Structural and Stratigraphic Framework, and Spatial Distribution of Permeability of the Atlantic Coastal Plain, North Carolina to New York

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By PHILIP M. BROWN, JAMES A. MILLER, *and* FREDERICK M. SWAIN

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By Philip M. Brown, James A. Miller, and Frederick M. Swain

ABSTRACT

This report describes and interprets the results of a detailed subsurface mapping program undertaken in that part of the Atlantic Coastal Plain which extends from the South Carolina and North Carolina border through Long Island, N.Y. Data obtained from more than 2,200 wells are analyzed. Seventeen chronostratigraphic units are mapped in the subsurface. They range in age from Jurassic(?) to post-Miocene. The purpose of the mapping program was to determine the external and internal geometry of mappable chronostratigraphic units and to derive and construct a permeability-distribution network for each unit based upon contrasts in the textures and compositions of its contained sediments.

The report contains a structure map and a combined isopach, lithofacies, and permeability-distribution map for each of the chronostratigraphic units delineated in the subsurface. In addition, it contains a map of the top of the basement surface. These maps, together with 36 stratigraphic cross sections, present a three-dimensional view of the regional subsurface hydrogeology. They provide focal points of reference for a discussion of regional tectonics, structure, stratigraphy, and permeability distribution. Taken together and in chronologic sequence, the maps constitute a detailed sedimentary model, the first such model to be constructed for the middle Atlantic Coastal Plain.

The chronostratigraphic units mapped record a structural history dominated by lateral and vertical movement along a system of intersecting hinge zones. Taphrogeny, related to transcurrent faulting, is the dominant type of deformation that controlled the geometry of the sedimentary model.

Twelve of the seventeen chronostratigraphic units mapped have depositional alinements and thickening trends that are independent of the present-day configuration of the underlying basement surface. These 12 units, classified as genetically unrooted units, are assigned to a first-order tectonic stage. A structural model is proposed whose alinements of positive and negative structural features are accordant with the depositional geometry of the chronostratigraphic units assigned to this tectonic stage. The dominant features of the structural model are northeast-plunging half grabens arranged en echelon and bordered by northeast-plunging fault-block anticlines. Tension-type hinge zones that strike north lie athwart the half grabens.

Five of the seventeen chronostratigraphic units mapped have depositional alinements and thickening trends that are accordant with the present-day configuration of the underlying basement surface. These five units, classified as genetically rooted units, are assigned to a second-order tectonic stage. A structural model is proposed whose alinements of positive and negative features are accordant with the depositional geometry of the chronostratigraphic units assigned to this tectonic stage. The dominant feature of this model is a graben that stands tangential to southeast-plunging asymmetrical anticlines. Tension-type hinge zones that strike northeast lie athwart the graben.

To account for the semiperiodic realinement of structural features that has characterized the history of the region and as a working hypothesis, we propose that the dominant tectonic element, which is present in the area between north Florida and Long Island, N.Y., is a unit-structural block, a "basement" block, bounded by wrench-fault zones. We propose that forces derived principally from the rotation and precession of the earth act on the unit-structural block and deform it. Two tectonic models are proposed. One model is compatible with the structural and sedimentary geometries that are associated with chronostratigraphic units assigned to a first-order tectonic stage. It features tension-type hinge zones that strike north and shear-type hinge zones that strike northeast. The other model is compatible with the structural and sedimentary geometries associated with chronostratigraphic units assigned to a second-order tectonic stage. It features tension-type hinge zones that strike northeast and shear-type hinge zones that strike north.

Using a working concept of a fixed system of intersecting hinge zones, we conclude that the geometry of the regional structural-sedimentary system is associated predominantly with the action of lateral compressive forces, and that vertical forces operative in the region are chiefly the resultants of compressional stress. A geographic distribution of sedimentary troughs in the region studied is discussed, together with the nature of their boundaries and cross structures during each of the two tectonic stages.

The correlation framework established in this report utilizes both formally designated stratigraphic units and informally designated working units. The latter are identified by letter symbols (A–I). For each chronostratigraphic unit mapped, we include lithologic and biostratigraphic descriptions. Paleontologic data, chiefly the occurrence and distribution of Ostracoda recovered from well cuttings and cores, were used in the subsurface mapping. Ostracoda and Foraminifera that are characteristic of the units mapped in the subsurface are listed in the text and are identified on the stratigraphic cross sections. Type reference sections in the subsurface are designated for each of the chronostratigraphic units mapped.

The measured combined thickness for beds of sand, shale, and carbonate are computed as percentages of the total thickness of the chronostratigraphic interval in which they occur. Using these data, seven lithologic percentage categories (lithofacies), based upon textural and chemical composition, are established. These categories encompass the observed percentage variability in the vertical occurrence of sand, shale, and carbonate in the sediment mass within the report area. The delineation of the different categories by means of boundary lines and patterns drawn on an isopach map is used to construct a lithofacies map for each of the 17 chronostratigraphic units mapped.

Each lithofacies is assigned a number, ranging from 1 to 7, indicative of its comparative position on a scale of relative intrinsic-permeability lithology. The number 1 is assigned to a very high intrinsic-permeability lithology, whereas the number 7 is assigned to a very low intrinsic-permeability lithology. The numbers, together with the areal distribution of a lithofacies to which each number is assigned, constitute a permeability-distribution map for each of the 17 chronostratigraphic units mapped.

The series of combined isopach, lithofacies, and permeability-distribution maps, together with the series of structure-contour maps, illustrate the distribution of intrinsic permeability in that part of the Atlantic Coastal Plain which extends from the South Carolina and North Carolina border through Long Island, N.Y.

INTRODUCTION

Since 1890, the U.S. Geological Survey in cooperation with State, county, and municipal agencies, has conducted local and statewide water-resources investigations along the Atlantic coast. These investigations met a local or immediate need for water information. The need for regional appraisal of ground-water resources has been recognized by management groups who are concerned with the beneficial development, utilization, and conservation of ground water in the Atlantic Coastal Plain where the population density and the attendant demand for ground-water supplies are great and are increasing.

Accordingly, in 1964, as part of a Federal research program, the U.S. Geological Survey established a project for a comprehensive evaluation of the regional subsurface geologic framework of the Atlantic Coastal Plain in the area extending from New York to Florida. This geologic framework controls the flow and storage of water in the area's aquifer systems.

The specific objective of the evaluation, a stratigraphic analysis, was to determine lithologic variance, both areally and vertically, and to relate this variance to the regional distribution of intrinsic permeability. In hydrologic investigations, the purpose of stratigraphic analysis is to establish a relation between the tectonic and sedimentary histories of an area and the stratigraphic control of permeability at borehole monitor sites in order to extrapolate this tectonic-structural-sedimentary-hydrologic relation into areas where no boreholes exist.

The investigation entailed a geometric analysis of a complex sedimentary system. The broad objectives were:

1. To identify the tectonic elements of the region and to interpret them in terms of a sequence of structural development.
2. To delineate and interpret sedimentary environments, describe the external and internal geometry of sediments associated with these environments, and to relate these environments to a preferred structural position and orientation during successive stages in the structural evolution of the region.
3. To identify regional stratigraphic units in the subsurface, by means of examination and interpretation of well cuttings and cores and geophysical and micropaleontological data and to establish a correlation framework for these units.
4. To determine a distribution of intrinsic permeability based upon a distribution of sediment compositions and textures.

The shapes and lithic properties of sedimentary units, functions of their depositional origin, exert a paramount control on the movement and storage of ground water within sedimentary basins. Hydrologic predictability follows geologic predictability that is established by means of stratigraphic analysis. Stratigraphic analysis is a blending of the tectonic and sedimentary histories of an area, wherein an evolving structural architecture, which results from a combination of tectonic and erosional-depositional forces, must account for and be compatible with the positions and compositions of the sedimentary units that it produces and which it leaves behind as a record.

Both regionally and locally, sedimentary units of the Atlantic Coastal Plain comprise a system of loosely joined lenses, each of which has a characteristic shape, texture, and mineral composition.

The external form and internal characteristics of the sedimentary lenses are here referred to as their external and internal geometries. Their geometries are controlled by the relative positive and negative expression of adjacent segments of a source-depositional system that includes but transcends the boundaries of the Coastal Plain.

The external geometry of the lenses includes their shape, thickness, distribution, and preferred alinement in the sedimentary basin. Their internal geometry includes mineral composition, grain size and shape, degree of sorting, and lithologic continuity or variability.

The material in each lens has a characteristic intrinsic permeability determined by its sedimentational characteristics. The shape, distribution, thickness, and alinement of the various lenses determines the regional distribution of intrinsic permeability. *One basic assumption is that lenses derived from similar sources and deposited under similar geologic conditions will have similar internal geometry and, therefore, similar* *intrinsic permeability. A further assumption is that a similar distribution of like lenses of like form in different stratigraphic intervals will result in a similar distribution of intrinsic permeability in the different stratigraphic intervals.* Obviously, prediction of intrinsic permeability and its distribution within local or regional aquifer systems depends on first establishing the external and internal geometries of local and regional sedimentary units.

During successive stages in the Mesozoic and Cenozoic depositional cycle, certain shifts took place both in the distribution and orientation of sediment lenses that exhibit a similar shape, that have a similar textural and compositional character, and that are in different layers of the sediment mass. The pattern of these shifts appears to be rotational rather than linear in nature. The shifts appear to have taken place semiperiodically from at least Jurassic time to the present. The rotational-type shifts in distribution and orientation of similar sediment lenses in different layers of the sediment mass suggest a regional structural history characterized by block faulting that was accompanied by a semiperiodic realinement of positive and negative structural features. The regional distribution of sediments does not support the concept of semiperiodic uplift or subsidence of positive and negative structures that maintained a fixed alinement during Mesozoic and Cenozoic time.

Compilation and preliminary interpretation of the data for various segments of the project were made jointly or separately by the authors.

Philip M. Brown, research geologist, planned the project, directed the work, wrote the report, and is responsible for the final interpretations expressed.

James A. Miller, geologist, described well cuttings and cores, constructed strip logs for key wells, prepared the report illustrations, and conducted or supervised various aspects of the geophysical-logging and sample-analysis programs.

Frederick M. Swain, research geologist, studied and identified the Ostracoda from selected wells and prepared lists of faunal occurrence and charts of environmental significance that aided the mapping program.

Early in the project, Joel O. Kimrey, hydraulic engineer, compiled borehole geophysical data, organized interpretive geophysical aspects of project work, and made other important contributions.

Thomas G. Gibson, micropaleontologist, aided the mapping program by identifying Foraminifera of Tertiary age from selected well cuttings and by interpreting their stratigraphic and environmental significance.

LOCATION OF AREA

That part of the Atlantic coast which extends from southern Florida through Long Island, N.Y., is the area covered by the hydrogeologic study (fig. 1).

For purposes of convenience and in terms of its tectonic and sedimentary history, the area may be divided arbitrarily into a relatively stable southern segment, extending from Florida into North Carolina and characterized by argillaceous-calcareous sediments, and a more mobile northern segment, extending from North Carolina to Long Island, N.Y., and characterized by arenaceous-argillaceous sediments.

This report describes the structures, sedimentary rocks, and permeability distribution in the more mobile northern segment of the project area (fig. 1).

ACKNOWLEDGMENTS

Numerous organizations have contributed data and suggestions to the project that are gratefully acknowledged.

Among colleagues of the U.S. Geological Survey, Henry Barksdale, Robert Bennett, Thomas Gibson, Milton Hackett, C. L. McGuinness, and Raymond Nace were particularly helpful in either the organizational or interpretive phases of project work.

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Personnel from the U.S. Geological Survey provided well locations and helped to assemble well cuttings and geophysical logs. These included Harlan Counts and Stephen Herrick, Georgia; George Siple, South Carolina; George Bain, Edwin Floyd, and Glenn Wyrick, North Carolina; Robert Wait, Virginia; Elliott Cushing, Frederick Mack, Claire Richardson, Edmond Otton, and Walter White, Maryland; Harold Gill and Allen Sinnott, New Jersey; and Julian Soren and N. M. Perlmutter, New York.

State Geologists and members of their staffs contributed significantly to the project through the loan of well cuttings and cores for study in Raleigh, by furnishing location maps for well sites, and by furnishing geophysical data and logs and other information from their files. This group included: P. E. LaMoreaux, State Geologist, Alabama Geological Survey; R. O. Vernon, former Director, Florida Geological Survey; the late Garland Peyton, former Director, and A. S. Furcron, former Director, Georgia Department of

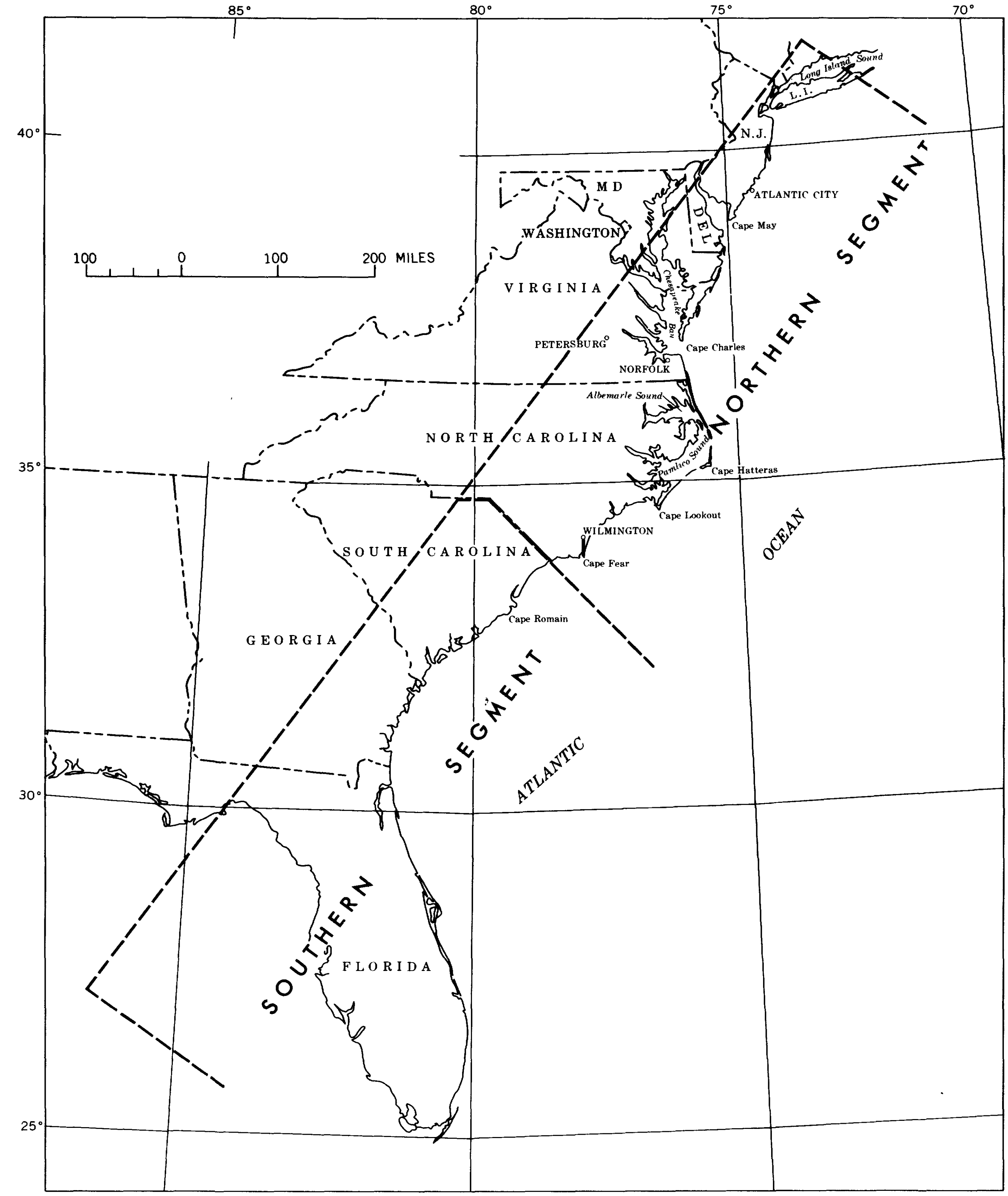

FIGURE 1.—Location map of the northern and southern segments of the project area and of the report area. The northern segment is described in this report.

Mines, Mining, and Geology; Henry Johnson, former State Geologist, South Carolina Development Board; Jasper Stuckey, former State Geologist, and Stephen Conrad, Director and State Geologist, office of Earth Resources, North Carolina; James L. Calver, Commissioner of Mineral Resources and State Geologist, Virginia Division of Mineral Resources; Kenneth N. Weaver, Director, Maryland Department of Geology, Mines, and Water Resources; Johann Groot, former State Geologist and Robert Jordan, State Geologist, Delaware Geological Survey; and Kemble Widmer, Director, New Jersey Department of Conservation and Economic Development.

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PREVIOUS WORK

Many ground-water reports, prepared by State and Federal agencies and published chiefly by State geological surveys, define and discuss the relation that exists between geologic systems and aquifer systems in States and local areas of the Atlantic Coastal Plain. No earlier attempts have been made to describe the Atlantic coast hydrogeologic system or any of its components as a regional unit.

Original accounts or reviews of the regional structure and subsurface stratigraphy of the Middle Atlantic States include publications by Richards (1945), Spangler and Peterson (1950), Murray (1961), and Maher (1965, 1971). In addition, many useful reports such as those of Cederstrom (1945), Anderson (1948), Spangler (1950), Swain (1951, 1952), Brown (1958), Jordan (1962), and Richards, Olmsted, and Ruhle (1962), discuss and interpret local structure and subsurface stratigraphy in the several States. Other reports are concerned primarily with geophysical interpretation of structure and sediment distribution for the continental shelf and adjacent areas of the Coastal Plain. From these reports, both general and specific concepts of regional structure and sediment-distribution patterns have evolved. Murray (1961) and Maher (1965, 1971) have reviewed, discussed, and illustrated these ideas in comprehensive detail. The concepts indicate a structural-sedimentary system whose geometry is controlled by vertical movement associated with tensional forces.

In a broad sense, the historical concepts suggest that a wedge of Mesozoic and Cenozoic sediments has accumulated on the shoreward limb of a northeast-southwest trending coastal geosyncline whose axis is well offshore (Kay, 1951, p. 82), and that the overall dip of the sediments is southeastward and roughly concordant with the slope of the precoastal basement surface upon which they rest. Published interpretations based upon geophysical data indicate that the general southeastward dip of the basement surface is locally reversed both on the Coastal Plain and the continental shelf and slope. (See U.S. Geological Survey and American Association of Petroleum Geologists, 1962).

Most authors believe that the Cape Fear arch and the Chesapeake-Delaware embayment, together with subsidiary structural warps that have a similar axial alinement (NW.-SE.), have had a cumulative controlling and (or) modifying effect on the type and distribution of Mesozoic and Cenozoic sediments as discussed by Murray (1961, p. 92-95). The long axes of these structures lie essentially normal to the axis of the geosyncline located well offshore.

On the emerged Coastal Plain, the maximum measured thickness of sediments is about 10,000 feet (3 km) in a well at Cape Hatteras, N.C. (Spangler, 1950, p. 105). In offshore parts of the Chesapeake-Delaware embayment, the thickness of sediments may exceed 20,000 feet (6 km) (Murray, 1961). According to Drake, Ewing, and Stockard (1968, p. 993-1010) sediments along the coastal margin beneath the continental shelf attain a thickness as great as 7 km (about 23,000 feet) in places, and beneath the continental rise they may attain a thickness as great as 10 km (about 33,000 feet).

Murray (1961, p. 93) described the composition of sediments along the Atlantic coast as follows:

> The Coahuilan(?), Comanchean, and Gulfian rocks are principally arenaceous-argillaceous; they vary from continental to marine. All contain a greater proportion of marine beds seaward. Lignitic materials are common adjuncts of these beds; glauconite is locally common in some. Tertiary strata include arenaceous, argillaceous, and calcareous facies. Glauconite and diatomaceous clay are predominant locally. Quaternary rocks consist of the usual unconsolidated arenaceous-argillaceous sediments with prominent graveliferous facies.

Murray (1961) provided a knowledgeable up-to-date review and analysis of pertinent geologic data and of its various interpretations in the Atlantic province.

His summations of the regional geologic framework also are accompanied by either stated or implied summations of the need for additional geologic data and interpretation. As he pointed out, in order to compare geologic events in one part of the region with those in another, it is necessary to establish regional chronostratigraphic units [1] within a framework of structural and tectonic credibility.

PURPOSE OF THIS REPORT

This report presents the results of a stratigraphic analysis in which 17 regional chronostratigraphic units were mapped in the subsurface to aid the discussion of regional tectonics, structure, stratigraphy, and hydrology.

In a stratigraphic analysis of this type, structural and tectonic interpretations do not follow a stratigraphic interpretation. They accompany it. As the various segments of the sedimentary model are constructed and pieced together, structural and tectonic interpretations are developed and tested concomitantly. The test is do they account for and are they compatible with the incomplete sedimentary model. Some interpretations are retained whereas others are rejected during the testing process. The testing process continues until the sedimentary model is complete and a mutually satisfying empirical relation is established between the sediment model, regional structural patterns, and a tectonic hypothesis.

Because of the complex nature of this mutually satisfying empirical relation in the report area and the need for establishing conceptual clarity in defining the relation, the three basic elements of the stratigraphic analysis are presented so that the discussions of the tectonic hypothesis and the structural framework precede the discussion of the stratigraphic model against which they were tested. Also, because our descriptive analysis of the basic geometry of the structural-sedimentary system includes new applications of geologic concepts, we have repeated some elements of the analysis in more than one part of the text. This should help to establish conceptual clarity about the empirical relation between tectonics, structure, sedimentation, and intrinsic permeability as they pertain to different facets of the analysis of a prototype tectonic area, the first of its kind to be documented.

The first segment of this report is an analysis of the regional structural architecture. Subsequent segments of the report include analyses of the stratigraphic framework, the spatial arrangement of sediments within that framework, and the regional distribution of intrinsic permeability as a function of lithologic variability. Schematic diagrams, geologic cross sections, structure-contour maps, isopach maps, lineisolith maps, and permeability-distribution maps provide focal points for the analysis and the discussion.

Stage names used in this report are from other sources.

[1] "A chronostratigraphic unit is a body of rock strata which is unified by representing the rocks formed during a specific interval of geologic time." International Subcommission on Stratigraphic Terminology (1960, p. 23).

STRUCTURAL ARCHITECTURE

INTRODUCTION

The Coastal Plain of the Middle Atlantic States is part of a large area of accumulation for Mesozoic and Cenozoic sediments in eastern North America. These sediments overlie in part the eastern flank of the Appalachian structural province. The post-Triassic sediments comprise a wedge-shaped mass that thickens seaward. Any valid discussion of the structural architecture of the area must account for and be compatible with the internal framework of the sediment wedge as well as with its external form. Previously published discussions of the regional structural architecture and hydrogeologic framework were based on the concept that the internal framework of the wedge mirrored its external form and that the wedge developed in response to vertical movements associated with gravity tectonism. This concept requires considerable modification according to our analysis of the internal framework of the sediment mass in the area that extends from Long Island, N.Y., through North Carolina.

In terms of both its structural and stratigraphic components, certain interpretive elements of the structural architecture of the depositional area bordering the Atlantic coast must be speculative and conjectural for two primary reasons:

1. The diastrophic forces that produce the structural architecture lie within, or are transmitted by, the earth's crust or mantle. The origin of the forces is speculative.
2. The time-space configurations of the structural architecture must be inferred and interpreted from incomplete sedimentary records.

Although discussion of the structural architecture must be partly speculative and must be limited by the observed sedimentary geometry, such discussion helps to frame the interrelations which exist between structural growth, sedimentary environments, the texture and composition of sediments, and the geologic control of ground-water flow and storage systems.

The post-Paleozoic structural and sedimentary geometries of the middle Atlantic Coastal Plain generally have been thought to be controlled or at least influenced in some manner by northwest to southeast-trending Paleozoic structural salients and recesses of the Appalachians (Murray, 1961, p. 91). Regional structural features such as the Cape Fear arch and the Chesapeake-Delaware embayment, which have their counterparts in Appalachian salients and recesses respectively, and which have northwest- to southeast-trending axes, are thought to have occupied fixed positions throughout Mesozoic and Cenozoic time. Epeirogenic movements, characterized by a mild overall subsidence, have been thought to dominate the coastal margin. Our analysis, which is based on delineation of the external and internal geometries of stratigraphic intervals that constitute the regional sediment mass, differs from these traditional ideas. From the differing alinements and internal character exhibited by different stratigraphic intervals within the regional sedimentary mass, we infer that a recurrent realinement or rotation of the axes of positive and negative structural features has occurred in the region semiperiodically. We conclude that the recurrent realinement was associated with three phases of crustal deformation that followed each other in predictable order. Phase 1 was succeeded by phase 2, phase 2 by phase 3, and phase 3 finally by phase 1 as a new series of crustal deformations was initiated. In phase 1, the axes of positive structural features (fault-block anticlines) and of adjacent negative structural features (half grabens) lie parallel to each other and are alined northeast-southwest. (fig. 2*A*). In phase 2, the axes of parallel positive structural features (compressional anticlines) and of adjacent negative features (compressional synclines) are alined northwest-southeast (fig. 2*B*). In phase 3, the axes of positive structural features (compressional anticlines) and of adjacent negative features (grabens) diverge; the axes of the positive features are alined northwest-southeast, whereas those of the adjacent negative features are alined north-south and north-northwest to south-southeast as shown in figure 2*C*.

Twelve of the seventeen stratigraphic sequences mapped are related genetically to phase 1 of crustal deformation, which is designated as the predominant or first-order tectonic stage. These 12 stratigraphic sequences have common depositional alinements with common patterns of depositional thickening and thinning, independent of the present configuration of the basement surface upon which they are superimposed.

Five of the seventeen stratigraphic intervals are related genetically to both phase 2 and phase 3 of crustal deformation, which when combined are designated as the subordinate or second-order tectonic stage. These five stratigraphic intervals have common depositional alinements, common patterns of depositional thickening and thinning, and are accordant with the present configuration of the basement surface upon which they are superimposed.

The stratigraphic sequences of the first-order tectonic stage (table 1) range from Jurassic to late Miocene in age. Their depositional geometry is not accordant with the present configuration of the basement surface upon which they are superimposed. Therefore, they are genetically unrooted with respect to the configuration of the present basement surface. The stratigraphic sequences of the second-order tectonic stage (table 1) range from Cretaceous and Jurassic(?) to post-Miocene in age. Their depositional geometry is accordant with the present configuration of the basement surface upon which they are superimposed. Therefore, they are genetically rooted with respect to the configuration of the present basement surface.

TABLE 1.—*The stratigraphic intervals and the structural alinements associated genetically with the first-order and second-order tectonic stages*

Associated stratigraphic units		
First-order tectonic stage	Second-order tectonic stage	
12 units: Rocks of late Miocene age, of Oligocene age, of Claiborne Age, of Sabine Age, of Midway Age, rocks of Cretaceous age composing Units A, B, C, D, E, and F, and rocks of Jurassic(?) age composing Unit I.	5 units: Rocks of post-Miocene age, of middle Miocene age, of Jackson Age, rocks of Cretaceous age, composing Unit G, and rocks of Cretaceous and Jurassic (?) age composing Unit H.	
Structural alinements at time of deposition		
First-order tectonic stage	Second-order tectonic stage	
	Prerupture phase of deformation	*Rupture phase of deformation*
Positive axes: NE.–SW., plunge NE. Negative axes: NE.–SW., plunge NE. Axes of adjacent positive and negative features are parallel. Directions of shear: Master shear set: NW.–SE. Complementary shear set: NE.–SW. Direction of tension: N.–S.	Anticlinal axes: NW.–SE., plunge SE. Synclinal axes: NW.–SE., plunge SE. Axes of adjacent positive and negative features are parallel. Direction of shear: Not developed. Direction of tension: Not developed.	Anticlinal axes: NW.–SE., plunge SE., and are residual from the prerupture phase of deformation. Trough axes: General N.–S., plunge S. Axes of adjacent positive and negative areas are tangential. Direction of shear: N.–S. Direction of tension: NE.–SW.

The presence of and the alternate manner of occurrence of both rooted and unrooted depositional se-

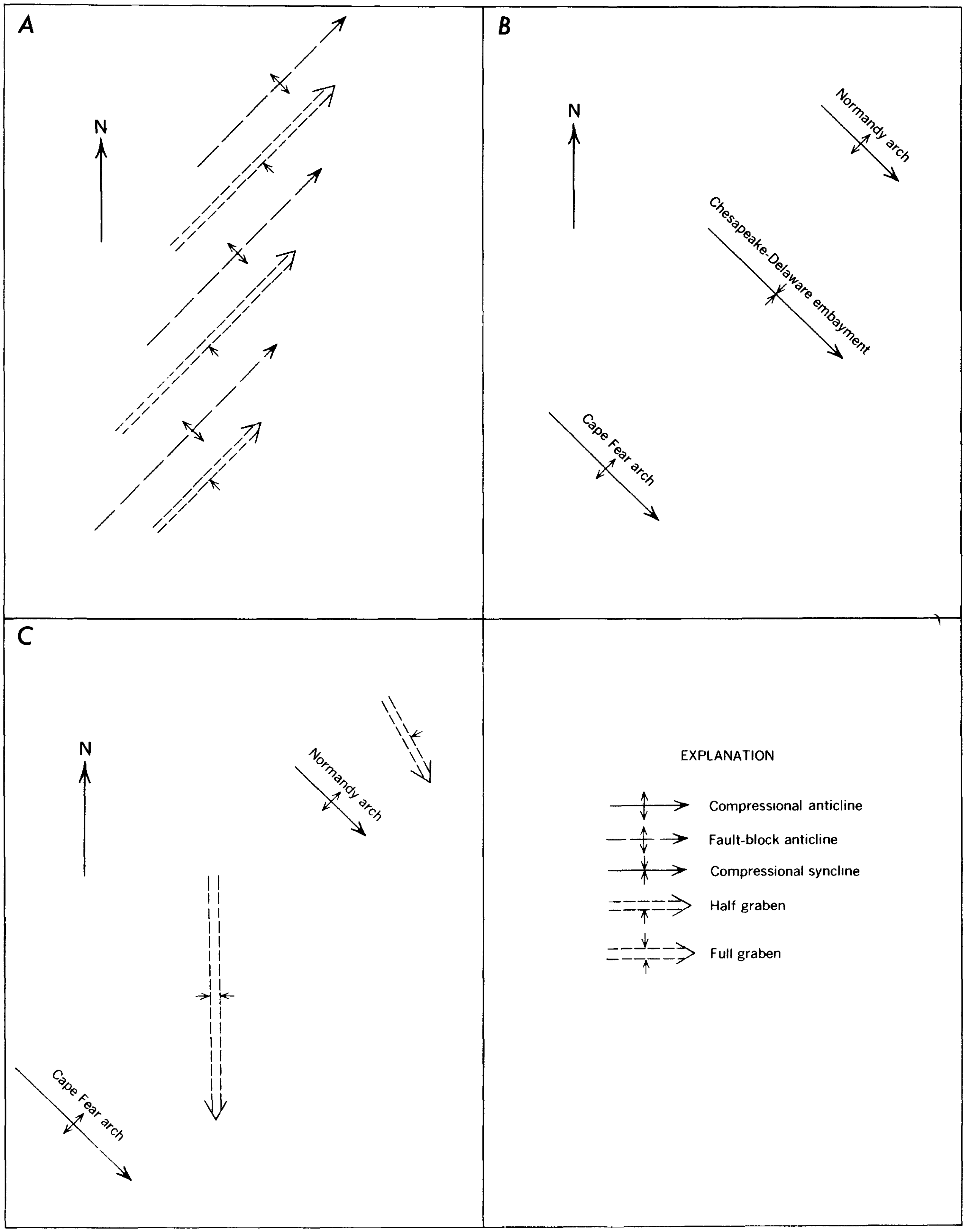


FIGURE 2.—Schematic diagram showing the alinements for positive and negative structural features that are associated genetically with each of the three phases of crustal deformation recognized in the report area. *A*. Phase 1. *B*. Phase 2. *C*. Phase 3.

quences in a stratigraphic succession of Mesozoic and Cenozoic age are not compatible with prevailing opinion that the geometric shape of the individual layers of the sediment wedge mirror its external form. The recurrent realinement (rotation) of positive and negative structural features, that are on a regionally subsiding basement surface and whose presence is inferred partly from sediment distribution patterns, is not compatible with the opinion that tensional forces alone control deformation of the Coastal Plain.

