of tropical soils and old-fashioned red barn paint. It is less common than the brown oxides in Delaware but occurs in small amounts. When heated, the brown oxides dehydrate to red hematite. This shift is reponsible for the color change in Iron Hill jasper which was mentioned previously.

Mixtures of iron oxides and jasper are called *gossans*. The gossan at Iron Hill lies below the soil, capping the rock from which it is derived. The iron oxides were mined by stripping away the soil and working the deposit by hand. Sizeable pits remain today on the crest of Iron Hill, their floors covered with a rubble of jasper boulders.

In stagnant but oxygen-rich waters, iron is precipitated from solution by iron-fixing bacteria. The iridescent, brittle film commonly seen on quiet water surfaces in bogs is not the scum of pollution but a natural deposit of limonite. Eventually this film will break through the surface tension of the water and sink to the bottom. The accumulation over years may form a substantial deposit of bog iron, limonite and goethite mixed with more or less leaf litter and clay. According to Booth (1841), such deposits were mined at a number of localities in Delaware: 1 mile and 10 miles west of Millsboro on Burton's and Green's Creeks, a few miles west of Georgetown, and on Little Creek about 2 miles south of Laurel. Similar small, local iron mining and smelting operations were common throughout the eastern United States through the first third of the nineteenth century, but did not survive the opening of the Great Lakes area, with its vast deposits of iron ore, coal, and limestone.

Greensands and clays rich in organic material provide reducing environments; that is, they are low in oxygen. Here minerals containing divalent or ferrous iron predominate; goethite and other ferric iron oxides do not form. Cretaceous and Miocene deposits of this type are exposed in Delaware, especially in the vicinity of the Chesapeake and Delaware Canal. Exposures of the Cretaceous Merchantville Formation in the canal near Summit Bridge have yielded nodules of siderite, $FeCO_3$, up to 12 cm (5 inches) across. Many of these nodules contain shrinkage cracks lined with iridescent crusts of pyrite crystals. The best locality was the bed of the canal itself, where nodules could be dug from the mud at low tide. Unfortunately for the collector, dredging in recent years has deepened the canal and obliterated these deposits.

However, the Merchantville cuts across Delaware in a band more than a mile wide (Pickett, 1970), and siderite nodules like those found in the canal certainly occur beneath the surface in this formation.

Small amounts of pyrite and marcasite (both FeS_2) are common in the greensands and clays of Delaware. Where exposed to the atmosphere, the sulfur may oxidize to sulfate, forming efflorescences of water-soluble melanterite, $FeSO_4.7H_2O$ on sheltered surfaces. During dry spells, the spoil banks along the C&D canal locally show blooms of this mineral. Other soluble sulfate species may be present as well, but have not been identified.

Reducing environments low in sulphur and high in phosphorus favor the formation of vivianite, $FE_3(PO_4)_2.8H_2O$. The second American locality for this mineral was Polk's marl pit (Booth, 1841) on one of the headstreams of the Bohemia River west of Middletown. Today vivianite is known to occur widely in sediments of the Atlantic coastal plain. Booth recounts the discovery at Polk's:

> While workmen were employed in the excavation, they observed it sparkle in the sun's light with the brilliancy of polished silver, which they attributed of course to the presence of that metal in the form of small spangles. A closer inspection proved them to be small crystals, with a brilliant, nearly adamantine luster, perfectly limpid when first obtained, but rapidly changing to blue by exposure to the air; and chemical analysis showed their constitution to be phosphoric acid, protoxide of iron, and water. They are the same as those found some years since at Mullica Hill in N. Jersey, and termed Mullicite by Dr. Thompson of Glasgow, who analysed them.

Mullicite is the same as vivianite, the name now used for the mineral. The change from colorless or white to blue on exposure to air is characteristic of vivianite and has been noted often. The change is irreversible and is caused by the oxidation of a fraction of the iron in vivianite from ferrous (divalent) to ferric (trivalent).

Several years ago Dr. Pickett of the Delaware Geological Survey and the author spent several afternoons in the headwaters of the Bohemia trying to locate the pit. The vagueness of the locality, changes in the stream courses, and slumping of the soft banks in the 130 years since Booth's report kept us from finding any trace, although as late as 1892 Dana noted Polk's marl pit as an exceptional locality for vivianite.

Vivianite forms below the water table in the almost complete absence of oxygen. When erosion lowers the water table and exposes vivianite to oxygenated water in the zone of aeration, it gradually oxidizes and breaks down into secondary iron phosphates, including rockbridgeite, $FeFe_4(PO_4)_3(OH)_5$, and lipscombite, $FeFe_2(PO_4)_2(OH)_2.4H_2O$. These minerals are found in greenish-black, fibrous to crumbly nodules a few millimeters across in a small marl pit in the Hornerstown Formation just south of the south branch of Drawers Creek on the Odessa-Armstrong Road (T. E. Pickett, personal communication). Their presence indicates that vivianite may occur at depth at this locality.

It is tempting to consider men who mistake tourmaline for coal or vivianite for silver as the ignorant, credulous denizens of a bygone era. However, a few months ago there was considerable excitement in the local papers over a supposed oil strike in southern Delaware. The region had been investigated in the 1950s by petroleum geologists and found barren, and it soon turned out that wistful thinking was the major ingredient in the new "strike." Ignorance about mineral deposits is not confined to the past.

Although not blessed with famous mineral deposits, Delaware displays a considerable number of mineral species in a wide variety of geologic settings. This variety is a reminder of the complexity and diversity of the earth's crust.

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APPENDIX

Alphabetical list of minerals found in Delaware, with notes on their occurrence and abundance.

abundant: unavoidable, a major constituent of some rock
common: widespread at certain localities
uncommon: restricted to few localities or only occasionally found
rare: few specimens or single report

Albite, $NaAlSi_3O_8$: See Plagioclase.

Almandine, $Fe_3Al_2(SiO_4)_3$: See Garnet.

Apatite, $Ca_5(PO_4)_3(F, OH)$: Blue prisms up to 7 cm in the Dixon's Quarry pegmatite, rare. With plagioclase and biotite in lenses in amphibolite, rare. Olive-green crystals up to 3 cm in quartz veins in the Wilmington Complex, rare. Fine-grained and nodular in greensand and marl, common.

Beryl, $Be_3Al_2Si_6O_{18}$: Light green crystals in pegmatites, rare.

Biotite: $K(Fe, Mg)_3AlSi_3O_{10}(OH)_2$: An abundant constituent of the Wissahickon Schist.

Bornite, Cu_5FeS_4: Rare small masses in veins in Wilmington Complex.

Calcite, $CaCO_3$: Cockeysville Marble, abundant. Flat rhombohedral crystals to 2 cm and vein fillings in Wilmington Complex, rare. Fossil shell material in Coastal Plain sediments, common.

Canbyite, complex hydrated ferric silicate: Thin crusts in veins of Wilmington Complex rare.

Chabazite, a calcium zeolite: Yellow rhombohedra to 5 mm in veins in Wilmington Complex, uncommon.

Chalcocite, Cu_2S: Small masses with other sulfides in veins in the Wilmington Complex, rare.

Chalcopyrite, $CuFeS_2$: Small masses with other sulfides in veins in the Wilmington Complex, rare.

Chlorite, complex magnesium sheet silicate: Green flakes to 2 cm in serpentine, uncommon.

Chromite, $FeCr_2O_4$: Small crystals and masses in serpentine, rare.

Chrysotile: See Serpentine.

Cordierite, $(Mg, Fe)_2Al_3Si_5O_{18}$: Grains and rough crystals to 1 cm in gneiss along the Brandywine, uncommon.

Dolomite, $CaMg(CO_3)_2$: Cockeysville Marble, abundant.

Galena, PbS: Small masses with other sulfides in veins in the Wilmington Complex, rare.

Garnet, $(Fe, Mn)_3Al_2(SiO_4)_3$: Variety almandine, common in schists in crystals to 2 cm; variety spessartine, crystals in pegmatites, uncommon. The spessartine shows black manganese oxide on weathering; almandine weathers rusty.

Glauconite, complex iron sheet silicate: Abundant as sand-sized grains in greensands and marls.

Goethite, $HFeO_2$: Abundant as a weathering product of iron-rich rocks and minerals. With limonite forms bog iron deposits.

Hematite, Fe_2O_3: Common with goethite. Forms red masses and deposits.

Hornblende, complex silicate: Abundant in amphibolites and hornblende gneiss.

Hypersthene, $(Mg, Fe)SiO_3$: Abundant in gneisses of Wilmington Complex. Crystal blades to 7 cm in the Brynhurst Woods gabbro, common.

Ilmenite, $FeTiO_3$: Common in small amounts in schists and gneisses.

Jasper, SiO_2: See quartz.

Kaolinite, $Al_2Si_2O_5(OH)_4$: Abundant weathering produce of feldspars of all Piedmont rocks. Local concentrations were mined for china clay in Colonial times.

Labradorite: See Plagioclase.

Laumontite, a calcium zeolite: With other zeolites and calcite in veins of Wilmington Complex rocks, rare.

Limonite, a mixture of ferric oxides and hydroxides: Abundant with geothite. Major constituent of bog ores.

Lipscombite, $FeFe_2(PO_4)_2(OH)_2.2H_2O$: A rare alteration product of vivianite (?) in greensand.

Magnesite, $MgCO_3$: Chalky masses from weathering of serpentine, uncommon.

Marcasite, FeS_2: With pyrite in sediments rich in organic material, uncommon.

Melanterite, $FeSO_4.7H_2O$: Forms by the weathering of pyrite on spoil heaps along the C&D Canal, uncommon. Water soluble.

Microcline, $KAlSi_3O_8$: Abundant in Wissahickon schists and gneisses; large masses and crystals to 10 cm in pegmatites, common.

Muscovite, $KAl_2AlSi_3O_{10}(OH)_2$: Flakes in Wissahickon schists, uncommon; books to 12 cm in pegmatites, common.

Natrolite, a sodium zeolite: With sulfides in veins in Wilmington Complex gneiss, rare – one specimen known.

Olivine, (mg, Fe) SiO_4: Mantled grains in Brynhurst Woods gabbro, common.

Pyrite, FeS_2: With other sulfides and canbyite in veins in Wilmington Complex, rare; with siderite and marcasite in Coastal Plain sediments rich in organic material, common.

Quartz, SiO_2: Abundant in schists and gneisses of the Wilmington Complex and in pegmatites. Crystals to 5 cm were found during the construction of the Dupont Country Club golf course. The major constituent of Coastal Plain sands and gravels. Jasper, a fine-grained variety stained yellow, brown, or red by iron oxides, is a common weathering product of mafic rocks, particularly in the serpentine barren and on Iron and Chestunut Hills.

Rockgridgeite, $FeFe_4(PO_4)_3(OH)_5$: With lipscombite as a weathering product of vivianite (?) in greensand, rare.

Serpentine, $Mg_3SiO_5(OH)_4$: Forms the serpentine barrens on the northwest side of Hoopes Reservoir (abundant); the asbestos form chrysotile is encountered in small amounts (uncommon).

Siderite, $FeCO_3$: With pyrite and marcasite in sediments rich in organic material; forms nodules to 15 cm. Common.

Sillimanite, Al_2SiO_5: A common constituent of schists and gneisses of the Wissahickon Formation. Large masses are found at Brandywine Springs State Park. Delaware state mineral.

Spessartine, $Mn_3Al_2(SiO_4)_3$: See Garnet.

Sphene, $CaTiSiO_5$: Microscopic grains in Wilmington Complex gneisses, uncommon; two specimens of crystals of 2 cm in pockets of feldspar gneiss from the Delaware Natural Historical Society collection are attributed to Claymont. Rare and doubtful.

Stilbite, a calcium zeolite: Crystals to 5 mm with other zeolites in viens in Wilmington Complex rocks, uncommon.

Talc, $Mg_3Si_4O_{10}(OH)_2$: Aggregates of soft, pearly flakes to 2 cm in serpentine, uncommon.

Tourmaline, a complex borosilicate: The schorl species found as small crystals in Wissahickon schist and Gneiss and as crystals to 30 cm (du-Pont, 1831) in pegmatite, common.

Tremolite, $Ca_2Mg_5Si_8O_{22}(OH)_2$: White blades to 7 cm in Cockeysville marble, common.

Vivianite, $Fe_3(PO_4)_2 . 8H_2O$: Small crystals and crystal clusters in greendsand or marl, rare. The classic locality at Middletown (Booth, 1841) is lost.

10

Fossils in Delaware

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THIS chapter is meant to serve as an overview of paleontological studies in Delaware. It summarizes several papers on fossils in Delaware and includes plates. The papers synthesized here are representative of the work done on Delaware fossils (mainly Foraminifera, Ostracoda, and Mollusca), but are by no means totally inclusive of investigations conducted in this field of research. A list of references is included for further information.

One of the most fossiliferous areas in the Atlantic Coastal Plain is the Chesapeake and Delaware Canal. Much work has been done in the Upper Cretaceous of Delaware in the Canal area. Groot et al. (1954) studied the marine Upper Cretaceous formations and fossils, and Richards and Shapiro (1963) investigated invertebrate macrofossils from the same areas. Pickett (1972) includes both a geologic history of the Chesa-

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peake and Delaware Canal area and illustrations from Groot et al. (1954) and Richards and Shapiro (1963). Mumby (1961) investigated Foraminifera from the Canal outcrops. Other studies on Delaware fossils include those by Swain and Kraft (1975) on Holocene Ostracoda in Delaware Bay, Pickett et al. (1971) on Cretaceous burrows in the Chesapeake and Delaware Canal, and Richards (1965) on the Mollusca and Foraminifera of the Omar Formation in the Columbia Group (Pleistocene of Delaware. A brief synthesis of each paper follows.

Swain and Kraft (1975) investigated the biofacies and microstructure of Holocene Ostracoda from tidal bays of Delaware. This paper describes a small fauna of 20 species of Ostracodes collected from tidal bays in southern Delaware. Their distribution and environmental characteristics are described, and four major biofacies were recognized: 1) silty clay bay biofacies representing most of the area, *Leptocythere* spp; 2) silty organic clay tidal-river biofacies with *Cyprideis* and *Perissocytheridea;* 3) tidal bay sand biofacies with *"Haplocytheridea"* and *Campylocythere;* and 4) tidal marsh mud biofacies with *Cytherura.*

Specimens of each species were studied with a scanning electron microscope. It was found that the epicuticle, or outer organic covering of the ostracode carapace, was developed in most specimens although calcification was usually poor. Irregularities and variations in the epicuticle surface (e.g., nodose, smooth, punctate, irrregular) probably reflect the structure of the underlying procuticle surface. Ostracodes also possess seta pore and sieve plates which emerge from pores in the procuticle. These setae may function as sensory, secretory, and/or protective structures. Characteristic variations in the outer surface of the procuticle as well as in the setae and sieve plates may be useful taxonomically.

It is also noted that diatoms scattered over the surface of one species are being covered by the epicuticle. These diatoms are regularly spaced and provide nodisity to the ostracode's shell.

See plates 1 through 5 which follow at the end of the chapter.

An important fossiliferous outcrop location in Delaware is the Pepper Creek Ditch near Frankford, Delaware. Richards (1965) cites the Omar Formation as one of the three fossiliferous exposures in the Columbia in Delaware. The material exposed at Pepper Creek Ditch at Route 113 near Frankford, Delaware, is of the Omar Formation, and is dominated by *Crassostrea virginica.* The Omar unit consists of alternating and silt layers, each a few feet thick, and it extends 50 feet below the ground surface. A date of approximately 32,000 years has been determined by C^{14} methods for a piece of wood located 24 feet below the land surface. Dates on shells from this locality are 34,000 ± 2,000 years, and + 37,000 years.

The fauna at the Pepper Creek site includes the following (Richards, 1965):

Mollusca
- *Crassostrea virginica* (Gmelin)
- *Odostomia (Chrysallida) dianthophila* H. W. Wells
- *O. (Chrysallida)* sp.
- *O. (Menestho) impressa* Say?
- *O. (M.) trifida* Totten?
- *O. (M.)* sp.
- *Cerithiopsis greeni* C. B. Adams
- *Cumingia tellinoides* Conrad
- *Noetia ponderosa* (Say)

Foraminifera
- *Elphidium clavatum* Cushman
- *E. florentinae* Shupack
- *Rotalia beccarii tepeda* Cushman

Groot et al. (1954) studied the marine Upper Cretaceous Formations of the Chesapeake and Delaware Canal. The purpose of their investigation was to determine that marine Cretaceous formations are present in northern Delaware on the basis of lithology and fossil content and to study their stratigraphic relationships. They divided the Upper Cretaceous in the Canal area into two groups: the Matawan and the Monmouth. The Matawan, stratigraphically lower than the Monmouth, was further divided into two Formations – the Wenonah and the Merchantville. Similarly, the Monmouth was divided into both the Red Bank and Navesink-Mount Laurel Formations. Pickett (1972) has revised this stratigraphy. A brief description of the revised Cretaceous Formations is included in this chapter, but the reader is referred to Pickett (1972) for a more detailed discussion.