We conclude that the geometry of the regional structural-sedimentary system is associated predominantly with the action of lateral compressional forces and that the vertical forces operative in the region are chiefly the resultants of compressional stress. Using various lines of evidence, that are derived principally from the study and interpretation of elements that comprise a sedimentary model (pls. 6–59) and from the relation between the sedimentary model and extant structures, we discuss the factors that have led us to the conclusion that the Atlantic Coastal Margin is a region of fault-trough deposits and is a segment of a taphrogenic province.

GENERAL DISCUSSION

The east coast of the United States between southern New England and Florida generally is considered a segment of an active Mesozoic and Cenozoic coastal geosyncline. The geosyncline has been described as a tensional province that extends for some 4,000 miles from north of the Island of Newfoundland to British Honduras in Central America (Murray, 1961). Traditionally, the segment between southern New England and Florida is considered a less mobile or less actively subsiding segment of the geosyncline than the Gulf-coast segment from Texas to Florida (Durham and Murray, 1967).

The concept of the tectonically active coastal geosyncline, assumes that various loci of subsidence have existed within or below the basement of the geosyncline itself and that, on balance, subsidence has been progressive seaward and has been accompanied by a progressive tilt seaward of parts of the coastal margin. With reference to the Gulf segment, Murray (1961) points out that the shift of depocenters in time and space comprises a complex pattern. The pattern described by Murray and associated with semiperiodic cyclic progressions and regressions includes lateral as well as gulfward shifts of depocenters. The pattern is quite variable spatially, more so in the region from East Texas to Mexico than in the region from East Texas to Alabama. In a subsiding system of this type and in the restrictive but broad regional sense, the respective directions, upbasin and downbasin, would be expected to remain relatively constant during progressive tilt seaward of parts of the coastal margin. As time-successive hingebelts (Weeks, 1959, p. 370) or axes of tilt developed, they generally shifted seaward as the loci of geosynclinal subsidence shifted seaward. Younger strata deposited on the tilted surface exhibit directions of stratigraphic strike and dip generally in accord with those of older strata deposited on the same tilted surface.

The interpretation of the geologic framework of the southern New England to Florida segment of the geosyncline has been not so much a product of investigation within the segment as it has been a product of the investigation of the adjacent Gulf segment. The Gulf segment has served as a type geosynclinal segment or model that has been used in a comparative sense to interpret the geology of the east-coast segment. This comparative relation is useful, but it constitutes an inertia of tradition that has inhibited independent interpretation of the east-coast segment of the geosyncline on the basis of its own geology.

The Gulf-coast segment of the geosyncline is structurally complex. Many detailed accounts of its structural complexities have been published but, as pointed out by Rainwater (1968, p. 125), its tectonic framework is not understood. The segment contains several generations of gravity-fault zones or flexure systems which mostly are considered to have developed in conjunction with the progressive downwarping of the coastal margin. These zones or systems comprise discontinuous segments of varying length that have arcuate to linear trends. An example would be the Mexia-Talco and related perimetrical faults (Durham and Murray, 1967). Where fault systems of different ages are present in a given area, the younger generally lie seaward from and virtually parallel to the older (Murray, 1961). This results in a series of characteristic and progressively younger steplike descents into the basin. This series of descents extends from the landward margin of the basin toward offshore loci of subsidence. Commonly, flexing or faulting is down-to-the-coast. Locally, faulting may be up-to-the-coast, and the steplike descent from the land toward the coast reversed.

Steplike descents from the land toward offshore areas in the Gulf segment are marked by the development of fault or flexure systems and the slumping of large blocks of sediment. No such phenomena are noted on the Atlantic coast. Only a moderate steepening of the basement slope, where it lies below about 5,000 feet, has been recognized on the Atlantic coast (Murray, 1961). The absence of steplike descents into an offshore area has led to the idea that a predominant unidirectional slope has existed on the Atlantic coast from post-Triassic time to the present, and that, historically, vertical movements in the region have been mild and intermittent. As an extension of this idea, the concept of gently dipping beds overlying a gently sloping basement surface has been illustrated by many writers, such as Anderson (1951, fig. 123) and Heezen, Tharp, and Ewing (1959, fig. 22). See figure 3. This stratigraphic concept is the basic concept common to both geologic and geophysical interpretations of the sedimentary framework of the Coastal Plain and contiguous offshore areas.

To summarize, prior interpretations of the geology of the Atlantic Coastal Plain generally have been based on one or more of the following assumptions: (1) that regional Mesozoic and Cenozoic structural expression has been controlled by gravity dominated deformation, (2) that the axes of positive and negative regional structures are parallel and have maintained a general northwest-southeast alinement, (3) that sedimentary alinements are accordant with the present-day regional structure, (4) that as regional subsidence progressed positive features, such as the Cape Fear Arch (Clark and others, 1912), were uplifted intermittently and negative features, such as the Chesapeake-Delaware embayment (Murray, 1961), were downwarped intermittently, (5) that the area's geologic units are thin on the positive areas and comparatively thick within the negative areas, and (6) that, in response to the intermittent regional tilt of the coastal margin toward the southeast, a sedimentary wedge was formed whose individual stratigraphic units mirrored its external form by striking northeast and by dipping gently and thickening evenly to the southeast.

Our regional analysis of sediment types and of their distribution patterns and orientations is not compatible with the foregoing. Instead, our sedimentary analysis indicates that the coastal margin is a margin where the principal mobility takes the form of block faulting or flexing, accompanied by a rotational realinement of the axes of positive and negative structures in the region, and occurring in conjunction with the initiation of differential rates of relative subsidence for crustal segments that are juxtaposed along elements of an intersecting hingebelt system, the components of which have one of three principal alinements (NE.–SW., NW.–SE., or N.–S.). Though the differential subsidence of adjacent segments of the Atlantic Coastal Plain, presumably due to flexing or faulting, has long been recognized (Murray, 1961, p. 92), there is no documentation to indicate that it took place at different rates and at different times along axes which intersect or that it was accompanied by a semiperiodic realinement of the axes of positive and negative structural features.

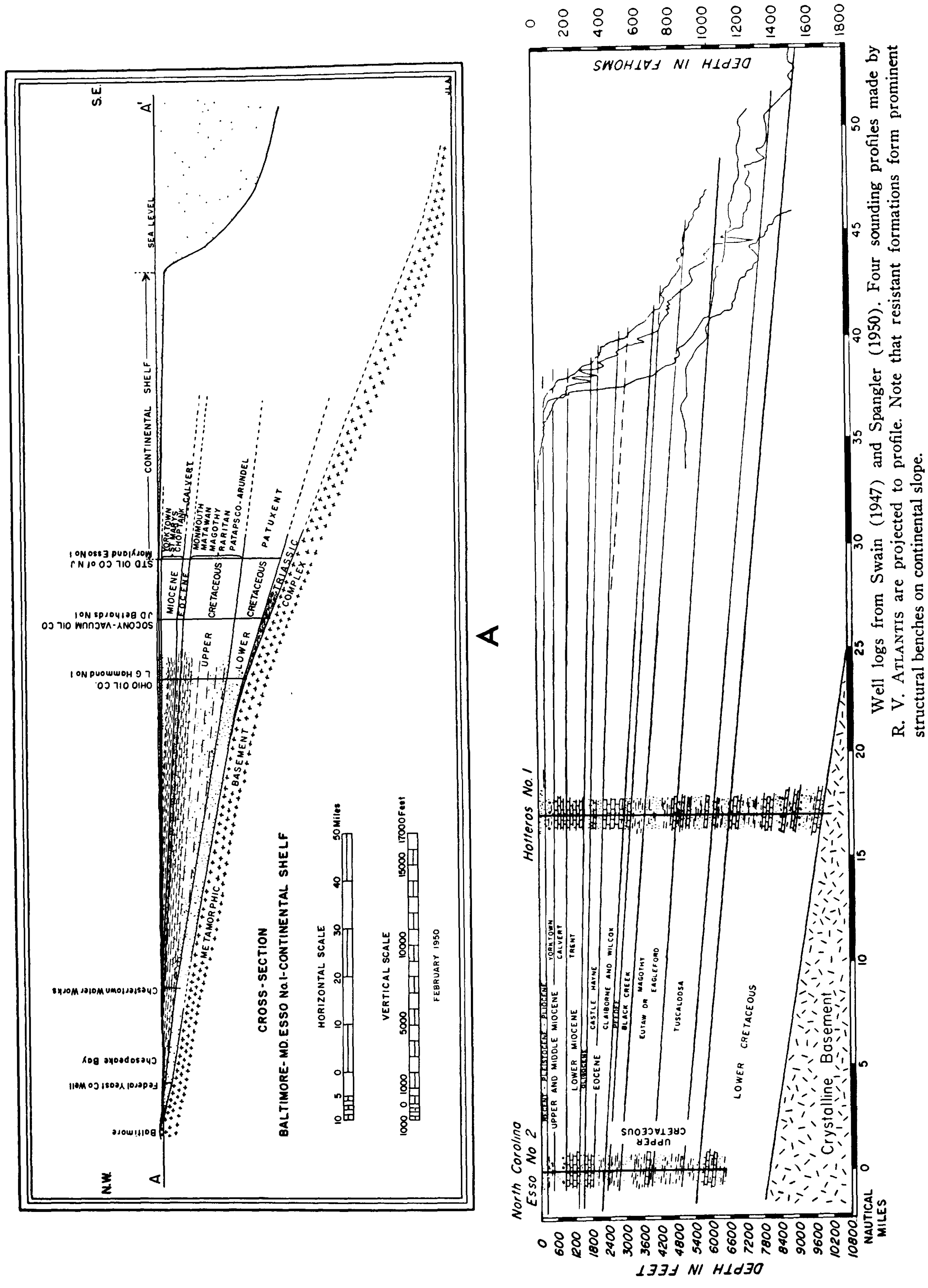
According to regional sediment distribution patterns, the semiperiodic realinement of the positive and negative structural fabric of the region was accompanied by major shifts in the direction of sediment flow. Associated with these shifts were significant changes in the directions of sediment thickening and of lithic continuity within successively deposited layers that comprise the regional sediment mass.

As a consequence of realinement of positive and negative structural features, two types of stratigraphic units are present in the Coastal Plain today—those with and those without genetic structural roots in the present-day configuration of the basement surface. Of the 17 stratigraphic units mapped in the report area, five of the units are rooted and 12 of the units are unrooted. Primary stratigraphic components (such as strike, dip, direction of maximum thickening, facies alinement, and lithic variability) of the rooted units generally are not accordant with those of the unrooted units.

In order to accommodate the distribution and the composition of both the rooted and unrooted stratigraphic units that we have mapped, we suggest that a type of wrench-fault tectonic framework, characterized by the development of fault troughs, has controlled the structural-sedimentary character of the coastal margin of the eastern United States between Florida and Long Island, N.Y., from at least Jurassic time to the present. The dominant forces in this tectonic framework are thought to be lateral compressive forces which have resultant and subordinate vertical components. They act in combination with gravitational forces. As suggested and discussed by Moody and Hill (1956) and Moody (1966), it is a reasonable speculation that the lateral compressive forces implicit in the hypothesis of wrench faulting are derived from the rotation and precession of the earth.

STRUCTURAL CONFIGURATION OF THE COASTAL MARGIN

Among recent publications, those of Drake, Ewing, and Sutton (1959), Drake, Ewing, and Stockard (1968), Murray (1961), Maher (1965, 1971), Durham and Murray (1967), and others have introduced or traced the development of current ideas about the structural configuration of the Atlantic Coastal Plain and Continental Shelf region of the eastern United States. These ideas constitute a loosely integrated genetic meld. It is associated in part with both Appalachian-type and Gulf-coast-type deformational models and, in part and more recently, with sea-floor spreading models as they pertain to a trailing plate margin. The structural configuration of the region, including both the presence and origin of its deep and shallow structures, is not understood. The various elements of the configuration need to be tested and unified in terms of a



Well logs from Swain (1947) and Spangler (1950). Four sounding profiles made by R. V. ATLANTIS are projected to profile. Note that resistant formations form prominent structural benches on continental slope.

FIGURE 3.—Geologic sections that illustrate the idea of a predominantly unidirectional slope for the Atlantic Coastal Plain. *A*. Baltimore, Md., to Esso well 1, continental shelf (from Anderson, 1951, fig. 123). *B*. Cape Hatteras, N. C. (from Heezen and others, 1959, fig. 22).

relation to a valid onshore sedimentary model. It is a reasonable assumption that an onshore sedimentary model may provide some clue as to the lack of geometric correspondence between structures of the onshore and offshore areas. In both a time and genetic sense, this lack of geometric correspondence involves the relation between onshore structures that lie normal and offshore structures that lie parallel to the trend of the coastal margin.

A group of basement structures with a general northwest-southeast axial trend has been described by many workers as characteristic of the Coastal Plain. (See Murray, 1961.) This group includes the Ocala arch (Florida and Georgia), the Savannah embayment (Georgia and South Carolina), the Cape Fear arch (South Carolina and North Carolina), and the Chesapeake-Delaware embayment (Virginia, Maryland, and Delaware). In addition to the aforementioned structures, this group includes a long recognized but unnamed positive basement structure which abuts the northeast flank of the Chesapeake-Delaware embayment and which trends northwest-southeast across the New Jersey Coastal Plain. This structure is herein named the Normandy arch and takes its name from Normandy Beach, N.J.

The origin of these onshore structures, which also extend offshore, is not understood. Murray (1961, p. 90–92) pointed out that they lie adjacent to and have the same axial trend as the salients and recesses of the Appalachians. He postulated that Appalachian salients and recesses controlled or influenced the location of the positive and negative structures on the Atlantic Coastal Plain in some way, possibly because of a dual genetic association with Precambrian geofractures trending northwest-southeast and manifest as zones of crustal weakness.

For the offshore area, Drake, Ewing, and Sutton (1959) showed the presence of a northeast-southwest-trending and buried basement ridge, and likened this ridge, or geanticlinal element, to Precambrian rocks separating miogeosynclinal and eugeosynclinal elements of the Appalachian system during Ordovician time. Drake, Ewing, and Stockard (1968) refined this earlier concept of offshore structural configuration and stated:

> The offshore structure consists of a series of troughs and ridges continuous throughout the region except for a line extending from the New England seamount group through New Jersey and Pennsylvania and continuing to the southwest. Offsets in topography, magnetic anomaly pattern, basement contours under the continental shelf and rise, and in the structure of the Appalachian system suggest that a right lateral fault extends through this area and a mid-Paleozoic age has been suggested for the displacement (Drake and Woodward, 1963). Since the offsets in structure as determined from seismic refraction measurements continue well beyond the edge of the continental shelf, one might conclude that the structures on the margin in this area date back at least to mid-Paleozoic time.

Since 1959, published speculation about the origin of these structures has involved one or more of a combination of processes that include faulting, compressional folding, intrusion, sediment loading, reef growth, and so forth. Predominantly, the time of their origin has been associated with the Paleozoic.

Published information suggests that the two differently alined groups of structures characteristic of the coastal margin, one lying offshore and the other lying onshore and extending offshore, are not cogenetic. We suggest that the two groups are cogenetic in the sense that both are thought to have developed in response to the action of lateral compressive forces and to be associated with nonconcurrent phases of Mesozoic and Cenozoic deformation and not with Paleozoic deformation. Our suggestion is based on the study of the onshore sedimentary model and interpretation as to the structural alinements which were present during deposition of the model's component layers.

Of the 17 stratigraphic sequences mapped in the report area, five (table 1) have depositional alinements that are accordant with the structural alinements recognized in the onshore area (fig. 4). The alinements shown in figure 4 were derived by superimposing the structural alinements associated with phase 3 of crustal deformation (fig. 2*C*) on the structural alinements associated with phase 2 of crustal deformation (fig. 2*B*). The five stratigraphic sequences that are accordant with the present basement topography range from transitional Cretaceous and Late Jurassic(?) (Unit H) to post-Miocene in age. The periodicity of their occurrence in the stratigraphic succession is shown in table 1.

In contrast, 12 of the stratigraphic sequences mapped (table 1) have depositional alinements that are not accordant with the present basement topography in the onshore area. These 12 sequences do not have genetic roots in the configuration of the basement surface as it is delineated by contours (pl. 5). Instead, their depositional alinements are accordant with a structural architecture (fig. 2*A*) which comprises a series of parallel basement ridges and troughs, arranged en echelon, whose axial trend is northeast-southwest. The 12 unrooted stratigraphic sequences range from Jurassic(?) (Unit I) to late Miocene in age. The periodicity of their occurrence in the stratigraphic succession is shown in table 1. The semiperiodic recurrence of the unrooted stratigraphic sequences during Mesozoic and Cenozoic time indicates that the northeast-southwest-trending positive and negative basement structures, with which they were associated at the time of their deposition, also were reestablished as

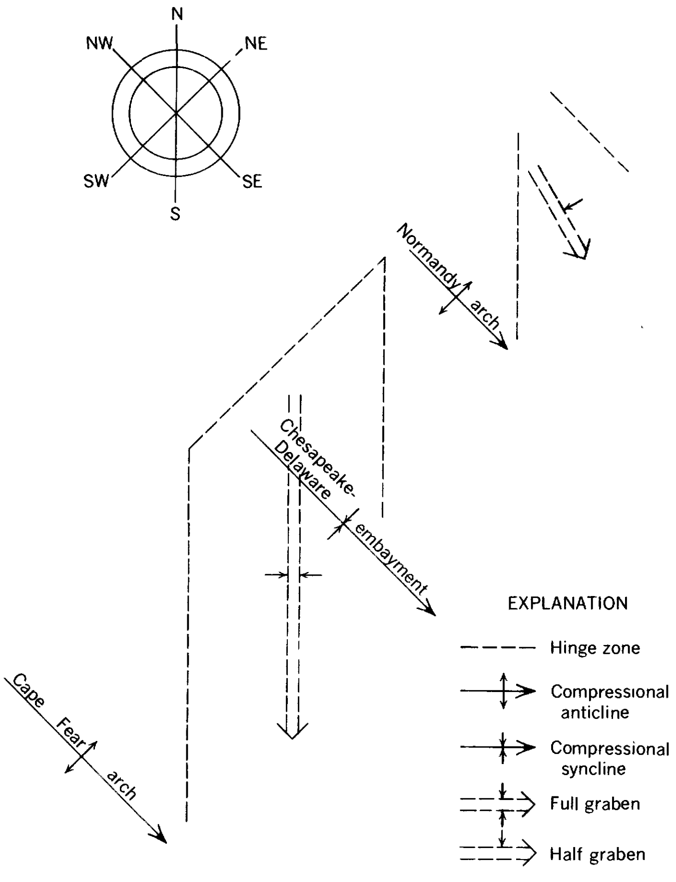


FIGURE 4.—Modern-day structural alinements that are present in the report area.

fault troughs semiperiodically during Mesozoic and Cenozoic time.

The onshore structural architecture (fig. 2*A*), which is not extant but which is judged to have been present during the time of deposition of each of the unrooted stratigraphic sequences, mirrors the general configuration of the offshore basement structure proposed by Drake, Ewing, and Sutton (1959) and Drake, Ewing, and Stockard (1968). The geometry of this onshore-offshore relation suggests to us that unrooted stratigraphic sequences also are present offshore, and that the seismic horizon identified by a seismic velocity of 5.6 kms^{-1} or greater (Drake, Ewing, and Stockard, 1968) may not represent acoustic basement in the offshore area adjacent to the Middle Atlantic States. Instead, this seismic horizon may be the surface of a deeply buried lithified section; perhaps a carbonate-evaporite section of probable early Mesozoic age that, like some onshore stratigraphic intervals, has no genetic roots in the present configuration of an underlying basement surface. Unrooted stratigraphic intervals offshore, like their counterparts onshore, would be associated genetically with a first-order tectonic stage and its characteristic structural architecture; northeast-trending fault-block anticlines that separate laterally adjacent half grabens (figs. 2*A* and 6*A*). The internal framework of the onshore sediment mass suggests that there is a geometric correspondence rather than a lack of such correspondence between onshore and offshore structure and, for reasons discussed later in this report, it is suggested that this correspondence is maintained seaward to the Bermuda Rise.

REGIONAL SYSTEM OF INTERSECTING HINGEBELTS AND ITS RELATION TO SEDIMENT DISTRIBUTION

Two main types of geologic boundaries are present in the report area; one type is physiographic and the other is structural. The present Fall Line, an erosional boundary, and the present shoreline, a depositional boundary, represent the physiographic type. They are ephemeral and transitory boundaries whose position at any one time may or may not coincide with the position of a structural boundary. From our interpretation of the geometric relations that are present among and within component layers of the regional sediment mass, we suggest that intersecting segments of a regional hingebelt system constitute the chief structural boundaries in the report area and that this system has developed within and is an integral part of the crystalline basement. The location and orientation of the first-order or principal segments of the inferred hingebelt system are shown in figure 5 and on the structure maps included in this report.

The position of some segments of the hingebelt system can be inferred because of an anomalous change in the slope of the basement surface or because of a change in the orientation of physiographic boundaries. More commonly, the positions of some segments may be inferred because of discordance that is present within the sediment mass that overlies basement rock. In plan, this includes the discordance between the different layers of the sediment mass with respect to the orientation of depositional alinements and facies-distribution patterns. In section, this includes the discordance between the different layers of the sediment mass with respect to patterns of depositional thickening and thinning and to patterns of textural and compositional variability.

In the onshore area, the abrupt to gradual change or increase in the slope of the basement surface has been recognized as a structural anomaly for many years and has been documented by numerous investigators. Murray (1961, p. 92–93) in discussing this slope break anomaly said:

> Although this feature is well documented in both published and unpublished reports no really satisfactory explanation of its origin

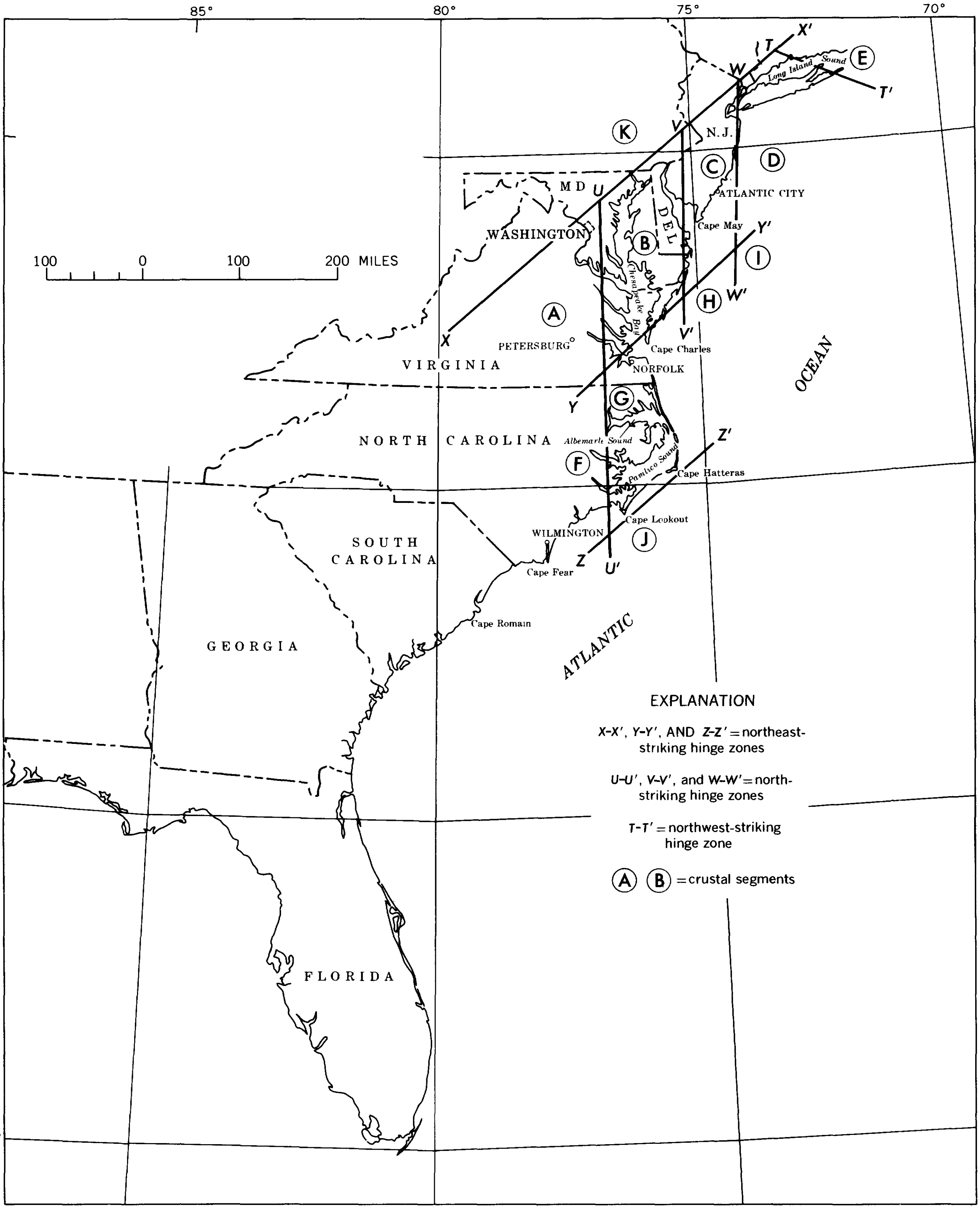


FIGURE 5.—The approximate location of the primary hinge zones in the report area.

has been advanced. . . . Some geologists have suggested that changes in the slope of the basement surface represent differentially-tilted peneplanes. Others believe that such variations in slope are due to regional faulting and flexing associated both with uplift of the continental platform and with sedimentary loading of the faulted and flexed margins.

When viewed in plan, changes in the slope of the basement surface and discordance manifest in the internal geometry of the sediment mass throughout the region form a distinct pattern. The pattern consists of three sets of parallel lines that are mutually transversal. One set trends northeast-southwest, a second set northwest-sourtheast, and the third set north-south.[2]

Segments of the inferred hingebelt system intersect to form angles of approximately 90° or 45°. The angles associated with the rotational realinement of positive and negative structures, realinement that took place semiperiodically during the time of deposition of the sediment mass, have these same values as derived from the internal geometry of the sediment mass. The values recognized for these angles suggest to us that the hingebelt system is synonymous with a crustal fault system which comprises essentially contemporaneous strike-slip and tensional faults.

Most of the basement surface is masked by a blanket of sediments. Therefore, the relative displacement of adjacent segments of the basement, on the opposite sides of a postulated hingebelt segment, must be inferred indirectly from either the presence or absence of discordance, both lateral and vertical, among the component parts of the regional sediment mass. Segments of the hingebelt system are thus not seen but are inferred from stratigraphic cross sections and from isopach-lithofacies maps for each of the 17 chronostratigraphic units mapped.

Relative to the fixed geographic location of the inferred hingebelt system, two distinct patterns for sediment distribution, that include both areal and vertical expression, are repeated semiperiodically, but not concurrently, on the sequence of isopach-facies maps in this report. One pattern is repetitive on the 12 maps for stratigraphic units of the first-order tectonic stage, the other on the five maps for stratigraphic units of the second-order tectonic stage.

Each of the two patterns may be satisfied by means of a structural model (fig. 6*A* and *B*). With respect to these models, the times and the rates of relative vertical displacement for adjacent crustal segments, on the opposite sides of the respective hingebelt segments, must be established from the discordance of laterally-adjacent sediment sections. In addition, directions of shear and directions of tension or, conversely, directions of no shear and no tension must be established with respect to the alinement of the individual hingebelt segments in both models.

The downbuilding recognized in different segments of the Coastal Plain forms a distinct pattern resulting from differential vertical displacement of adjacent crustal blocks on the opposite sides of the various hingebelt segments. The pattern is recognized by the differences in the thickness of contemporary sediment sections that lie on mutually adjacent crustal blocks. The pattern is definitive with respect to the times during which downbuilding did or did not occur along all of the hingebelt segments shown in figure 6. The pattern of relative downbuilding also is definitive, insofar as the comparative rates at which it took place along hingebelt segments alined either northeast-southwest or north-south is concerned.