Richards and Shapiro (1963) studied the Upper Cretaceous fauna at Biggs Farm, near the eastern end of the Canal. The lowermost formation at Biggs Farm Locality is reported to be the Mt. Laurel-Navesink (Groot et al., 1954). It is thought that the fauna here lies in the lower part of the Monmouth group, near the Matawan-Monmouth boundary. Age relationships of this macrofauna correlate with those determined by Mumby's (1961) Foraminiferal study of the same area. Fossil evidence indicates that the Mt. Laurel-Navesink Formation in Delaware is slightly older than the Mt. Laurel of New Jersey.

One hundred eleven species of mollusks have been identified in this highly fossiliferous zone, along with remains of Coelenterate, Porifera, Annelida, Brachiopoda, and Crustacea. The fauna is characterized by a great variety and number of species, with the majority of the fauna small or medium in size. The fossils are marine, and details of their preservation suggest that the fauna probably lived on a sandy bottom in water 50 to 100 feet in depth. The identifications of plates 6 through 10 have been modified and updated by Pickett (1972).

Pickett's (1972) "Guide to Common Cretaceous Fossils of Delaware" contains illustrations of fossils from the Chesapeake and Delaware Canal, (Plates 11 through 17) and a geologic history and synthesis of work that has been done in the Canal area. The Cretaceous units in the C&D Canal area consist of six formations deposited from Early Cretaceous to Mid Eocene under somewhat varied environmental conditions. Briefly, these include: 1) Potomac Formation – deltaic environment; 2) Magothy Formation – shoreline environment; 3) Merchantville Formation – shallow, open marine (ammonite *Placenticeras*); 4) Englishtown Formation – shoreline environment, drop in sea level *(Ophiomorpha* burrows*)*; 5) Marshalltown Formation – shallow, open marine environment, possibly embayed (pelecypoda, gastropoda); 6) Mt. Laurel Formation – shallow open marine environment, possibly embayed (mollusca) (see Figure 1).

Most fossils collected in the canal area are steinkerns, or internal molds, which makes valid identification difficult. Locations for collecting fossils are indicated on a map included in Pickett (1972). It should be noted, however, that the locations are on federally controlled lands. Small-scale collecting for private collections is permitted in restricted areas. The author and the Delaware Geological Survey urge the conservation of these scientific and educationally important fossil localities.

All formations in the C&D Canal contain trace fossils such as crustacean and worm burrows and borings. The Cretaceous deposits at the C&D Canal also include fossilized fish and reptilian bones, especially in the Marshalltown and Mt. Laurel Formations. The Magothy and Merchantville Formations often contain lignitized wood, which is frequently encrusted with pyrite.

The illustrations included in Pickett's paper are reprinted from the Delaware Geological Survey Bulletin #3 (Groot et al., 1954) and Report of Investigations #7 (Richards and Shapiro, 1963), both of

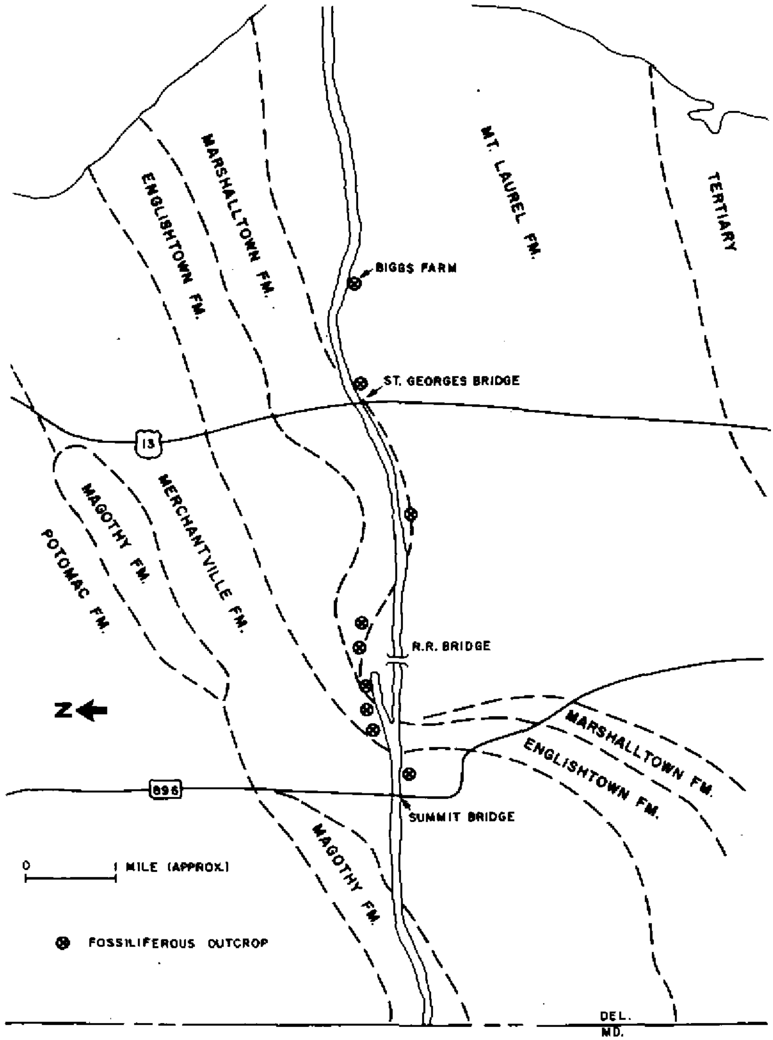

Figure 1. Geology of the Chesapeake and Delaware Canal (from Pickett, 1972).

which are presently out of print. The identifications have been revised and are as accurate as possible.

Pickett et al., (1971) discuss nodulose, sandy, burrow tubes found in Upper Cretaceous sediments of the Chesapeake and Delaware Canal. Morphologic evidence indicates that the tubes were made by a Cretaceous decapod crustacean similar to the modern mud shrimp *Callianassa major* Say (see plate 18). Burrows of this organism are limited to the upper neritic and littoral zones, and therefore should be useful in mapping ancient shorelines. The burrows are valuable paleoenvironmental indicators, and seem to be environmentally rather than stratgraphically controlled.

Mumby (1961) discusses and describes Upper Cretaceous Foraminifera from marine formations along the Chesapeake and Delaware Canal. The abstract from Mumby's dissertation serves as a summary of her paper. Figures of Foraminifera from Delaware are also included in plates 19 through 29.

> One hundred sixty two species and subspecies of Foraminifera have been identified from the Upper Cretaceous of Delaware and Maryland. Of these, 151 from Delaware and 1 from Maryland have been figured. Four new species, *Bullapora cylindrica, Vingulina delawarensis, Renssella delawarensis,* and *Hedbergella delawarensis,* and one new subspecies, *Grienbetitria cretacea trangularis,* have been described. Species and subspecies recorded for the first time from the United States include *Ataxophragmium beisseli* Cushman, *Rugoglobigerina rugosa subrugosa* Gandolfi, *Globotruncana bulloides bulloides* (Vogler), *G. lapparenti tricarinata* (Quereau), and *G. mariei* Gandolfi.

A study of the 151 species and subspecies of Foraminifera from the Mt. Laurel Formation along the Chesapeake and Delaware Canal indicates that the age of the Mt. Laurel Formation in Delaware is not the same as it is in New Jersey. Both planktonic and benthonic index species suggest an upper Campanian age for the microfauna and a very close similarity with the microfaunas of the upper Taylor marl, Saratoga chalk, upper Selma chalk, Neylandville marl, and lowermost Ripley formation of the Gulf Coast. Correlations based on megafossils conflict with those based on Foraminifera in both the Atlantic and Gulf Coast regions. If megafossil shell beds were used as approximate depth indicators, and planktonic and carefully selected benthonic Foraminifera were used as age indicators, a comparison of their relationship to one another in various areas should provide another tool for historical geology.

Since the Mt. Laurel is overlain by a sand consisting predominantly of quartz rather than glauconite and since no faunal break is evident in the sand between the Wenonah and the Red Bank (?), the Navesink Formation is considered absent from the Canal area. The meager Foraminifera from the Red Bank (?) Formation are not significantly different from those in the underlying Mt. Laurel; therefore, the correlation of this formation with the Red Bank of New Jersey is questioned. All but one of the few species from the Merchantville are also similar to those from the Mt. Laurel. The 1400- to 1420-foot section of the Hammond Well near Salisbury, Maryland, contains approximately 60 species in common with the Mt. Laurel, but all the samples from the Monmouth Formation south and east of Washington, D.C., yield faunas younger than any from the Canal. They also indicate a near-shore environment in contrast to the open ocean or large bay, upper neritic, crater reef environment of the Mt. Laurel fauna. The Marshalltown at Fellowship, New Jersey, contains an abundant microfauna similar to that of the Delaware Mt. Laurel, but slightly older and probably from a more shallow or nearer-shore environment. The similarity of the Merchantville and Mt. Laurel foraminiferal faunas suggests that the intervening unfossiliferous Wenonah sand was deposited during a short period of time.

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PLATE 1

Figure

1a-f. *Perissocytheridea brachyforma* Swain.
a. Left side of shell; X 56. b. Enlargement of midventral surface showing a sieve plate, sensory seta, and studded or finely nodose labyrinthic surface due to projection of portions of calcified procuticle into epicuticle; X 568. c. Enlargement of sieve plate with a median septum at base of which lies the sensory knurled seta; X 1, 118. d, e. Enlargements of knurled seta; X 2, 795 and X 11, 180 respectively. f. Enlargement of a ventrally located sieve plate of smaller size than preceding; X 2,795. Locality 197, Pepper Creek, Delaware.

2a, b. *Haplocytheridea* aff. *H. setipunctata* (Brady).
a. Right side of shell; X 47. b. Enlargement of surface showing crowded pit areas that in part contain setae and poorly preserved sieve plates and sparsely nodose interpit areas that represent projections of procuticle into epicticle; around and in pits epicuticle absent and surface of procuticle is exposed; X 227. Locality 273, Rehoboth Bay Delaware.

3a, b. *Haplocytheridea* aff. *H. setipunctata* (Brady).
a. Left side of shell; X 47. b. Enlargement of surface of shell; X 227, showing depressions that in part contain poorly preserved sieve plates, and sparsely nodose interspaces; epicuticle interpreted as forming surface of interspaces; underlying procuticle exposed in pits. Locality 273, Rehoboth Bay, Delaware.

4a, b. *Cytherura vestibulata* Hall.
a. Right side of male shell; X 103. b. Enlargement of part of anterodorsal surface showing normal pores and lines of intersection of plates of epicuticle and perhaps of the underlying procuticle in narrow surface ridges; X1,030. Locality 245, Indian River Bay, Delaware.

5a-c. *Cytherura vestibulata* Hall.
a. Right side of female shell; X 86. b. Enlargement of median surface; X 860, showing normal pores and intersection of plates of epicuticle and perhaps of the underlying procuticle in narrow surface ridges; surface covered with epicuticle; X 4,300. Locality 264, Indian River Bay, Delaware.

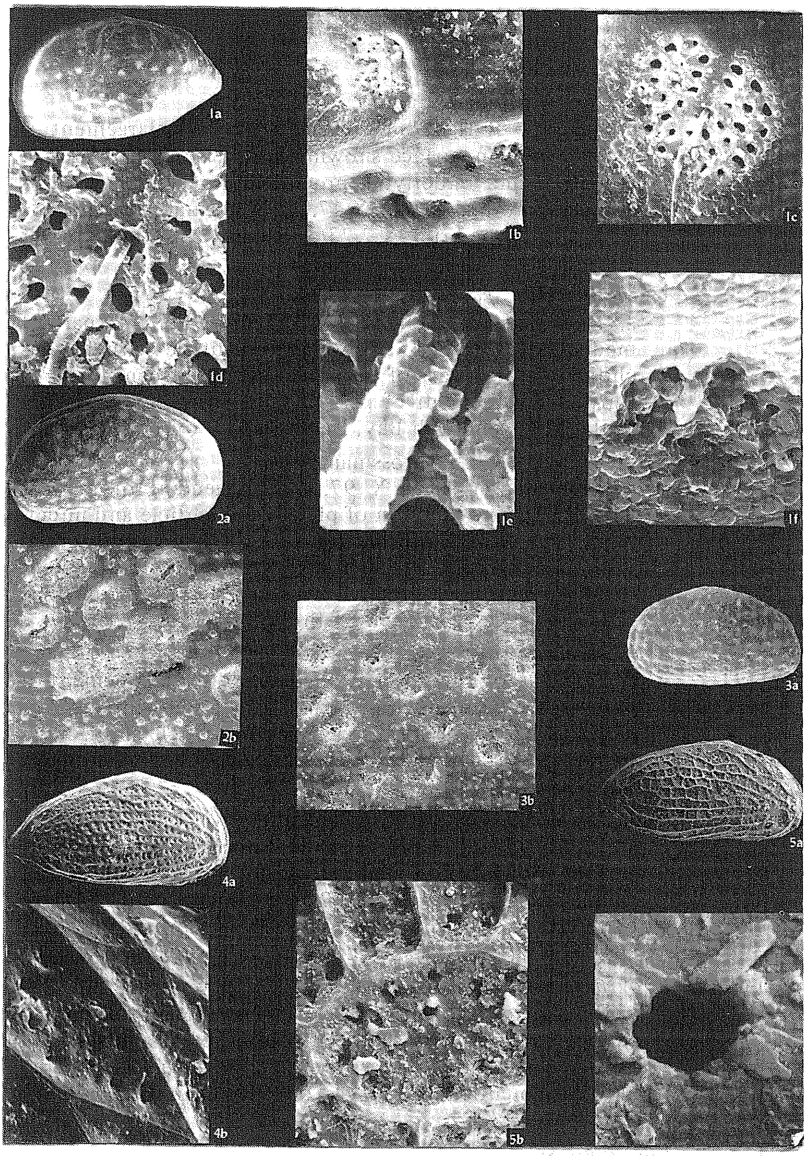
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PLATE 2

Figure

1a-d. *Cytherura vestibulata* Hall.
a. Exterior of right male valve; X 81. b. Enlargement of part of median surface showing intersections of plates of epicuticle and underlying procuticle along narrow ridges and some normal canals; X 473. c. A normal pore and seta with a thickened rim; X 2,236. Locality 247, Indian River Bay, Delaware.

2a-c. *Cytherura* cf. *C. corensis* Grossman.
a. Right side of shell; X 97. b. Enlargement of part of median surface; X 559, showing epicuticle with fibrous chitin of outer part of procuticle reflected beneath it. c. Further enlargement of part of same surface; X 989. Locality 270, Rehoboth Bay, Delaware.

3a, b. *Cytherura* cf. *corensis* Grossman.
a. Left side of shell; X 97. b Enlargement of part of surface showing junction of plates of epicuticle and underlying procuticle along narrow surface ridges, and normal pores of two types: (1) large with little or no development of raised rims and (2) small with raised crateriform rims; X 473. Locality 270, Rehoboth Bay, Delaware.

4a, b. *Cytherura* cf. *C. forulata* Edwards.
a. Left side of an imperfect shell; X 99. b. Enlargement of part of surface showing normal canals and junction of plates of epicuticle and underlying procuticle along crests of narrow surface ridges; X 507. Locality 212, Indian River Bay, Delaware.

5a-c. *Cyprideis* aff. *C. locketti* (Stephenson).
a. Right side of shell; X 25. b. Enlargement of part of surface showing sieve plate areas and normal pore seta of simple and branched type; X 249. c. Enlargement of a sieve plate area, normal pore and seta; surface covered with epicuticle; X 2,494. Locality 228, Indian River, Delaware.

6a-c. *Eucythere* aff. *E. triangulata* Puri.
a. Exterior of right valve; X 99. b. Enlargement of part of surface showing sieve plates, normal pores, and setae; X 507. c. Enlargement of a sieve plate area; surface covered here by epicuticle; X 2,494. Locality 223, Indian River Bay, Delaware.

7a, b. *Eucythere* sp.
a. Right side of probably immature setose shell; X 99. b. Enlargement of surface showing epicuticle, the underlying exocuticle, and possibly a small portion of endocuticle near center of picture; X 512. Locality 208, Indian River Bay, Delaware, near mouth of Indian River.

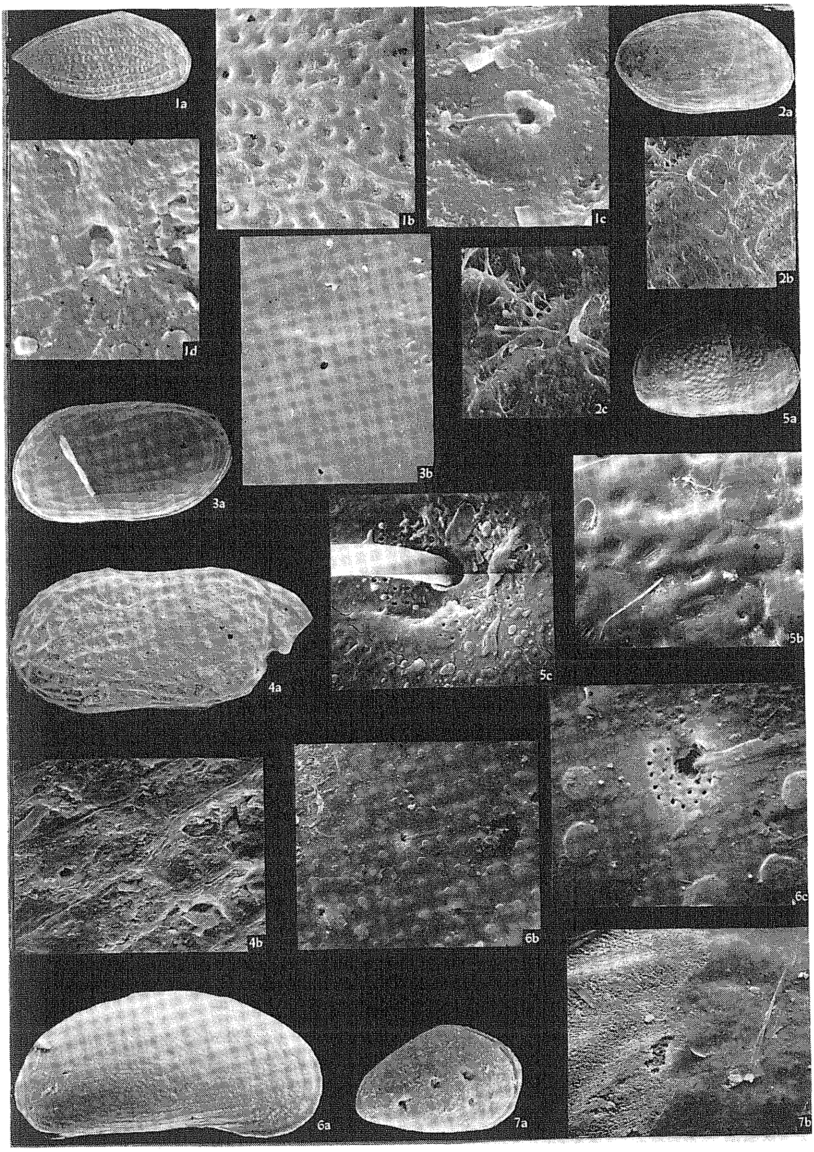
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PLATE 3

Figure

1a, b. *Leptocythere* aff. *L. pellucida* (Baird).
a. Left side of shell; X 85. b. Enlargement of seta, knurled proximally; X 8,084. Differs from *L. pellucida* in having sinuous longitudinal ridge. Specimen appears to have a heavily developed epicuticle. Locality 209, Indian River Bay, Delaware.

2a-d. *Cytheromorpha* aff. *C. curta* Edwards.
a. Left side of shell; X 86. b. Enlargement of part of surface showing a sieve plate area, scattered secretory setae, and the close packed polygonal structure of the cuticle surface around the sieve plate; X 2,150. c. Further enlargement of sieve plate, X 4,300 showing minute nodose cuticular structure of sieve plate surface and a few secretory setae. d. Further enlargement of a different sieve plate showing details of nondosity of cuticle surface; X 9,890. It appears that the nodose structures are reflected in epicuticle from underlying procuticle. Locality 284, Little Assawoman Bay, Delaware.

3a-c. *Cytheromorpha* aff. *C. curta* Edwards.
a. Right side of shell; X 100 b. Enlargement of a sieve plate area; X 2,408, showing part of a seta on right side of sieve plate and minute nodose structure reflected in epicuticle from underlying procuticle. c. Part of surface around a normal pore and seta (knurled proximally), and both nodose and polygonal structure of cuticle; X 2,408. Polygonal structures interpreted as being structure of epicuticle. Locality 228, Indian River, Delaware.

4a-f. *Cytheromorpha* aff. *C. curta* Edwards.
a. Right side of weakly calcified somewhat shrunken shell; X 99. b. Enlargement of part of surface; X 512. c. Enlargement of part of area of preceding showing minute polygonal structure of epicuticle, minute nodose structure of procuticle and secretory setae; X 2,537. d. Enlargement of nodose and polygonal structures and setae; X 10,320. e. Enlargement of nodes showing small ridges on some of them; X 51,170. f. Part of surface in a different area showing a normal pore and numerous secretory setae; X 512. Locality 208, Indian River, Delaware.

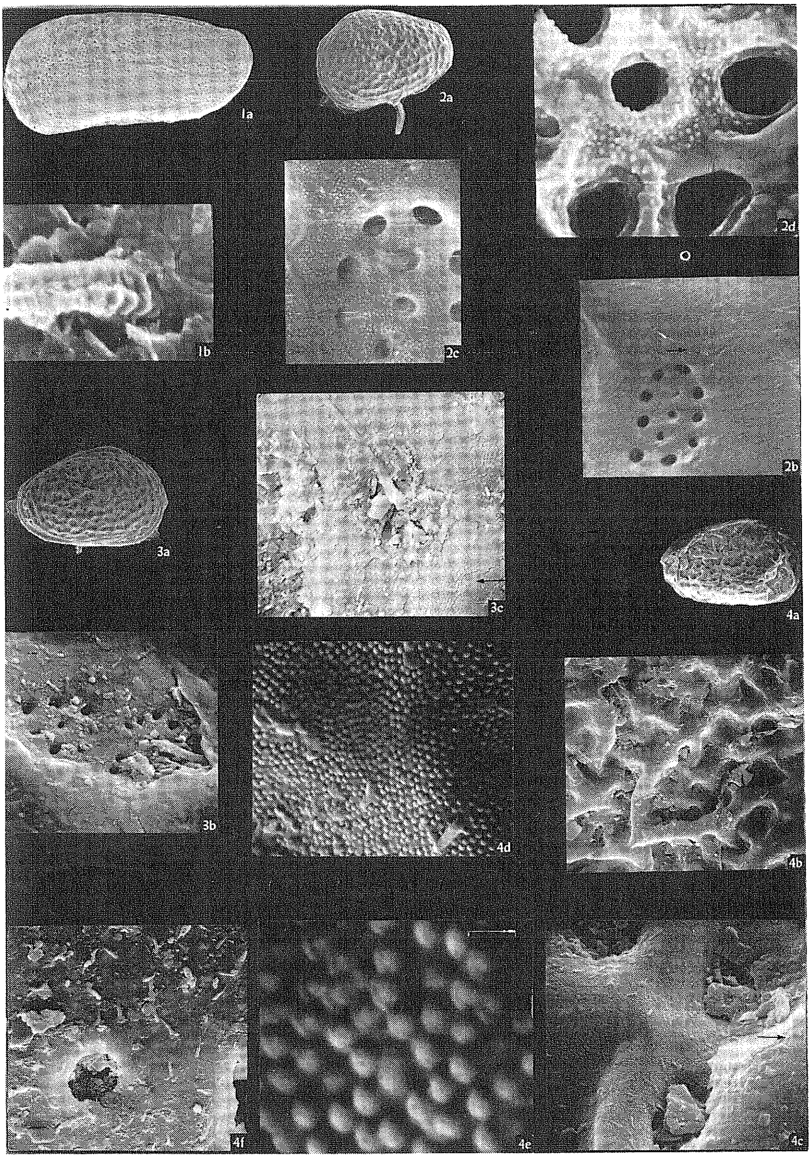
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PLATE 4

Figure

1a, b. *Cylindroleberis psitticina* Darby.
a. Left side of shell; X 47. b. Enlargement of part of surface; X 882, showing surface epicuticle. Locality 282, Little Assawoman Bay, Delaware.

2a, b. *Leptocythere* cf. *L. nikraveshae* Morales.
a. Right side of a collapsed shell; X 112. b. Enlargement of part of surface; X 538, showing areas of smooth epicuticle underlain by spongy-textured procuticle. Locality 181, Indian River Bay, Delaware.

3a, b. *Leptocythere* cf. *L. nikraveshae* Morales.
a. Left side of a partly collapsed shell; X 99. b. Enlargement of part of surface of shell showing spongy surface of procuticle and intervening pits lined with smooth epicuticle?; secretory setae occur in several places; X 516. Locality 227, Indian River Bay, Delaware.

4a, b. *Leptocythere* cf. *L. nikraveshae* Morales.
a. Right side of shell; X 56. b. Enlargement of part of surface; X 560, showing areas of epicuticle, procuticle and secretory setae. Locality 178, Indian River Bay, Delaware.

5a, b. *Leptocythere* aff. *L. angusta* Blake.
a. Dorsal view of shell; X 99. b. Enlargement of part of surface; X 516, showing roughened surface of procuticle secretory setae. Locality 227, Indian River Bay, Delaware.

6a-c. *Leptocythere* aff. *L. crispata* (Brady).
a. Right side of shell; X 43. b. Enlargement of parts of surface of shell; X 434, showing areas of epicuticle on ridges and underlying procuticle. c. Part of first thoracic leg; X 868, showing setose fringe on outside lateral margin. Locality 264, Indian River Bay, Delaware.

7a, b. *Leptocythere* aff. *L. castanea* Sars.
a. Left side of shell; X 108. b. Enlargement of part of surface showing irregular outer surface of procuticle; X 538. Locality 177, Indian River Bay, Delaware.

8a, b. *Leptocythere* aff. *L. crispata* (Brady).
a. Left side of shell; X 97. b. Enlargement of part of surface showing epicuticle to be smooth on ridge crests, wrinkled on slopes of depressions and terminating around normal pores; X 473. Locality 268, Indian River Bay, Delaware.

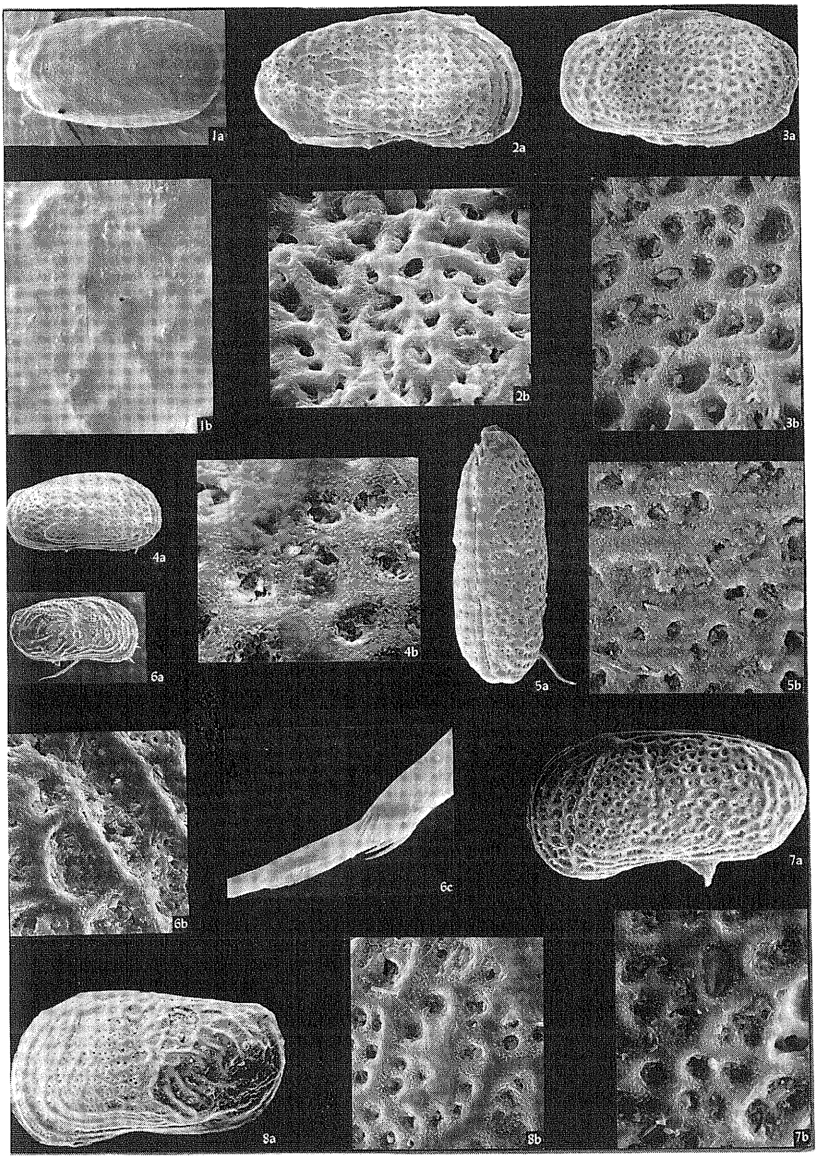
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PLATE 5

Figure

1a, b. *Leptocythere* cf. *L. castanea* Sars.
a. Left valve exterior; X 56. b. Enlargement of part of surface, showing smooth areas of epicuticle, as well as roughened areas that reflect structure of underlying procuticle; X 560. Locality 181, Indian River Bay, Delaware.

2a, b. *Echinocythereis?* aff. *E.? clarkana* (Ulrich and Bassler).
Immature shell. a. Right side of shell; X 110. b. Enlargement of normal pore, sieve plate and part of proximally knurled seta; X 5,160, also showing minutely nodose epicuticle. Locality 177, Indian River Bay, Delaware.

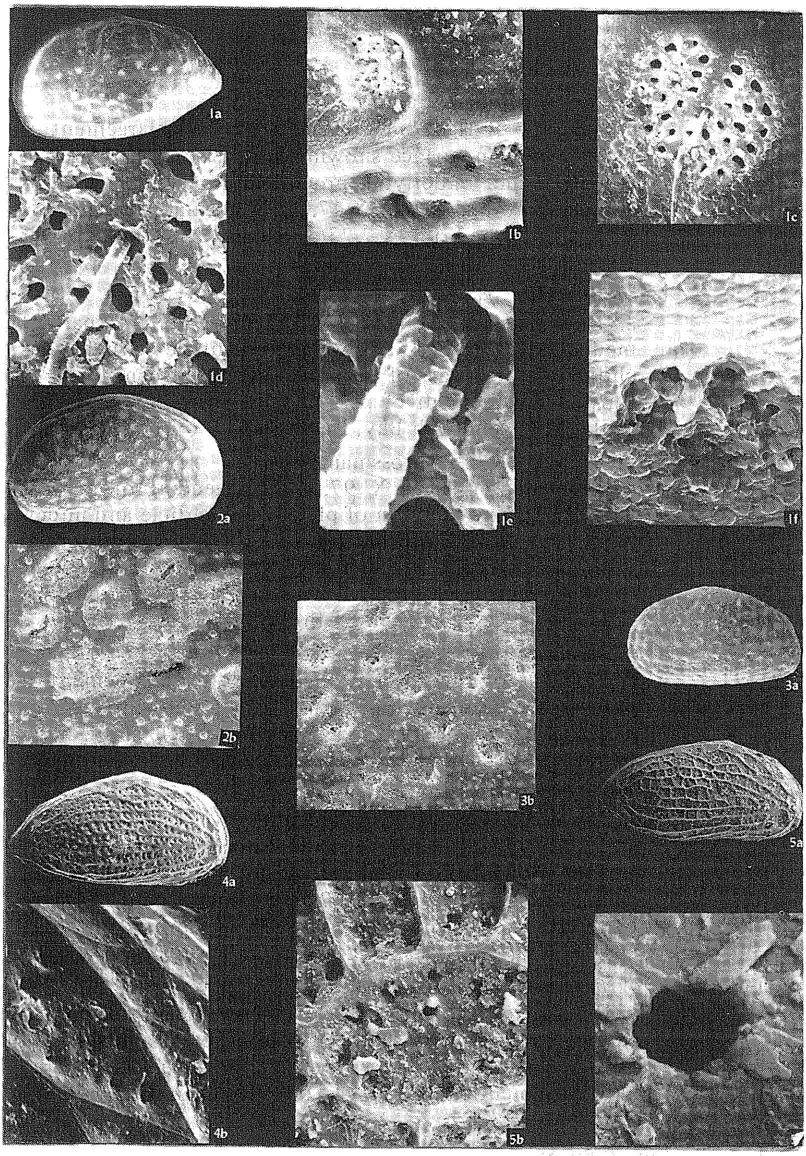
3a, b. *Paradoxostoma* aff. *P. hodgei* Brady.
a. Left side of shell; X 99. b. Enlargement of surface showing epicuticle, normal pore with narrow rim, and seta; X 2,365. Locality 223, Indian River Bay, Delaware.