If the depositional thickening of contemporary sedimentary sections on the relatively depressed side of these hingebelt segments is examined, the following relation may be established. At any one time the depositional thickening on the relatively depressed side of the hingebelt segments which have one alinement appears to be about five times greater than the depositional thickening on the relatively depressed side of the hingebelt segments which have the other alinement. In the absence of significant variance in the rate of sediment supply, the differences in the thickness of contemporaneous sections may be attributed to different rates of downbuilding that have taken place on the relatively depressed side of the hingebelt segments alined northeast-southwest and north-south respectively. For convenience we have designated the more rapid rate of downbuilding as the primary rate of relative downbuilding and the less rapid rate of downbuilding as the secondary rate of relative downbuilding. When these rates of relative downbuilding are considered with respect to the times at which they have occurred along hingebelt segments that have one of two alinements, the following relations may be expressed:

1. During a *first-order* tectonic stage, the primary rate of relative downbuilding occurs on the east side of hingebelt segments that are alined north-south, and the secondary rate of relative downbuilding occurs in the southeast side of hingebelt segments that are alined northeast-southwest (fig. 6*A*).
2. During a *second-order* tectonic stage, the primary rate of relative downbuilding occurs on the southeast side of hingebelt segments that are alined northeast-

[2] These orientations coincide with those recognized by Hobbs (1904) as being characteristic of three of the four principal lineaments that he observed in the Atlantic border region. He established these lineaments by means of geomorphologic observation, and attributed them to the presence of a crustal fracture field. Our findings were developed from an independent study of subsurface data. They support the earlier work of Hobbs (1904, 1911).

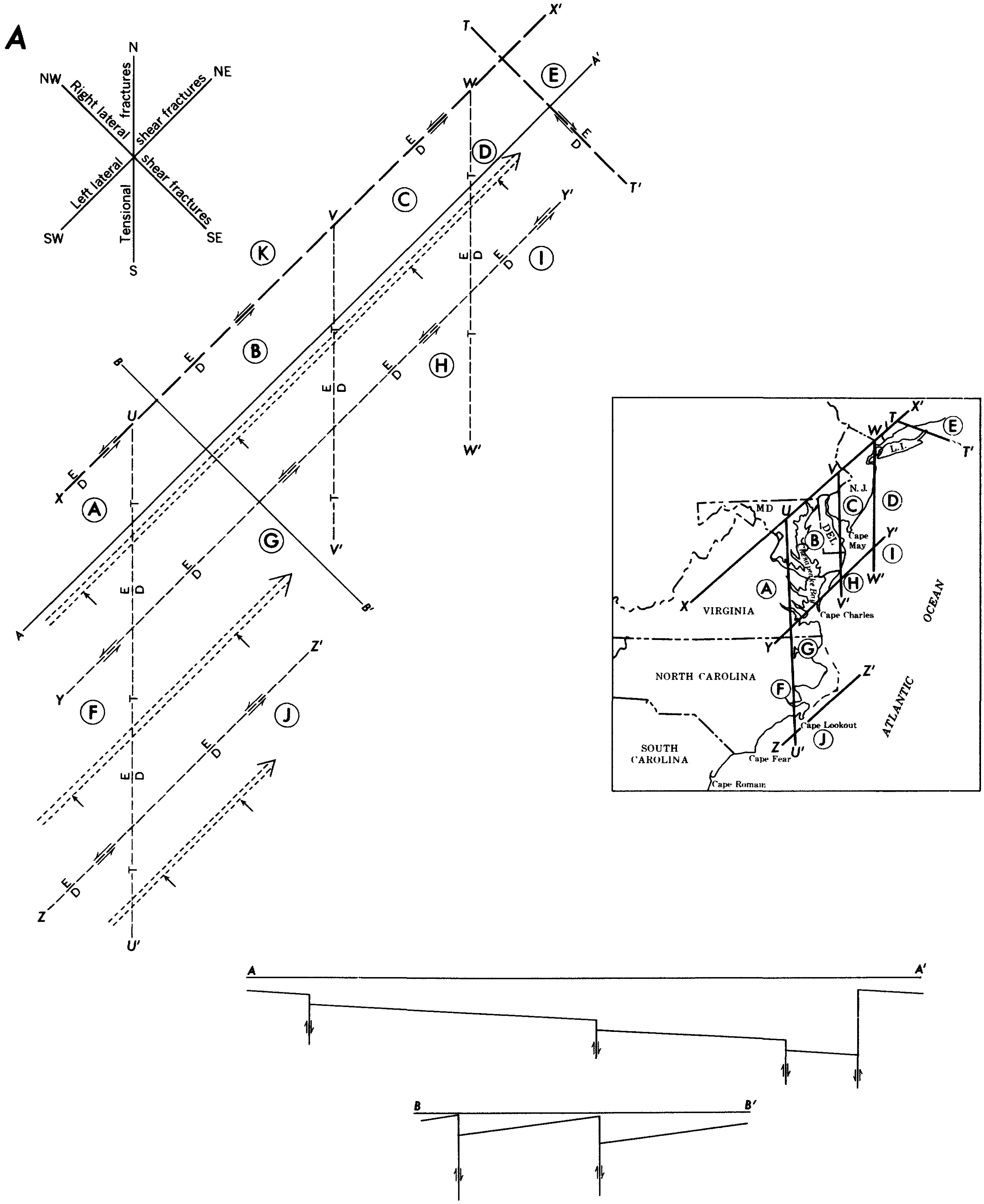


FIGURE 6.—Structural models for the first-order tectonic stage (*A*) and for the second-order tectonic stage (*B*).

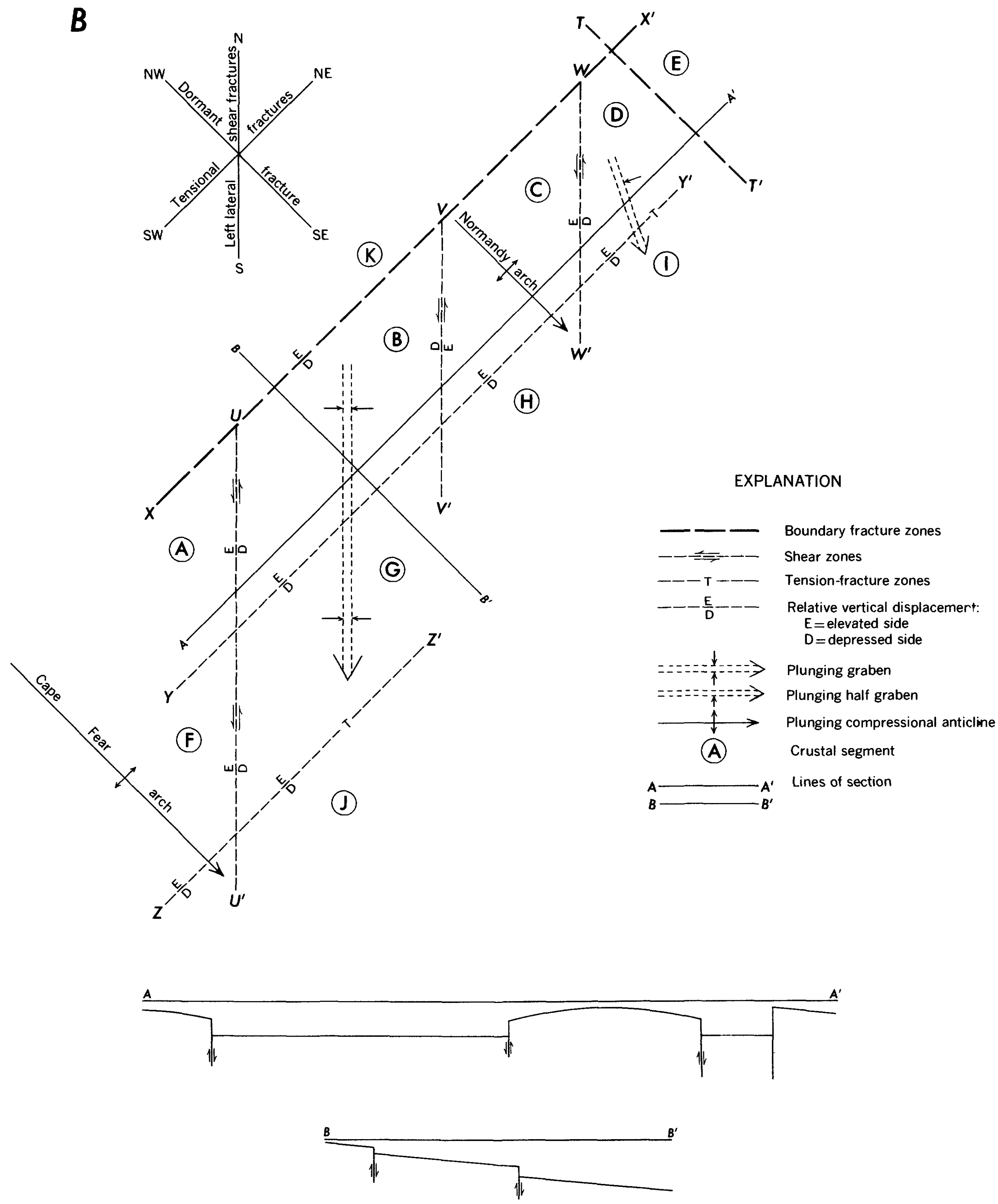


FIGURE 6.—Continued.

southwest, and the secondary rate of relative downbuilding occurs on the relatively depressed side of hingebelt segments that are alined north-south (fig. 6*B*).

These two statements may be combined into the following fundamental statement that explains, in part, the observed discordance within the regional sediment mass: When there is a shift from a first-order to a second-order tectonic stage and conversely, the two observed rates of relative downbuilding are transposed with respect to hingebelt segments that are alined northeast-southwest and north-south (fig. 6*A* and *B*).

Because hingebelt segments that have these two alinements intersect to form angles of about 45°, it is a logical assumption that these hingebelt segments are associated with a direction of tension and a direction of shear respectively. If we associate a primary rate of relative downbuilding with a direction of tension and a secondary rate of relative downbuilding with a direction of shear, it follows that the direction of tension and the direction of shear are transposed when there is a shift from a first-order to a second-order tectonic stage, and conversely. This relation is shown in figure 6*A* and *B*. It is derived from the internal geometry of the sediment mass.

STRUCTURAL MODELS

In order to design structural models that satisfy the sedimentary geometry mapped, geologic relations observed in plan as well as in section must be considered. Any apparent sense of transcurrent movement inferred along a hingebelt segment must satisfy the observed offsets in sediment distribution patterns or in belts of geophysical anomalies along the segment. Any apparent sense of transcurrent movement or combination of movements along one or more hingebelt segments must be consistent with the apparent clockwise rotation (realinement) of positive and negative structural axes that takes place in the region when there is a shift from a first-order to a second-order tectonic stage or with the apparent counterclockwise rotation (realinement) of positive and negative structural axes that takes place when there is a shift from a second-order to a first-order tectonic stage.

From a consideration of geologic relations observed in both plan and section, we suggest that two structural models (fig. 6*A* and *B*) are the least number of models required in order to satisfy the observed and inferred geologic relations within the report area. The structural model illustrated in figure 6*A* satisfies the relations observed in both plan and section for the sedimentary geometries of the 12 unrooted chronostratigraphic units included within the first-order tectonic stage. Its structural elements and their sense of alinement are accordant with the presence and alinement of structural elements inferred to have been present at the times of deposition of the unrooted units. The structural model illustrated in figure 6*B* satisfies the relations observed in both plan and section for the sedimentary geometries of the five rooted chronostratigraphic units included within the second-order tectonic stage. Its structural elements and their sense of alinement are accordant with the presence and alinement of structural elements inferred to have been present at the times of deposition of the rooted units.

In addition to obvious differences in the presence and alinement of structural elements associated with each of the models, several other important differences may be seen as follows:

1. During a first-order tectonic stage (fig. 6*A*), the hingebelt segment labeled $T\text{–}T'$ lies in the plane of an active right-lateral transcurrent fault. The fault has a large vertical component that acts to depress crustal blocks D and I relative to block E. During a second-order tectonic stage (fig. 6*B*), the transcurrent fault is dormant and no additional displacement of crustal blocks D and I relative to block E occurs.
2. With respect to the hingebelt segments that are alined northeast-southwest and north-south respectively, a direction of tension and a direction of shear, together with their corresponding rates of relative downbuilding, are transposed in the two models.
3. With respect to the hingebelt segment designated as $V\text{–}V'$ in both models, crustal blocks C and H are depressed relative to crustal blocks B and G in figure 6*A*, whereas in figure 6*B* the relative displacement is reversed and crustal blocks B and G are depressed relative to crustal blocks C and H.

The report area is a small segment of a much larger geographic area in which the same general geologic conditions recognized in the report area may also be recognized or inferred. The boundary of the larger geographic area corresponds with the boundary of what may be considered to be a large crustal segment or crustal block that is designated a unit-structural block in this report. The probable boundary of the unit-structural block and the probable nature of the dynamic conditions along its boundary, with respect to mutually adjacent unit-structural blocks, cannot be observed directly. Indirectly, they may be inferred by comparison of adjacent areas with respect to various geologic criteria. These criteria include the presence of different rock types, the relative vertical and lateral displacement of sedimentary rocks and of other rock types, contrasts in sediment thickness, the structural divergence, contrasts in topographic expression, and the offsets observed in the pattern of magnetic anomalies.

Interpreting various combinations of these criteria, a probable boundary for the unit-structural block may be established (fig. 7). The block's northeast boundary segment coincides with an extension, in this report, of the lineament designated by Hobbs (1904, pl. 45) as the "lower Connecticut line" and, in part, with the Kelvin displacement (Drake and Woodward, 1963). The block's southwest boundary segment coincides with the extension, in this report, of the south Florida fault or flexure zone of Pressler (1947). The block's northwest boundary segment coincides with the trend of the Brevard shear zone as extended by Moody (1966, fig. 1). The block's southeast boundary segment is postulated to lie along and parallel to the eastern border of the Bermuda Rise in a zone that is marked by high amplitude magnetic anomalies (Vogt and others, 1971) and by the transition from a smooth ocean-floor topography on the west to a relatively rough ocean-floor topography on the east.

As defined in this report, the unit-structural block is a rectangular area bounded by crustal shear zones. The sides alined northwest-southeast are a little more than 1,100 miles long, and the sides alined northeast-southwest are a little less than 1,100 miles long.

ANALYSIS OF THE MECHANICS OF DEFORMATION

To account for the alternate occurrence of two discordant structural-sedimentary systems in the report area, some method of analysis is required that will

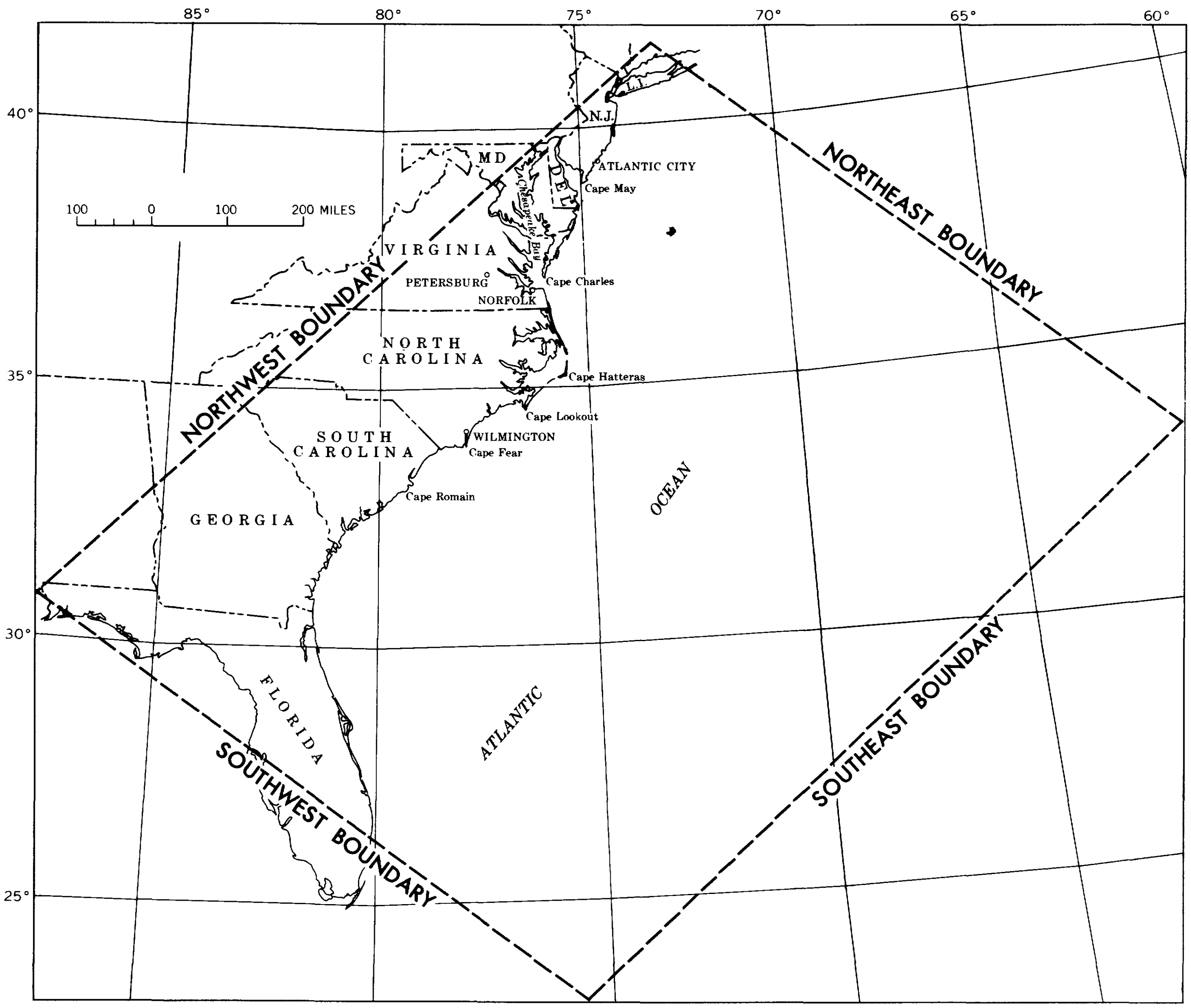


FIGURE 7.—The approximate geographic location of the unit-structural block.

serve to unify the observed or inferred discordant geometries. Analysis of the mechanics of deformation may be used to construct tectonic models (pl. 1) and to develop an overall tectonic hypothesis that unifies the discordant geometries. Each of the two structural systems (fig. 6*A* and *B*) represents a different deformational response of the unit-structural block to either internal or external forces. Any plausible analysis of the mechanics of block deformation must account not only for the occurrence of two nonconcurrent structural systems, but also for the semiperiodicity of their occurrence. Because of the angular relation between the structural alinements associated with one structural system and the structural alinements associated with the other structural system, we conclude that the dominant forces which have deformed the unit-structural block operated in a horizontal plane. We conclude further that the forces are lateral compressive forces, that they originate externally from the unit-structural block, and that they are transmitted either along or across the boundary between the unit-structural block and mutually adjacent unit-structural blocks.

A primary compressional force with a meridional alinement would satisfy the right-lateral and left-lateral sense of relative displacement that occurs along the block's boundary faults (pl. 1*A*) during a first-order tectonic stage. This orientation for a primary compressive force acting on a crustal block bounded by what may be presumed to be regmatic shears is the orientation proposed by Moody and Hill (1956, p. 1230) for a primary compressive-stress axis in developing their hypothesis of "wrench-fault tectonics." As discussed and as pointed out by Moody (1966, p. 506), forces with a meridional alinement as well as forces with an equatorial alinement could be derived from the rotation and precession of the earth. An axis alined east-west and perpendicular to the line of pressure may be designated as the principal axis of extension (pl. 1*A*). The deformational response of the unit-structural block, subjected to a primary compressive stress can be described in terms of inequalities of resistance in the plane perpendicular to the primary compressive-stress axis. Essentially, this analysis incorporates the principles cited by Becker (1893, p. 55–57) in his classic paper entitled, "Finite Strain in Rocks." He described the relation between stress, strain, and rupture when a rock mass subjected to an inclined pressure rested against a rock mass with a relatively yielding resistance and stated:

> An inclined pressure acting on a tabular mass of rock is equivalent to a direct pressure and a tangential force. This last, with the resistance necessary to keep the center of inertia of the rock at rest, forms a couple. If the rock is surrounded by masses of comparatively feeble resistance, it will then rotate until the couple is exactly balanced by the resistance to rotation. The rock is thus subjected to the action of a simple pressure and two balanced couples, constituting a simple shear, neither of the axes of which coincides with the line of pressure.

He also described the relation between stress, strain, and rupture when a rock mass subjected to an inclined pressure rested against a rock mass with a relatively unyielding resistance and stated:

> When a tabular mass of rock subjected to inclined pressure rests against a mass which does not yield considerably, the free couple which results from the tangential component of the pressure and the resistance of the supporting mass can only be equilibrated by strain in the rock itself.

During what we have designated a first-order tectonic stage, the deformational response of the block to a primary compressive stress with a meridional alinement is a response controlled by a relatively yielding resistance in a plane perpendicular to the primary stress axis (pl. 1*A*), and $PP' > RR'$. In response to the inequality, the block's boundary shears become active transcurrent faults. Movement continues until such time as a new balance is attained and $PP' = RR'$. From indirect observation as to the relative magnitude of shear displacement that has occurred along the boundaries of the block, we suggest that the dominant or master-shear set is the right-lateral set, striking northwest, and that the complementary set is the left-lateral set, striking northeast. As the block is rotated it changes shape; its axis of maximum shortening is alined north-south and its axis of maximum elongation is alined east-west. As was shown for a similar case in experiments carried out by Mead (1920, p. 512), when a block is subjected to rotational stress and rupture occurs, a set of vertical tension fractures develops perpendicular to the block's axis of maximum elongation and two sets of vertical shear fractures may develop parallel to the directions of shearing movement. In the present case, which involves deformation of a unit-structural block, it is inferred that a set of vertical tension fractures, which strike north, has developed perpendicular to the block's axis of maximum elongation, and that one set of vertical shear fractures, which strike northeast, has developed parallel to the block's complementary boundary shears (pl. 1*A*). No sedimentary evidence indicates that a second set of shear fractures, striking northwest and lying parallel to the block's master boundary shears, ever developed. The absence of a second shear set may be related to the anisotropy and inhomogeneity of the block; directional resistances within the block may be unequal and planes of shear have developed only in the direction of easiest relief.

During a first-order tectonic stage the axes of compressional anticlines and synclines, if such features formed, would be expected to have an east-west alinement and to lie perpendicular to the block's axis of maximum shortening. The regional sedimentary geometry indicates that such structural features never developed, and that the axes of positive and negative structural features which did develop on the block during a first-order tectonic stage had a northeast-southwest alinement parallel to the strike of the complementary shear set. From this relation we conclude that the northeast-striking ridges that formed on the block during a first-order tectonic stage were fault-block anticlines or asymmetrical flexures resulting from vertical displacements associated with transcurrent movement along planes of shear that died out upward (fig. 6*A*). The intervening troughs have a half-graben structural form; the northwest border of a trough lies on the depressed side of a shear fracture and the southeast or opposite border of a trough lies on the elevated side of a shear fracture. The distribution of the stratigraphic sequences included in the first-order tectonic stage and the structural model (fig. 6*A*) derived from their distribution are satisfied by the alinement of shear and tension fractures shown on the tectonic model illustrated on plate 1*A*.

If a gradual increase in the magnitude of the reacting or resistant forces that are alined east-west occurs, they may eventually become equal in magnitude to the acting compressive forces alined north-south. Perhaps such an increase in magnitude for the reacting forces is related to the piling up of material toward the ends of finite shears (see Chinnery, 1963, 1965) or to subcrustal drag. When inequality no longer exists in a horizontal plane between the forces compressing the block and the forces opposing extension of the block, the horizontal couples that lie in the respective planes of both the master-shear set and its complementary set become balanced (pl. 1*B*). No transcurrent motion occurs on the fault zones that lie in these planes and the unit-structural block's four boundary fault zones become frozen or dormant. The freezing of the boundary fault zones marks the close of a first-order tectonic stage and the beginning of a second-order tectonic stage.

The unit-structural block is now subjected to two sets of direct compressive forces, P–P' and R–R', that are equal and that act along lines that lie perpendicular in a horizontal plane. Inasmuch as two or more forces may be replaced by a single resultant force, we may designate S, S', T, and T' as resultant forces that replace the four coplanar, concurrent forces P, P', R, and R' (pl. 1*B*). The unit-structural block now is subjected to two sets of direct compressive forces acting along axes that stand perpendicular and that are alined northeast-southwest (S–S') and northwest-southeast (T–T'). The strain on the block can only be reduced by its deformation. It is inferred that the deformation occurs in two phases; a phase that precedes rupture and a phase that accompanies rupture. In the report area, the structural alinements that are associated with the phase of deformation which precedes rupture are illustrated in figure 2*B*. The structural alinements that are associated with the phase of deformation which accompanies rupture are illustrated in figure 2*C*.

During what we have designated a second-order tectonic stage and in the initial phase of deformation, compressional features that are alined northwest-southeast develop on the block. If the block were an isotropic mass, the compressional features could have developed perpendicular to S–S' and to T–T'. However, if there is any inequality of resistance in planes lying perpendicular to S–S' or T–T', respectively, the compressive axis that lies perpendicular to the plane of maximum resistance will constitute the primary compressional axis within the block. Compressional features developed on the block will have a preferential alinement in that they will lie perpendicular to the block's primary compressional axis and parallel to the block's axis of maximum resistance. Therefore, for the force system under consideration and in order to satisfy the structural alinements of figure 2*B*, wherein the axes of compressional features are alined northwest-southeast, the block's primary compressional axis must be alined northeast-southwest and the block's axis of maximum resistance must be alined northwest-southeast as shown on plate 1*B*. The converse relation would be true if it were necessary to satisfy, genetically, the structural alinements of the Appalachians, for example, wherein the compressional features have a northeast-southwest alinement.

During a second-order tectonic stage and in the phase of deformation that precedes rupture, a series of northwest-striking anticlines and synclines of various orders of magnitude form on the unit-structural block. Several of the more prominent examples of these features in the report area are the Cape Fear arch (South Carolina and North Carolina), the Chesapeake-Delaware embayment (Virginia, Maryland, and Delaware), and the Normandy arch (New Jersey), all of which have axes that strike northwest.

When the intensity of deformation becomes so great that cohesion is overcome, the block ruptures. Tensional fractures that strike northeast develop parallel to the block's primary compressive axis. Planes of maximum shearing stress, alined north-south and east-west, lie at an angle of 45° on either side of the block's primary compressive axis. Planes of actual shear that strike north develop on the block. They coincide with planes of maximum shearing stress alined north-south. There is no sedimentary evidence to indicate that planes of shear develop in association with planes of maximum shearing stress alined east-west. Something may be said here concerning the coincidence of planes of actual shear with planes of maximum shearing stress in the present analysis. In most geologic systems it is assumed that planes of actual shear stand at an angle of less than 45° to the direction of compression, and the average value assigned to the angle is generally ±30° (Moody and Hill, 1956, p. 1210). The assumption is based upon an average value assigned to the coefficient of friction for rocks. The assumption acknowledges the relationship between friction and cohesion, wherein the larger the coefficient of friction the smaller the angle of fracture, and the greater the cohesion the larger the angle of fracture.

So far as the present analysis of the mechanics of a geologic system is concerned, a reasonable assumption is that preexisting planes of weakness, that strike north, developed in the unit-structural block during some earlier stage of deformation. As indicated by Hobbs (1904, p. 504) these planes of weakness may be very old. They may constitute elements of the earth's regmatic shear pattern (Sonder, 1947). They may have been further weakened as a result of tensional forces developed within the block during a preceding first-order tectonic stage. During a second-order tectonic stage, when the strain becomes so great that cohesion is overcome and the block ruptures, the preferential orientation for planes of rupture would coincide with the alinement of the preexisting planes of weakness. The rupture would consist of relative horizontal motion in these planes of weakness. As inferred from the regional sedimentary geometry, shear fractures that strike north are characteristic of a second-order tectonic stage. In order to explain the coincidence of these actual planes of shear with the alinement of planes of maximum shearing stress under the mechanical condition set forth, the assumption that the unit structural block contains preexisting planes of weakness is more tenable than the assumption that it is an isotropic frictionless mass. The alinements for directions of shear and directions of tension that developed in the report area during a second-order tectonic stage are illustrated on plate 1*B*.

To summarize: during a second-order tectonic stage the unit-structural block undergoes two sequential phases of deformation; an initial phase that precedes rupture and a subsequent phase that accompanies rupture. In the initial phase, a syncline, flanked by asymmetrical anticlines forms on the block. The axes of these structures are alined northwest-southeast. When rupture of the block occurs, fracture-bounded full and half grabens develop. These fracture-bounded grabens, whose long axes have a general north-south alinement, lie at an angle to the long axes of the asymmetrical anticlines or arches, the Cape Fear arch and the Normandy arch. Alinement of the positive and negative structural features associated with the two phases of deformation that characterize the second-order tectonic stage is illustrated in figure 4. Solid lines represent the axes of the initially developed syncline and flanking anticlines. Dashed lines represent the subsequently developed fracture-bounded graben. During a second-order tectonic stage, a shift in the axial alinement of a primary depocenter (Murray, 1961), between the Cape Fear and Normandy arches, accompanies the transition from a syncline alined northwest-southeast to a superimposed graben alined north-south.

Distribution of the stratigraphic sequences included in the second-order tectonic stage and the structural model (fig. 6B) derived from their distribution are satisfied by the tectonic model illustrated on plate 1*B*.

For two of the boundary shear zones postulated for the unit-structural block, there are several seeming or real conflicts between suggestions made previously and suggestions made here (pl. 1*A* and table 1) with respect to the sense of relative displacement inferred along the shear zones and the latest times of such displacement.

Previously, Moody (1966, p. 483 and fig. 8) in discussing the Brevard zone, which we consider to coincide with the northwest boundary of the unit-structural block, suggested that the time of origin of the Brevard zone was Precambrian, that it resulted from lateral compressive stress with an equatorial alinement, that the sense of relative displacement was right lateral, and that the latest structural movements along it were pre-Cretaceous. From our interpretation of the internal geometry of the onshore sediment mass, we suggest that from Jurassic time onward the sense of relative displacement on the Brevard zone was left lateral, that the movement resulted from lateral compressive stress with a meridional alinement, and that the latest structural movement along the zone is late Miocene. Because Moody's and our suggestions as to the sense of relative displacement differ in point of time, they are not incompatible for the same shear zone.

Similarly, Drake and Woodward (1963) in discussing the Kelvin displacement, which we consider to coincide in part with the northeast boundary of the unit-structural block, suggest that the relative sense of displacement was right lateral and that the latest structural movement, along what they consider to be its onshore extension, was pre-Cretaceous. From our interpretation of the internal geometry of the onshore sediment mass, we suggest that the sense of relative lateral displacement along the northeast boundary of the unit-structural block from Jurassic time onward was right lateral, and that the latest structural movements are late Miocene. The two suggestions are in conflict with respect to the time of latest structural movements along the inferred shear zone. This is because Drake and Woodward (1963) recognized no movement (offsets) with respect to Cretaceous and younger Coastal Plain sediments, whereas we recognize semiperiodic rotational movement (realinement) with respect to Cretaceous and younger sediments that lie on the unit-structural block adjacent to the shear zone.