4a-c. *Loxoconcha* cf. *L. purisubrhomboidea* Edwards.
a. Right side of male shell; X 45. b. Enlargement of part of surface; X 450, showing elongate sieve plate, normal pore and distal part of proximally knurled seta; X 4,515; epicuticle surface is shown. Locality 264, Indian River Bay, Delaware.

5a-c. *Loxoconcha* cf. *L. purisubrhomboidea* Edwards.
a. Left side of female shell; X 50. b. Enlargement of part of surface showing smooth but incomplete epicuticle, underlying granular procuticle, pits, sieve plates, normal pores and setae; X 247. c. Detail of a sieve plate, normal pore and seta, and rimlike margin of epicuticle around sieve plate; a few chitin fibers in procuticle appear in lower part of photograph; X 2,473. Locality 228, Indian River, Delaware.

6a-c. *Proteoconcha* ? *P. multipunctata parva* (Edwards).
a. Left side of shell; X 45. b. Enlargement of part of surface, showing roughened surface of calcified procuticle, and a sieve plate; X 989. c. Detail of sieve plate; X 4,515. Locality 184, Indian River Bay, Delaware.

7a-e. *Monoceratina* ? aff. *M.* ? *stimulea* (Schwager).
a. Right side of male? shell; X 56. b. Right side of female ? shell; X 56. c. Enlargement of part of surface of 7a, showing surface of epicuticle and adhering specimens of *Cocconeis* in several stages of covering by epicuticle and of dissolution; X 516. d. Enlargement of part of surface of another specimen; X 559, showing patterned nature of epicuticle that may have been caused in part by previous attachment of diatoms and two *Cocconeis* in different stages of entombment and dissolution. e. Enlargement of part of surface of 7b showing unburied (upper right) and buried (upper left) *Cocconeis;* X 593. Locality 182, Indian River Bay, Delaware.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(Explantion of plates 6 through 10; formation names indicate origin of specimen; the species is not necessarily restricted to that formation.)

PLATE 6

Figure

1. *Cliona cretacica* Fenton and Fenton, sponge in *Exogyra* sp. (X1). Mount Laurel Formation.

2. *Hemiaster* sp. (Morton), echinoid, (X1). Englishtown Formation.

3. *Gervilliopsis ensiformis* (Conrad), pelecypod, (X1). Merchantville Formation.

4., 5. *Cucullaea neglecta* Gabb, pelecypod, (X1). Marshalltown Formation.

6. *Cucullaea vulgaris* Morton, pelecypod, (X1). Merchantville Formation.

7. *Glycimeris mortoni* (Conrad), pelecypod, (X5/8). Merchantville Formation.

8. *Inoceramus proximus* Tuomey, pelecypod, (X1). Englishtown Formation.

9. *Ptennipteria?* sp., pelecypod, (X1).

10. *Pteria laripes* (Morton), pelecypod, (X1).

11. *Pulvinites argenteus* Conrad?, pelecypod, (X1). Merchantville Formation.

12. *Ostrea monmouthensis* Weller?, pelecypod, (X1). Marshalltown Formation.

13. *Ostrea falcata* Morton, pelecypod, (X1). Marshalltown Formation.

14. *Ostrea mesenterica* Morton, pelecypod, (X1-1/2). Mount Laurel Formation.

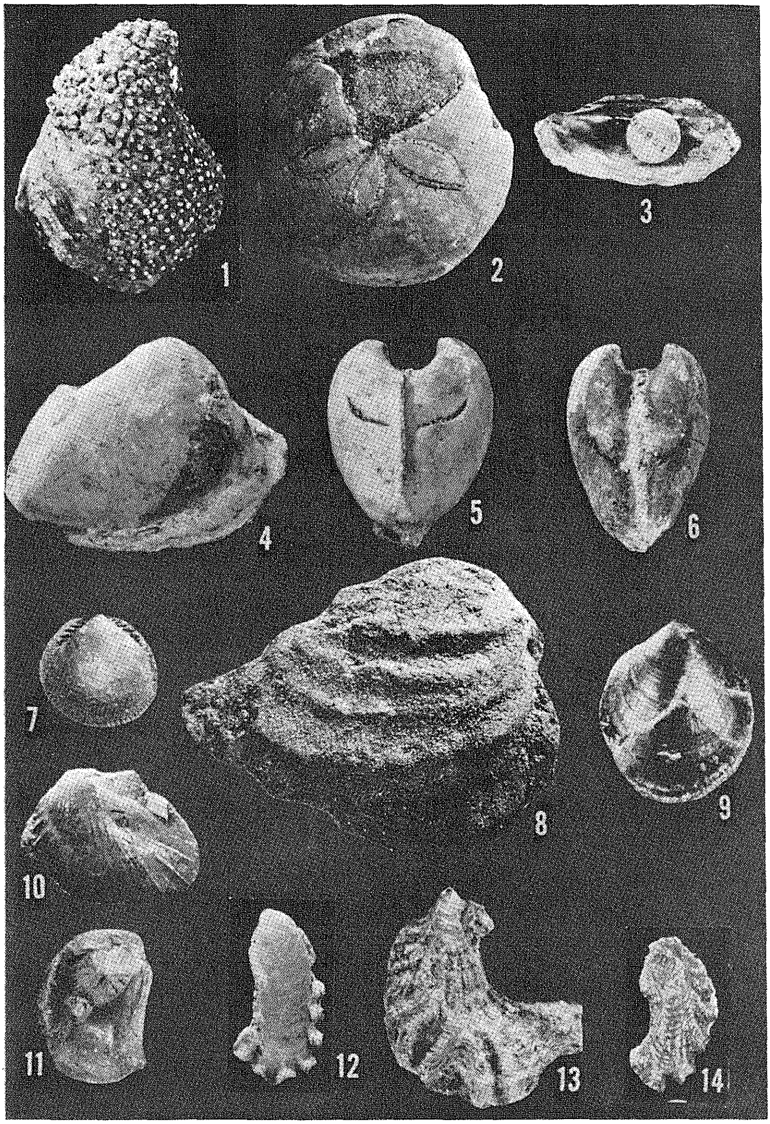
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PLATE 7

Figure

1. *Exogyra ponderosa* Roemer, pelecypod, (X1/2). Marshalltown Formation.
2. *Exogyra ponderosa erraticostata* Stephenson?, pelecypod, (X1/2). Marshalltown Formation.
3. *Exogyra costata* Say, pelecypod, (X1). Mount Laurel Formation.
4. *Pyncnodonte mutabilis* (Morton), pelecypod, (X1/2). Marshalltown Formation.
5. *Pecten whitfieldi* Weller, pelecypod, (X2). Marshalltown Formation.
6. *Anomia tellinoides* Morton, Pelecypod, (X1). Mount Laurel Formation.
7. *Lithophaga ripleyana* Gabb, pelecypod, (X1-1/2). Mount Laurel Formation.

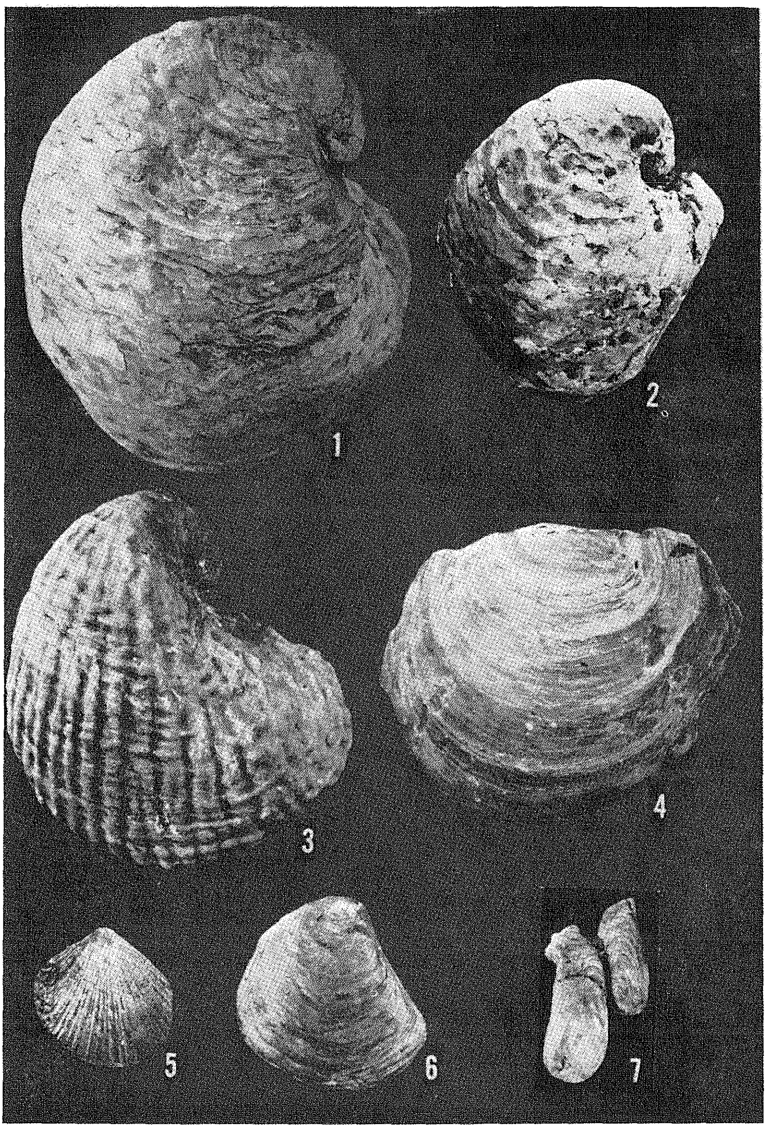
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PLATE 8

Figure

1. *Pholadomya occidentalis* Morton, pelecypod, (X1). Merchantville Formation.
2. *Liopistha protexta* (Conrad), pelecypod, (X1). Marshalltown Formation.
3. *Cymella bella* Conrad var., pelecypod (X3). Merchantville Formation.
4. *Crassatella* sp., pelecypod, (X1). Mount Laurel Formation.

5., 6. *Granocardium tenuistriatum* (Whitfield), pelecypod, (X1). Marshalltown Formation.

7. *Trachycardium* cf. *C. longstreeti* Weller, pelecypod, (X2). Merchantville Formation?
8. *Linearia metastriata* Conrad, pelecypod, (X1). Merchantville Formation.
9. *Unicardium umbonata* (Whitfield), pelecypod, (X1). Marshalltown Formation.
10. *Corbula bisulcata* Gabb, pelecypod, (X1-1/2). Mount Laurel Formation.
11. *Panopea decisa* Conrad, pelecypod, (X1). Merchantville Formation.
12. *Cyprimeria* cf. *C. excavata* (Morton), pelecypod (X1). Marshalltown Formation.

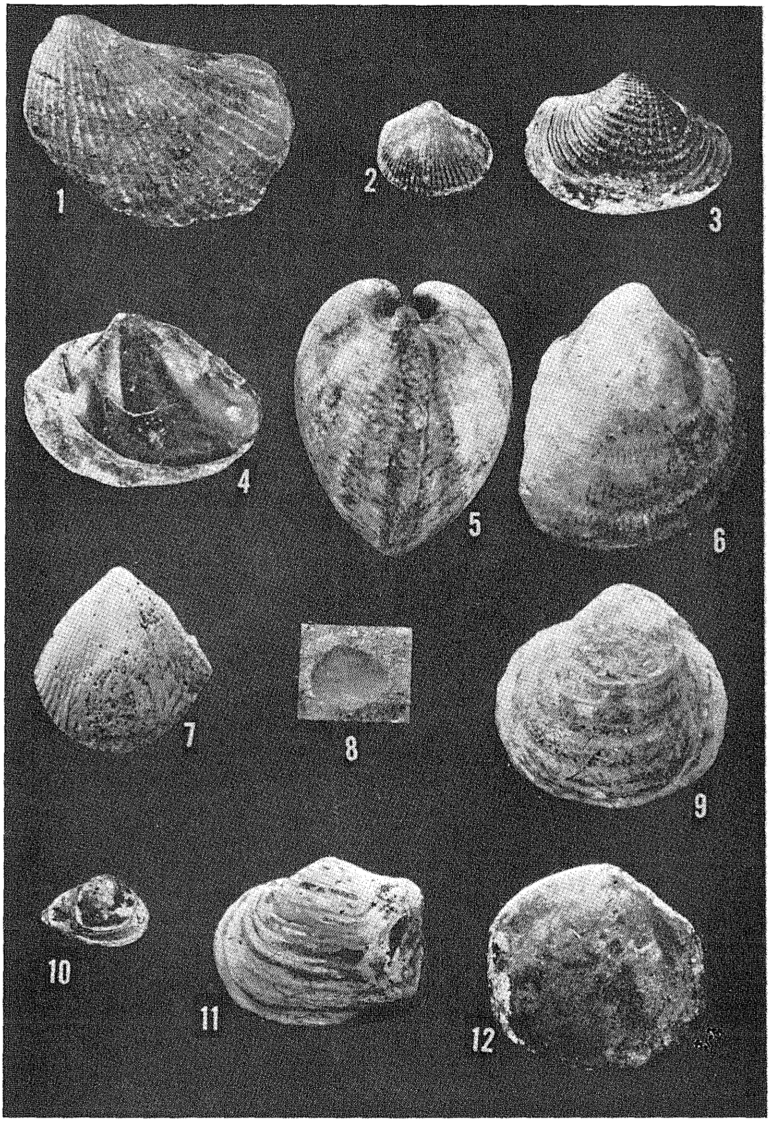
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PLATE 9

Figure

1. *Gyrodes crenata* (Conrad)?, gastropod, (X1), Marshalltown Formation.
2. *Turritella encrinoides* Morton?, gastropod, (X1-1/2). Marshalltown Formation.
3. *Turritella trilira.* Johnson, gastropod, (X2). Mount Laurel Formation.
4. *Piestochilus bella* (Gabb), gastropod, (X1). Merchantville Formation.
5. *Volutomorpha? delawarensis* Gabb, gastropod, (X1). Chesapeake and Delaware Canal.
6. *Volutomorpha conradi* (Gabb), gastropod, (X1). Merchantville Formation.
7. *Avellana bullata* (Morton), gastropod, (X1). Marshalltown Formation.
8. *Napulus octoliratus* (Conrad), gastropod, (X1-1/2). Marshalltown Formation?
9. *Pyropsis* sp. (Tuomey)? gastropod, (X1). Marshalltown Formation.
10. *Anchura?* sp. Conrad?, gastropod, (X1). Marshalltown Formation.

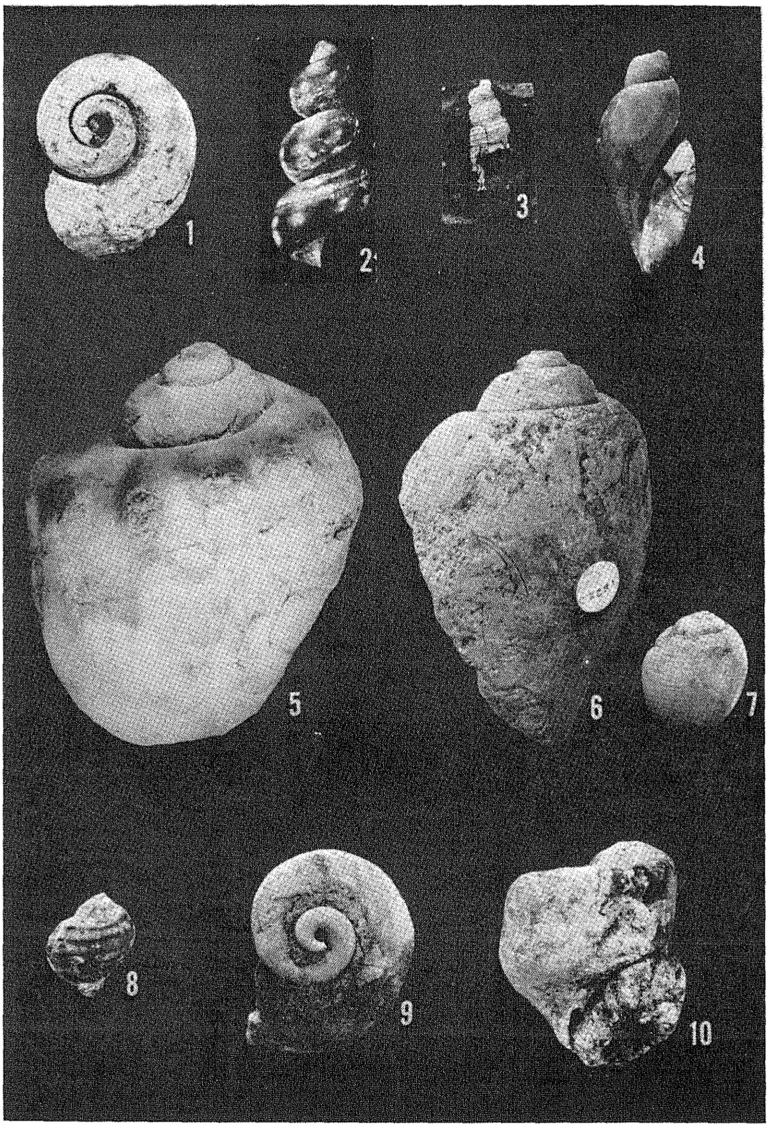
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PLATE 10

Figure

1., 2. *Belemnitella americana* (Morton), cephalopod (squid), (X1). Mount Laurel Formation.