REGIONAL COMPONENTS OF TILT

The preceding discussion has dealt primarily with alinements and origins of fold and fault-block structures that are inferred to have developed in response to either rotational or irrotational stress acting in a horizontal plane. Regionally as well as locally, various components of tilt developed in response to rotational stress acting in a vertical plane. In the sense that the term is used in this report, we define a component of tilt as the descending slope (gradient) that is established as a result of the relative vertical displacement of adjacent crustal blocks or of component segments of the same block.

Interpretation of the internal geometry of the onshore-sediment mass indicates to us that three primary components of regional tilt have been dominant from at least Jurassic time to the present. They are a northeast component, a northwest component, and a southeast component. Together, they comprise the primary or residual-acting components of a regional tilt system. Overall, the regional sediment mass thickens toward the east, probably in accordance with a resultant component of the northeast and southeast components of tilt.

From inspection of depositional patterns within the various segments of the sediment mass, it seems that the northeast and northwest components of tilt were the principal acting regional components during the times of deposition of the 12 stratigraphic units assigned to the first-order tectonic stage. It also seems that the southeast component of tilt, dominant in the region at present, was the principal acting regional component during the times of deposition of the five stratigraphic units assigned to the second-order tectonic stage.

The northeast and northwest components of tilt are inferred to have developed in response to the action of four horizontal couples (pl. 1*A*). These components of tilt seem to be derived from vertical components of movement that are resultants of transcurrent movement which took place semiperiodically along the four boundary shear zones of the unit-structural block. We suggest that the southeast component of tilt was established as a consequence of compensatory subsidence that followed semiperiodic uplift of the Bermuda Rise.

The probability that relatively large-scale vertical displacements may accompany wrench faulting or that such displacements may create structural form along and adjacent to the fault zone has received scant attention in the literature. As a result of observational analysis, Moody and Hill stated (1956, p. 1230) that they "believe that vertical components of movement along elements of the regmatic shear pattern vary from as much as 50 percent to as little as 3 or 4 percent of the horizontal." Chinnery (1965), using a simplified fault model and making calculations based on elasticity theory, emphasized that vertical displacements must accompany transcurrent movement on finite shears. He suggested that these displacements in the plane of a transcurrent fault could be as large as 8 percent of the relative lateral displacement. He also pointed out that the pattern of vertical displacements could be extremely complex and the deformation permanent, even in adjacent areas a considerable distance from the fault plane. Chinnery and Petrak (1968) suggest that topographic features, some of which are elongate, parallel and adjacent to the fault zone, may develop in response to vertical movement associated with horizontal fault displacement.

If two mutually adjacent unit-structural or crustal blocks are separated by a high-angle transcurrent boundary fault, the relative vertical displacement associated with the predominant lateral movement on the fault could cause subsidence of one crustal block relative to an adjacent crustal block and thus generate a fault-block anticline flanked by a trough. Moody and Hill (1956, p. 1239, fig. 24) diagrammed this relation to demonstrate the possible genesis of an asymmetrical geosyncline and the development of geosynclinal sedimentary suites in a structural system dominated by the vertical displacement associated with a single wrench fault. In a similar manner, and for the present case where the unit-structural block under discussion is bounded by what we consider to be two primary left-lateral and two primary right-lateral wrench-fault zones, the relative vertical displacement of the unit-structural block (A) with respect to its mutually adjacent unit-structural blocks (B, C, D, and E) is diagrammed in figure 8*A*. The following relation is evident with respect to adjacent blocks and their common boundary shears:

1. Block A is depressed relative to block B along the trend of the Brevard shear zone as extended by Moody (1966).
2. Block A is depressed relative to block C along the trend of the shear zone that coincides with the extension in this report of the "lower Connecticut line" of Hobbs (1904).

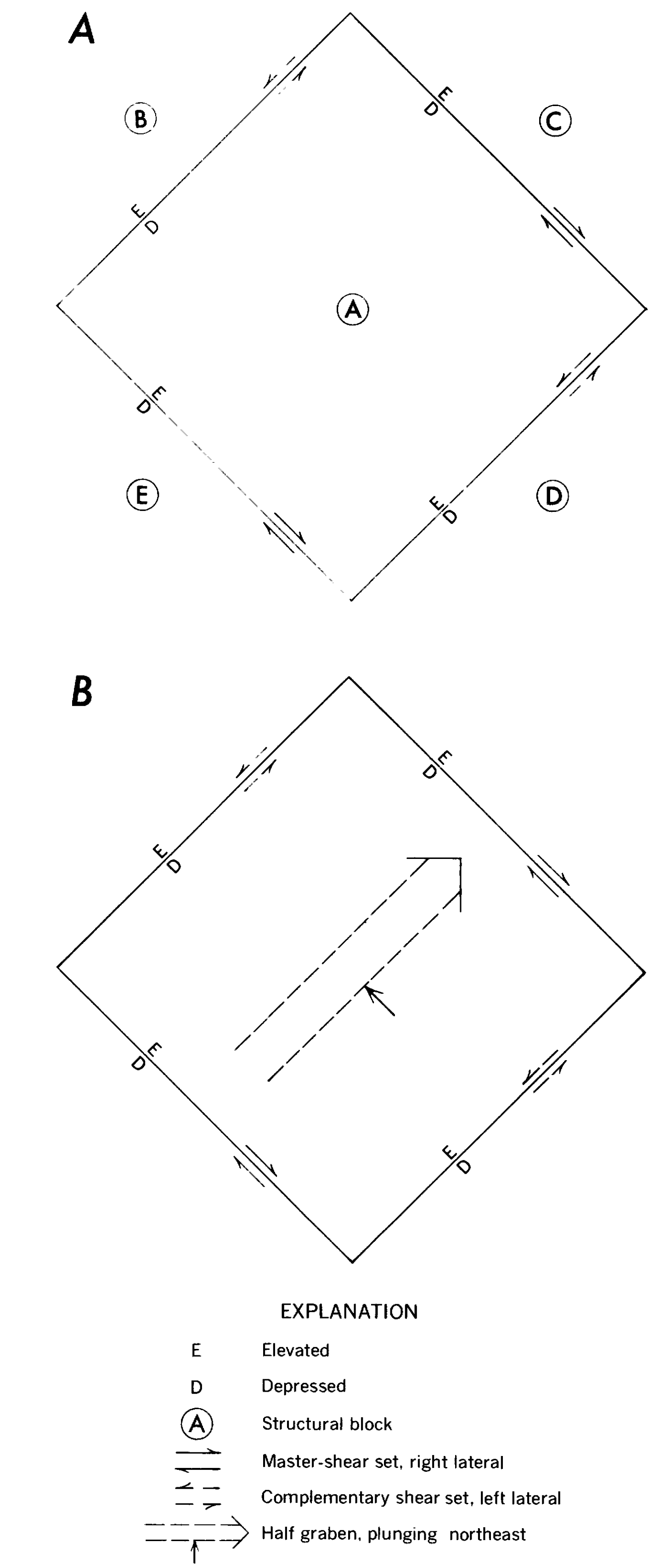


FIGURE 8.—*A*. The vertical displacement of the unit-structural block (A) relative to mutually adjacent structural blocks (B, C, D, and E), first-order tectonic stage. *B*. The half-graben structural form assumed by the unit-structural block in response to relative vertical displacements along its boundaries.

3. Block A is relatively elevated with respect to block D along the trend of a shear zone postulated in this report as bordering the Bermuda Rise on the east.
4. Block A is relatively elevated with respect to block E along the trend of the shear zone that coincides with the extension in this report of the south Florida fault or flexure zone of Pressler (1947).

As a result of these relative vertical displacements, two primary components of tilt are developed with respect to the attitude of opposite sides of the unit-structural block. One primary component of tilt is toward the northeast—from the common boundary of block A and block E toward the common boundary of block A and block C. A second primary component of tilt is toward the northwest—from the common boundary of block A and block D toward the common boundary of block A and block B. If the axis of the unit-structural block that lies normal to the northwest-trending master shear set is designated its principal axis of tilt, the asymmetrical structural form assumed by the block is that of a half graben whose axis plunges toward the northeast (fig. 8*B*). In this view, the half-graben structural form for a regional surface of subsidence (a geosyncline) is derived from relative vertical displacements along the block's boundary shear zones. This structural form satisfies the northeast and northwest components of tilt which are inferred from the internal geometry of the onshore sediment mass.

Because it is pervasive at present, the southeast component of regional tilt has almost exclusively dominated geologic and geophysical interpretation in the Atlantic coastal area. This component of tilt has been attributed (Kay, 1951; Drake and others, 1959; Dietz, 1963; Ringwood and Green, 1966; and others) to geosynclinal subsidence along the continental margin of the eastern United States, with the loci of subsidence presumed to lie within or beneath the basement of the geosyncline. In this view, the regional tilt toward the southeast is intrageosynclinal and develops in response to downwarping of the geosyncline's northwest flank in the direction of its axis of subsidence that trends northeast and lies some distance offshore. Common to published proposals (Dietz, 1963; Hess, 1962; Lovering, 1958; Ringwood and Green, 1966; and others), the mechanism of subsidence requires some type of crustal change within or beneath the basement of the geosyncline—such as transition from mineral phases of lesser density to mineral phases of greater density and a corresponding reduction in volume beneath the area or areas of subsidence. Commonly, as proposed by Dietz (1963), the mechanism of subsidence has been accommodated by assuming a juxtaposition of continental and oceanic crust at or adjacent to the base of the continental slope. However, Worzel (1965) shows that there is a wide zone of transition between crust of continental thickness and crust of oceanic thickness seaward of the continental slope. Deducing structure from seismic and gravity evidence, he interpreted the transition zone to be about 300 km wide along a line of section extending southeast from Cape May, N. J., and about 100 km wide along a line of section extending east of Cape Hatteras, N. C.

The temporal history of the southeast component of regional tilt, recorded in the geometry of the onshore sediment mass, shows that the component was dominant intermittently from Jurassic time to the present, that it was chiefly dominant when stratigraphic units of the second-order but not the first-order tectonic stage were deposited, and that it was less often dominant historically than the northeast component of regional tilt. This suggests that the southeast component of tilt developed in response to subsidence which took place principally during phase 3 in the cycle of crustal deformation (see p. 7 and fig. 2*C*) when, in a situation analagous to that described by Moody (1966, p. 507), the unit-structural block, after rupture, probably would have been freed from lateral compression and have reacted to the sum of vertical forces to which it was subjected. The temporal history of the southeast component of tilt also suggests that the subsidence may represent a reactive response to uplift that took place during a previous phase of crustal deformation.

The subsidence of the crust west of the Bermuda Rise during a second-order tectonic stage would be geometrically compatible with the postulated uplift of the Bermuda Rise during a first-order tectonic stage in that the subsidence would represent volumetric compensation for the uplift. This is consistent with the idea of Engelen (1964, p. 91) that, "The peripheral depression around the Bermuda Rise is the volumetric compensation of the rising central bulge." The inferred uplift of the Bermuda Rise, in response to the action of vertical resultants of compressional stress, would be accompanied by a transition from mineral phases of greater density to mineral phases of lesser density, as suggested by the crustal structure shown for the Bermuda Rise (Heezen and others, 1959, p. 80 and fig. 35), whereas the subsidence of the crust west of the Bermuda Rise would take place as a result of a compensatory transition from mineral phases of lesser density to mineral phases of greater density. In this view, the wide zone of transition (Worzel, 1965), between crust of continental thickness and crust of oceanic thickness, represents continental crust undergoing oceanization (thinning) in compensatory response to the semiperiodic uplift of the Bermuda Rise. A semiperiodic subsidence for the crust west of the Bermuda Rise satisfies the temporal history of the southeast component of tilt that is recorded in the onshore sediment mass.

The interrelations among components of the regional tilt system are complex and the system is not amenable quantitatively to vector analysis. There are several principal reasons for this. Primary components of tilt, dominant during one tectonic stage, often carry over into the succeeding stage as residual and subordinate components. There is considerable variance with respect to the time of duration for any one dominant component of tilt. Local components are superimposed on regional components of tilt.

Within the sediment mass, contrasting patterns of textural and compositional character, together with the occurrence of differently alined depositional thickening trends, mirror the resultant expressions of both primary and residual-acting components of tilt during the time of deposition of each of the stratigraphic units mapped. These patterns and alinements, that are similar for those stratigraphic units grouped within a tectonic stage, permit a first approximation prediction of regional intrinsic-permeability distribution (fig. 9).

External source areas, relatively uplifted with respect to the unit-structural block, lie adjacent to the block along its northwest and northeast boundaries. During a first-order tectonic stage and when the northeast and northwest components of regional tilt are dominant, the block is tilted toward the bordering source areas. The result of this relation is that sediments deposited on the block and adjacent to the source areas become increasingly coarse in the directions in which they thicken (fig. 9*A*). During a second-order tectonic stage and when the southeast component of regional tilt is dominant, that part of the block adjacent to the bordering source areas is tilted away from these areas. The result of this relation is that sediments deposited on the block and adjacent to the source areas become increasingly fine in the direction in which they thicken (fig. 9*B*). Although it represents an oversimplification, the resultant expression of these relations may be stated as follows: for the onshore sediment mass as a whole, the sediments thicken toward the east and become increasingly coarse toward the northeast.

A group of smaller crustal blocks comprises the unit structural block. A subregional tilt system, derived from the relative vertical displacement of this group of smaller blocks, is superimposed on the regional tilt system. The control that the subregional tilt system exerts upon the three-dimensional distribution of sediments in local areas is examined in connection with discussion of the geometry of sedimentary troughs that are characteristic of the first-order and second-order tectonic stages.

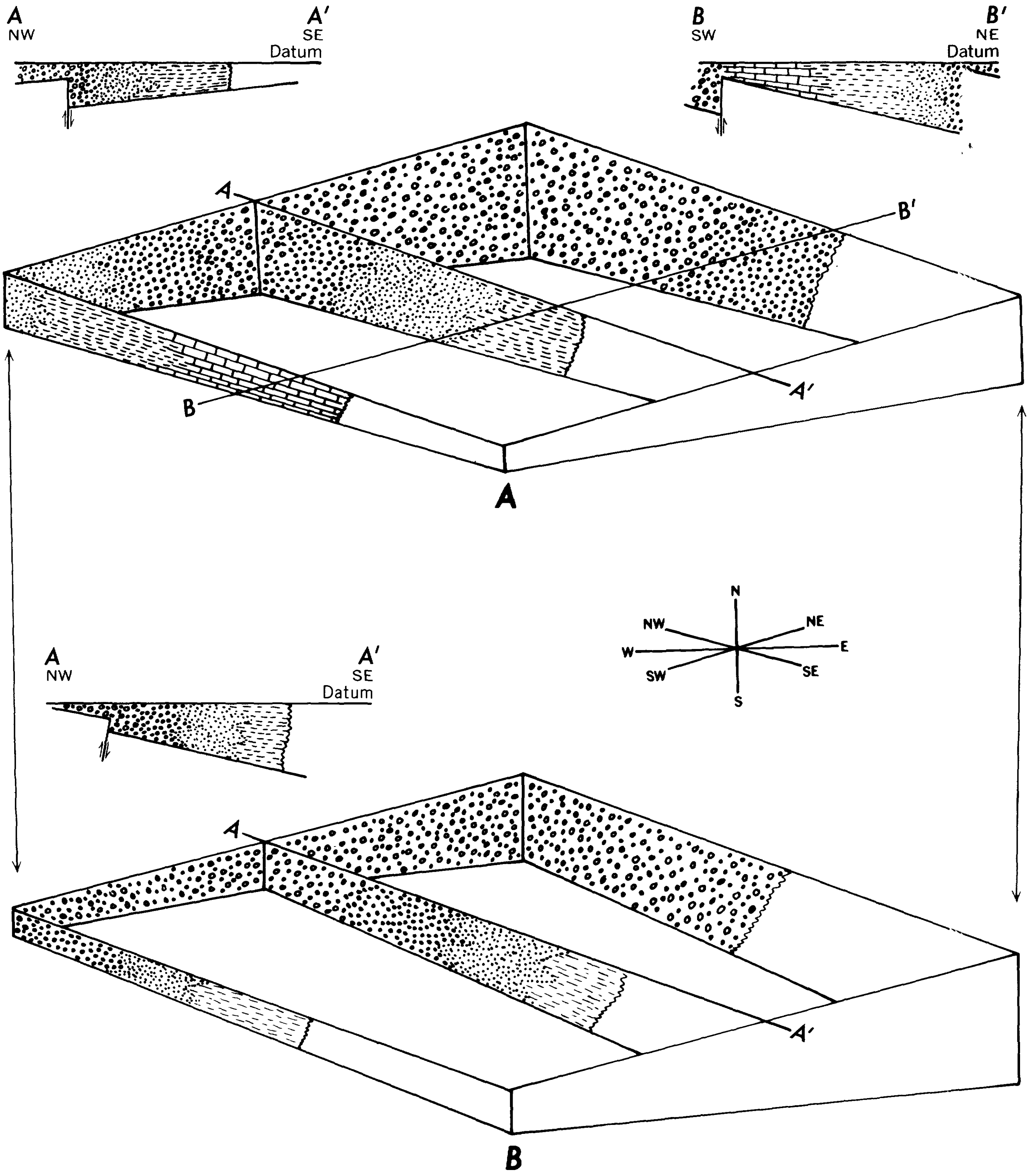


FIGURE 9.—The general sediment types and the depositional thickening patterns that are associated with the first-order tectonic stage (*A*) and with the second-order tectonic stage (*B*).

THE GEOGRAPHIC DISTRIBUTION OF SEDIMENTARY TROUGHS AND THE NATURE OF THEIR STRUCTURAL BOUNDARIES AND CROSS STRUCTURES BETWEEN NORTH CAROLINA AND LONG ISLAND, NEW YORK

During both first and second-order tectonic stages, sedimentary troughs are established on the surface of the unit-structural block. The long axes of troughs that are established during a first-order tectonic stage lie at an angle to the long axes of troughs that are established during a second-order tectonic stage. The structural boundaries of the troughs and zones of flexure, or of internal displacement, within the troughs are determined by the position of inferred crustal faults that are synonymous with elements of the hingebelt system. The troughs are fault troughs. The distribution of sedimentary troughs relative to the position inferred for the fault zones is illustrated diagrammatically in figure 6.

In the report area and during a first-order tectonic stage, two major sedimentary troughs are established on the surface of the block. They are arranged en echelon, are offset to the north, and their respective long axes strike northeast (fig. 6*A*). During a second-order tectonic stage, sedimentary troughs are formed during two sequential phases of crustal deformation. In the intial phase of deformation that precedes rupture, troughs form whose long axes lie parallel to the long axes of adjacent positive features. In a subsequent phase of deformation that accompanies rupture, troughs form whose long axes intersect the long axes of adjacent positive features. In the subsequent phase of trough development two sedimentary troughs are established on the surface of the unit-structural block. They are arranged en echelon, are offset to the northeast, and their respective long axes strike north and north-northwest (fig. 6*B*).

Elements of the fault-zone system and the structural blocks which they bound within the larger unit-structural block are identified by letter symbol in figure 6. The figure is useful in developing a conceptual understanding of the three-dimensional geology that we have mapped in the report area. The sense of inferred horizontal movement on the fault zones is indicated by conventional two parallel half-arrow symbols. The sense of inferred relative vertical displacement for crustal segments on the opposite sides of both shear and tensional fault zones is indicated by the letter E on the relatively elevated side and the letter D on the depressed side. Designation of relative vertical displacement does not imply that the fault zones extend to the land surface. They are inferred crustal fault zones that die out upward and that are recognized principally on the basis of both lateral and vertical discordance within the sedimentary mass. In the report area, the relative vertical displacement of crustal segments on opposite sides of the inferred fault zones seems to be expressed topographically as subdued fault-block anticlines or, more commonly, as asymmetrical or monoclinal flexures. It seems likely that a wide variety of both positive and negative structural configurations might result from recurrent horizontal movements on transcurrent fault zones as suggested by Chinnery and Petrak (1968, p. 523), particularly in those regions where wrench-fault zones intersect.

THE GEOMETRY OF SEDIMENTARY TROUGHS, FIRST-ORDER TECTONIC STAGE

During a first-order tectonic stage, for reasons discussed in the section "Analysis of the Mechanics of Deformation," two types of fractures, shear and tension, develop on the unit-structural block. The shear fractures strike northeast and are alined parallel with the block's complementary boundary shears. The horizontal component of movement on these fractures is left lateral. The tension fractures strike north and lie perpendicular to the block's east-west axis. In figure 6*A*, the lineaments designated $X–X'$, $Y–Y'$, and $Z–Z'$ indicate the approximate position of shear fractures, with $X–X'$ being a segment of the block's northwest boundary shear. The lineaments designated $U–U'$, $V–V'$, and $W–W'$ indicate the approximate position of tension fractures. The lineament designated $T–T'$ indicates the approximate position of a segment of a shear fracture that strikes northwest, the block's northeast boundary shear. The horizontal component of movement on this boundary shear is right lateral.

The relative vertical displacement of crustal segments that lie on the opposite sides of the northeast-striking shear fractures ($X–X'$, $Y–Y'$, and $Z–Z'$) is such that crustal segments on their southeast side are depressed relative to crustal segments on their northwest side. The relative vertical displacement of adjacent crustal segments results in the establishment of topographically subdued fault-block anticlines or asymmetrical flexures whose axes coincide with the northeast-striking planes of shear. Any two mutually adjacent fault-block anticlines or flexures that strike northeast bound half grabens that comprise regional sedimentary troughs. Depending upon their degree of topographic expression, the fault-block anticlines or flexures act as structural barriers that effectively separate two mutually adjacent sedimentary troughs or, more commonly, they act as sill-like structural barriers that provide a limited connection between mutually adjacent troughs.

In figure 6*A*, the crustal segments A, B, C, and D lie between two adjacent shear fractures designated by the lineaments *X–X′* and *Y–Y′*. They lie on the relatively depressed side of the fracture *X–X′* and on the relatively elevated side of the fracture *Y–Y′*. The structural form assumed by the combined segments (A through D) is that of a half graben and it mirrors the structural form of the unit-structural block. In a similar geometry, the crustal segments F and G lie between two adjacent shear fractures, designated by the lineaments *Y–Y′* and *Z–Z′*. They lie on the relatively depressed side of the fracture *Y–Y′* and on the relatively elevated side of the fracture *Z–Z′*. The structural form of the combined segments (F and G) also is that of a half graben and it too mirrors the structural form of the unit-structural block. The plunge of the long axes of positive and negative areas, superimposed on the unit-structural block, is toward the northeast, a direction that coincides with the dominant component of regional tilt established during a first-order tectonic stage as a result of vertical components of lateral movement on the northwest-striking master-shear set.

Two components of local tilt, northwest and southeast are characteristic of the half-graben structures. The component of tilt toward the northwest is intragraben in nature. It is established as a result of the relative vertical displacement of the opposite flanks of a half graben; the northwest flank is depressed relative to the southeast flank (fig. 6*A*). The component of tilt toward the southeast is intergraben in nature. The tilt is established as a result of the relative vertical displacement of laterally adjacent half grabens along a mutual shear boundary; that is, the half graben that lies on the southeast side of *Y–Y′* is depressed relative to the half graben that lies on the northwest side of *Y–Y′* (fig. 6*A*).

The north-striking tension fractures, *U–U′*, *V–V′*, and *W–W′*, lie athwart the structural-sedimentary half grabens at an angle of about 45°. They are cross fractures that determine the position of local axes of tilt (zones of internal displacement) in the northeast-striking half grabens. As shown in figure 6*A*, the relative vertical displacement of adjacent crustal segments that lie on the opposite sides of a tension fracture is such that a crustal segment on the eastern side of a fracture is depressed relative to a crustal segment on its western side; that is, segment B is depressed relative to segment A, segment C is depressed relative to segment B, and so forth. A local component of tilt toward the east is established as a result of the relative vertical displacement of crustal segments that lie on the opposite sides of tension fractures.

Along the northeast boundary of the unit-structural block, designated by *T–T′*, crustal sements D and I (on the block) are depressed relative to crustal segment E (external to the block). A local component of tilt toward the southwest results from this relative displacement.

In summary, local components of tilt are produced by the relative vertical displacement of crustal segments that lie on the opposite sides of fractures which strike northeast, north, and northwest respectively. The tilts toward the northwest and the southeast are produced by the relative vertical displacement of crustal segments that lie on the opposite sides of northeast-striking shear fractures (*X–X′*, *Y–Y′*, and *Z–Z′*, fig. 6*A*). The tilt toward the east is produced by the relative vertical displacement of crustal segments that lie on the opposite sides of north-striking tension fractures (*U–U′*, *V–V′*, and *W–W′*, fig. 6*A*). The tilt toward the southwest is produced by the relative vertical displacement of crustal segments that lie on the opposite sides of a northwest-striking shear fracture (*T–T′*, fig. 6*A*). The 12 stratigraphic units deposited during a first-order tectonic stage have a depositional configuration that is congruent with all or part of the structural surface shown in figure 6*A*.

THE GEOMETRY OF SEDIMENTARY TROUGHS, SECOND-ORDER TECTONIC STAGE

During the second-order tectonic stage, for reasons discussed in the section "Analysis of the Mechanics of Deformation," the deformation of the unit-structural block occurs in two phases, an initial phase that precedes rupture and a subsequent phase that accompanies rupture. Whereas the alinement of the axes of positive features remains the same during both phases, that of the negative features does not. The trough alinement that is characteristic of rupture is superimposed on the trough alinement that is characteristic of the prerupture phase of deformation.

In the initial phase of deformation, positive and negative compressional features develop on the block. These features (the Cape Fear arch, the Normandy arch, and the intervening Chesapeake-Delaware embayment) lie parallel to each other and their respective long axes strike northwest. In the subsequent phase of block deformation, the trough pattern that develops on the block is fracture controlled. A graben and a modified half graben form as a consequence of the relative vertical displacement of crustal blocks on the opposite sides of these fractures. The long axes of these negative structures stand tangential to the long axes of positive features established during the prerupture phase of deformation (fig. 4).

For the five stratigraphic units of the second-order tectonic stage, available well data are insufficient to estimate at what point in their depositional history the fracture-controlled trough pattern developed. We will limit further discussion of the structural-sedimentary trough system, characteristic of a second-order tectonic stage, to that part which develops in response to the deformation that accompanies rupture of the unit-structural block.

In this tectonic stage, for reasons discussed in the section "Analysis of the Mechanics of Deformation," two types of fractures, shear and tension, are established on the unit-structural block at the time of its rupture. The shear fractures strike north and the tension fractures strike northeast (pl. 1*B*).

In figure 6*B*, the lineaments designated *U–U′*, *V–V′*, and *W–W′* indicate the approximate position of north-striking shear fractures. The sense of horizontal movement on these fractures is judged to be left lateral. The lineaments designated *X–X′*, *Y–Y′*, and *Z–Z′* indicate the approximate position of northeast-striking tension fractures. The lineament *X–X′* also is a segment of the northwest-boundary shear zone of the unit-structural block. The lineament designated *T–T′* is a segment of the northeast-boundary shear zone of the unit-structural block. During a second-order tectonic stage, no horizontal movement is manifest along this boundary shear zone and we consider it to be dormant or frozen.

The relative vertical displacement of crustal segments that lie on the opposite sides of the north-striking shear fractures does not seem to be a vertical component of lateral movement on the fractures but is induced by local deformation. These fractures stand tangential to either the Cape Fear arch or the Normandy arch, respectively (fig. 6*B*). Along these fractures, crustal segments on the sides adjacent to the structural arch are uplifted relative to crustal segments on the opposite sides of the fractures. Along *U–U′*, crustal segments A and F are uplifted relative to crustal segments B and G; along *V–V′*, crustal segments C and H are uplifted relative to crustal segments B and G; and along *W–W′*, crustal segments C and H are uplifted relative to crustal segments D and I.

As shown in figure 6*B*, crustal segments B and G are depressed along the fractures *U–U′* and *V–V′* relative to the crustal segments on the opposite sides of these fractures. Segments B and G comprise a graben, whose long axis strikes north, that stands tangential to the Cape Fear arch and to the Normandy arch, respectively. Crustal segments D and I, depressed relative to segments C and H, also are depressed relative to segment E along the fracture *T–T′*. The relative vertical displacement along this latter fracture is residual. It develops during a first-order tectonic stage and carries over into a second-order tectonic stage as an inactive component of displacement. During a second-order tectonic stage, crustal segments D and I comprise a modified half graben that stands tangential to the Normandy arch.

Two components of local tilt, east and west, develop in response to the relative vertical displacement of adjacent crustal segments that lie on the opposite sides of the north-striking hingebelt zones. Along *U–U′* and *W–W′* the local tilt is east, whereas along *V–V′* the local tilt is west.

During a second-order tectonic stage and for reasons given previously, the southeast component of regional tilt is the dominant component. This component is manifest along the tensional hingebelt zones (*X–X′*, *Y–Y′* and *Z–Z′*, figure 6*B*) where, as inferred from the geometry of the sediment mass, crustal segments on the southeast side of these zones are depressed relative to adjacent segments on their northwest side. However, because these tensional zones lie athwart the long axes of both positive and negative structures, the degree to which the southeast component of regional tilt is developed locally varies along different segments of these zones. The tilt is developed to a greater degree where the tensional hingebelt zones (axes of flexure) lie athwart the troughs and to a lesser degree where the zones lie athwart the arches.

In summary, east or west components of local tilt are manifest along shear-type hingebelt zones (*U–U′*, *V–V′*, and *W–W′*, fig. 6*B*) that strike north. A southeast component of regional tilt is manifest along tensional-type hingebelt zones (*X–X′*, *Y–Y′*, and *Z–Z′*, fig. 6*B*) that strike northeast. The five stratigraphic units associated genetically with a second-order tectonic stage have a depositional configuration that is congruent with all or part of the structural surface shown in figure 6*B*.

STRATIGRAPHIC FRAMEWORK

GENERAL DISCUSSION AND REVIEW

The language and sense of stratigraphic interpretation along the east coast of the United States are rooted historically in stratigraphic concepts associated with vertical components of movement and lateral continuity and not with lateral components of movement and lateral discontinuity. Some of this language may be adapted to stratigraphic interpretation associated with lateral components of movement, but the adaptation for comparative purposes requires significant redefinition and qualification of many terms of the language. Many stratigraphic terms that have been used to describe the geologic framework of the Atlantic region either originated in or were applied previously in the adjacent Gulf region that is characterized by vertical components of movement. Therefore, the actual or implied meaning of stratigraphic terms is consistent with rock-stratigraphic and biostratigraphic relationships that are associated with vertical movement. When these terms—and the nomenclatural terms especially—are used in the Atlantic region, where rock-stratigraphic and biostratigraphic relationships are associated with both lateral and vertical components of movement, ambiguity may be avoided by drawing contrasts between essentially contemporaneous geologic units and the manner in which they were emplaced in the adjacent regions. Such contrasts are developed frequently throughout this report.

Commonly and in a comparative sense, the gross differences in structure and stratigraphy in the two adjacent regions have been attributed to differences in relative vertical movement. Cumulative subsidence in the Gulf region has been considered to be much greater than that in the Atlantic region. The concept of relative differential subsidence has been accompanied by the assumption that a significantly greater thickness of Mesozoic and Cenozoic sediments occurs in the Gulf region than in the Atlantic region. Various estimates have been made concerning the maximum thickness attained by sediments in the two regions. Thicknesses given by Murray (1961), 40,000 to 50,000 feet for the Gulf region and 20,000 to 25,000 feet for the Atlantic region, probably represent an average of the other estimates and would indicate a relative sediment thickness ratio of about 2:1 for the Gulf and Atlantic regions. We suggest that there may be little significant difference in the maximum thickness of sediments in the two regions and that sediments in the Atlantic region may attain a thickness somewhat in excess of 45,000 feet. This estimate for maximum sediment thickness is based upon extrapolation of onshore thickening trends for stratigraphic units, that are recognized in North Carolina, into offshore areas, adjacent to the unit-structural block's northeast boundary shear. The estimate is not incompatible with seismic evidence in the offshore area south of New England. No rock type or rock surface such as "basement" has a characteristic velocity. Geophysical results that are interpreted geologically depend upon the geologic model that is assumed in making the interpretation. For reasons that were discussed in the section "Regional Components of Tilt," some stratigraphic units thicken predominantly toward the northeast whereas others thicken predominantly toward the southeast. Overall, the resultant direction for the depositional thickening of sediments is towards the east. Differences in the maximum thickness attained by sediments in the two provinces seem to be related to time of deposition. The variable rates of mobility, inferred from rates of sedimentation observed in the two regions, seem to be related to different types and times of deformation but not necessarily to different amounts of deformation.

From the extrapolation of known data, sediment fill of early Mesozoic age seems to be greater than that of late Cenozoic age in the Atlantic region, whereas sediment fill of late Cenozoic age seems to be greater than that of early Mesozoic age in the Gulf region, if the sediment thickness is measured along the Louisiana coast. In a comparative time sense, the chief development of the Atlantic region as a depositional basin seems to parallel the early development of the Gulf Interior Basin (see Murray, 1961, fig. 6.2a). Offshore segments of the Atlantic basin, therefore, might be expected to contain a thick sedimentary section that corresponds in age to pre-Jurassic and Jurassic sediments of the Gulf region—the Eagle Mills to Cotton Valley sequence and including, perhaps. some younger early Coahuilan equivalents (see Murray, 1961, p. 278, fig. 6.1). The basal stratigraphic unit (Unit I) that we have recognized in onshore wells within the report area is judged to be Jurassic in age.

The conceptual understanding of the geologic framework of the Atlantic region has been influenced by several obvious links between Gulf-region stratigraphic concepts and Atlantic-region stratigraphic interpretations. One such link concerns the common practice of assuming a similar mode of origin for interregional sedimentary units that have an indicated or suggested time equivalency. Another is the converse assumption of a time equivalency for interregional sedimentary units that have a similar mode of origin and which occupy a similar position in the stratigraphic column. One result of this practice has been the assumption of interregional isochroneity along strike for purposes of correlation. An example is the correlation of the Tuscaloosa Formation of Gulf region and Atlantic region usage. The assumption has been made also that broad regional onlap and offlap sequences associated with cyclic phenomena, transgression and regression, occurred in phase in both regions. The assumption has been linked to concepts of interregional or eustatic changes in sea level which, presumably, were induced by synchronous diastrophism or some other causative force which is unknown but had common effects on sedimentation in both regions. This method of geologic correlation in the Atlantic province seems to have developed, a priori, as one of those assumptions that seem intuitively acceptable—if not embarrassed by abundant facts.

The geologic recognition of a "type" or standard reference section, together with the establishment of certain boundary criteria for many Gulf region stratigraphic units, is related to and defined by the periodicity of cyclic phenomena, transgression and regression, that swept across areas of the Gulf region (see descriptions by Murray, 1961, p. 227–477). The regional and subregional occurrences of these phenomena have been attributed to changes occurring in a quasi-balanced system of uplift and subsidence and seem to be related to an excess of sediment relative to subsidence, for regression, and to a deficency of sediment relative to subsidence, for transgression (Rainwater, 1964). The stratigraphic nomenclature of the Gulf region has become coupled with the cyclic phenomena in common usage, as for example, Jackson (transgression) and Sabine (regression). As these and similar stratigraphic terms were extended into the Atlantic region to denote a degree of interprovincial time equivalency, the concept of a transgressive or regressive manner of emplacement, that was associated with specific stratigraphic units in the Gulf region, accompanied the introduction of the unit name into the Atlantic region. Perhaps more than any other one contributing factor, this type of interregional conceptual association, applied to geologic correlations throughout the Atlantic region and in all segments of the geologic column, has up to the present time thwarted factual interpretation of the eastern margin of the United States south of New England in terms of its own geology.

The broad regional concepts, and many of the local nuances associated with the transgressive and regressive cycling of sediments in response to vertical components of movement in a system dominated by gravity deformation, have been concisely presented and argued for many geologic provinces throughout the world (see Beloussov, 1962) and for the Gulf region in particular (see Murray, 1961, and Rainwater, 1964, 1968). Characteristically, these presentations and arguments include three major elements—the lithic description, the geometry of distribution, and the proposed relative time-rate of migration, upbasin or downbasin, for a linked series of environmentally controlled sedimentary units. From place to place, as local depocenters shift either seaward or landward and expand or contract in response to changes in a state of balance between subsidence and sediment input, a considerable lateral shifting of both source and depositional areas may have occurred along the peripheral landward margin of the regional basin. However, the regional directions, upbasin (landward) and downbasin (seaward), are considered to remain essentially constant during successive cycles of deposition, with the result that the strike and dip of younger strata are in general accord with the strike and dip of older strata within the province, at least in a broad regional sense.

The sedimentary geometry of the Atlantic region always has been interpreted according to this same concept, wherein an upbasin direction (NW.) and a downbasin direction (SE.) remained constant as subsidence of the coastal margin progressed. This concept has been accompanied by the assumption that Mesozoic and Cenozoic rocks in the province comprise a monoclinal wedge of sediments, which strike northeast and dip southeast, both in a depositional and in a structural sense. These directions of regional strike and regional dip have governed stratigraphic interpretation within the province. However, and for reasons that we have discussed previously, regional geologic units that comprise the stratigraphic succession within the province do not have this assumed constancy either in their areas of occurrence or in their directions of depositional strike and dip as shown by the internal geometry of the onshore sediment mass. This lack of constancy indicates that the directions, upbasin and downbasin, had variable rather than constant azimuths during successive depositional cycles. Therefore, time relations and stratigraphic interpretations that are based upon a concept of fixed azimuths for these directions should be revised.

CORRELATION FRAMEWORK

Correlation charts commonly are used for the synthetic depiction of chronologic reference in stratigraphic interpretation. Charts may include both formally designated stratigraphic units and informally designated working units.

Comparison of the structural geometry and sedimentary framework for different parts of the Atlantic province discloses significant differences in basic structural form. These differences are manifested in widths of coastal plains, their landforms and shoreline configurations, and in the types, distribution patterns, and thicknesses of their component sediments. Structural form is the paramount control upon the degree of lithologic or biologic equivalency that may or may not prevail, either within or between provinces, because it determines the position and areal extent of depositional environments. In order to make time-space comparisons between depositional sequences in the two regions, the sequences must be related to each other within some framework of common chronologic reference. This reference or correlation framework must illustrate rock equivalency and superposition, but it must also be cognizant of the structural control that has influenced them.

The regional correlation framework and its current nomenclature that have been established to record the equivalence of rock strata and the order of their occurrence along the east coast of the United States owe their parentage to both the Atlantic and the Gulf regions. Gulf-oriented terminology, with one connotation as to rock and time-rock meanings, has been integrated with Atlantic-oriented terminology, with a different connotation as to rock and time-rock meanings. Thus an illegitimate framework of correlation has been formulated whose nomenclature reflects undefined antecedents and ambiguous rock, time-rock, and time equivalencies. If the geologic events themselves are not ambiguous, they have been made to seem so by the attempt to record and synthesize them within an unnatural and artifically contrived grouping of equivalencies rooted to a concept of gravity deformation.

Professor Grover E. Murray, who long has been identified with the more practical aspects of stratigraphy in the Gulf and Atlantic provinces, recognized the impracticality of certain aspects of synthetic grouping in regional stratigraphic work when he stated (1961, p. 279) "It seems fundamental that a clear image of the stratigraphic and historical record is possible only from a distinct conceptual and working separation of time, time-rock, rock, and biologic units." In 1961, Murray's analysis of stratigraphy in the Gulf and Atlantic regions, which he described as segments of one coastal province, established this separation by use of the provincial stage to designate a provincial time-rock unit comprising a subdivision of a series. This usage replaced the dual rock and time-rock usage commonly associated with the term "group" in stratigraphic interpretation within the region. Murray referred to the provincial stage as the basic chronostratigraphic unit in the Gulf and Atlantic segments of the coastal geosyncline. He defined the provincial stage as encompassing strata that had the same or different lithologies and which were judged to be isochronous. We have followed this concept in establishing an order of occurrence for 17 chronostratigraphic units mapped in the report area. The boundaries of these units may coincide with the boundaries of rock-stratigraphic units in a given area and the intervals of time which they represent may be defined paleontologically.

As has been pointed out previously by many investigators, a clearly recognized degree of lithologic and biologic equivalency exists between the Gulf and the Atlantic regions. However, the degree of equivalency is subject to question and review as new data become available. The stratigraphic nomenclature in vogue at any one time reflects changing ideas about the degree of lithologic and biologic equivalency and contrast that is recognized.

Two contrasting methods of correlation have characterized efforts to systematize the subsurface stratigraphy within the Atlantic region. One method has consisted of the lateral extension of chronostratigraphic units from the Gulf region into the Atlantic region to include subsurface rocks of the same or different lithology that apparently are correlative. The other method has consisted of projecting outcropping lithic units into the subsurface. Neither method, either by itself or in combination, has been entirely satisfactory.

Lateral extension of chronostratigraphic boundaries from the Gulf region into the Atlantic region is a satisfactory method for establishing interregional correlation as long as these boundaries coincide with physical changes reflected in the rocks of the Atlantic region. When the physical change reflected in rocks of the Atlantic region is out of phase with the physical change reflected in rocks of the Gulf region, the interregional extension of chronostratigraphic boundaries is not practical. During Cenozoic time, the physical changes reflected in the rocks of the two regions seem to be sufficiently in phase to warrant extension of chronostratigraphic boundaries from the Gulf region into the Atlantic region. Because Mesozoic chronostratigraphic boundaries, when extended from the Gulf region into the Atlantic region, do not coincide with physical changes reflected in the Mesozoic rocks of the Atlantic region, we have, for practical purposes, not applied the Mesozoic stage terms of the Gulf region to the Atlantic sequence at this time. Their approximate relation to chronostratigraphic nomenclature of the Gulf region is shown on plate 2. As additional data become available, more precise placement of the Atlantic Coastal Mesozoic units (A–I) into the Gulf chronostratigraphic framework will be possible.

Projection of lithic units that are recognized in outcrop into the subsurface within the Atlantic region is not advisable. Criteria available for the recognition and separation of many outcropping geologic units are quite local, and they should not be used to extend units a significant distance into adjacent subsurface sections. In the past, the extension into the subsurface of many local surface formations has been premature and has led in many instances to a totally unrealistic juxtaposition of sedimentary facies in a supposed dip direction. In our judgement, the historical concept of the region's structural framework and its effect on sediment distribution, accompanied by inaccuracy in the establishment of time and rock equivalencies, negates use of the correlation framework currently in vogue along the east coast of the United States if any reasonably accurate interpretation of the subsurface geologic relationships is to be achieved.

Because of the inaccuracies which result from the use of the prevailing correlation framework as a vehicle for expressing either the equivalency or the superposition of the province's subsurface geologic units, we propose that it be modified. We use 17 regional chronostratigraphic units. We propose an informal classification for the Mesozoic part of the geologic column. It consists of letter designations, I to A, for nine regional geologic sequences that range from Jurassic(?) to Late Cretaceous in age. These lettered geologic sequences constitute informal chronostratigraphic sequences of regional extent containing a lithology or lithologies judged to be of the same age. In general the boundaries of these units coincide with the boundaries of depositional sequences that are recognized in the project area. A type reference section in the subsurface (pl. 3) is designated for each unit for purposes of objective reference. The informal rather than the formal designation of these units in no way interferes with utility insofar as their description and cartographic presentation are concerned. A more formal designation of these units by selection of a name would be premature until investigative work in the southern part of the project area has been completed, until the density of wells in the region provides much more subsurface data than are now available, and until the relation of these units to formally designated geologic units now recognized in areas of outcrop is better established. In the meantime, the informal or open-end nomenclature used to designate geologic units of Mesozoic age seems to offer descriptive flexibility and maximum utility for purposes of describing the stratigraphic geometry that we observe in the region.

In this report the nomenclatural designation of Cenozoic rock sequences follows, with some modification, that used by Murray (1961) in which he extended chronostratigraphic boundaries from the Gulf region into the Atlantic region. Eight units of Cenozoic age have been mapped in the subsurface during the present study. They include rocks that range in age from Midwayan to post-Miocene.

The 17 regional units mapped in the report area are listed and their approximate relation to the chronostratigraphic framework of the Gulf region is indicated on the correlation chart (pl. 2). The superposition and the boundaries of these regional units were established in wells that penetrated "basement" and which are chiefly in the ocean-bordering tier of counties in eastern North Carolina. In that area diagnostic marine sections are more numerous, more uniform, and thicker than in other sections of the report area. Following the delineation of these sequences in key wells, they were extended into other deep wells adjacent to the ocean in the Middle Atlantic States. The sequences were then extended into succesively more shallow wells and toward the inner margin of the Coastal Plain. The lateral and updip extension of these sequences was based upon lithologic continuity, lithologic association, and faunal control as interpreted from the study of well cuttings which was supplemented by interpretation of borehole geophysical logs. Correlation is consistent with the boundaries of depositional sequences throughout the region of study. Correlation is consistent with, but not necessarily bounded by, faunal control that was established chiefly from the occurrence and identification of Ostracoda, supplemented by the identification of Foraminifera, in cores and cuttings. In several instances correlation of Mesozoic rocks was aided by palynologic identifications and interpretations that were made available to the project by the personnel of Chevron Oil Co., Jackson, Miss.

Evaluation of the geohydrologic interpretations in published reports for the area, supplemented by preliminary study of well cuttings and geophysical data upon which the geologic interpretations in these reports are based, revealed certain inconsistencies with respect to construction of a regional geohydrologic framework. These inconsistencies disclosed the need for a complete restudy of the basic subsurface geologic data for the region. Accordingly, before making the interpretations expressed in this report we examined the cores, cuttings, geophysical data, and biological data that were available for more than 2,200 wells in the report area. Some of these data, obtained from 209 wells that are considered to be key wells, appear on 36 geologic cross sections (pls. 23–59).

Paleontologic support for the lithologic correlations is derived chiefly from identification and zonation of Ostracoda and, to a much lesser extent, from identification of Foraminifera. Commonly, Ostracoda occur more frequently and abundantly than do Foraminifera in the well cuttings and cores examined because of the marginal marine nature of much of the sedimentary section. The Ostracoda and Foraminifera listed in table 2 are easily recognized and widely distributed species found in the subsurface. We consider these species to be characteristic of the regional rock sequences mapped.

The identification and zonation of the Ostracoda obtained from many of the key wells were undertaken chiefly by F. M. Swain. He prepared lists that identified the various Ostracoda, established their probable biostratigraphic range, and gave the depth at which they occurred in well sections. Project personnel selected various Foraminifera as being representative of depositional sequences in local areas. Thomas G. Gibson made specific identification of many of the Foraminifera. Project personnel made other identificatons.

Faunal, structural, lithologic and geophysical data were considered and evaluated in making the stratigraphic interpretations. In general, the boundaries of biostratigraphic units coincide with the boundaries of lithostratigraphic units.

In this report, paleontologic identifications are made solely for the purpose of establishing a regional permeability-distribution network. No complete listing is given of the Ostracoda or Foraminifera, that were identified in each well section. The various Ostracoda and Foraminifera, and the listing of their occurrence in specific wells, are available for examination at the project office in Raleigh, N.C.

A supplementary paleontological report, "Some Lower Cretaceous, Jurassic(?), and Triassic Ostracoda from the Atlantic Coastal Region, for use in Hydrogeologic Studies," by Swain and Brown (1972) describes and illustrates characteristic Ostracoda of Cretaceous and Jurassic(?) age that were obtained from 46 of the wells used to prepare this report. In the supplementary report, the discussion of the subsurface distribution of Ostracoda, with respect to given wells and well depths, is facilitated by making parenthetic reference to the cross sections in this report. The two reports are companion reports, each of which supplements the basic data presented separately in the other report.

The regional geologic cross sections (pls. 23–58) lack space in which to list or spell out the names of all the characteristic species that were identified in cuttings from any given section of a borehole. Therefore, on the cross-section sheets we show only the first (highest) occurrence of one or more characteristic species, some of which may occur commonly in a given well section. A combination letter-number symbol identifies the species on the cross-section sheets. The species are listed in table 2, together with their identifying letter-number symbol. Rarely, a species characteristic of a given stratigraphic unit regionally may occur also in a younger stratigraphic unit locally. In this event, the same species may be shown on the cross sections as occuring twice in the same borehole—once according to its highest occurrence in the unit for which it is characteristic and, again, according to a noncharacteristic occurrence in a younger unit.

Swain established the paleontological zonation of the Ostracoda that is utilized in this report. In the regional distribution pattern of the Ostracoda, he recognizes both assemblage zones and concurrent range zones. The following definitions of these zones are quoted from a project report prepared by Swain.

The *Assemblage Zone* is based on two or more species that comprise a group of stratigraphically useful, rather abundant, easily recognizable forms that are typically preceded and succeeded in time by other groups of species, but are of restricted geographic distribution, and may also occur in marine and non-marine or other biofacies. The *Concurrent-Range Zone* is established by one or more species that are the same, or different, in their vertical ranges (which may or may not exactly coincide with the established zone boundaries), are common and easily recognizable, and are more widespread in distribution than those of the Assemblage Zone. Inter-regional correlation may be based on Concurrent-Range Zones but not commonly on Assemblage Zones, Localized subzones of Concurrent-Range Zones are here referred to as Assemblage Subzones. Localized subzones of Assemblage Zones are referred to as Subzones. Assemblage Zones are based on endemic species, whereas Concurrent-Range Zones are based on migratory species.

TABLE 2.—*Ostracoda and Foraminifera designated on the cross-section sheets as being characteristic of the chronostratigraphic units mapped*

Cross-section symbol	*Fossil*
Late Miocene unit:	
LM–1	*Aurila conradi* (Howe and McGuirt)
2	*Trachyleberis exanthemata* (Ulrich and Bassler)
Middle Miocene unit:	
MM–1	*Cytheretta spencerensis* Smith
2	*Murrayina gunteri* (Howe and Chambers)
3	*Cibicides concentricus* (Cushman)
4	*Siphogenerina lamellata* Cushman
5	*Robulus americanus* (Cushman) var. *spinosus* (Cushman)
6	*Spiroplectammina mississippiensis* (Cushman)
7	*Uvigerina calvertensis* Cushman
Vicksburgian-Chickasawhayan unit:	
OL–1	*Leguminocythereis* cf. *L. scarabaeus* Howe and Law
2	*Aurila* cf. *A. kniffeni* Howe and Law
3	*Cytheromorpha* cf. *C. vicksburgensis* Howe
4	*Cushmanidea* cf. *C. vicksburgensis* (Howe)
5	*Eucytherura* sp. aff. *E. mariannensis* Weingeist
6	*Pararotalia* cf. *P. byramensis* (Cushman)
7	*Nonion advenum* (Cushman)
8	*Gaudryina jacksonensis* Cushman
9	*Textularia subhauerii* Cushman
10	*Uvigerina vicksburgensis* Cushman and Ellisor
11	*Discorbis* cf. *D. alveata* Cushman
Jackson Stage:	
J–1	*Bulimina jacksonensis* Cushman
2	*Angulogerina danvillensis* Howe and Wallace
3	*Plectofrondicularia virginiana* Cushman and Cederstrom
4	*Cibicides speciosus* Cushman and Cederstrom
5	*Cibicides sculpturatus* Cushman and Cederstrom
6	*Siphonina tenuicarinata* Cushman
7	*Actinocythereis gibsonensis* (Howe and Garrett)
Claiborne Stage:	
ME–1	*Actinocythereis davidwhitei* (Stadnichenko)
2	*Acanthocythereis*? *stenzeli* (Stephenson)
3	*Hermanites rukasi* (Gooch)
4	*Hermanites pellucinoda* (Swain)
5	*Hermanites* sp. aff. *H. pellucinoda* (Swain)
6	*Hazelina couleycreekensis* (Gooch)
7	*Marginulina cooperensis* Cushman
8	*Asterigerina texana* (Stadnichenko)
9	*Cibicides westi* Howe
10	*Cibicides danvillensis* Howe and Law
Sabine Stage:	
LE–1	*Haplocytheridea leei* (Howe and Garrett)
2	*Trachyleberidea goochi* (Swain)
3	*Subbotina inaequispira* (Subbotina)
4	*Globorotalia wilcoxensis* Cushman
5	*Pseudohasterigerina wilcoxensis* (Cushman)
Midway Stage:	
P–1	*Opimocythere marylandica* (Ulrich)
2	*Brachycythere plena* Alexander
3	*Hazelina* cf. *H. aranea* (Jones) subsp. *A.*
4	*Hermanites midwayensis* (Alexander)
5	*Hermanites gibsoni* Hazel

TABLE 2.—*Ostracoda and Foraminifera designated on the cross-section sheets as being characteristic of the chronostratigraphic units mapped*—Continued

Cross-section symbol	Fossil
Midway Stage—Continued:	
P–6	*Acanthocythereis princegeorgensis* Hazel
7	*Globorotalia pseudomenardi* Bolli
8	*Globorotalia aequa* Cushman and Renz
9	*Gaudryina mcleani* Hofker
10	*Vaginulinopsis(?) crisfieldensis* McLean
11	*Pseudouvigerina* cf. *P. naheolensis* Cushman and Todd
12	*Anomalinoides midwayensis* (Plummer)
13	*Robulus midwayensis* Plummer
14	*Citharina plummoides* Plummer
Cretaceous Unit A:	
A–1	*Brachycythere rhomboidalis* (Berry)
2	*Veenia arachoides* (Berry)
3	*Amphicytherura copicosta* Crane
4	*Anomalina pseudopapillosa* Carsey
5	*Anomalina rubiginosa* Cushman
6	*Tritaxia trilatera* (Cushman) Cushman
7	*Robulus navarroensis* (Plummer)
8	*Dorothia* cf. *D. bulleta* (Carsey) Plummer
Cretaceous Unit B:	
B–1	*Brachycythere sphenoides* (Reuss)
2	*Cythereis gapensis* (Alexander)
3	*Veenia paratriplicata* (Swain)
4	*Henryhowella* cf. *H. spoori* (Israelsky)
5	*Cythereis* cf. *C. plummeri* Israelsky
6	*Cythereis bicornis* Israelsky
7	*Cythereis bicornis levis* Crane
8	*Microcosmia* cf. *M. rogersensis* Crane
9	*Globorotalites conicus* (Carsey)
10	*Planulina dumblei* (Applin)
11	*Kyphopyxa christneri* (Carsey)
12	*Bolivinoides decorata* (Jones) var.
Cretaceous Unit C:	
C–1	*Brachycythere nausiformis* Swain
2	*Citharina texana* (Cushman)
3	*Planulina austiniana* Cushman
Cretaceous Unit D:	
D–1	*Cythereis ornatissima* (Reuss)
Cretaceous Unit E:	
E–1	*Cythereis eaglefordensis* Alexander
2	*Cythereis fredricksburgoides* Swain and Brown
3	*Cytheropteron eximum* Alexander
Cretaceous Unit F:	
F–1	*Fossocytheridea lenoirensis* Swain and Brown
2	*Eucythere semiglypta* Swain and Brown
3	*Cythereis* cf. *C. dentonensis* Alexander
4	*Epistomina* cf. *E. charlottae* Vieaux
5	*Coskinolinoides texanus* Keijzer
Cretaceous Unit G:	
G–1	*Schuleridea hatterasensis* Swain
2	*Asciocythere rotunda* (Vanderpool)
3	*Asciocythere triangularis* Swain
4	*Eocytheropteron trinitiensis* (Vanderpool)
5	*Eocytheropteron tumoides* (Swain)
6	*Fabanella lanceolata* (Swain)
7	*Fabanella leguminoidea* (Swain)
8	*Cypridea (C.) wyomingensis* Jones

TABLE 2.—*Ostracoda and Foraminifera designated on the cross-section sheets as being characteristic of the chronostratigraphic units mapped*—Continued

Cross-section symbol	Fossil
Cretaceous Unit G—Continued:	
G–9	Chara seeds (plant fossils—Gyrogonites of the Charophyta *Clavator harrisi* Peck and *Atopochara trivolis* Peck)
Cretaceous Unit H:	
H–1	*Fabanella tumidosa* (Swain)
2	*Hutsonia collinsensis collinsensis* Swain and Brown
3	*Hutsonia blandoidea* Swain and Brown
4	*Schuleridea* cf. *S. acuminata* Swartz and Swain
5	*Schuleridea* cf. *S. pentagonalis* Swartz and Swain
6	*Paraschuleridea curta* Swain and Brown
7	*Otocythere* sp. Swain and Brown
8	*Choffatella decipiens* Schlumberger

CONSTRUCTION OF GEOLOGIC MAPS AND CROSS SECTIONS

Structure-contour, isopach, and line-isolith maps constitute the subsurface geologic maps in this report. The maps, together with 36 stratigraphic cross sections, were constructed to show both the horizontal and vertical relations among the 17 chronostratigraphic sequences mapped. The data obtained from more than 2,200 wells were evaluated prior to constructing the maps and cross sections. From this group, 580 were selected as key wells from which the data were most representative of local subsurface geologic conditions. The key wells constitute the principal control points where quantitative data were obtained and used to construct the maps and cross sections. The locations for key wells are shown on plate 4.

In the text and on the cross sections, wells are identified according to the State and county in which they are located, according to the type of well which they represent, and according to an assigned project number. The wells are further identified by their coordinates of latitude and longitude on stratigraphic cross sections. For practical reasons, the names of States and counties are abbreviated in well citations. The abbreviations for the States are those commonly used. The abbreviations used for the counties are as follows:

North Carolina

County		County	
Beaufort	BEA	Craven	CR
Bertie	BER	Cumberland	CUM
Bladen	BL	Currituck	CUR
Brunswick	BR	Dare	DA
Camden	CAM	Duplin	DU
Carteret	CAR	Edgecombe	ED
Chowan	CHO	Gates	GA
Columbus	COL	Greene	GR

North Carolina—Continued

County		*County*	
Halifax	HAL	Pasquotank	PAS
Hertford	HE	Pender	PEN
Hoke	HO	Perquimans	PER
Hyde	HY	Pitt	PI
Jones	JON	Richmond	RI
Lenoir	LEN	Robeson	RO
Martin	MAR	Sampson	SA
Moore	MO	Scotland	SC
New Hanover	NH	Washington	WAS
Northampton	NOR	Wayne	WAY
Onslow	ON	Wilson	WIL
Pamlico	PAM		

Virginia

County		*County*	
Accomack	AC	King George	KG
Caroline	CAR	King William	KW
Charles City	CC	Lancaster	LAN
City of Chesapeake[1]	CHE	Middlesex	MID
		Nansemond	NAN
City of Norfolk[1]	NOR	New Kent	NK
City of Portsmouth	POR	Northampton	NON
		Northumberland	NOD
City of Virginia Beach[1]	VB	Prince George	PG
		Prince William	PW
Essex	EX	Richmond	RI
Gloucester	GLO	Southampton	SO
Hanover	HAN	Surry	SUR
Henrico	HEN	Sussex	SUS
Isle of Wight	IW	Westmoreland	WES
James City	JC	York	YK
King and Queen	KQ		

Maryland

County		*County*	
Anne Arundel	AN AR	Prince Georges	PG
Calvert	CAL	Queen Annes	QA
Caroline	CAR	Somerset	SOM
Cecil	CEC	St. Marys	StM
Charles	CHA	Talbot	TAL
City of Baltimore[2]	BC	Wicomico	WIC
Dorchester	DOR	Worcester	WOR
Kent	KT		

Delaware

County		*County*	
Kent	KT	Sussex	SUS
New Castle	NC		

New Jersey

County		*County*	
Atlantic	AT	Gloucester	GL
Burlington	BU	Monmouth	MON
Camden	CAM	Ocean	OC
Cape May	CM	Salem	SAL
Cumberland	CU		

New York

County		*County*	
Nassau	NA	Suffolk	SUF

[1] Has replaced one or more counties as a political subdivision in the past several years.
[2] Political entity that is separate from Baltimore County.

Rock samples and geophysical data were obtained from four types of wells; producing water wells (P); stratigraphic test wells, not cored (T); stratigraphic test wells, cored (C); and wildcat oil wells (OT). The parenthetic letter symbols are those used for wells, cited in the text and on the cross sections, to designate the specific type of well. In the citations for individual wells, a number follows the letter symbol designating well type. The number is a project number, one of a sequence of numbers assigned to wells drilled in any one county and from which data were received during the project. A complete citation for a well, NC–DA–OT–10, indicates that the well is in North Carolina, in Dare County, that it is a wildcat oil well, and that it is the tenth well in Dare County from which data were received during the project.

For each of the 580 wells selected as key wells, a top and thickness were determined for each chronostratigraphic unit occurring and where applicable, the elevation of the top of the "basement" surface was determined. These basic interpretive data are assembled and listed in tables kept on file at the project offices in Raleigh, N. C. The tabular arrangement of the well data is according to the State and county in which each well is located. These basic geologic data are available also in automated form. Requests for these data should be sent to the Chief Hydrologist, U.S. Geological Survey, Washington, D. C. 20242. Each request should specify whether the data are desired in the form of printed tables, magnetic tape, or punch cards. The physical samples and original geophysical logs for wells used in our investigation generally are available in the offices of the respective State Geologists in the States where the wells are located.