3., 4. *Callianassa mortoni* Pilsbry, crustacean (crab claw), (X1). Merchantville Formation.

5. *Menabites (Delawarella) delawarensis* (Morton), cephalopod, (X1). Merchantville Formation.

6. *Baculites ovatus* Say, cephalopod, (X1). Mount Laurel Formation.

7. *Ophiomorpha nodosa* Lundgren, burrow of the mud-shrimp *Callianassa*, (X1). Englishtown Formation.

8. *Thalassinoides* sp., crustacean burrow, (X1). Marshalltown Formation?

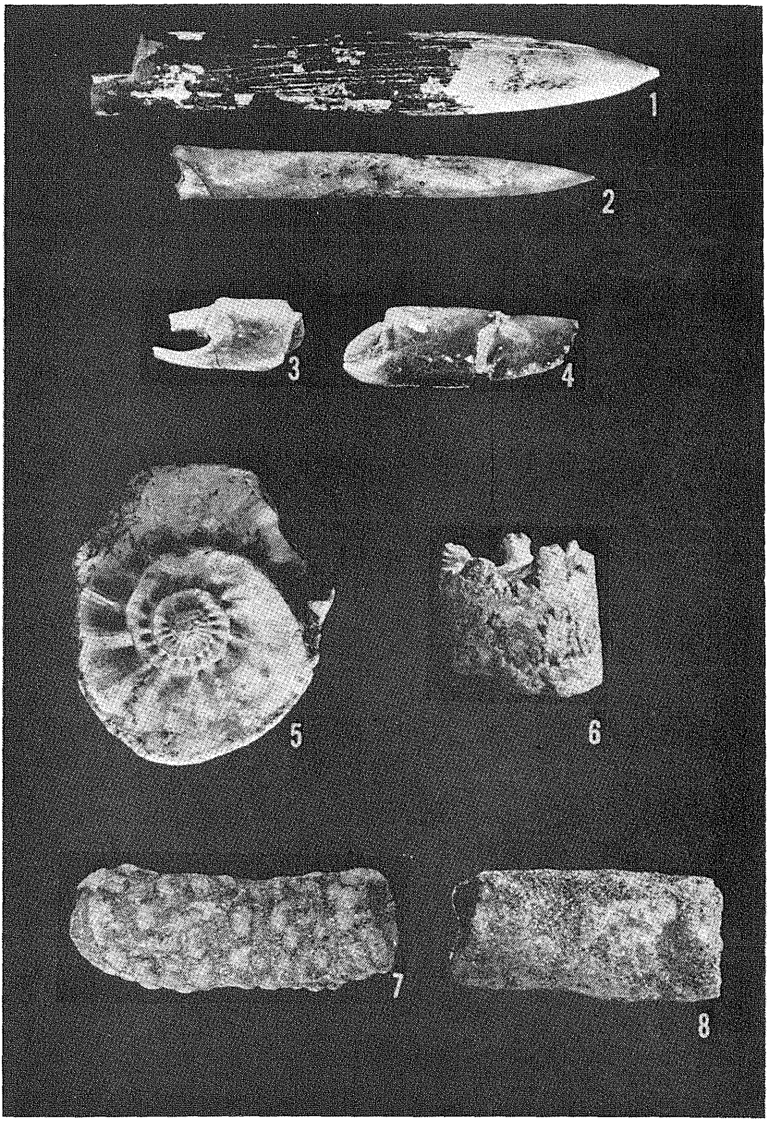
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PLATE 11
(All from Biggs Farm locality)

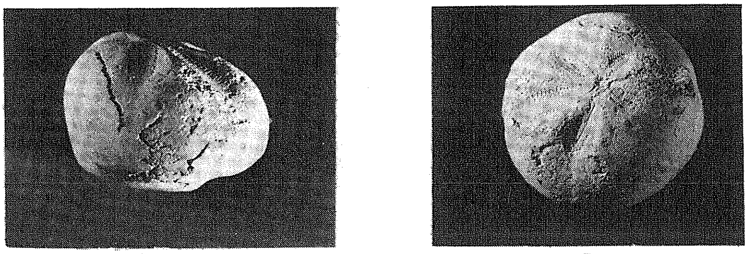
Figure

1 A, B. *Hemiaster* sp., echinoid, (X1.2).

2. *Serpula* sp., annelida?, (X4).

3. *Terebratulina cooperi* Richards and Shapiro n. sp., brachiopod, (X4).

4 A-L. *Terebratulina cooperi* Richards and Shapiro n. sp., brachiopod, growth series.



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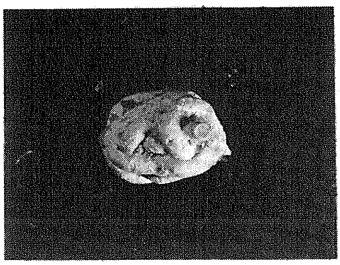

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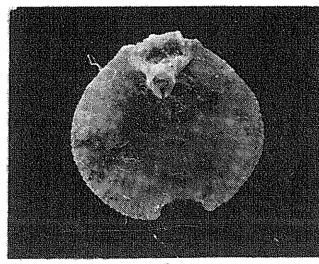

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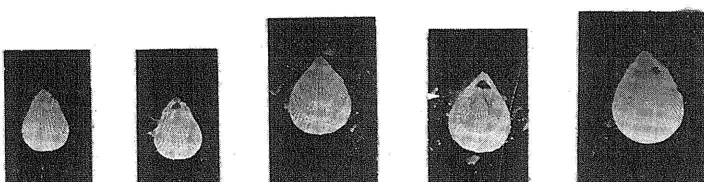

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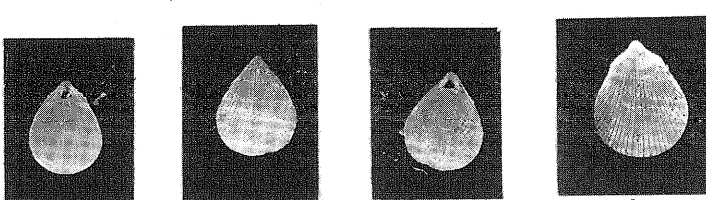

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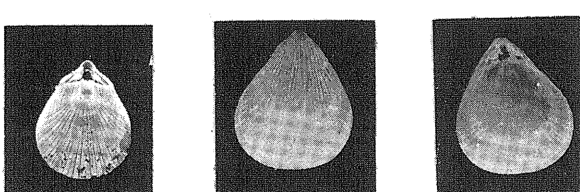

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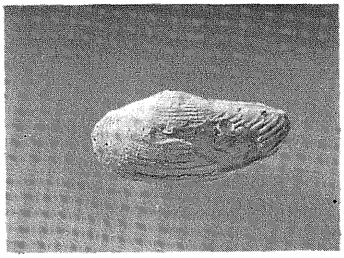
PLATE 12
(All from Biggs Farm locality; all pelecypods)

Figure

1. *Nuculana pittensis* (Stephenson), (X3).
2. *Nuculana stephensoni* Richards, (X2).
3. *Nemodon enfaulensis* (Gabb), (X2).
4. *Nemodon grandis Sohli* Richards and Shapiro n. subsp., (X2).
5. *Postligata crenata* Wade, (X2.2).
6. *Pteria* sp., (X2).
7. *Lucina parva* Stephenson, (X3).
8. *Protocardia parahillana* Wade, (X3).



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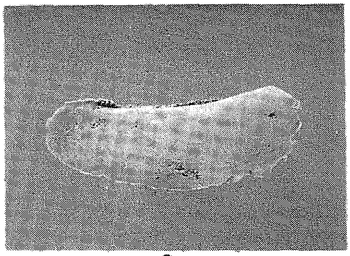

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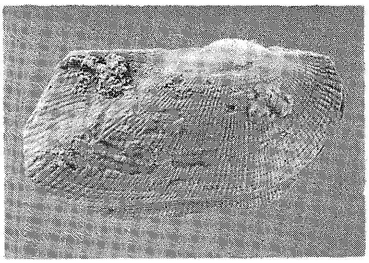

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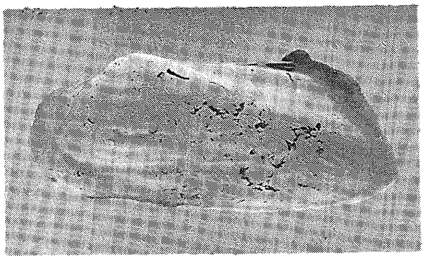

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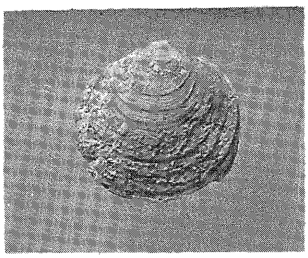

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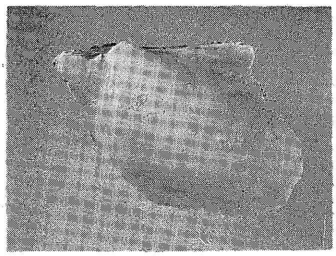

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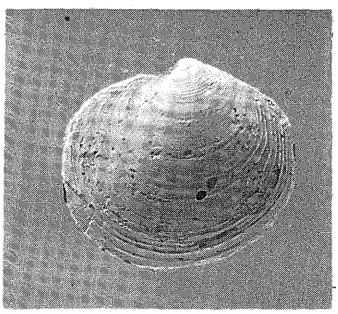

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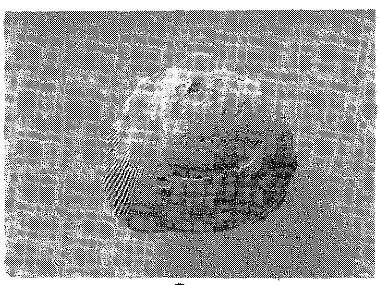


8

PLATE 13
(All from Biggs Farm locality; all pelecypods)

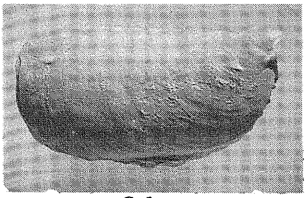
Figure

9 A, B. *Ostrea mesenterica?* Morton, (X1).

10. *Isocardia bulbosa* Stephenson, (X3).

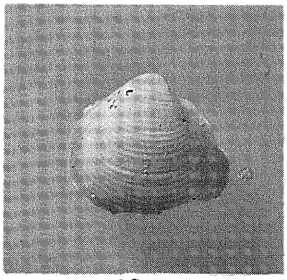
11. *Solyma* sp., (X2)

12 A, B. *Tellina georgiana* Gabb, (X2).



9A

9B



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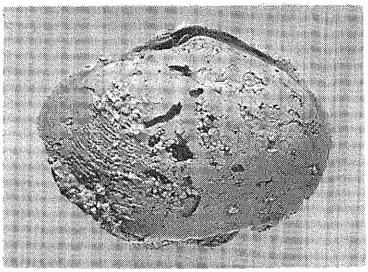

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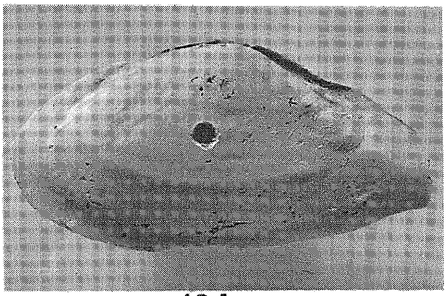
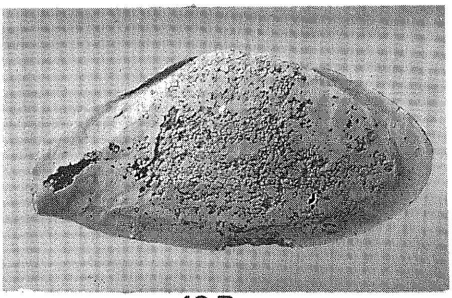


12A



12B

PLATE 14
(All from Biggs Farm locality; all gastropods)

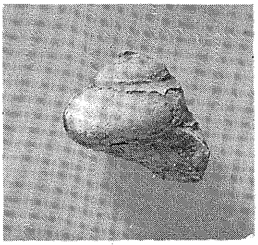
Figure

1 A-C. *Calliomphalus americanus* Wade, (X3).

2 A-C. *Calliomphalus nudus* Sohl, (X3).

3 A-C. *Margaritella* sp., (X3).

4 A, B. *Belliscala crideri* Stephenson, (X2).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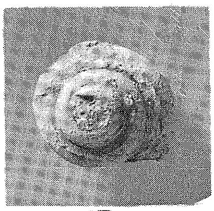
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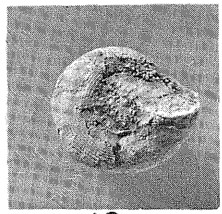
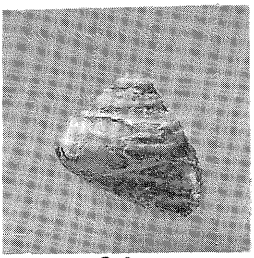

1C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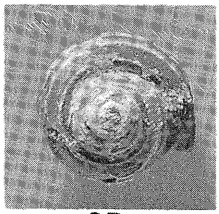
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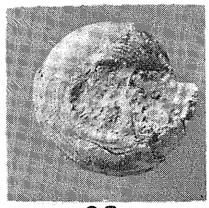
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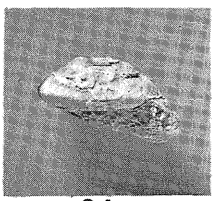
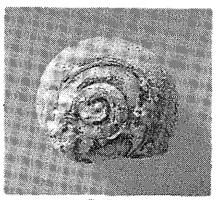

3A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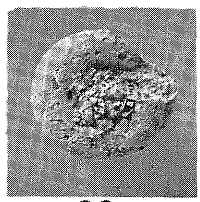
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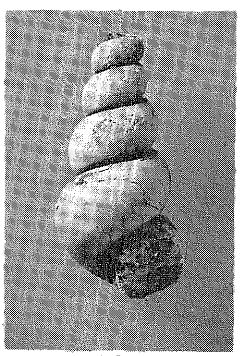
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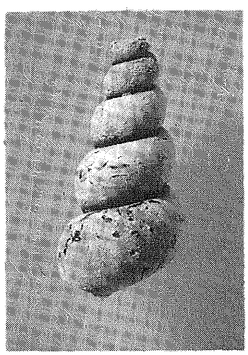
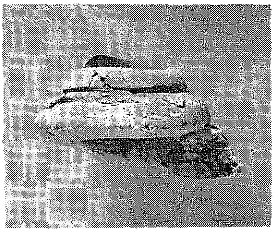

4B

PLATE 15
(All from Biggs Farm locality; all gastropods)

Figure

5 A-C. *Architectonica* cf. *A. voragiformis* Stephenson, (X2).

6 A-C. *Calliomphalus* sp., (X3).



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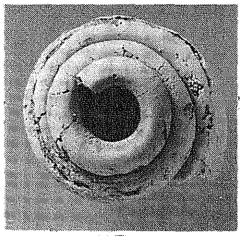

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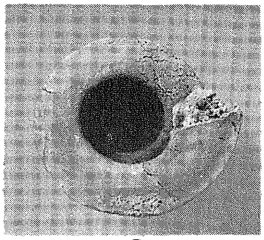

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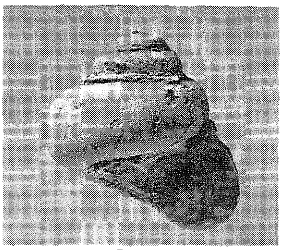

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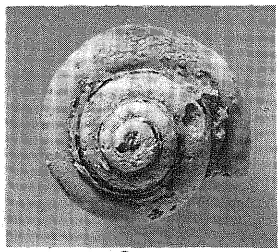

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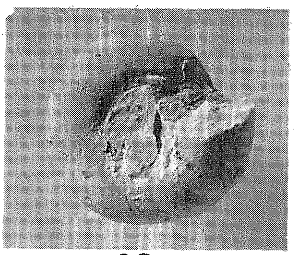


6C

PLATE 16
(All from Biggs Farm locality; all gastropods)

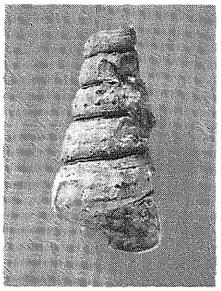
Figure

1 A, B. *Cerithium weeksi* Wade, (X3).

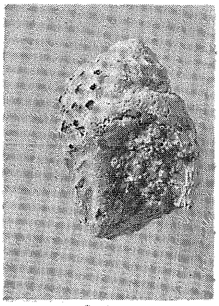
2 A, B. *Morea cancellaria corsicanensis* Stephenson, (X2).

3 A, B. *Acteon? throckmortoni* Stephenson, (X2).

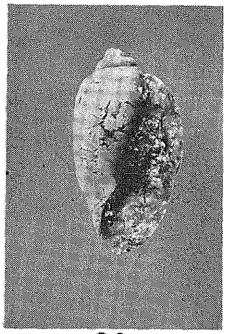
4 A-C. *Goniocylichna* sp., (X4.5).



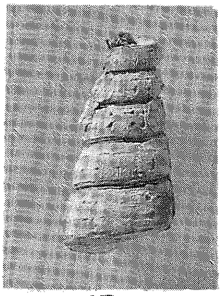
1A



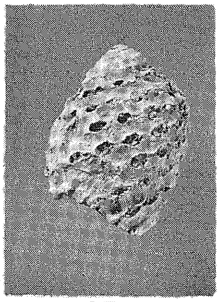
2A



3A



1B



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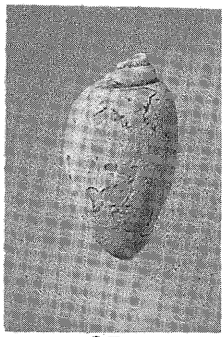

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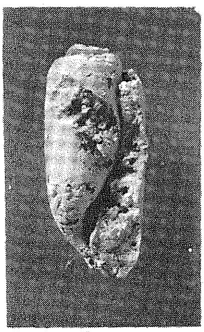
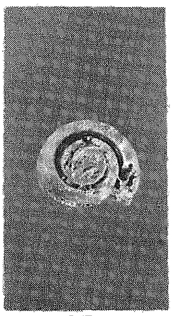
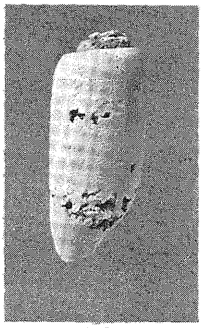


4A



4B



4C

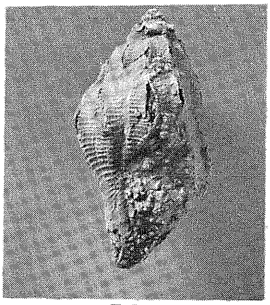
PLATE 17
(All from Biggs Farm locality; all gastropods)

Figure

5 A, B. *Rhombopsis marylandicus* (Gardner), (X2).

6 A-C. *Cypraea grooti* Richards and Shapiro, n. sp., (X2).

7 A-C. *Anisomyon jessupi* Richards and Shapiro n. sp., (X2).



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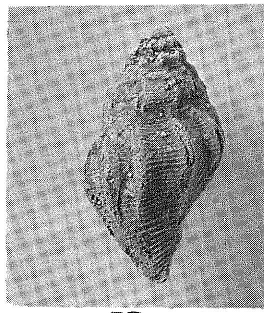

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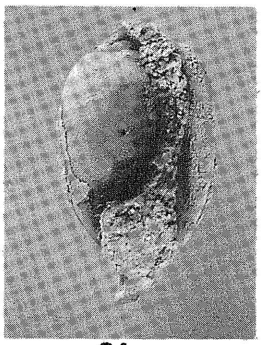

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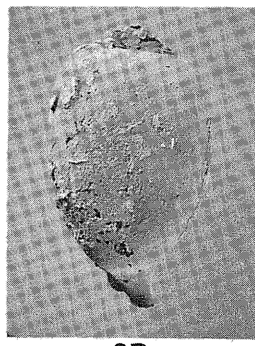

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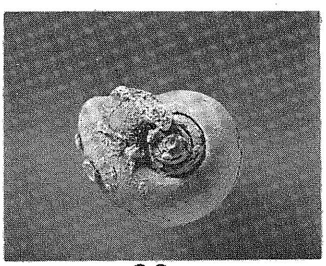

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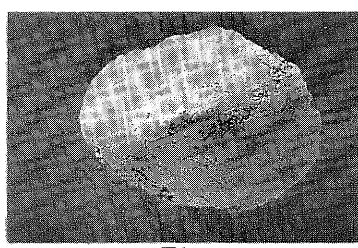

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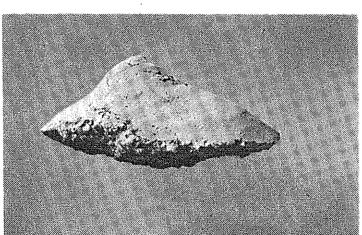

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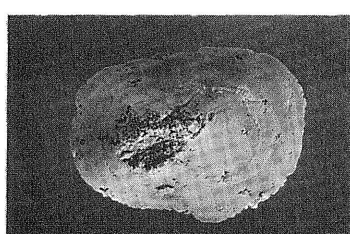

7C

PLATE 18

Figure

1.-4. Cretaceous burrows of a callianassid crustacean, Delaware; all X-1/2 except Figure 2, which is X-3/4.

5. Cretaceous cheliped of *Callianassa mortoni* Pilsbry, Mt. Laurel Formation, Delaware; X 2.

6. Living *Callianassa major* Say from Sapelo Island, Georgia.

7. Burrow exposure in Englishtown Formation at St. Georges, Delaware.

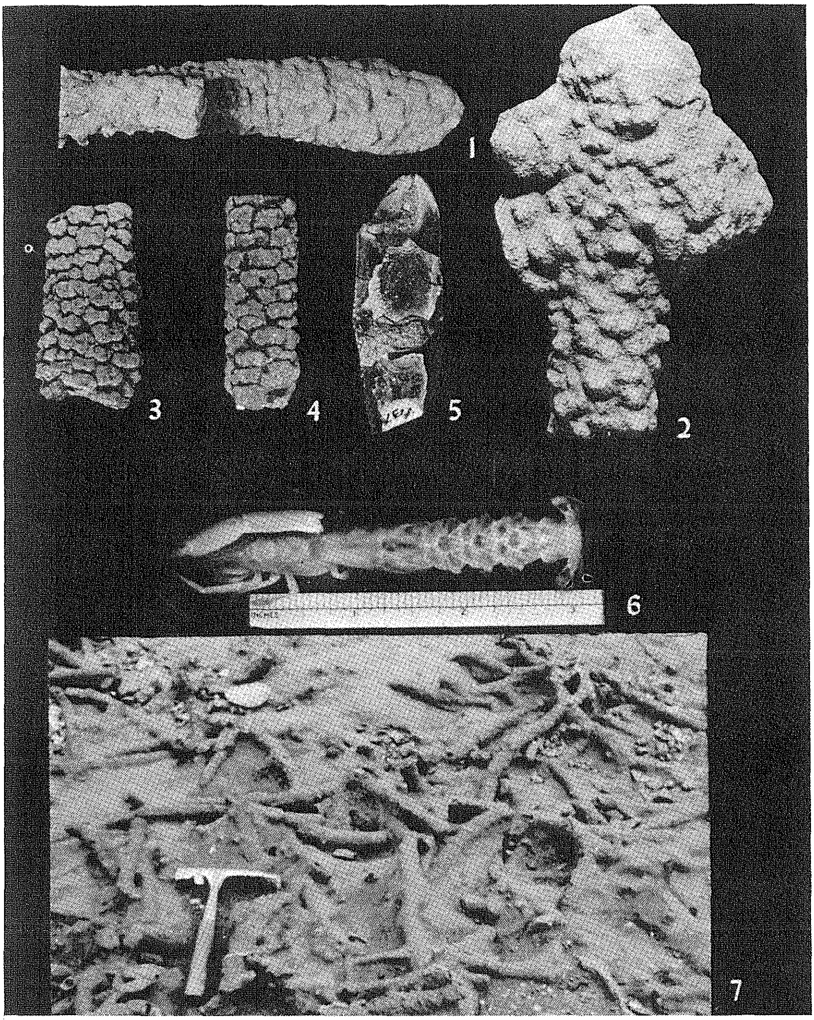
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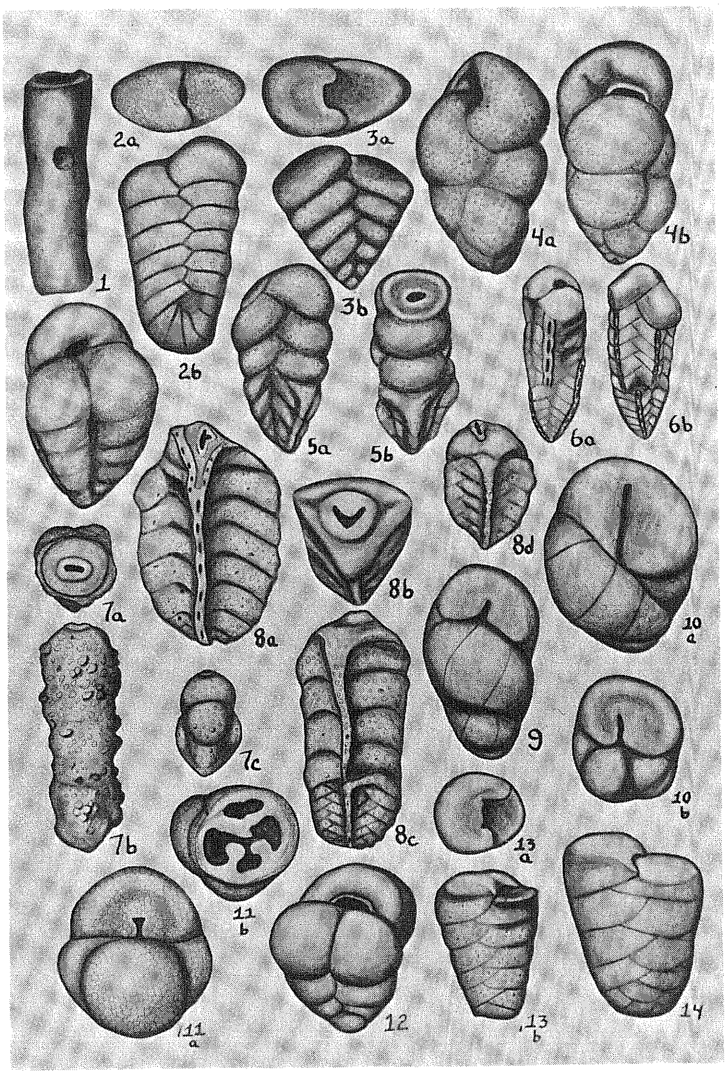
PLATE 19

Figure

1.	*Bathysiphon* cf. *B. alexander.* Cushman 50x.
2a-b.	*Spiroplectamina semicomplanata* (Carsey) x210
3a-b.	*Textularia* cf. *T. ripleyensis* W. Berry x120
4a-c.	*Gaudryina bulloides* Olsson x100, x 170
5a-b.	*Gaudryina monmouthensis* Olsson x100
6a-b.	*G. (Siphogaudryina) stephensoni* Cushman x60
7a-c.	*Pseudoclavulina clavata* (Cushman) x55
8a-d.	*Clavedinoides insignis* (Plummer) x30, x55
9.	*Arenobulimina footei* Jennings x145
10a-b.	*A. Americana* Cushman x140, x150
11a-b.	*Ataxophragmium beisseli* Cushman x115, x45
12.	*Eggerella Kurti* (Jennings) x135
13a-b.	*Marseonella oxycona* (Reuss) x55
14.	*M. Conica* Olsson x135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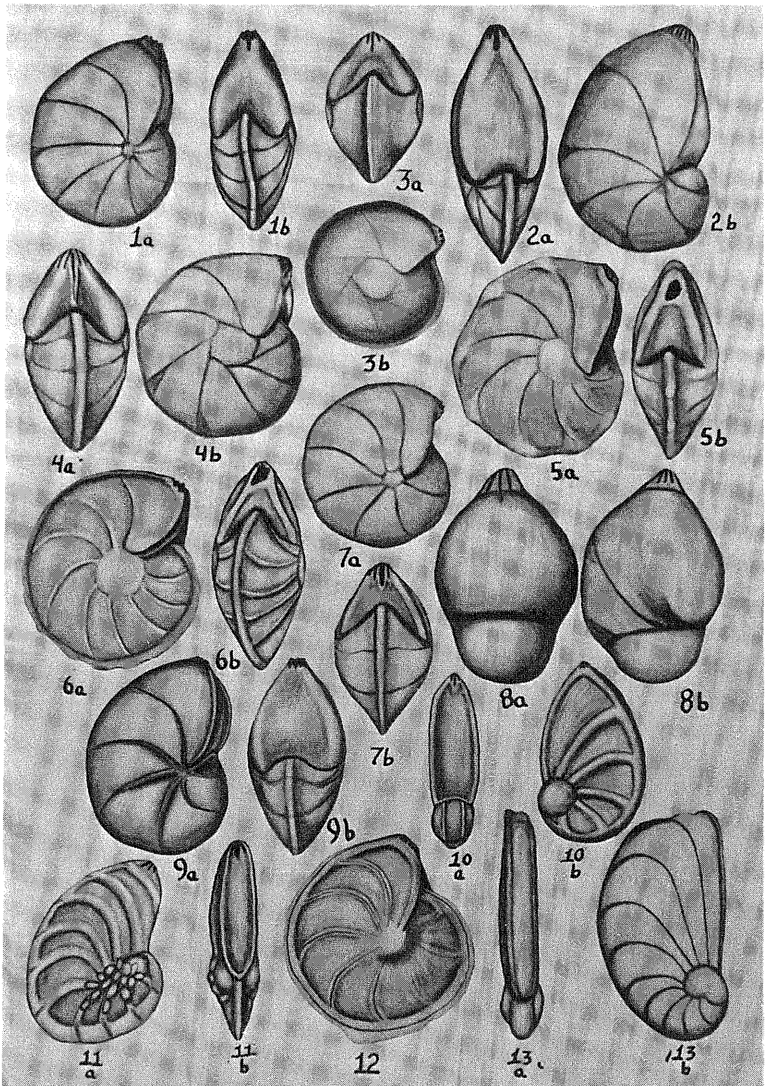
8c
8d
9
10 a
10 b
11 a
11 b
12
13 a
13 b
14

PLATE 20

Figure	
1a-b.	*Robulus aldrichi* Sandridge x50
2a-b.	*R. discrepans* (Reuss) x135
3a-b. 4a-b.	*R. macrodiscus* (Reuss) x65
5a-b.	*R. pondi* Cushman x40
6a-b.	*R. pendo-secans* Cushman x35
7a-b.	*R. pendo-secans* Cushman x35
8a-b.	*R. oligostegious* (Reuss) x155
9a-b.	*Lenticulina mavicula* (d'Orbigny) x70
10a-b.	*Planularia* sp. A. x180
11a-b.	*Planularia* sp. B x180
12.	*Robulus Munsteri* (Roemer) x125
13a-b.	*Planularia* sp. C x150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7b
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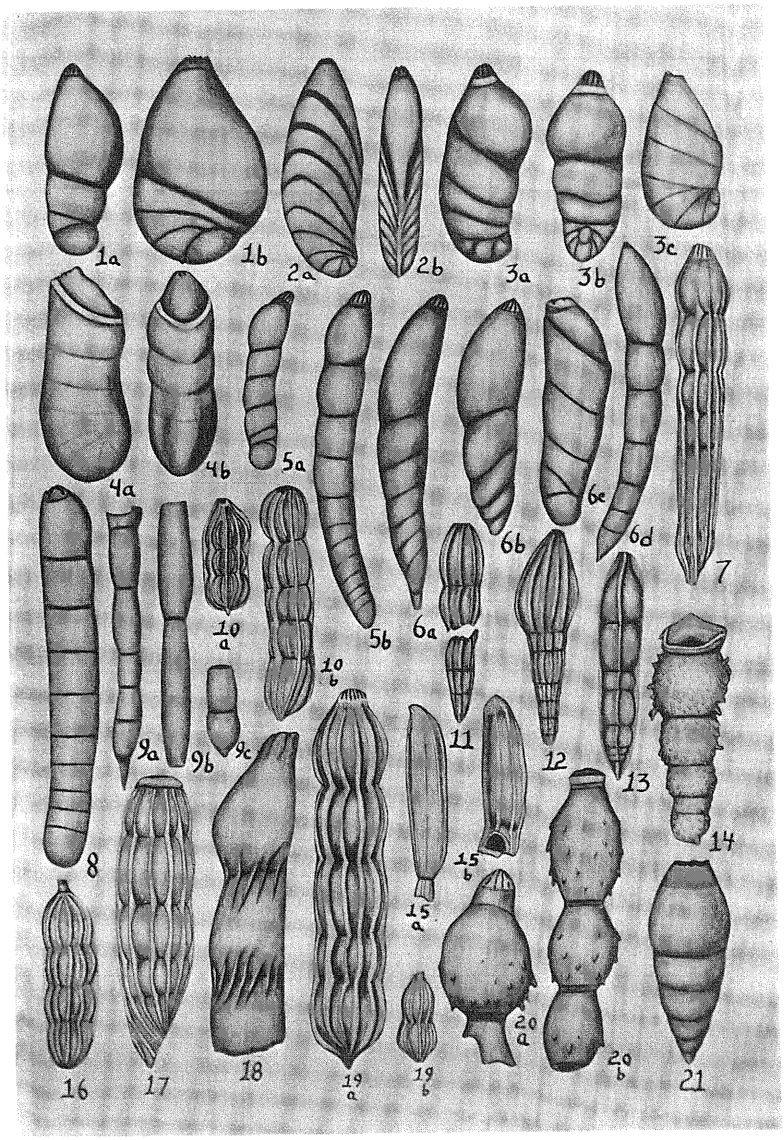
8b
9a
9b
10 a
10 b
11 a
11 b
12
13 a
13 b