The report contains 18 structure-contour maps. Both equal-spacing and interpretive-spacing methods were used to draw the contours. In addition to the structure-contour map of the basement surface (pl. 5), there is a structure-contour map drawn on the top of each of the 17 chronostratigraphic sequences mapped (pls. 7–22). The report contains 17 isopach maps, one for each of the 17 units mapped, on which are superimposed line-isoliths (pls. 7–22).

The report includes 36 regional stratigraphic cross sections (pls. 23–58) and one composite of several cross sections (pl. 59). The cross sections include 209 different wells. The lines of section are shown on plate 4. Within the constraints imposed by the availability of wells of suitable depth for which rock samples and geophysical logs were obtainable, the stratigraphic cross sections were constructed to illustrate regional rather than local relations among the chronostratigraphic sequences mapped. In order to combine an adequate presentation of sediment composition with an appropriate sense of geologic continuity, it was necessary to group shallow wells and deep wells on the same cross section in some instances. On these cross sections, this practice necessitated the use of dual vertical scales because of space limitations. Where dual scales are used, one well is shown twice; once at one vertical scale and again at the other vertical scale.

Discussion of the methods used to construct the line-isolith maps is covered in the section "Construction of the Relative Instrinsic-Permeability Networks.

The structure-contour, isopach, and line-isolith maps, together with the stratigraphic cross sections, constitute a quantitative three-dimensional presentation of the subsurface geology which we recognize in the region.

LITHOSTRATIGRAPHIC DESCRIPTION AND BIOSTRATIGRAPHIC DISCUSSION OF REGIONAL CHRONOSTRATIGRAPHIC UNITS

During the investigation, Miller prepared summary descriptions of lithostratigraphic units in the region and Swain prepared summary descriptions of biostratigraphic units. Each regional chronostratigraphic unit was determined by methods given on page 33. In this report, for practical reasons, the boundaries of the chronostratigraphic units have been made to coincide with the boundaries of rock-stratigraphic (lithostratigraphic) units. Generally, but not always, the boundaries of the chronostratigraphic units also coincide with the boundaries of biostratigraphic units.

In the following discussion of regional depositional sequences, the summary descriptions by Miller and Swain have been unified and amplified by the senior author, and certain changes have been made in the descriptions to establish consistency in the report's nomenclature.

MESOZOIC ERA

JURASSIC SYSTEM—ROCKS OF JURASSIC (?) AGE

UNIT I—ROCKS OF UNIT I

The strata of Unit I occur in only three wells: NC–DA–OT–10, where they are 708 feet thick; MD–WOR–OT–11, where they are 526 feet thick but were not fully penetrated; and NJ–CM–OT–1, where they are 39 feet thick. They are immediately overlain by the strata of Unit H, and in North Carolina (NC–DA–OT–10) and New Jersey (NJ–CM–OT–1) they lie on crystalline basement rock.

Unit I is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit I are shown on plate 6.

Lithologic description

In North Carolina the unit consists of coarse feldspathic sand that contains a minor amount of gravel and that is interlayered with thinly bedded red and green shale. In Maryland the unit consists predominantly of gray shale and a subordinate amount of green shale, brown shale, and fine feldspathic sand.

The lithologic character of representative sections in Unit I in Maryland and New Jersey is illustrated on geologic cross-section *R–R′* (pl. 40). Unit I is distinguished from Unit H by its larger amount of feldspar and by its characteristic electric-log pattern.

The reference section for Unit I (pl. 3) is 708 feet feet thick and is designated as the interval between 9,145 and 9,853 feet in NC–DA–OT–10, Cape Hatteras, N.C. The lithologic character of the reference section is illustrated on geologic cross-section *Z′–Z″* (NC–DA–OT–10, pl. 50).

Biostratigraphic discussion

No fauna was recovered from this unit. Its depositional environment is considered to be continental. On the basis of the fauna near the base of the overlying unit (Unit H), Unit I is judged, provisionally, to be Late Jurassic(?) in age.

JURASSIC AND CRETACEOUS SYSTEMS—ROCKS OF CRETACEOUS AND LATE JURASSIC(?) AGE

UNIT H—ROCKS OF UNIT H

Unit H occurs in wells from New Jersey through North Carolina but is absent in wells on Long Island, N. Y. The maximum measured thickness of Unit H was 2,072 feet in a well (MD–WOR–OT–11, pl. 35) near Ocean City, Md. The minimum measured thickness was 50 feet in a nonsection well (VA–SUS–T–6) near Homeville, Va. Unit H contains both marine and nonmarine sediments; they are chiefly marine in North Carolina and chiefly nonmarine in Virginia and northward. The transition from marine to nonmarine rocks is apparent if sections in adjacent wells in northeastern North Carolina and southern Virginia are compared; for example, compare the marine section in NC–CUR–OT–12 with the nonmarine section in NC–CAM–OT–10 (section *J–J′*, pl. 32) and the marine section in NC–CUR–OT–12 (section *J–J′*, pl. 32) with the nonmarine section in VA–NOR–T–12 (section *H–H′*, pl. 31).

The lithologic contrasts between Unit H and the overlying and underlying chronostratigraphic units are illustrated on the geologic cross sections. Unit H is associated genetically with a second-order tectonic stage. Structure and isopach-lithofacies maps for Unit H are shown on plate 7.

Lithologic description

Unit H is predominantly marine in eastern North Carolina and includes three distinct lithic units; a lower limy unit, a middle clastic unit, and an upper limy unit. The lithologic character of the "lower limy unit" is illustrated in NC–DA–OT–10 (pl. 50), be tween the depths of 8,485 and 9,145 feet, where it consists chiefly of dolomite and oolitic to sandy limestone, with some sand, shale, and anhydrite. The lithologic character of the "middle clastic unit" is illustrated in NC-HY-OT-11 (pl. 50), between the depths of 6,480 and 7,105 feet, where it consists of coarse to fine, sparsely feldspathic sand interbedded with red and green shale. The lithologic character of the "upper limy unit" is illustrated in NC-DA-OT-10 (pl. 50), between the depths of 7,735 and 8,170 feet, where it consists of fossiliferous sandy limestone, markedly oolitic in streaks, interbedded with red and brown sandy shale.

In Virginia and northward, Unit H is chiefly nonmarine, except in local areas adjacent to the ocean, and consists of fine to coarse sand, commonly feldspathic, interbedded with varicolored shale, chiefly red and brown. The lithology in this part of Unit H is illustrated in wells on section *M-M'* (pl. 35). In New Jersey, Unit H contains a greater percentage of medium to coarse sand and a lesser percentage of shale than in other areas of its occurrence.

In a regional sense, the strata of Unit H are distinguished from the strata of overlying and underlying units by their characteristic electric-log and gamma-log patterns and, where fossiliferous, by their contained Ostracoda. In North Carolina the strata are distinguished from those of overlying Unit G by their high incidence of lime. In Virginia and northward, the strata are more sandy and feldspathic and are less massively bedded than those of Unit G in areas where both chronostratigraphic units are present.

The reference section for Unit H (pl. 3) is 1,120 feet thick and is designated as the interval between 6,116 and 7,236 feet in NC-HY-OT-11, Pamlico Sound, N. C. The lithologic character of the reference section is illustrated on section *Z'-Z''* (NC-HY-OT-11, pl. 50).

Biostratigraphic discussion

Unit H is correlated with the upper part of La Casita Stage, the Durango Stage, the Nuevo León Stage, and the lower part of the Trinity Stage, undifferentiated, and their typical strata in the Gulf region. A Late Jurassic(?) age is suggested for beds in the lower part of Unit H. Ostracoda that suggest this biostratigraphic equivalence have been obtained from only two wells in the Coastal Plain. *Schuleridea* cf. *S. acuminata* Swartz and Swain and *S.* cf. *S. pentagonalis* Swartz and Swain were identified previously in the Hatteras Light well 1, North Carolina (NC-DA-OT-10), from depths of 9,100 to 9,116 feet (Swain, 1952). A Late Jurassic(?) age is suggested for these beds because the two species occur in and, insofar as known, are restricted to the marine facies of the Late Jurassic Schuler Formation of northern Louisiana (Swartz and Swain, 1946). On the basis of this interregional distribution the *Schuleridea* cf. *S. acuminata* Concurrent Range Zone is established for the deposits containing the two species.

The Anchor Gas Co. Dickinson well 1, near Cape May, N. J. (NJ-CM-OT-1), yielded *Otocythere* sp. from depths of 6,060 to 6,070 feet. Judged from occurrence of similar forms in the Jurassic of Europe (Triebel and Klingler, 1959), the species inhabited brackish waters. A structurally similar form, *Looneyella* Peck, occurs in freshwater Lower Cretaceous deposits. Because of the apparent restriction in its known distribution and the brackish- to freshwater-facies nature of its ecology the species of associated forms may eventually be found to form an assemblage zone. At present, there is insufficient information to establish a definite faunal zone. Beds at the base of Unit H (Portlandian?-early Neocomian? undifferentiated) are represented by different facies in the Dickinson well (NJ-CM-OT-1) as compared to the Hatteras Light well (NC-DA-OT-10). The specific relationship of the two facies remains undetermined.

Correlation of these beds with the Cotton Valley Group of the LaCasita Stage of the Gulf region is suggested by the occurrence of *Schuleridea* cf. *S. acuminata* in the North Carolina well. The Cotton Valley Group is generally believed to represent the Kimmeridge and overlying Portland-Purbeck Stages of Western Europe (Imlay, 1943; Swain, 1944). More recently, however, Casey (1967) has suggested that the upper part of the Purbeckian-Portlandian of England may be of Early Cretaceous (Neocomian) age.

Ostracoda characteristic of the upper and middle part of Unit H occur chiefly in wells in North Carolina and rarely in wells in Maryland (MD-WOR-OT-11) and New Jersey (NJ-CM-OT-1). Two more or less laterally equivalent assemblage zones, one marine, and the other brackish water are represented. The marine zone, named the *Paraschuleridea curta* Assemblage Zone, is characterized by the following species: *Paraschuleridea curta* Swain and Brown, *Paraschuleridea* sp., *Taxodiella* sp., *Juvenix* sp., and *Protocythere* sp. aff. *P. inornata* Kaye. The brackish-water zone, named the *Hutsonia collinsenis collinsensis—Cypridea* (*C.*) *menevoides* Assemblage Zone, is characterized by the following species: *Hutsonia collinsensis collinsensis* Swain and Brown, *Hutsonia collinsensis* subsp., *Hutsonia blandoidea* Swain and Brown, *Cypridea* (*C.*) *menevoides* Swain and Brown, *Cypridea* (*C.*) subsp., and *Fabanella tumidosa* Swain. Only *Hutsonia collinsensis collinsensis* of this assemblage zone has been found in Unit H outside of North Carolina. It occurs in the subsurface in Maryland and New Jersey.

The subsurface distribution and vertical range of species characteristic of Unit H in the report area is given by Swain and Brown (1972).

Biostratigraphic correlation of a part of Unit H with the Hosston Formation and the Sligo Formation of Durango and Nuevo León Ages and with rocks of Trinity Age in Louisiana is suggested by the occurrence of *Fabanella* spp. which are abundant in those units in the Gulf region. The occurrence of *Cypridea* (*C.*) *menevoides* suggests a possible correlation with the Wealden nonmarine beds, Neocomian, of England, in which a similar species is found.

In general, Foraminifera are either sparse or absent in Unit H and, where present, are poorly preserved. No Foraminifera were recovered from Unit H in the area of its occurrence (pl. 7) that lies to the north of Currituck County, N.C. From Currituck County southward through Carteret County, *Choffatella decipiens* Schlumberger has been identified in the cuttings from Unit H in a number of wells. The greatest number of specimens from any one well, more than 50, were recovered from cuttings in the Bayland well 1, Carteret County, N. C. (NC–CAR–OT–5, pl. 57), between the depths of 5,200 to 5,280 feet. The occurrence of *Choffatella decipiens* Schlumberger apparently is confined to Unit H in the report area.

CRETACEOUS SYSTEM—ROCKS OF CRETACEOUS AGE

UNIT G—ROCKS OF UNIT G

Unit G has an areal distribution similar to that of Unit H; compare plate 8 and plate 7. The maximum measured thickness for Unit G was 1,720 feet in a well (NC–DA–OT–12, pl. 51) in Pamlico Sound, N.C. The minimum measured thickness was 127 feet in a well (MD–CAL–T–29, pl. 37) at Prince Frederick, Md. Unit G contains both marine and nonmarine sediments; they are chiefly marine in North Carolina and chiefly nonmarine in Virginia and northward. The zone of transition between marine and nonmarine sediments is in northeastern North Carolina.

The lithologic contrasts between Unit G and overlying and underlying chronostratigraphic units are illustrated on the geologic cross sections. Unit G is associated genetically with a second-order tectonic stage. Structure and isopach-lithofacies maps for Unit G are shown on plate 8.

Lithologic description

In North Carolina, Unit G is chiefly marine and consists predominantly of layers of red, green, and gray shale interbedded with subordinate layers of fine to medium micaceous sand. In wells in the tier of counties which border the ocean (pls. 50 and 51), Unit G contains thin beds of sandy limestone and fossiliferous limestone. Locally, limestone comprises as much as 20 percent of the unit and is not concentrated in a particular part of the unit. Minor occurrences of anhydrite were noted in Unit G in NC–DA–OT–9 and NC–DA–OT–12 (pl. 51). In North Carolina, the less characteristic, nonmarine sequences within Unit G are represented in NC–WAS–OT–2 (pl. 48) and in NC–CAM–OT–10 (pl. 32.)

In Virginia and northward, Unit G is chiefly nonmarine, but contains minor amounts of marine limestone in NJ–CM–OT–1 (pl. 40) and layers of calcareous sand in MD–WOR–OT–11 (pl. 40) and in MD–WOR–OT–10 (pl. 39). Overall, Unit G contains thick layers (100 ft. or more) of massive red and brown shale with subordinate amounts of fine to medium micaceous sand. The overall lithologic character of Unit G in Virginia is illustrated on section *H–H′* (pl. 31) and, in Maryland, on section *M–M′* (pl. 35).

In Delaware and New Jersey, massive red, gray, and white shale continues to be dominant within Unit G and the subordinate amount of micaceous sand retains its fine-grained character. In both New Jersey and northern Delaware, Unit G contains a high percentage of both siderite and hematite (see section *Q–Q′*, pl. 39 and section *R–R′*, pl. 40). Locally, medium to coarse sand is developed, principally in response to structural arching, as illustrated in VA–NOR–T–12 and VA–IW–T–8 (pl. 31) and in DEL–NC–OT–4 (pl. 39).

On a regional basis, Unit G is distinguished from overlying and underlying chronostratigraphic units by its characteristic electric-log and gamma-log patterns, massive bedding, predominantly red color, and micaceous aspect, and, where fossiliferous, by contained fauna. In addition, the relatively high percentage of siderite and hematite in Unit G in New Jersey is a distinguishing feature.

The reference section (pl. 3) for Unit G is 942 feet thick and is designated as the interval between 4,092 and 5,034 feet in NC–CAR–OT–5, near Atlantic in Carteret County, N. C. The lithologic character of the reference section is illustrated on section *Z′–Z″* (NC–CAR–OT–5, pl. 50).

Biostratigraphic discussion

Unit G is correlated with the middle and upper part of the Trinity Stage and its typical strata in the Gulf region. Two concurrent range zones, one marine and the other brackish water, are recognized. The marine zone, named the *Asciocythere rotunda* Concurrent Range Zone, is characterized by the following species: *Asciocythere rotunda* (Vanderpool), *Asciocythere triangularis* Swain, *Asciocythere elongata* Swain and Brown, *Asciocythere*? *rugosa* Swain and Brown, *Schuleridea hatterasensis* Swain, *Schuleridea anterofossulata* Swain and Brown, *Ovocytheridea*? sp., *Cythereis* sp. aff. *C. lamplughi* Kaye, *Cythereis praeornata* Swain and Brown, *Eocytheropteron trinitiensis* (Vanderpool), and *Eocytheropteron tumoides* (Swain). In the Atlantic coastal region, most species characteristic of this zone are known only from the North Carolina subsurface, but *Asciocythere rotunda, Eocytheropteron trinitiensis,* and *Cythereis praeornata* occur in the northern Gulf region in rocks of Trinity Age, including the Pine Island, Rodessa, Ferry Lake, Mooringsport, and Paluxy Formations (Swain and Brown, 1964).

The brackish-water zone, named the *Fabanella lanceolata-Cypridea* (*C.*)*wyomingensis* Concurrent Range Zone, is characterized by the following species: *Fabanella lanceolata* (Swain), *Cypridea* (*C.*) *wyomingensis* Jones, *Hutsonia*? cf. *H.*? *microrugosa* Swain, *Fabanella tumidosa* (Swain), *Fabanella leguminoidea* (Swain), *Fabanella lanceolata* (Swain), *Klieana*? sp., *Pseudobythocythere*? sp., and *Mandelstamia*? sp.

In the report area, nearly all these species are restricted in occurrence to the subsurface in North Carolina, but *Klieana*? sp. also occurs in the New Jersey subsurface (NJ–CM–OT–1). *Cypridea* (*C.*) *wyomingensis* occurs in rocks of Trinity Age of the northern Gulf of Mexico region and in the Early Cretaceous of Wyoming. The form assigned to *C. wyomingensis* from the Upper Jurassic Schuler Formation of Arkansas (Swartz and Swain, 1946) is more densely and finely pustulose than typical *wyomingensis* and probably is a different species.

The subsurface distribution and vertical range of species characteristic of Unit G in the report area is given by Swain and Brown (1972).

No Foraminifera have been recovered from Unit G in the area of its occurrence (pl. 8) that lies to the north of Dare County, N. C. From Dare County southward through Carteret County, a few poorly preserved Foraminifera that may include *Orbitolina* sp. have been recovered from recrystallized bioclastic limestone in Unit G.

Two species of Charophyta, *Clavator harrisi* Peck and *Atopochara trivolis* Peck, occur commonly near the base of Unit G in wells that are adjacent to the present coastline in North Carolina, Maryland, and New Jersey. The occurrence of these species apparently is confined to Unit G in the report area.

UNIT F—ROCKS OF UNIT F

Unit F is continous in the subsurface from Long Island, N. Y., to North Carolina. The maximum measured thickness for Unit F was 1,267 feet in a well (MD–WOR–OT–10, pl. 39) near Berlin, Md. The minimum measured thickness was 20 feet in a well (NC–WAY–T–1, pl. 26) at Mount Olive, N. C. Unit F is chiefly nonmarine west of a line extending from Lake Waccanaw, Columbus County, N. C., to Greenville, Pitt County, N. C., and northeast to Cape Henry, Va. Locally, in parts of Northampton and Halifax Counties, N. C., and in Southampton County, Va., Unit F contains lagoonal deposits that are separated from the more or less continuous marine beds to the east by a belt of coarse nonmarine clastics. North of Cape Henry, Va., marine beds have been recognized in only four wells: MD–WIC–OT–11 and MD–WOR–OT–10 in Maryland and NJ–CUM–OT–8 and NJ–CM–OT–1 in New Jersey.

The lithologic contrasts between Unit F and overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. Unit F is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit F are shown on plate 9.

Lithologic description

The strata of Unit F are medium to thin bedded and consist predominantly of yellow fine to medium sand interlayered with red and brown shale, Along the inner margins of the Coastal Plain, the unit contains beds of coarse sand which are thick and extensive compared to those within underlying units. Siderite occurs commonly to abundantly, increasing in amount toward the inner margin of the Coastal Plain. Ankerite is a major sediment constituent in Delaware and adjacent parts of New Jersey. In North Carolina, New Jersey, and Maryland, subsurface marine sections contain some green shale, thin layers of limestone, and a few shell beds.

In North Carolina, section *E–E′* (pl. 27) illustrates the down-to-the-basin facies progression in Unit F, and sections *Z–Z′*, *Z′–Z″*, and *Z″–Z‴* (pls. 49, 50, and 51) illustrate its marine facies. The representative lithology of Unit F in Virginia is illustrated on section *H–H′* (pl. 31); that in Maryland is shown on section *M–M′* (pl. 35). Section *Q–Q′* (pl. 39) illustrates the high shale content of the strata in Unit F in northern Delaware. Section *R–R′* (pl. 40), across a segment of New Jersey, shows Unit F to be marginal marine in NJ–CUM–OT–8 and to be less marine toward the south in NJ–CM–OT–1.

In a regional sense, Unit F may be distinguished from the strata of overlying and underlying units by its characteristic electric-log patterns and particularly by its gamma-log patterns, by its yellow to brown color and thin bedding as compared to the underlying units, by its relatively high concentration of siderite and (or) ankerite, and by a high percentage of coarse well-sorted sand in wells along the inner margin of the Coastal Plain. The ostracodes are diagnostic where present.

The reference section (pl. 3) for Unit F is 83 feet thick and is designated as the interval between 161 and 244 feet in NC–HAL–T–2, near Scotland Neck, N. C.

The lithologic character of the reference section is illustrated on section *U–U′* (NC–HAL–T–2, pl. 43).

Biostratigraphic discussion

Unit F is correlated with the Fredericksburg Stage and the Washita Stage, undifferentiated, and their typical strata in the Gulf region. A marine concurrent-range zone and a brackish-water assemblage zone are recognized. The marine zone, named the *Eocytheropteron tumidum—E. greenvillensis* Concurrent-Range Zone, contains the following characteristic species: *Eocytheropteron tumidum* (Alexander), *Eocytheropteron greenvillensis* Swain and Brown, *Clithrocytheridea halifaxensis* Swain and Brown, *Cythereis* sp. aff. *C. glabrella* Triebel, *C.* cf. *C. dentonensis* Alexander, *Dolocytheridea? caledonensis* Swain and Brown, *D. oertlii* Swain and Brown, *Eucythere semiglypta* Swain and Brown, *Cytherella* cf. *C. ovata* (Roemer), *Monoceratina?* sp., *Metacytheropteron? bicostatum* Swain and Brown, *Protocythere* sp. 1, and *Isocythereis?* sp. This group of species is restricted mainly to the North Carolina subsurface according to current data. However, *Cythereis* cf. *C. dentonensis* also occurs in New Jersey (NJ–CM–OT–1) and *Eucythere semiglypta* in Maryland and New Jersey (MD–WOR–OT–11 and NJ–CM–OT–1). Correlation of Unit F with the Washita and Fredericksburg Stages and their typical strata in the Gulf region is based on the dual occurrence of *Eocytheropteron tumidum* and *Cythereis* cf. *C. dentonensis.*

The brackish-water zone, named the *Fossocytheridea lenoirensis* Assemblage Zone, contains the following characteristic species: *Fossocytheridea lenoirensis* Swain and Brown, *Eucytheroides pustulosa* (Swain), *Orthonotacythere delicatula* Swain and Brown, and *Perissocytheridea odomensis* Swain and Brown. The brackish-water nature of the zone is inferred from the modern estuarine and other low-salinity occurrences of *Perissocytheridea* and *Orthonotacythere.* Although *F. lenoirensis* and *E. pustulosa* are most common in the subsurface of eastern North Carolina, they have also been found in Maryland (MD–WOR–OT–10 and MD–WIC–OT–11). The areal distribution in the subsurface and the vertical range of many of the Ostracoda characteristic of Unit F are given by Swain and Brown (1964, 1972).

Foraminifera are rare to absent in Unit F. Locally, in some parts of Northampton and Halifax Counties, N. C. (NC–NOR–T–12, NC–HAL–T–2, and NC–HAL–T–12), tiny arenaceous Foraminifera, gen. and sp. indet., occur in thin-bedded black clay which is intercalated with thick-bedded sideritic sand. A few specimens of *Coskinolinoides texanus* Keijzer have been recovered from wells in Dare, Hyde, and Carteret Counties, N. C. Specimens of *Epistomina* cf. *E. charlottae* Vieaux occur rarely in the upper part of Unit F in a few wells in North Carolina, Maryland, and New Jersey. A cursory examination of Foraminifera that occur in the upper part of Unit F in a well (NJ–OC–T–1) at Island Beach, N. J., suggests that Unit F may be correlative in part with the Del Rio Clay of Texas.

UNIT E—ROCKS OF UNIT E

Unit E is continuous in the subsurface from Long Island, N. Y., to North Carolina. The maxmum measured thickness for Unit E was 635 feet in a well (NC–HY–OT–6, pl. 30) southeast of Lake Mattamuskeet in North Carolina. The minimum measured thickness was 28 feet in a well (NC–BER–P–8, pl. 29) at Aulander, N. C. Unit E is marine to marginal marine in most of North Carolina and in southeast Virginia; nonmarine in Delaware and Maryland; marine to marginal marine in New Jersey; and nonmarine on Long Island, N. Y.

The lithologic contrasts between Unit E and overlying and underlying units are illustrated on the report's geologic cross sections. Unit E is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit E are shown on plate 10.

Lithologic description

In North Carolina and southeast Virginia, the marine beds consist predominantly of gray shale interlayered with sandy and shelly limestone. The percentage of limestone increases seaward. Fine sand is a minor constituent. Nonmarine beds are well developed in the subsurface between Martin County, N. C. and Isle of Wight County, Va. They consist primarily of red micaceous shale interlayered with coarse sand which contains chalcedony as a characteristic constituent. Sections *G–G′*, *G′–G″*, and *X–X′* (pls. 29, 30, and 46) illustrate the progressive development of facies within Unit E. Section *H–H′* (pl. 31) illustrates the development of the marginal-marine facies in southeast Virginia. Here Unit E is thin bedded and contains fine sand and gray micaceous shelly shale.

North of Virginia, Unit E is chiefly marginal marine and less characteristically, as on Long Island, it is nonmarine. Unit E consists predominantly of green, gray, and brown lignitic and micaceous shale with minor occurrences of fine sand and traces of shell. About 40 feet of limestone occur in NJ–CM–OT–1 (pl. 40) in New Jersey. Section *R–R′* (pl. 40) illustrates a characteristic facies progression within Unit E: from nonmarine (NJ–CAM–P–2 and NJ–CAM–P–4), into marginal marine (NJ–CU–OT–8), into marine (NJ–CM–OT–1), and back into nonmarine (MD–WOR–OT–11).

In a regional sense, Unit E is distinguished from overlying and underlying units by its characteristic electric-log and gamma-log patterns and by its ostracode fauna. In nonmarine sections in North Carolina, the occurrence of chalcedony is a distinguishing characteristic of Unit E. In Virginia and to the north, Unit E is characteristically finer grained, less sideritic, and contains a much higher percentage of shell material, where marginal marine or marine, than overlying and underlying units. Overall, Unit E is distinguished by the lithologic constancy of its marginal-marine strata.

The reference section (pl. 3) for Unit E is 270 feet thick and is designated as the interval between 2,216 and 2,486 feet in NC–DA–OT–11, in Albemarle Sound, N. C. The lithologic character of the reference section is illustrated in section Z''–Z''' (NC–DA–OT–11, pl. 51).

Biostratigraphic discussion

Unit E is correlated with the Woodbine Stage and its typical strata is the Gulf region. The strata in Unit E comprise both a brackish-water or lagoonal facies and a marine facies.

The following species of Ostracoda occur in the brackish-water or lagoonal facies: *Centrocythere annulopapillata* Swain and Brown, *Orthonotacythere delicatula* Swain and Brown, *Perissocytheridea odomensis* Swain and Brown, *Dolocytheridea? bosquetoides* Swain and Brown, *Dolocytheridea oertlii* Swain and Brown, *Asciocythere macropunctata* Swain, and *Schuleridea* sp.

A marine facies is widely distributed in the subsurface from North Carolina to New Jersey. Ostracoda that are characteristic of this facies include *Cythereis eaglefordensis* Alexander, *Cytheropteron* (*Cytheropteron*) *eximum* Alexander, and *Cythereis fredericksburgoides* Swain and Brown. The vertical range of these three species may be more restricted in the Middle Atlantic States than in other areas of their occurrence. The *Cythereis eaglefordensis—C. fredericksburgoides* Assemblage Zone is proposed for the marine facies of Unit E.

Few Foraminifera occur in Unit E. Facies with a near-shore to brackish-water aspect contain a few arenaceous species. Their occurrence is restricted chiefly to local areas in Carteret and Onslow Counties, N. C. Future study of these locally developed arenaceous assemblages may establish the presence of species which can be used for interregional correlation. None were recognized during the present mapping program.

UNIT D—ROCKS OF UNIT D

Unit D covers extensive areas in North Carolina and in adjacent parts of southeast Virginia. From Virginia northward to Long Island, N. Y., the unit is discontinuous and occurs mainly in the tier of counties that border the ocean. The maxmum measured thickness for Unit D was 398 feet in a well (NC–HY–OT–6, pl. 29) southeast of Lake Mattamuskeet, N. C. The minimum measured thickness was 10 feet in an exploratory test well (NC–NOR–T–8, pl. 31) northeast of Seaboard, N. C. For the most part Unit D is nonmarine to marginal marine, except in local areas in New Jersey and North Carolina where it is chiefly marine.

The lithologic contrasts between Unit D and overlying and underlying units are illustrated on the report's geologic cross sections. Unit D is genetically associated with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit D are shown on plate 11.

Lithologic description

In North Carolina, nonmarine strata are thin- to medium-bedded blocky shales, mostly red but also brown to yellow, that contain coarse and subordinate fine feldspathic sands, characteristically stained red. Hematite and gravel are common constitutents. Unit D contains numerous marine lenses in a narrow northeast-trending area bounded by Washington County, N. C. on the northwest and by a line that extends from Bogue Inlet to the mouth of the Alligator River on the southeast. In this narrow area, coarse to fine feldspathic sand and shale are interlayered with numerous thin beds of shell material, sandy limestone, and calcareous sand. Unit D is consistently marine in Hyde and Tyrrell Counties, N. C., where it attains maximum thickness. Marine facies are nearly encircled by marginal marine facies as illustrated on sections G–G', (pl. 29), G'–G'' (pl. 30), Y–Y' (pl. 47), and Y'–Y'', (pl. 48).

In Maryland, Unit D contains thin-bedded fine sand and gray shale with minor amounts of shell material as illustrated on section M–M' (pl. 35). In NJ–OC–T–1 (section S–S', pl. 41) in Ocean County, N. J., Unit D consists of gray to white lignitic shale with thin beds of chalky limestone.

In a regional sense, Unit D may be distinguished from overlying and underlying units by its characteristic electric-log and gamma-log patterns and, locally, by its Ostracoda. The red-stained sands and the concentrations of hematite, gravel, and feldspar also are characteristic of the unit.