PLATE 21

Figure	
1a-b.	*Marginulina bullata* Reuss x160
2a-b.	*M. cretacea* Cushman x95
3a-c.	*M. Texasensis* Cushman x50, x90
4a-b.	*M.* cf. *M. Texasensis* Cushman x115
5a-b.	*Dentalina basiplanata* Cushman x60, x25
6a-d.	*D. basitorta* Cushman x80, x100
7.	*D. confluens* Reuss x25
8.	*D. megalopolitana* Reuss x45
9a-c.	*D. consobrina* d'Orbigny x60
10a-b.	*D. alternata* (Jones) x60
11.	*Nodosaria alternistriata* Morrow x130
12.	*N. fusula* Reuss x135
13.	*N. navarroana* Cushman x105
14.	*N. Aspera* Reuss x60
15a-b.	*N. gracilitatis* Cushman x60
16.	*N. proboscidea* Reuss x100
17.	*N. obscura* Reuss x60
18.	*Dentalina solvata* Cushman x80
19a-b.	*Nodosaria affinis* Reuss x40
20.	*Chrysalogonium* sp. x100
21.	*Pseudoglandulina lagenoides* (Olszeuski) x105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9a
9b
9c
10 a
10 b
11
12
13
14
15 a
15 b
16
17
18
19 a
19 b
20 a
20 b
21

PLATE 22

Figure	
1a-b.	*Saracenaria triangularis* (d'Orbigny) x45
2a-b.	*Vaginulina* sp. A. x60, x85
3.	*Vaginulina* sp. A. x60, x85
4a-b.	*V. Taylorana* Cushman x30, x45
5.	*V. Taylorana* Cushman x30, x45
6.	*V. Wadei* Kelley x95
7a-b.	*Citharina multicostata* (Cushman) x50, x40
8. 9.	*Palmula suturalis* (Cushman) x45
10. 11.	*Frondicularia clarki* Bagg x45
12.	*F. Cuspidata* Cushman x65
13. 14.	*F. archiaciana* d'Orbigny x65
15.	*F. Cordata* Roemer x55
16.	*F.* sp. x95
17.	*Lagena sulcata semiinterrapta* W. Berry x440
18.	*L substriata* ? Williamson x140
19.	*L. lineata* (Williamson) x105
20.	*L. adepta* Jennings x100
21.	*L. amphora pancicostata* Franke x110
22.	*L. apiculata* Reuss x140
23.	*L.* cf. *L. globosa* Montagu x135
24.	*L. hispida* Reuss x130
25.	*L. acuticosta* Reuss x125
26.	*Bullapora laevis* (Sollas) x30
27.	*B. cylindrica n.* sp. x40 holotype

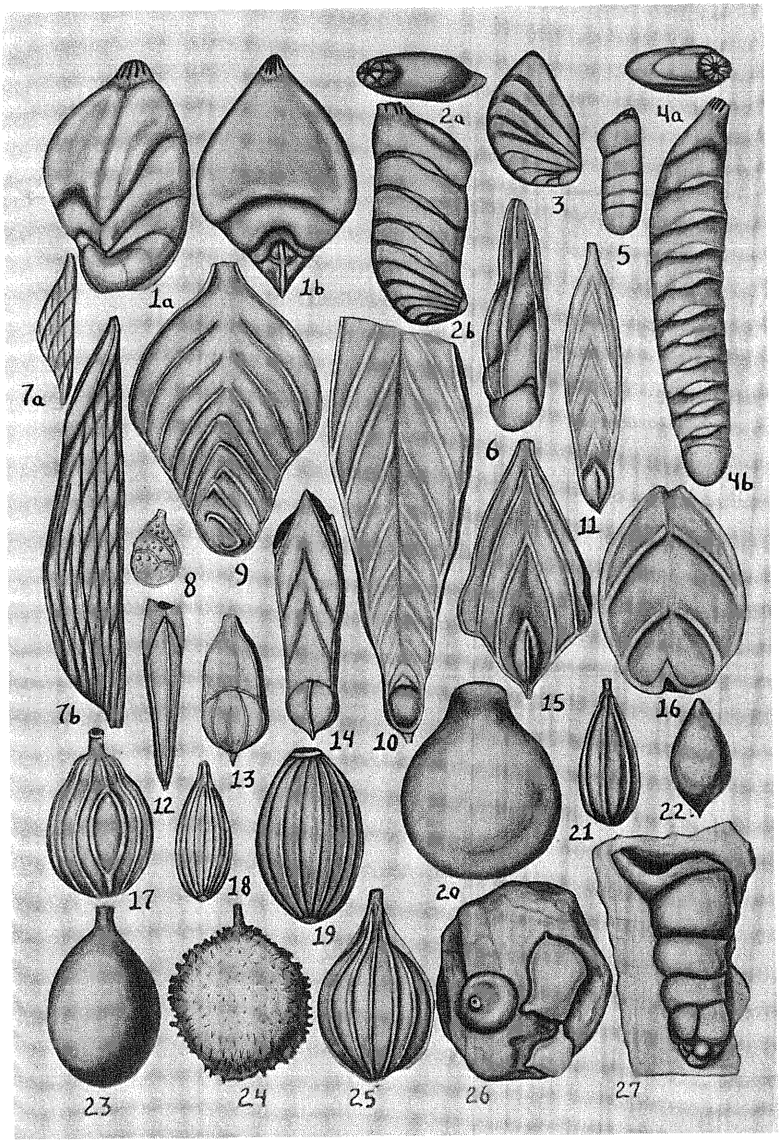
1a
1b
2a
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PLATE 23

Figure	
1a-b.	*Guttulina adhaerens* (Olszewski) x130
2a-b.	*G. problema* d'Orbigny x40
3a-b.	*Globulina lacrina* Reuss x80
4a-b.	*G. prisca* Reuss x100
5.	*G. lacrima subshaerica* (Berthelin) x135, x90
6a-c. (b)?	*G. lacrima subshaerica* (Berthelin) x135, x90
7a-b.	*Pyrulina gutta* d'Orbigny x45
8a-c.	*Sigmonorphina semitecta Aergueiana* (Fornasini) x135
9.	*Bolivinopsis rosula* (Ehrenberg) x100
10.	*Ramulina arhadephiana* Cushman x115
11.	*Globulina lacrina subspharica* (Berthelin) x120
12a-b.	*Nonionella cretacea* Cushman x160
13.	*Guembelitria cretacea* Cushman x180
14.	*Grienbetitria cretacea trangularis* n. subsp. x 180
15a-b.	*Hetrohelix globulosa* (Ehrenberg) x130
16a-b.	*H. globocarmata* (Cushman) x130
17a-b.	*H. ultimatumida* (White) x175
18a-b.	*H. navarroensis* Loeblich x175
19a-b.	*H. pseudotessera* (Cushman) x160

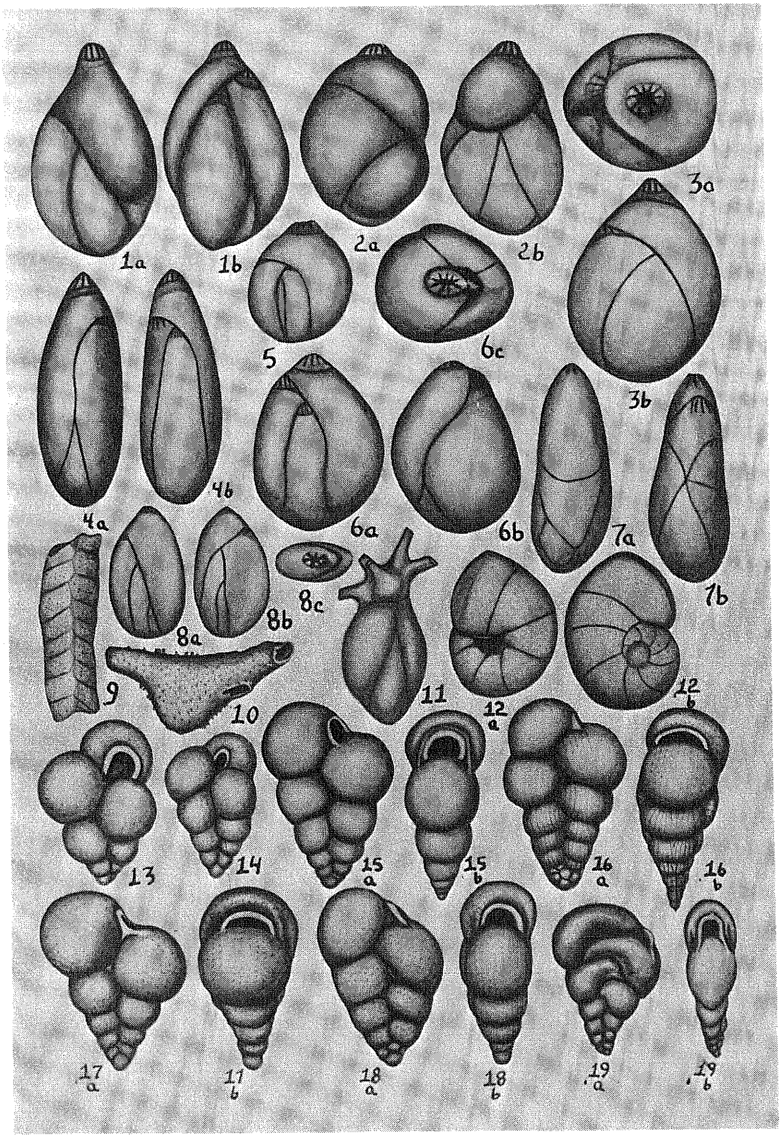
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PLATE 24

Figure

1a-b.	*H. Bulchra* (Brotzen) x140
2a-b.	*Psensloguenbelina costulata* (Cushman) x150
3a-b.	*P.* aff. *elegans* (Rzehak) x140
4a-b.	*Heterohelix striata* (Ehrenberg) x145
5a-b.	*Bolivinoides decoratus decoratus* (Jones) x85
6a-b.	*B.* cf. *B. praecursor* Reiss x140
7a-b.	*B.* cf. *B. pustulata* Reiss x140
8.	*Eouvigerina americana* Cushman x165
9.	*E. hispida* Cushman x200
10a-b.	*Bolitinitella eleyi* Cushman x160
11. 12.	*Bulliminella carseyal plana* Cushman & Parker x195, x170
13. 14.	*B. Carseyal* Plummer x200
15.	*Bulimina tortilis* Reuss x185
16. 17.	*B. prolixa* Cushman & Parker x185
18a-b.	*Buliminella vitrea* Cushman & Parker x190
19.	*B. Fabilis* Cushman & Parker x190
20. 21.	*Bulimina kickapooensis* Cole x80

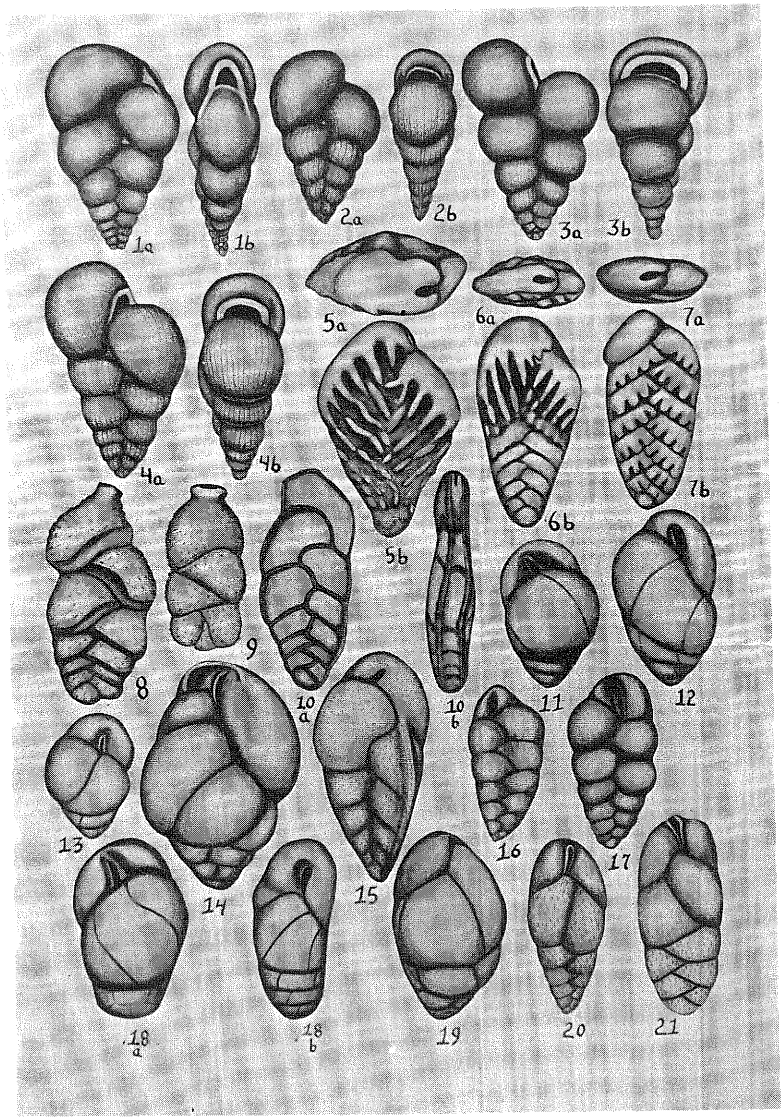
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PLATE 25

Figure

1-2.	*Bulimina reussi* Morrow x150
3.	*B. reussi navarroensis* Cushman & Parker x180
4-7.	*Niobulimina spinosa* Cushman & Parker x180
8a-b.	*Bulimina rudita* C&P x180
9-10.	*Niobulimina canadensis* Cushman & Wickenden x185
11a-b.	*Vingulina tegulata* Reuss x120
12a-13b.	*Vingulina delawarensis* n. sp. x250, 265
14a-b.	*Renssella delawarensis* n. sp. x135
15a-b.	*Entosolenia ordignyana* (Seguenza) x145
16a-b.	*E. marginata* (Walker & Boys) x190
17.	*Nodosarella monmouthensis* Olsson x180
18.	*N. Stephensoni* (Cushman) x115
19.	*N. alexanderi* (Cushman) x115
20a-22b.	*Bolivina cretosa* Cushman x165
23-24.	*Loxostona plaitum* (Carsey) x55
25-26.	*L. Gemmum* (Cushman) x55
27-28.	*Bolivina incrassata* Reuss x55
29.	*Nodosarella monmouthensis* x100