The reference section (pl. 3) for Unit D is 310 feet thick and is designated as the interval between 1,041 and 1,351 feet in NC–WAS–OT–2 west of Lake Phelps in North Carolina. The lithologic character of the reference section is illustrated on section Y'–Y'' (NC–WAS–OT–2, pl. 48).

Biostratigraphic discussion

Unit D is correlated with the middle and upper parts of the Eagle Ford Stage and its typical strata in the Gulf region.

The only species of ostracode found to occur commonly in Unit D is *Cythereis* cf. *C. ornatissima* (Reuss).

Comparisons of the American specimens were made with specimens in the British Museum. The English specimens were identified by T. R. Jones from the chalk marl at Didcot Station, Berkshire, and by F. Chapman from the Gault at Copt Point, Folkestone, and at Black Fen, Dorset. These specimens are coarsely pitted, rugose, with low to moderate and narrow median ridge, and with the median tubercle well developed. The American forms here referred to as *ornatissima* fit the English examples reasonably well.

No Foraminifera exclusive to Unit D were recovered in the report area.

UNIT C—ROCKS OF UNIT C

Unit C has a broad areal distribution in North Carolina. It is absent in Virginia, except in local areas in Accomack County and in the city of Virginia Beach. In Maryland it occurs chiefly in the area northeast of Chesapeake Bay from whence it extends through Delaware and New Jersey and to Long Island, N. Y. The maximum measured thickness for Unit C was 420 feet in a well (NC–DA–OT–12, pl. 51) in Pamlico Sound, N. C. The minimum measured thickness was 8 feet in a nonsection well (NC–CHO–P–16) in northern Chowan County, N. C. In North Carolina, Unit C is chiefly marginal marine but is nonmarine in Robeson and Cumberland Counties west of a line that extends northward through the central parts of Pitt, Martin, and Bertie Counties. From Maryland northward, Unit C is both marginal marine and nonmarine. Marginal-marine sequences are best developed in wells adjacent to the coast and nonmarine sequences are best developed in wells that lie adjacent to the inner margin of the Coastal Plain and on Long Island, N. Y.

The lithologic contrasts between Unit C and overlying and underlying units are illustrated on the report's geologic cross sections. Unit C is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit C are shown on plate 12.

Lithologic description

In North Carolina Unit C is predominantly thick bedded. Where the unit is marginal marine it consists of fine to medium sand and gray to black fissile shale; glauconite, lignite, mica, and shell material are common accessories. Thin beds of limestone are characteristic of Unit C in the area enclosed by a line which extends northeastward from Lake Waccamaw to the mouth of the Roanoke River, east to the vicinity of NC–DA–OT–11 in Albemarle Sound, and south to near Hatteras Inlet. These beds, discontinuous, sandy, and rarely shelly, are usually less than 10 feet thick. Where Unit C is nonmarine it consists of brown to white micaceous shale and tan coarse sand. A distinctive red shale occurs near the base of the unit in most test wells in Onslow County and to the north. The attitude and thickness of Unit C are illustrated on section *C–C′* (pl. 25) and section *E–E′* (pl. 27). A facies progression for the unit is illustrated on section *F–F′* (pl. 28), section *G–G′* (pl. 29), and section *G′–G″* (pl. 30).

In Maryland, Delaware, New Jersey, and on Long Island, Unit C is relatively thin bedded and consists of gray to brown shale and fine to medium sand, except in those areas delineated on plate 18 as 75–100 percent sand. In these latter areas, the sand is medium to coarse and well sorted. In wells where Unit C is marginal marine, it is shelly, in part, and contains considerable hematite and lignite and occasionally siderite and mica. In the area transected by section *R–R′* (pl. 40), Unit C shows no well developed facies progression.

In a regional sense, Unit C may be distinguished from overlying and underlying units by its characteristic electric-log and gamma-log patterns and by its contained fauna. It is considerably more marine than underlying units and it is more micaceous and lignitic and contains a greater percentage of sand than Unit B which overlies it.

The reference section (pl. 3) for Unit C is 410 feet thick and is designated as the interval between 406 and 816 feet in NC–PEN–OT–6 in northeast Pender County, N. C. The lithologic character of the reference section is illustrated on section *C–C′* (NC–PEN–OT–6, pl. 25).

Biostratigraphic discussion

Unit C is correlated with the Austin Stage and its typical strata in the Gulf region. A marine zone, named the *Brachycythere nausiformis* Assemblage Zone, is here recognized, although an extensive study has not been made of the Ostracoda in Unit C. *Brachycythere nausiformis* Swain, *Cythereis* cf. *C. bicornis* Israelsky, and *Cythereis austinensis* Alexander occur in wells from North Carolina to New Jersey and, together with species that occur locally such as *Asciocythere macropunctata* Swain, are useful in identifying Unit C in the subsurface.

Foraminifera are not abundant in Unit C and, where present, consist of only a few species. However, *Citharina texana* (Cushman) and *Planulina austiniana* Cushman, which seem to be confined to Unit C and which occur in a significant number of wells, are useful in identifying Unit C in the subsurface throughout the report area.

UNIT B—ROCKS OF UNIT B

The areal distribution of Unit B (pl. 13) is similar to that previously shown for Unit C (pl. 12). Unit B is widely distributed in North Carolina, largely absent in Virginia, widely distributed in Maryland northeast of Chesapeake Bay, and extends across Delaware and

New Jersey into Long Island, N. Y. The maximum measured thickness for Unit B was 652 feet in a well (NC–HY–OT–11, pl. 50) in Pamlico Sound, N. C. The minimum measured thickness was 21 feet in a nonsection well (MD–AN AR–P–36) at Sandy Point, Anne Arundel County, Md. Both the attitude and thickness of beds near the top of the unit are very irregular, especially in North Carolina, because of erosion. Unit B is chiefly marginal marine in North Carolina and is generally more marine to the north.

The lithologic contrasts between Unit B and overlying and underlying units are illustrated on the report's geologic cross sections. Unit B is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit B are shown on plate 13.

Lithologic description

In North Carolina, Unit B is predominatly a dark-gray to black shale and, less commonly, a sandy shale containing glauconite, lignite, mica, and shell fragments as common accessories. Locally, where the unit contains a large amount of sand, the sand is thick-bedded, medium to fine, and commonly glauconitic. Calcareous shale and (or) thin beds of sandy limestone are present in wells in New Hanover, Brunswick, Carteret, Pamlico, and Dare Counties. In general, the limestone occurs in conjunction with an increase in the thickness of the unit.

The progression of facies in this unit is illustrated on section *E–E′* (pl. 27), section *Y′–Y″* (pl. 48), and section *Q–Q′* (pl. 39).

In the northern part of the report area, the unit is more marine and contains a higher percentage of chalk, sandy limestone, and calcareous shale than it does in the southern part of the report area. This represents a transposition in the relative geographic location of marine and nonmarine deposits with respect to the chronostratigraphic units described previously. Overall, Unit B consists chiefly of gray shale that may be calcareous and sparsely to heavily glauconitic. Glauconite is a dominant accessory in the unit chiefly along the inner margin of the Coastal Plain. Unit B contains chalky limestone in DEL–SUS–OT–5 and in NJ–CM–OT–1 (pl. 37) and calcareous sands in numerous wells in Maryland and New Jersey. Change in the lithic character of Unit B, that occurs in the northern half of the project area, is illustrated on section *R–R′* (pl. 40).

In a regional sense, Unit B is distinguished from overlying and underlying units by its characteristic electric-log and gamma-log patterns and by its fauna where present. In general, Unit B is more shaly and calcareous than overlying and underlying units and its sands are finer.

The reference section (pl. 3) for Unit B is 468 feet thick and is designated as the interval between 1,354 and 1,822 feet in NC–CAR–OT–11, near Merrimon, Carteret County, N. C. The lithologic character of the reference section is illustrated on section *Y′–Y″* (NC–CAR–OT–11, pl. 48).

Biostratigraphic discussion

Unit B is correlated with the Taylor Stage and its typical strata in the Gulf region. The unit contains a large and abundant variety of ostracode species, especially in North Carolina, where it is widely distributed, but many of the species also range into younger and older units. Species that are characteristic of Unit B are all marine and include: *Veenia paratriplicata* (Swain), *Cythereis quadrialira* Swain, *Cythereis* cf. *C. verricula* Butler and Jones, and *Brachycythere* cf. *B. sphenoides* (Reuss). *Brachycythere* cf. *B. sphenoides* and *Cythereis* cf. *C. verricula* occur in Tayloran strata in the Gulf region and *Cythereis quadrialira* is recorded from the Upper Cretaceous of southwestern Minnesota. The *Brachycythere* cf. *B. sphenoides—Cythereis quadrialira* Concurrent-Range Zone is established for this group of Ostracoda.

Foraminifera occur commonly to abundantly in Unit B in the area extending from North Carolina to New Jersey. In a number of wells, *Globorotalites conicus* (Carsey) and *Bolivinoides decorata* (Jones) var. occur at or near the top of Unit B; *Kyphopyxa christneri* (Carsey) occurs in the middle part of Unit B and ranges downward into Unit C; and *Planulina dumblei* (Applin) occurs throughout Unit B. These readily recognizable species are useful in identifying Unit B throughout the report area. The planktonic Foraminifera, coccoliths, and other microfossils that are known to occur in Unit B in wells have not been studied in detail.

UNIT A—ROCKS OF UNIT A

Unit A occupies the same general area as Units B and C, except that its area of occurrence extends west of the Potomac River and into King George County, Va. The maximum measured thickness for Unit A was 386 feet in a well (NC–NH–T–13, pl. 24) west of Murraysville, New Hanover County, N. C. The minimum measured thickness was 8 feet in a well (NC–CHO–T–3, pl. 47) at Valhalla, Chowan County, N. C. In well sections, Unit A is marginal marine to marine and, as was true with Unit B, marine deposits are more prevalent in the northern half than in the southern half of the report area.

The lithologic contrasts between Unit A and overlying and underlying units are illustrated on the report's geologic cross sections. Unit A is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for Unit A are shown on plate 14.

Lithologic description

In North Carolina where Unit A is marine to marginal marine, it is more thinly bedded than Unit B and consists of gray sandy glauconitic shale and medium to fine shaly sand, both of which are micaceous and shelly.

Limestone, rare in Unit A, occurs in a few wells in northern Dare County and in the New Hanover and Pender County area. As shown on section $G'-G''$ (pl. 30), the unit consists of calcareous siltstone in NC-HY-OT-11. A characteristic facies change, wherein Unit A becomes more sandy in the direction of the present coastline, is illustrated on section $X-X'$ (pl. 46).

In the northern half of the report area, Unit A is marine to marginal marine and consists chiefly of fine to medium glauconitic sand interbedded with green to brown shale. Where marine, the unit contains a higher percentage of limestone and chalk than it does farther south. Mica, lignite, and shell are common accessories in clastic sections. Minor occurrences of chalk are noted in DEL-KT-P-3 (pl. 56) and NJ-CM-OT-1 (pl. 54). A characteristic facies progression for Unit A is illustrated on section $Q-Q'$ (pl. 39).

In a regional sense, Unit A is distinguished from overlying and underlying units by its characteristic electric-log and gamma-log patterns and by its microfauna. Unit A is thiner bedded, lighter in color, and contains more and coarser sand than Unit B.

The reference section (pl. 3) for Unit A is 386 feet thick and is designated as the interval between 37 and 423 feet in NC-NH-T-13, west of Murraysville, New Hanover County, N. C. The lithologic character of the reference section is illustrated on section $B-B'$ (NC-NH-T-13, pl. 24).

Biostratigraphic discussion

Unit A is correlated with the Navarro Stage and its typical strata in the Gulf region. The following species of Ostracoda are among those characteristic of Unit A in the report area: *Haplocytheridea ulrichi* (Berry), *Haplocytheridea carolinensis* (Brown), *Amphicytherura copicosta* Crane, *Amphicytherura curta* (Jennings), *Veenia arachoides* (Berry), and *Brachycythere rhomboidalis* (Berry). *H. ulrichi* occurs in the Providence Sand of Georgia, the Ripley Formation of Georgia, the Nacatoch Sand of Arkansas, the Monmouth Formation of Maryland, and the Peedee Formation of North Carolina. *Amphicytherura copicosta* is present in the Ripley Formation of Alabama, the Nacatoch Sand of Texas, the lower part of the Prairie Bluff Chalk of Alabama, and the Providence Sand of Alabama and Georgia. *Veenia arachoides* is found in the Monmouth Formation of Maryland, the *Lituola* Zone (lower Navarroan) of Texas, the Ripley Formation of Georgia, the Nacatoch Sand of Arkansas, and the lower part of the Prairie Bluff Chalk of Alabama. This species occurs also in the Marlbrook Marl (Tayloran) of Arkansas. *Brachycythere rhomboidalis* occurs in the Monmouth Formation of Maryland and in Navarroan and Tayloran strata in the Gulf region.

In addition, a characteristic and apparently unique group of species represented by the genus *Velarocythere* Brown (restricted) occurs in beds of Unit A in Pitt, Lenoir, and Bladen Counties, eastern North Carolina. The species represented are: *V. scuffeltonensis* Brown, *V. legrandi* Brown, *V. cacumenata* Brown, and *V. eikonata* Brown. *Veenia arachoides* (Berry), also representative of this unit, was placed in *Velarocythere* in the original description of that genus, but on the basis of hingement and longitudinal surface ornamentation *arachoides* is closer to *Veenia*. The *Velarocythere* faunule is restricted to a medium and coarse sparsely glauconitic sand facies. The *Veenia arachoides-B. rhomboidalis* fauna is not so restricted and although it does occur in the sand facies, it is best developed in the shale facies. The *Velarocythere* sands are best developed near the top of Unit A in North Carolina and are generally not present farther north.

The characteristic Ostracoda of Unit A form the *Veenia arachoides—Brachycythere rhomboidalis* Concurrent-Range Zone. The *Velarocythere* Assemblage Subzone of this concurrent-range zone is provisionally proposed for Unit A in east-central North Carolina.

In most wells, Foraminifera are common to abundant in Unit A. Benthonic species that are characteristic of and useful in identifying the unit in the report area include: *Tritaxia trilatera* (Cushman) Cushman, *Dorothia* cf. *D. bulletta* (Carsey) Plummer, *Robulus navarroensis* (Plummer), *Anomalina pseudopapillosa* Carsey, and *Anomalina rubiginosa* Cushman. The planktonic Foraminifera and other microfossils that are recognized in Unit A in wells have not been studied.

CENOZOIC ERA

TERTIARY SYSTEM

PALEOCENE SERIES

MIDWAY STAGE—ROCKS OF MIDWAY AGE

Midwayan strata, marine throughout the report area, are widely distributed in the subsurface from eastern North Carolina through New Jersey, but are absent in wells on Long Island, N. Y. The maximum measured thickness for beds in this chronostratigraphic unit was 350 feet in a well (NJ-OC-T-1, pl. 41) at Island Beach, Ocean County, N. J. The minimum measured thickness was 10 feet in a well (VA-PG-P-3), pl. 52) south of Hopewell, Va. The maximum thickness contoured is > 450 feet in Queen Annes County, Md., and seaward of Cape May and Atlantic Counties, N.J. (pl. 15).

The lithologic contrasts between rocks of Midway Age and rocks of overlying and underlying units are illustrated on the report's geologic cross sections. This chronostratigraphic unit is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for the Midwayan unit are shown on plate 15.

Lithologic description

Overall, rocks of Midway Age are characterized by a high percentage of glauconite (from ±10 to ±90 percent) and by green to greenish-gray shale and subordinate amounts of sand. The sand is shaly and is chiefly medium, except in downtrough areas where it is fine. In Delaware and New Jersey, the strata are more calcareous (chalky) than in other areas, but in all areas they contain thin layers of sandy and shelly glauconitic limestone. Minor amounts of vuggy dolomite are common in wells in Virginia, Maryland, and northeastern North Carolina. Rocks that contain the highest percentage of glauconite are in southern Virginia.

In North Carolina, section *G–G′* (pl. 29) and section *G′–G″* (pl. 30), that show a thinning of the strata toward the present coast, illustrate a characteristic facies progression. The irregular attitude and uneven thickness of strata that is characteristic of the unit are illustrated on section *W–W′* (pl. 45).

In Virginia, rocks of Midway Age contain less limestone than in the other States in the report area. A pink shale, not the Marlboro Clay but similar to it lithologically, occurs in sections of Midway Age from Prince George County northward into Westmoreland County. Section *K–K′* (pl. 33) illustrates the characteristic facies progression for rocks of Midway Age in Virginia. These rocks are absent in the Norfolk, Va., area as shown on section *C–C′* (pl. 25) and section *H–H′* (pl. 31).

In Maryland, the rocks of Midway Age consist of fine to coarse glauconitic sand, green to greenish-gray shale, and occasional layers of sandy and shelly glauconitic limestone. The sand in the upper part of the section usually is stained yellow and is waterpolished. Section *F–F′* (pl. 28) and section *O–O′* (pl. 37) illustrate the nature of the facies progression and the development of thickening trends for rocks of Midway Age in Maryland.

In Delaware, the lithologic character of these rocks ranges from a glauconitic, slightly ferruginous sand in New Castle County to a chalk in Sussex County. Section *Q–Q′* (pl. 39) illustrates the nature of this facies progression across Delaware and into an adjacent segment of Maryland.

In New Jersey, section *R–R′* (pl. 40) illustrates much the same type of facies progression, except that the progression is from a medium glauconitic sand (NJ-CAM-P-4) through increasing percentages of shale (NJ-CAM-T-2 and NJ-CU-OT-8), into chalk (NJ-CM-OT-1), and back into shale (MD-WOR-OT-11) in eastern Maryland.

In a regional sense, rocks of Midway Age are distinguished from the rocks of overlying and underlying chronostratigraphic units by their characteristic electric-log and, particularly, gamma-log patterns and by their microfauna. These rocks are further distinguished by a high percentage of glauconite, by the occurrence of yellow-stained sand, and, in Delaware and New Jersey, by white to mottled-tan chalk.

The reference section (pl. 3) for rocks of Midway Age is 332 feet thick and is designated as the interval between 263 and 595 feet in MD-TAL-T-4, at Wades Point, Talbot County, Md. The lithologic character of the reference section is illustrated on section *FF–FF′* (MD-TAL-T-4, pl. 58).

Biostratigraphic discussion

The Ostracoda characteristic of rocks of Midway Age in the subsurface of the Middle Atlantic States include: *Opimocythere marylandica* (Ulrich), *Cythereis reticulodacyi* Swain, *Hermanites midwayensis* (Alexander), *Hermanites gibsoni* Hazel, *Hazelina alexanderi* Hazel, *Hazelina* cf. *H. aranea* (Jones) subsp. *A.*, *Acanthocythereis princegeorgensis* Hazel, *Brachycythere plena* Alexander, and *Loxoconcha notoaulax* Munsey. *C. reticulodacyi* and *L. notoaulax* have been recorded from the Coal Bluff Marl member of the Naheloa Formation of Alabama (Munsey, 1953). *H. aranea* subsp. *A.* has been recorded from the Kincaid and Wills Point Formations of Texas, the Clayton Formation of Alabama and Mississippi, and the Porters Creek Clay of Mississippi. *B. plena* has been found in the Kincaid and Wills Point Formations of Texas, in Midwayan strata in Arkansas, and in the Clayton and Porters Creek Clay of Alabama and Mississippi, in addition to Atlantic coast occurrences (Alexander, 1934; Murray and Hussey, 1942; Kline, 1943; Harris and Jobe, 1951; Gordon and others, 1958; Brown, 1958; and Hazel, 1968).

The *Brachycythere plena* Concurrent-Range Zone is established for this chronostratigraphic unit.

The foraminiferal fauna of this unit is large. Species that are characteristic and which help to identify rocks of Midway Age in the subsurface include: *Globorotalia pseudomenardi* Bolli, *Globorotalia elongata* Glaessner, *Globorotalia angulata* (White), *Globorotalia aequa* Cushman and Renz, *Citharina plummoides* (Plummer), *Anomalinoides midwayensis* (Plummer), *Robulus midwayensis* Plummer, *Vaginulinopsis*(?) *crisfieldensis* McLean, *Pseudouvigerina* cf. *P naheolensis*, and *Gaudryina mcleani* Hofker.

EOCENE SERIES

Sabine Stage—Rocks of Sabine Age

Rocks of Sabine Age have a similar but a somewhat more restricted areal distribution than rocks of Midway Age in that they occur in two widely separated areas rather than extending continuously throughout the report area. In North Carolina, they are widely distributed in Carteret County and extend northeastward into the outer counties of the Coastal Plain. They constitute a distinctive reentrant that lies beneath Albemarle Sound and that extends westward into eastern Bertie County.

Rocks of this unit are absent throughout most of Virginia. They are chiefly confined to the counties that comprise Virginia's Northern Neck, from whence they extend across central Maryland, through Delaware, and across most of New Jersey. The maximum measured thickness for rocks of Sabine Age was 351 feet in a well (NC–DA–OT–12, pl. 51) in Pamlico Sound, N. C. The minimum measured thickness was 12 feet in a nonsection well (NC–CHO–P–16) at Small's Crossroads, Chowan County, N. C. These rocks are marine to marginal marine throughout their extent in the subsurface.

The lithologic contrasts that occur between rocks of Sabine Age and rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. This unit is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for the Sabinian unit are shown on plate 16.

Lithologic description

Overall, rocks of Sabine Age contain a much greater percentage of carbonate in the southern one-half than in the northern one-half of the report area. They are glauconitic but less so than rocks of Midway Age.

In North Carolina, these rocks consist of fine glauconitic sand, commonly calcareous and shelly, and tan to light-green siltstone and shale. Beds of sandy shell limestone are common and occasionally the limestone is dolomitic, as in parts of Dare and Camden Counties. Section Z–Z' (pl. 49), section Z'–Z'' (pl. 50), and section Z''–Z''' (pl. 51) illustrate the facies progression within this unit in North Carolina.

In Virginia, Maryland, Delaware, and New Jersey, these rocks consist of fine to medium silty glauconitic sand and green to gray shale. Minor limestone occurs where the percentage of shale is high. Chalk is present in Cape May County, N. J. (NJ–CM–OT–1). Pink shale, that probably corresponds to the Marlboro Clay Member of the Nanjemoy Formation, occurs throughout southern Maryland and in King George County, Va. Section N–N' (pl. 36) illustrates a characteristic facies progression for rocks of Sabine Age recognized in wells in Virginia: from fine to medium glauconitic sand in King George County, to a dominant shale in Westmoreland and Richmond Courties, and back to a coarse glaucontitic sand in Middlesex County. Section O–O' (pl. 37), from Charles County, Md., to Cape May County, N. J., illustrates the facies progression for these rocks where they are alternately marine and marginal marine in adjacent wells. Section R–R' (pl. 40) illustrates the facies progression in New Jersey, where shales generally are calcareous.

In a regional sense, rocks of Sabine Age are distinguished from the rocks of overlying and underlying chronostratigraphic units by their characteristic electric-log and gamma-log patterns and by their microfaunas. Rocks of this unit are less glauconitic than rocks of the Midwayan unit. The shales, in particular, are a lighter green, almost a pistachio color in some places.

Two reference sections (pl. 3) were selected for rocks of Sabine age; one in the southern and one in the northern part of the report area. The southern reference section, 173 feet thick, is designated as the interval between 1,572 and 1,745 feet in NC–CAR–OT–5, near Atlantic, Carteret County, N. C. The lithologic character of this reference section is illustrated on section Z'–Z'' (NC–CAR–OT–5, pl. 50). The northern reference section, 60 feet thick, is designated as the interval between 122 and 182 feet in MD–CHA–P–30, near Indian Head, Charles County, Md. The lithologic character of this reference section is illustrated on section P–P' (MD–CHA–P–30, pl. 38).

Biostratigraphic discussion

In the Middle Atlantic States Sabinian strata are characterized by *Xestoleberis*? *longissima* Schmidt, *Hazelina aquia* (Schmidt), *Haplocytheridea leei* (Howe and Garrett), and *Trachyleberidea goochi* (Swain).

T. goochi, a form with a sharply pointed posterior, is very much like *T. prestwichiana* (Jones and Sherborn) from the Ypresian (lower Eocene) of Belgium and England. *T. goochi* occurs commonly in Delaware and New Jersey and less commonly to the south in this unit. Other representative species have a wider geographic distribution in the Atlantic Coastal region. Because diagnostic interregional species rarely occur in this unit the assemblage is here referred to as the *Haplocytheridea leei* Assemblage Zone. Additional data may indicate that the zone ranges downward locally into strata of the Midway Stage. Many other ostracode species occur in Sabinian strata throughout the report area but their vertical ranges are not restricted to this chronostratigraphic unit.

The foraminiferal faunas of this unit are not well known. Of the species that occur in this unit, many range upward into Claibornian strata or downward into Midwayan strata. The following Foraminifera identified by Thomas Gibson seem to be characteristic of and help to identify the unit in the subsurface: *Subbotina inaequispira* (Subbotina), *Globorotalia wilcoxensis* Cushman, and *Pseudohasterigerina wilcoxensis* (Cushman).

Claiborne Stage—Rocks of Claiborne Age

Rocks of Claiborne Age occur in two separate areas in the Middle Atlantic States. One area lies in eastern North Carolina and the other extends from southeastern Virginia through Maryland and Delaware into northern New Jersey. The rocks are marine in North Carolina and marginal marine from Virginia northward. The maximum measured thickness for these rocks was 847 feet in a well (NC–CAR–OT–5, pl. 49) in Carteret County, N. C. The minimum measured thickness was 9 feet in a well (VA–JC–T–10, pl. 53) near Jamestown, James City County, Va.

The lithologic contrasts that occur between rocks of Claiborne Age and the rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. This unit is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for the Claibornian unit are shown on plate 17.

Lithologic description

In North Carolina, rocks of Claiborne Age consist chiefly of molluscan limestone that grades laterally into bryozoan limestone and downward into calcareous sand. The molluscan limestone, that is part of a reef complex, is the dominant lithologic unit. It is massive and consists of the casts and molds of original shell material that exhibit significant secondary recrystallization. The underlying sand is moderately calcareous in its upper part and highly calcareous in its lower part in the deeper wells in Carteret County. In North Carolina, the characteristic lithology of rocks of Claiborne Age is illustrated on numerous cross sections. (See section *E–E'*, pl. 27; section *G–G'*, pl. 29; section *X–X'*, pl. 46; section *Z–Z'*, pl. 49; section *Z'–Z"*, pl. 50; and section *Z"–Z'''*, pl. 51.) In local areas, rocks of this age have been deposited in channels cut in older rocks, as illustrated on section *U–U'* (pl. 43) and on section *V–V'* (pl. 44). Section *X–X'* (pl. 46) illustrates a characteristic facies progression for rocks of this chronostratigraphic unit.

In Virginia and northward, these rocks consist of gray to green micaceous shale with medium grained highly glauconitic and slightly shelly sand, which is more prominent in Virginia, Maryland, and northern Delaware than in southern Delaware or New Jersey. Minor layers of sandy glauconitic limestone occur sporadically. In Virginia and southern Maryland, the glauconite in these strata commonly is oxidized, is brown to reddish brown, and resembles the oxidized glauconite in Jacksonian strata in Delaware and New Jersey. Section *O–O'* (pl. 37) and section *Q–Q'* (pl. 39) illustrate a characteristic facies progression for rocks of Claiborne Age in the northern part of the report area.

In a regional sense, these rocks are distinguished from the rocks of overlying and underlying units by their characteristic electric-log and gamma-log patterns and by their microfauna. In Virginia and southern Maryland, the occurrence of oxidized glauconite is a distinguishing characteristic of these rocks. In Delaware and New Jersey the rocks are predominantly shale in contrast with the predominantly sandy nature of the rocks in overlying and underlying chronostratigraphic units.

Two reference sections (pl. 3) are selected for these rocks; one in the southern and one in the northern part of the report area. The southern reference section, 626 feet thick, is designated as the interval between 794 and 1,420 feet in NC–CAR–OT–7, north of Harkers Island, Carteret County, N. C. The lithologic character of this reference section is illustrated on section *Z'–Z"* (NC–CAR–OT–7, pl. 50). The northern reference section, 70 feet thick, is designated as the interval between 90 and 160 feet in VA–WES–T–8 at George Washingtons Birthplace National Monument, Westmoreland County, Va. The lithologic character of this reference section is illustrated on section *N–N'* (VA–WES–T–8, pl. 36).

Biostratigraphic discussion

Species of Ostracoda characteristic of Claibornian strata in the report area are: *Acanthocythereis*? *stenzeli* (Stephenson), *Haplocytheridea goochi* (Stephenson), *Actinocythereis davidwhitei* (Stadnichenko), *Cytheropteron variosum* Martin, *Buntonia howei* (Stephenson), *Hermanites pellucinoda* (Swain), *Hermanites* sp. aff. *H. pellucinoda* Swain, and *H. rukasi* (Gooch). In subsurface sections that are essentially barren of other Ostracoda, *H. rukasi* may be the only species that occurs. Many other ostracode species occur in rocks of Claiborne Age but they also occur in older rocks in the region.

All of the species listed, except *H. pellucinoda*, occur in rocks of Claiborne Age in the Gulf province (Stephenson, 1946; R. C. Howe, 1963). The ostracode zone characteristic of this chronostratigraphic unit is designated the *Acanthocythereis*? *stenzeli-Actinocythereis davidwhitei* Concurrent-Range Zone.

Except where its rocks consist of leached molluscan limestone, this unit generally contains large and well preserved foraminiferal faunas for which little information is available. These faunas seem to vary markedly in different sections and in different parts of any one section. Foraminifera that are characteristic of and useful in identifying the rocks of Claiborne Age mapped in the subsurface include: *Cibicides danvillensis* Howe and Wallace, *Cibicides westi* Howe, and *Marginulina cooperensis* Cushman. In addition, *Asterigerina texana* (Stadnichenko) occurs in large numbers near the base of the unit in a number of wells throughout the report area. Locally, *Buliminella robertsi* (Howe and Ellis), *Cibicides ouachitaensis* Howe and Wallace, *Eponides carolinensis* Cushman, *Marginulina cocoaensis* Cushman, and *Planularia* cf. *P. georgiana* Cushman and Herrick are characteristic of the unit.

Jackson Stage—Rocks of Jackson Age

In the report area rocks of Jackson Age occur only in wells outside North Carolina. These rocks occur commonly in wells in southeast Virginia and extend northward in the subsurface across the outer limits of the Coastal Plain into Maryland, south and central Delaware, and New Jersey. In New Jersey they occur chiefly in Cumberland, Cape May, Atlantic, and Ocean Counties. The rocks are shallow marine throughout the area of their occurrence. The maximum measured thickness was 370 feet in a well (NJ–CM–OT–1, pl. 40) in Cape May County, N. J. The minimum measured thickness was 11 feet in a well (VA–SUR–P–1, pl. 33) on Hog Island in the James River in southeast Virginia.