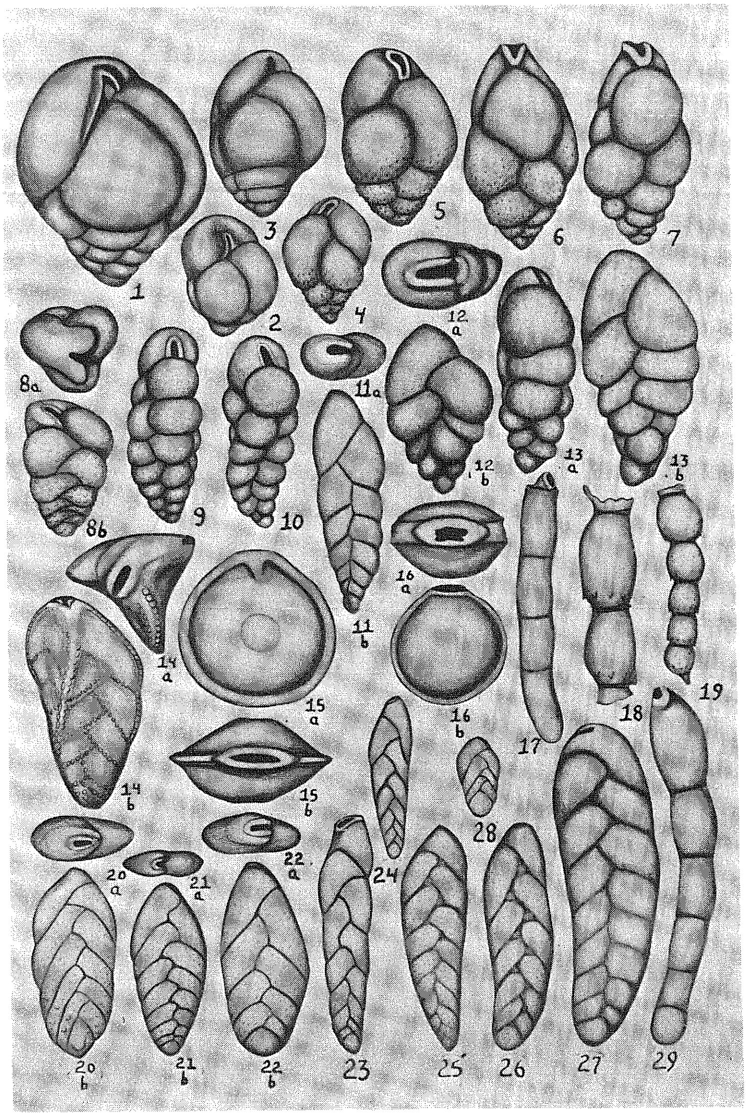
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PLATE 26

Figure

1a-c.	*Discorbis* cf. *D. amicers* Shifflett x165
2a-c.	*D.* cf. *D. baintoni* Mallory x190
3a-c.	*Quedrimorphina allomorphinoides* (Reuss) x130
4a-c.	*Valvulineria cretacea* (Carsey) x110
5a-c.	*V.* cf. *V. involuta* Cushman & Dusenbury x135
6a-c	*Gyroidina micheliniana* (d'Orbigny) x75
7a-c	*Gyroidinoides depressa* (Alth) x185
8a-c.	*Gyroidiona turgida* (von Hagenow) x120

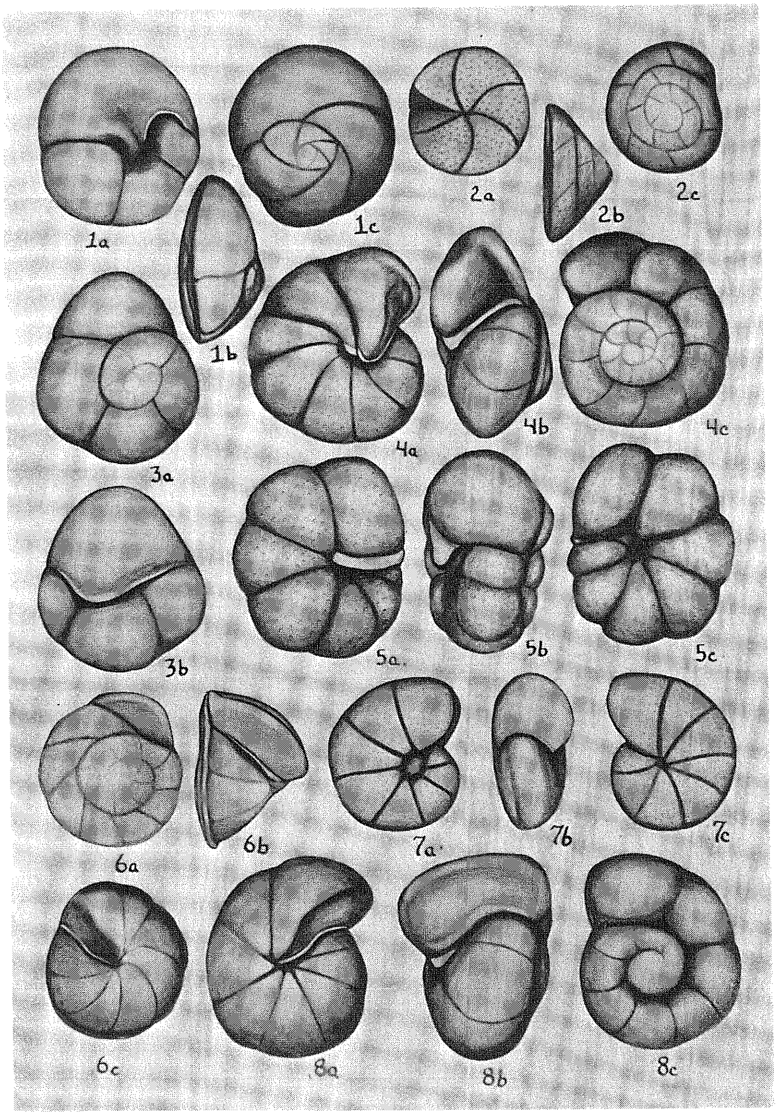
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PLATE 27

Figure

1a-c.	*Gyroidina nitida* (Reuss) x160
2a-c.	*Eponides* sp. x115
3a-c.	*Psendoparralla glabrata* (Cushman) x175
4a-c.	*P.* cf. *P. glabrata* (Cushman) x180
5.	*Allomorphina trochoides* (Reuss) x165
6a-b.	*Pullenia cretacea* (Cushman) x160
7a-b.	*P. americana* (Cushman) x160
8a-c.	*Anomalinoides pinguis* (Jennings) x80
9a-c.	*A. nelsoni* (W. Berry) x90
10a-c.	*Planolina nacatrochensis* (Cushman) x105

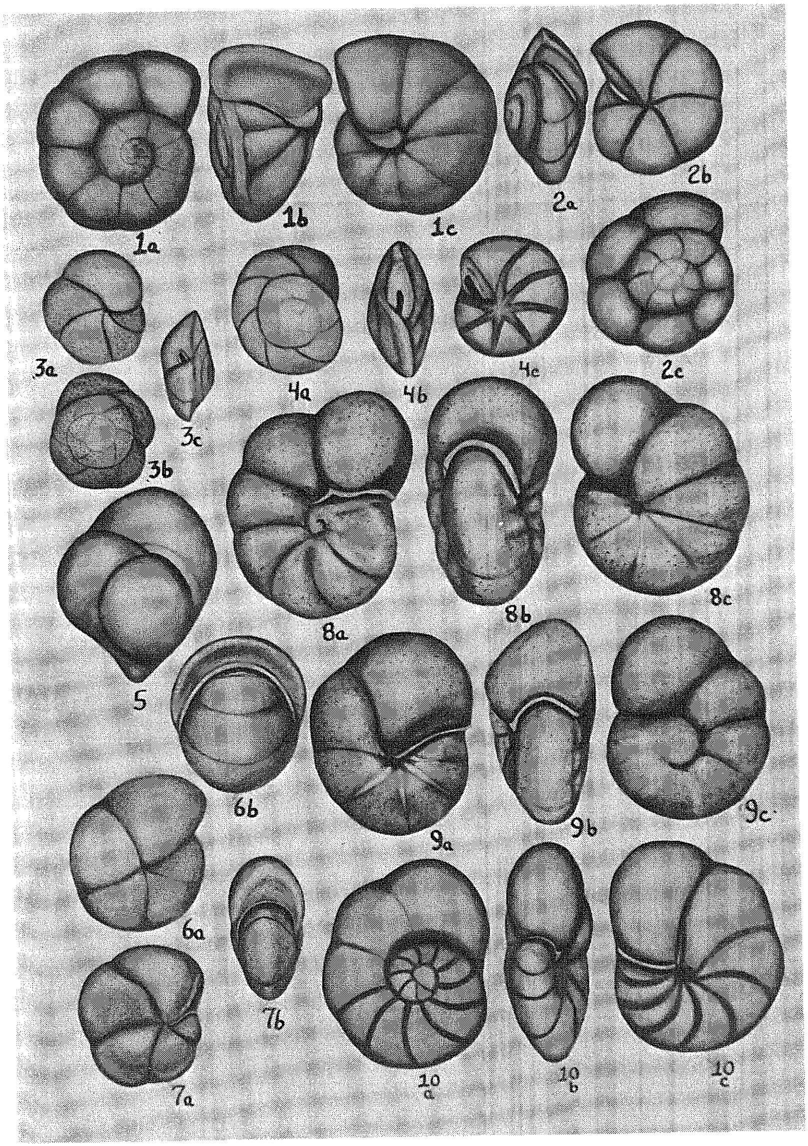
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PLATE 28

Figure

1a-c.	*Planulina taylorensis* (Carsey) x55
2a-4b.	*Planomalina escheri* (Kaufman) x140 "messinae" type 2a-b; "biforminata" stage of "escheri" type 3a-b, 8 chambered "escheri" type 4a-b.
5.	*Schachoina multispinata* (Cushman & Wickenden) x170
6a-c.	*Hedbergella delawarensis* n. sp. x200
7a-c.	*Globotruncana arca* area (Cushman) x90
8a-c., 9.	*Rugoglobigerina rugosa subrugosa* Gandolfi x120, x85

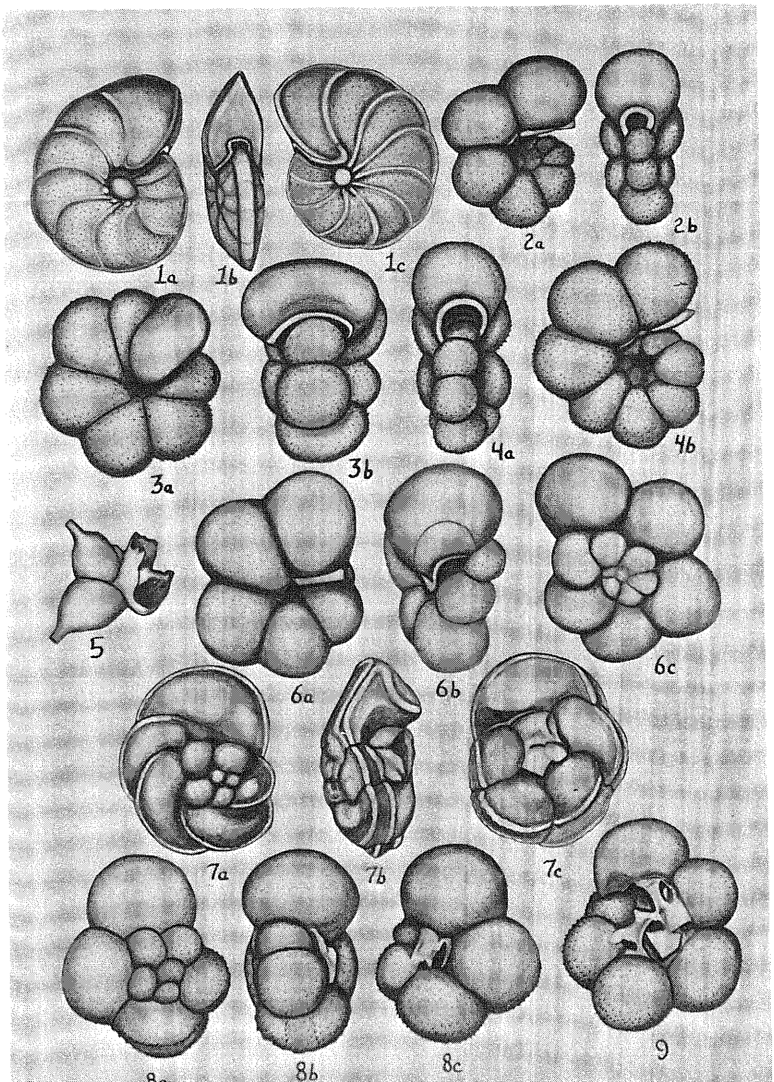
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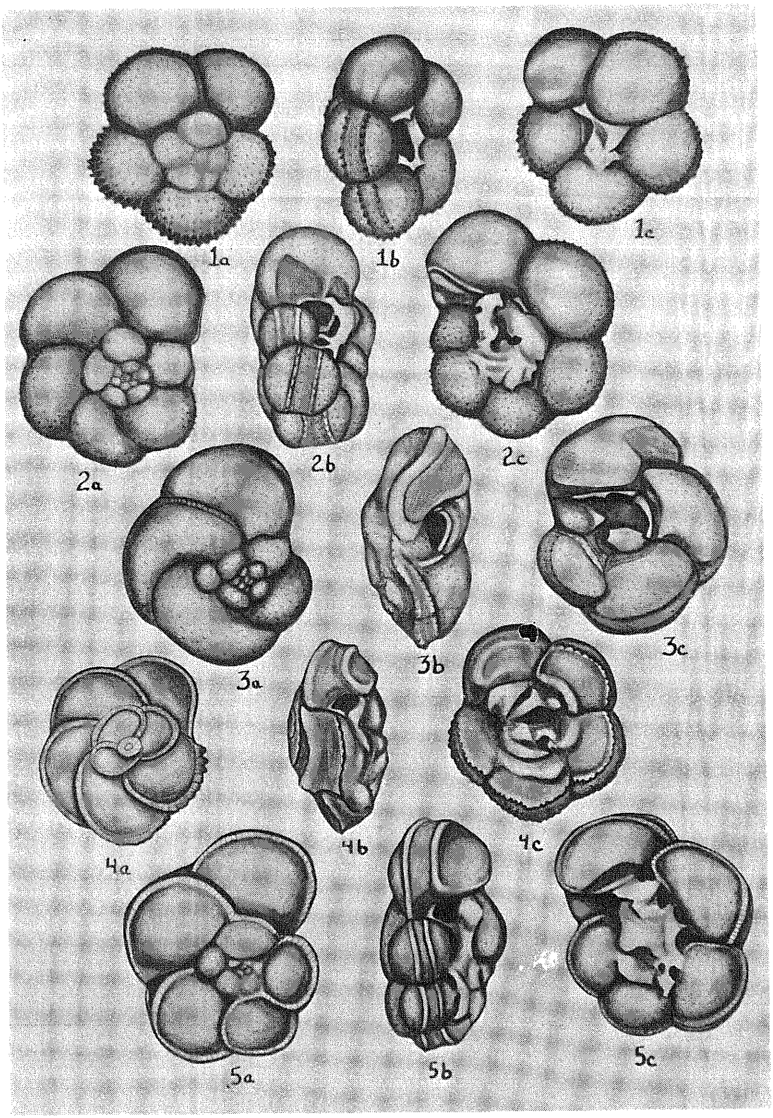
PLATE 29

Figure

1a-c.	*Globotrnucava bulloides* (Volger) x85 *(lapparenti)* propable misidentification
2a-c.	*G. mariei* Gandolfi x85
3a-c.	*G. fornicata fornicata* (Plummer) x90
4a-c.	*G. lapparenti tricarinata* (Quereau) x90
5a-c.	*G. ventricosa* (White) x90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Dr. Ronald J. Gibbs (College of Marine Studies): Marine Geochemistry, Continental Shelf Sediment Transport

Dr. Billy P. Glass (Geology Department, Joint appointment with College of Marine Studies): Tektites and Microtektites, Marine Geology

Dr. Robert R. Jordan (State Geologist and Director – Delaware Geological Survey, Geology Department, Joint appointment with College of Marine Studies): Sedimentary Petrology, Stratigraphy, and Structure of Atlantic Coastal Plain

Dr. John C. Kraft (Chairperson – Geology Department, Joint appointment with College of Marine Studies): Coastal Sedimentology, Geology as Applied to Archaeology

Dr. Peter B. Leavens (Geology Department): X-ray Crystallography, Systematic Mineralogy

Dr. Thomas E. Pickett (Delaware Geological Survey): Stratigraphy and Sedimentology, Structural Geology of Delaware

Dr. John H. Schuenemeyer (Department of Statistics and Computer Science): Geostatistics

Dr. Robert E. Sheridan (Geology Department, Joint appointment with College of Marine Studies): Marine Geophysics and Geology, Continental Margins

Dr. Frederick M. Swain (Geology Department, Joint appointment with College of Marine Studies): Micropaleontology, Organic Geochemistry

Mr. John H. Talley (Delaware Geological Survey): Hydrogeology, Subsurface Geology

Dr. Allan M. Thompson (Geology Department): Metamorphic Petrology of the Appalachian Piedmont, Sedimentology and Paleoenvironment Analysis

Dr. Robert D. Varrin (Director – Water Resources Center, Coordinator of Research University of Delaware, Joint appointment with Geology Department and Department of Civil Engineering): Hydrogeology, Geomorphology

Dr. John F. Wehmiller (Geology Department, Joint appointment with College of Marine Studies): Organic Geochemistry, Chemistry of Estuarine and Marsh Environments

Mr. Kenneth D. Woodruff (Delaware Geological Survey): Hydrogeology, Subsurface Geology

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