The lithologic contrasts between rocks of Jackson Age and the rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. This Jacksonian unit is associated genetically with a second-order tectonic stage. Structure and isopach-lithofacies maps for the Jacksonian unit are shown on plate 18.

Lithologic description

Overall, rocks of Jackson Age consist of glauconitic green to gray shale and fine to medium glauconitic sand. In New Jersey and Delaware, these rocks commonly contain brown to reddish-brown oxidized glauconite. Minor amounts of glauconitic limestone occur in several wells (VA–SUR–P–1 and DEL–SUS–T–7). A thin bed of tan chalk occurs in NJ–CM–OT–1. For rocks of Jackson Age, the dominant facies trend is alined north-south. The lithic character and thickness trend for these rocks in Virginia are illustrated on section *N–N′* (pl. 36). Section *BB–BB′* (pl. 53), that lies at a right angle to section *N–N′* (pl. 36), illustrates their lithologic character in southeastern Virginia and adjacent counties in Maryland. Section *O–O′* (pl. 37), section *Q–Q′* (pl. 39), and section *R–R′* (pl. 40) illustrate their lithologic character and facies progression in Delaware and New Jersey.

In a regional sense, rocks of Jackson Age are distinguished from the rocks of overlying and underlying chronostratigraphic units by their characteristic electric-log and, particularly, by their gamma-log patterns and by their Foraminifera. Brown oxidized glauconite is a characteristic of these rocks in Delaware and New Jersey. Where these rocks overlie rocks of Claiborne Age they contain a higher percentage of sand than the underlying rocks.

The reference section (pl. 3) for Jacksonian strata is 275 feet thick and is designated as the interval between 720 and 995 feet in DEL–SUS–OT–5, east of Bridgeville, Sussex County, Del. The lithologic character of the reference section is illustrated on section *Q–Q′* (DEL–SUS–OT–5, pl. 39).

Biostratigraphic discussion

Two species of ostracodes, *Actinocythereis* sp. aff. *A. gibsonensis* (Howe and Garrett) and *Henryhowella* cf. *H. evax* (Ulrich and Bassler) (=?*H. echinata* Puri), have been recovered from rocks of Jackson Age during the present study. *Actinocythereis gibsonensis*, which has been recorded in two wells, occurs in Jacksonian strata in the Gulf region. In the report area, *Henryhowella* cf. *H. evax* commonly occurs in rocks of Jackson Age as well as in rocks of middle Miocene age. The species also has been recorded (Poozer, 1965) from the Cooper Marl of Oligocene age in South Carolina.

Rocks of Jackson Age contain a large foraminiferal fauna in Virginia and a sparse foraminiferal fauna in Maryland, Delaware, and New Jersey. Foraminifera that are characteristic of and help to identify rocks of this unit mapped in the subsurface include: *Angulogerina danvillensis* Howe and Wallace, *Bulimina jacksonensis* Cushman, *Cibicides speciosus* Cushman and Cederstrom, *Cibicides sculpturatus* Cushman and Cederstrom, *Plectofrondicularia virginiana* Cushman and Cederstrom, and *Siphonina tenuicarinata* Cushman.

Previously, the name Chickahominy Formation was proposed by Cushman and Cederstrom (1945) for subsurface strata of Jackson Age in Virginia, and the name Piney Point Formation was proposed by Otton (1955) for subsurface strata of Jackson Age in Maryland.

During the current study, the Chickahominy Formation has been identified in numerous wells in Virginia, whereas the Piney Point Formation, described by Otton (1955, p. 85), has not been recognized in wells. Otton defined the Piney Point Formation as consisting of "hitherto unnamed glauconitic sands and interspersed shell beds of Jackson age lying above the Nanjemoy formation and below the Calvert formation. . . ." He designated a type section for the Piney Point Formation as the section between 220 and 270 feet in a well at Piney Point, St. Marys County, Md. We have examined the original material from the type section. It contains the following ostracodes, all of which are characteristic species for the Claibornian chronostratigraphic unit mapped in this report: *Actinocythereis davidwhitei* (Stadnichenko), *Acanthocythereis*? *stenzeli* (Stephenson), *Hermanites pellucinoda* (Swain), *Hermanites rukasi* (Gooch), and *Clithrocytheridea smithvillensis* (Stephenson). The foraminifer *Asterigerina texana* (Stadnichenko) also occurs in the type section of the Piney Point Formation. It is an index species for strata of Claiborne Age in both the Gulf and Atlantic regions. Inasmuch as the type section of the Piney Point Formation appears to be Claiborne rather than Jackson in age, we suggest that this formational name should not be used to designate sediments of Jackson Age in the subsurface of Maryland, Delaware, and New Jersey as is being done presently. The name Chickahominy Formation is available for these deposits.

OLIGOCENE SERIES

VICKSBURGIAN-CHICKASAWHAYAN UNIT—ROCKS OF OLIGOCENE AGE

In this report, rocks of Oligocene age include rocks of both the Vicksburg Stage and the Chickasawhay Stage as described by Murray (1961, p. 394–404). In the following discussion the rocks are included within a Vicksburgian-Chickasawhayan unit. These rocks have a limited geographic distribution in the Middle Atlantic States; they are recognized in North Carolina but not in the States to the north. In North Carolina, these rocks extend northeast from the South Carolina and North Carolina boundary to the south shore of Albemarle Sound. The maximum measured thickness for this chronostratigraphic unit was 542 feet in a well (NC–CAR–OT–7, pl. 50) north of Harkers Island, Carteret County, N. C. The minimum measured thickness of the unit was 24 feet in a well (NC–ON–T–27, pl. 44) east of Catherine Lake, Onslow County, N. C.

The lithologic contrasts between rocks of Oligocene age and rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. This chronostratigraphic unit is associated genetically with a first-order tectonic stage. Structure and isopach-lithofacies maps for the Vicksburgian-Chickasawhayan unit are shown on plate 19.

Lithologic description

Vicksburgian-Chickasawhayan strata consist chiefly of light-gray to tan algal and shell limestone in which the original shell material has been removed by circulating ground water and in which recrystallization has occurred. Locally, as in northern Dare County, the percentage of clastics is relatively high, as illustrated by the coarse sand and brown shale in the wells on section *Z''–Z'''* (pl. 51). In Pender and Onslow County wells, this unit contains significant amounts of calcareous sand. (See section *C–C'*, pl. 25, and section *Z–Z'*, pl. 49). As may be noted on these sections, the facies progression has a general east-west alinement; an alinement that is not characteristic of the facies progression in the other regional chronostratigraphic units.

Rocks of this unit are distinguished from the rocks of overlying and underlying chronostratigraphic units by their electric-log and gamma-log patterns and by their microfaunas. The occurrence of algal limestone is a distinguishing feature in some strata. In general, rocks of this unit show a greater degree of recrystallization and are more massive than the underlying rock of Claiborne Age. But on the basis of lithologic contrast alone, it is difficult to separate the rocks of these two chronostratigraphic units locally.

The reference section (pl. 3) for rocks of Oligocene age is 542 feet thick and is designated as the interval between 252 and 794 feet in NC–CAR–OT–7, north of Harkers Island, Carteret County, N. C. The lithologic character of the reference section is illustrated on section *D–D'* (NC–CAR–OT–7 , pl. 26).

Biostratigraphic discussion

The Ostracoda that are representative of and help to identify rocks of Oligocene age in North Carolina are: *Leguminocythereis* cf. *L. scarabaeus* Howe and Law, *L.* aff. *L. scarabaeus* Howe and Law, *Pontocythere* cf. *P. rosefieldensis* (Howe), *Eucythere chickasawhayensis* Howe, *Aurila* cf. *A. kniffeni* Howe and Law, *Cushmanidea*? cf *C. vicksburgensis* (Howe), and *Cytheromorpha* cf. *C. vicksburgensis* Howe. Some of these species seem to have had a preference for different environments. *L.* cf. *L. scarbaeus* occurs most commonly in a sandy shelf facies, *Aurila* cf. *A. kniffeni* in a calcareous reef facies, and *Cushmanidea* cf. *C. vicksburgensis* and *Cytheromorpha* cf. *C. vicksburgensis* in a shelly, lagoonal, brackish-water(?) facies. However, *L.* cf. *L. scarabaeus* and *A.* cf. *A. kniffeni* may occur together in the same facies locally.

The ostracode zone characteristic of the Vicksburgian-Chickasawhayan unit is designated the *Leguminocythereis* cf. *L. scarabaeus-Aurila* cf. *A. kniffeni* Concurrent-Range Zone. This concurrent-range zone is representative of at least part of the Oligocene deposits that occur elsewhere in the Atlantic Coastal Plain outside the present study area. For example, some of its members have been found in the Cooper Marl of South Carolina (Pooser, 1965). *L. scarabaeus* has several close relatives, such as *L.* aff. *L. scarabaeus* Howe and Law, *L. cookei* Howe and Law, and *L. verrucosus* Howe and Law of the Oligocene, and *L.*? *twomeyi* (Ulrich and Bassler) of the Miocene. Further work is necessary to clarify the relation of these species.

Foraminiferal faunas are abundant to scarce in this chronostratigraphic unit. They are abundant in the sand and calcareous sand sections, whereas they are scarce or absent in leached molluscan limestone and recrystallized marl sections. Some species that are characteristic of and which help to identify rocks of Oligocene age mapped in the subsurface are: *Pararotalia* cf. *P. byramensis* (Cushman), *Nonion advenum* (Cushman), *Gaudryina jacksonensis* Cushman, *Textularia subhaueri* Cushman, *Uvigerina vicksburgensis* Cushman and Ellisor, and *Discorbis* cf. *D. alveata* Cushman.

Scattered deposits, possibly younger than Oligocene in age, that consist chiefly of recrystallized marl, shell hash, or sandy molluscan limestone occur locally in parts of Carteret, Craven, Jones, and Onslow Counties, N. C. These deposits, recognized in discontinuous low-profile outcrops and shallow excavations, are somewhat unique within the regional Coastal Plain depositional system in that they have no appreciable distribution in the subsurface away from their local areas of occurrence and no demonstrable facies equivalents in the subsurface. Kellum (1926), Richards (1950), Druid Wilson (oral commun., 1964), and others have considered these scattered deposits to be early Miocene in age as determined from their contained macrofossils. In their areas of occurrence, these deposits occupy depressions, formed prior to their deposition, in underlying molluscan limestones of both Oligocene and Eocene age. The lithologic character, areal distribution, thickness, and possible early Miocene age of these deposits suggest regressive deposition that accompanied structural realinement during tectonic stage transition, the transition from the first-order tectonic stage of Oligocene time to the second-order tectonic stage of middle Miocene time. These deposits have no regional hydrologic significance and, in this report, they are included with rocks of Oligocene age for mapping purposes.

MIOCENE SERIES

Middle Miocene Unit—Rocks of Middle Miocene Age

Strata of middle Miocene age are continuous in the subsurface from Carteret County, N. C., northward to Monmouth County, N. J. They are chiefly marine to marginal marine, but are nonmarine in some wells along the inner margin of the Coastal Plain in Maryland and to the north. The maximum measured thickness for rocks of middle Miocene age was 1,201 feet in a well (MD–WIC–OT–11, pl. 35) near Ocean City, Wicomico County, Md. The minimum measured thickness was 5 feet in a well (NC–BER–P–4, pl. 29) near Merry Hill, Bertie County, N. C.

The lithologic contrasts between rocks of middle Miocene age and rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. The middle Miocene unit is associated genetically with a second-order tectonic stage. Structure and isopach-lithofacies maps for the middle Miocene unit are shown on plate 20.

Lithologic description

In general, the unit consists of massive green to brown shale that commonly is diatomaceous in North Carolina, Virginia, and Maryland. In local areas, beds of shell and of phosphatic sand are common and may be dominant in the section. The lithologic character and complexity of the unit in areas where it contains phosphate are illustrated in NC–BEA–T–26 (section *X–X′*, pl. 46) between the depths of 94 and 170 feet. This unit contains minor amounts of dolomite and limestone throughout the Middle Atlantic States.

In North Carolina the unit is more complex lithologically than in Virginia and northward. Limestones and dolomites are more common and the individual strata are thinner than to the north. Diatomaceous clay occurs less commonly than in Virginia and areas to the north, but is present in most areas shown on the lithofacies map (pl. 20) as 75–100 percent shale in North Carolina. The sand is mostly medium and is sparsely to dominantly phosphatic. The unit contains algal chalk in NC–HY–OT–6 (pl. 30). Strata found in North Carolina, in wells north of Albemarle Sound, resemble strata that occur in wells in Virginia rather than strata in wells south of Albemarle Sound. The facies variation and the structural complexity of this unit are illustrated on section *G–G′* (pl. 29), section *G′–G″* (pl. 30), section *Z–Z′* (pl. 49), section *Z′–Z″* (pl. 50), and section *Z″–Z‴* (pl. 51).

In Virginia, the unit consists chiefly of massive pale-green to brown shale that is diatomaceous and shelly as illustrated in VA–MID–P–8 (section *N–N′*, pl. 36). In Nansemond, Isle of Wight and James City Counties, the unit consists chiefly of medium grained slightly phosphatic sand. In the northern part of Virginia the unit is slightly glauconitic. A characteristic facies change, from a high percentage of shale through a sandy section and back into a high percentage of shale, is illustrated on section *N–N′* (pl. 36).

In Maryland, the shales, mostly green to brown, diatomaceous, and slightly glauconitic, remain dominant in the section. However, the unit contains more sand, chiefly fine to medium, and shell than in Virginia. Beds in the upper part of this unit contain coarse shelly sand and shell hash where they cross structural highs. (See MD–WIC–OT–11, MD–WOR–OT–11, MD–StM–T–27, pl. 35, and MD–CAL–T–29, pl. 37). The lithologic character of beds that occur in this unit in Maryland is illustrated on section *M–M′* (pl. 35).

In Delaware and New Jersey, the unit is marginal marine to nonmarine. Throughout most sections of these States the lithologic character of the unit is essentially the same as in Maryland. Toward the inner margin of the Coastal Plain, fine to medium grained sand and shale, that are micaceous, pyritic, and lignitic, are common.

In a regional sense, rocks of middle Miocene age

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may be distinguished from the rocks of overlying and underlying units by their electric-log and, particularly, by their gamma-log patterns and by their microfauna. Massive green and brown shale, phosphatic sand, brown dolomite, and diatomaceous beds are diagnostic.

The reference section (pl. 3) for rocks of middle Miocene age is 242 feet thick and is designated as the interval between 368 and 610 feet in VA–NOR–T–12 at Norfolk, Va. The lithologic character of the reference section is illustrated on section *H–H′* (VA–NOR–T–12, pl. 31).

Biostratigraphic discussion

The following species of Ostracoda are representative of rocks of middle Miocene age in the report area: *Murrayina gunteri* (Howe and Chambers), *M. howei* Puri, *Cytheretta spencerensis* Smith, *C. inequivalvis* (Ulrich and Bassler), *Henryhowella evax* Ulrich and Bassler, and *Echinocythereis*? *clarkana* (Ulrich and Bassler). These species are marine. They occur in rocks that presumably are of middle Miocene age in Florida but have not been found in the western part of the Gulf province. Other species of Ostracoda, that occur in rocks of middle Miocene age in the report area, are rare or range into younger deposits.

The *Cytheretta spencerensis—Murrayina gunteri* Assemblage Zone is established for rocks of middle Miocene age.

In this unit the distribution of foraminiferal faunas exhibits no constant pattern. Some beds contain large numbers of Foraminifera. Other beds, particularly those that contain the phosphatic sand and clay in North Carolina and Virginia and glauconitic sand in New Jersey, contain a small number of Foraminifera. Species that are characteristic of and which help to identify rocks of middle Miocene age mapped in the subsurface include: *Cibicides concentricus* (Cushman), *Robulus americanus* (Cushman) var. *spinosus* (Cushman), *Siphogenerina lamellata* Cushman, *Spiroplectammina mississippiensis* (Cushman), and *Uvigerina calvertensis* Cushman.

Late Miocene Unit—Rocks of Late Miocene Age

Strata of late Miocene age are developed chiefly in eastern North Carolina and southeastern Virginia and to a lesser extent in Maryland, Delaware, and New Jersey. Numerous outliers of these strata are recognized in North Carolina, Virginia, and New Jersey. In North Carolina and Virginia the unit is chiefly marine whereas it is chiefly marginal marine to the north of Virginia. The maximum measured thickness for the late Miocene unit was 590 feet in a well (NC–DA–OT–9, pl. 51) in Pamlico Sound, N. C. The minimum measured thickness was 10 feet in a nonsection well (NC–JON–T–8) southeast of Ravenwood, Jones County, N. C.

The lithologic contrasts between rocks of late Miocene age and the rocks of overlying and underlying chronostratigraphic units are illustrated on the report's geologic cross sections. This late Miocene unit is associated genetically with a first-order tectonic stage. Structural and isopach-lithofacies maps for the late Miocene unit are shown on pl. 21.

Lithologic description

In North Carolina, Virginia, and in most of Maryland (except for eastern counties), rocks of late Miocene age consist of gray highly shelly clay and fine to medium clayey and shelly sand. Generally, glauconite is a minor constitutent in the clay. In North Carolina, beds of limestone are common and attain a maximum thickness of 170 feet in NC–HY–T–3 (section *Z′–Z″*, pl. 50), located adjacent to a structural high that extends northeast from Carteret County to Dare County. Beds of shell hash are prominent in this same area. In North Carolina, the characteristic lithology and facies progression within the late Miocene unit are illustrated on section *F–F′* (pl. 28), on section *G–G′* (pl. 29), and on section *G′–G″* (pl. 30). In Virginia, they are illustrated on section *BB–BB′* (pl. 53).

In eastern Maryland, Delaware, and New Jersey, rocks of late Miocene age consist chiefly of medium to coarse micaceous and slightly shelly sand, in which lignite and hematite occur in trace amounts. The lithologic character of the unit in Maryland, Delaware, and New Jersey is illustrated on section *BB′–BB″* (pl. 54) and on section *M–M′* (pl. 35).

In a regional sense, rocks of late Miocene age may be distinguished from the rocks of overlying and underlying units by their characteristic electric-log and particularly, by their gamma-log patterns and by their microfaunas. Shell beds in a gray shale are diagnostic of this unit.

The reference section (pl. 3) for rocks of Late Miocene age is 461 feet thick and is designated as the interval between 100 and 561 feet in NC–CUR–OT–12 near Coinjock, Currituck County, N. C. The lithologic character of the reference section is illustrated on section *Z″–Z‴* (NC–CUR–OT–12, pl. 51).

Biostratigraphic discussion

The biostratigraphic boundary for the Ostracoda does not coincide with the late Miocene-post-Miocene time-stratigraphic boundary in the report area. Generally, however, Ostracoda are diagnostic with respect to the two chronostratigraphic units in that they are relatively abundant in strata of late Miocene age and are rare or absent in strata of post-Miocene age. Locally, as in parts of southeast Virginia and southeast North Carolina, they may be relatively abundant in strata near the base of the post-Miocene unit.

The following species occur commonly in strata of late Miocene age in wells in the report area (Species that have not been recorded from deposits of post-Miocene age are marked with an asterisk); *Puriana rugipunctata* (Ulrich and Bassler), *Puriana mesacostalis* (Edwards), *Actinocythereis exanthemata* (Ulrich and Bassler), **Xestoleberis? ventrostriata* Swain, *Aurila conradi* (Howe and McGuirt), *Loxoconcha purisubrhomboidea* Edwards, *Orionina vaughani* (Ulrich and Bassler), *Neocytherideis* cf. *N. triplistriata* (Edwards), *Pontocythere rugipustulosa* (Edwards), **Murrayina* n. sp. aff. *M. howei* Puri.

In addition, the following species occur less commonly: *Thaerocythere schmidtae* (Malkin), *Hemicytherura* cf. *H. howei* Puri, *Cytheretta burnsi* (Ulrich and Bassler), *Radimella confragosa* (Edwards), *Caudites sellardsi* Howe and Neill, *Proteoconcha multipunctata* (Edwards), *Camplocythere laeva* Edwards, *Bairdia laevicula* Edwards, and *Cytheropteron subreticulatum* van den Bold. The first three species have not been found in deposits of post-Miocene age; the others range into deposits of Pliocene age, and *R. confragosa, C. sellardsi, C. subreticulatum,* and *B. laevicula* have been reported in Holocene deposits.

The ostracodes that are characteristic of rocks of late Miocene age in the Middle Atlantic States occur in other areas but are not well developed as a zone elsewhere. The Caribbean assemblages described by van den Bold (1963, 1966) include some of the species listed above, such as *R. confragosa, O. vaughani,* and *C. subreticulatum,* but these species may have different ranges there than in the Atlantic coastal region.

The ostracode zone that extends from the late Miocene unit into the lower part of the post-Miocene unit is designated the *Aurila conradi-Thaerocythere schmidtae* Assemblage Zone. *R. confragosa* is abundant in the late Miocene Duplin Marl and overlying Pliocene Waccamaw Formation of southeastern North Carolina and northern South Carolina. It is selected to represent a *Radimella confragosa* subzone of the *Aurila conradi-Thaerocythere schmidtae* Assemblage Zone. *R. confragosa* was used also by van den Bold (1966) as a zonal indicator in the upper Miocene. *Thaerocythere schmidtae* on the other hand has not been found in the Duplin (Miocene) and Waccamaw (Pliocene) but occurs in the Yorktown Formation of late Miocene age in Virginia and Maryland. The *Thaerocythere schmidtae* Subzone of the *A. conradi-Thaerocythere schmidtae* Assemblage Zone is here considered somewhat older than, but partly equivalent to, the *R. confragosa* Subzone.

The late Miocene and (or) Pliocene ostracodes are chiefly marine. Some of the forms, such as *R. confragosa* and some species of *Cytheromorpha,* suggest lagoonal or estuarine conditions.

The late Miocene unit contains abundant foraminiferal faunas in most areas of its occurrence in North Carolina and Virginia. From Maryland through New Jersey, the unit contains very few Foraminifera. Where present, Foraminifera are chiefly diagnostic in terms of their large numbers, and few, if any, have a range that is restricted to this unit. Foraminifera that are characteristic of and that help to identify rocks of late Miocene age mapped in the subsurface include: *Cancris sagra* (d'Orbigny), *Discorbis assulata* Cushman, *Discorbis candeiana* (d'Orbigny), *Eponides mansfieldi* Cushman, *Nonion pizzarense* Berry, *Textularia gramen* (d'Orbigny), and *Textularia mayori* Cushman.

PLIOCENE, PLEISTOCENE, AND HOLOCENE SERIES, UNDIFFERENTIATED

POST-MIOCENE UNIT—ROCKS OF POST-MIOCENE AGE

Strata of post-Miocene age are widely distributed from North Carolina to Long Island, N. Y. The strata are marginal marine to nonmarine, chiefly the latter. The maximum measured thickness for beds in this chronostratigraphic unit was 212 feet in a well (NC–DA–OT–14, pl. 28) near East Lake, Dare County, N. C. The minimum measured thickness was 8 feet in a well (NC–PEN–OT–8, pl. 49) northeast of Vista, Pender County, N. C.

The lithologic contrasts between strata of post-Miocene age and the strata of underlying chronostratigraphic units are illustrated on the report's geologic cross section. This unit is associated genetically with a second-order tectonic stage. Structural and isopach-lithofacies maps for the post-Miocene unit are shown on plate 22.

Lithologic description

In North Carolina, rocks of post-Miocene age are marginal marine east of a line that extends northward from the mouth of the New River in Onslow County, to the Chowan River at the Gates and Hertford County line, and thence northeast toward Cape Henry, Va. In this area, rocks consist chiefly of blue to tan to brown fine to medium sand that is both clayey and shelly. In several wells in Pamlico Sound (NC–DA–OT–11, NC–HY–OT–11, and NC–DA–OT–12) the rocks chiefly consist of shell hash. The lithologic character of these rocks is illustrated on section *E–E′* (pl. 27), section *F–F′* (pl. 28), section *G–G′* (pl. 29), section *G′–G″* (pl. 30), section *Z–Z′* (pl. 49), section *Z′–Z″* (pl. 50), and section *Z″–Z‴* (pl. 51).

In Virginia, these rocks are nonmarine, except in areas that are on the southwest and northeast sides of the mouth of Chesapeake Bay. The rocks are chiefly medium to coarse clayey sand with thin beds of red, brown, and yellow clay. Pyrite, limonite, and feldspar are common accessories. Locally, channel gravels are abundant and widely distributed. The lithologic character of these rocks in Virginia is illustrated on section *C–C′* (pl. 25).

In Maryland, these rocks are nonmarine except in MD–WIC–OT–11 (pl. 35) where they are marginal marine. Commonly, wells in Dorchester, Worcester, and Wicomico Counties penetrate abandoned channels that contain coarse sand and gravel. To the west of Chesapeake Bay, the rocks consist of yellow and brown fine to medium sand and interlayered shale. The lithologic character of these rocks in Maryland is illustrated on section *M–M′* (pl. 35).

In Delaware and New Jersey, the rocks are marginal marine in only two wells, NJ–CM–OT–1 and NJ–OC–T–1. Elsewhere in these States, these rocks are nonmarine and consist of fine to medium sand and red to brown clay. The lithologic character of these rocks in New Jersey is illustrated on section *R–R′* (pl. 40) and on section *S–S′* (pl. 41). On long Island, N. Y., the rocks have a dominant glacial character and are illustrated on section *EE–EE′* (pl. 57). Weiss (1954) described an interglacial marine deposit, the Gardiners Clay, that is developed locally on Long Island and occurs at or near the base of the post-Miocene chronostratigraphic unit.

In a regional sense, rocks of post-Miocene age may be distinguished from the rocks of underlying units by their characteristic electric-log and gamma-log patterns and by their highly oxidized character.

The chief reference section (pl. 3) for nonmarine rocks of post-Miocene age is 70 feet thick and is designated as the interval between +208 and +138 feet in NC–SC–P–2 at Maxton, Scotland County, N. C. The lithologic character of this reference section is illustrated on section *B–B′* (NC–SC–P–2, pl. 24). A supplementary reference section (pl. 3) for marginal-marine rocks is 182 feet thick and is designated as the interval between +2 and −180 feet in NC–HY–OT–6 south of Lake Mattamuskeet, N. C. The lithologic character of this reference section is illustrated on section *G′–G″* (NC–HY–OT–6, pl. 30).

Biostratigraphic discussion

The occurrence and zonation of the ostracodes in the lower part of this chronostratigraphic unit was elaborated upon in the biostratigraphic discussion of the late Miocene chronostratigraphic unit. No diagnostic species of post-Pliocene Ostracoda were obtained from well material in the report area and this part of the geologic section typically is devoid of ostracodes in the wells studied.

Valentine (1971) has recorded an ostracode assemblage of 82 species from the Norfolk Formation of late Pleistocene age in southeastern Virginia. Seventy of the species recorded from the Norfolk Formation are still living in marine environments along the east coast. Some live only north of Cape Hatteras, N. C., whereas others live only south of Cape Hatteras. An analysis of the temperature tolerance of the species that are still living and that also were recorded from the Norfolk Formation suggested to Valentine that the temperature of marine waters in the Norfolk area during late Pleistocene time was higher than at present.

Valentine (1971), with respect to Holocene ostracodes of the present Atlantic Continental Shelf area of the United States, recognized four biofacies and two faunal provinces. The faunal provinces are separated primarily at Cape Hatteras, N. C., and include Bryozoa and other invertebrates as well as ostracodes. The marine Holocene faunas are poorly preserved or absent in most of the wells studied for this report.

In general, the rocks of post-Miocene age do not contain Foraminifera, except locally where species that occur in rocks of late Miocene age also occur in this chronostratigraphic unit. In some wells *Elphidium excavatum* (Terquem) and *Elphidium incertum* (Williamson) occur in large numbers and in the absence of other species.

DESCRIPTIVE AND QUANTITATIVE SEDIMENTARY GEOMETRY

The 17 chronostratigraphic units may be grouped, according to a genetic association and for descriptive convenience, with one or the other of two tectonic stages that we consider to have prevailed alternately in the region (table 1). The grouping, based on analysis of the internal geometry of the regional sediment mass, represents the initial step in establishing a regional systematization of hydrogeologic associations. Twelve chronostratigraphic units belong to the tectonic stage in which northeast-striking positive and negative features prevailed. This is designated as the predominant or first-order tectonic stage. Five chronostratigraphic units belong to the tectonic stage that, in the final structural phase, is characterized by northwest-striking positive features and by negative features tangential to the positive features. This is designated as the subordinate or second-order tectonic stage. The structural-depositional alinements which are characteristic of each tectonic stage, and which are summarized in table 1, are discordant in part. The structural alinements and the distribution pattern for sediments that are associated with a second-order tectonic stage prevail today and have prevailed since the end of late Miocene time in the report area. As discussed previously and as illustrated by their grouping in table 1, five of the 17 units mapped are associated genetically with the second-order tectonic stage, now extant. They are: Unit H, Unit G, the Jacksonian Unit, the middle Miocene Unit. and the post-Miocene Unit. Although some of these units are widely separated in geologic time, they contain rocks whose depositional boundaries exhibit the same alinement and whose pattern of facies distribution is quite similar. The strata within these five sequences exhibit constancy with respect to the alinement of shorelines, the configuration of shorelines, the directions of their depositional strikes and dips, and the alinements of their facies progression—all of which are fundamental factors in establishing the external and internal geometry of aquifers and estimating their ability to store and transmit water.

The 12 chronostratigraphic units that belong to the first-order tectonic stage are: Unit I, Unit F, Unit E, Unit D, Unit C, Unit B, Unit A, the Midwayan unit, the Sabinian unit, the Claibornian unit, the Vicksburgian-Chickasawhayan unit, and the late Miocene unit. These units, some of which also are widely separated in geologic time, contain rocks whose depositional boundaries exhibit the same alinement and whose pattern of facies distribution is quite similar. When viewed in plan, the depositional boundaries and overall facies-distribution pattern observed for the strata in one group of chronostratigraphic units lie at an angle to the depositional boundaries and overall facies-distribution pattern observed for the strata in the other group of chronostratigraphic units. Thus, within the sediment mass, the external and internal geometry of certain layers exhibits an angular discordance with respect to the geometry of other layers.

To facilitate discussion of this discordant geometry, it is necessary to consider the nature and complexity of the offlap and onlap relations that occur among rocks with both similar and dissimilar patterns of distribution. In coastal areas where a landmass lies adjacent to a marine depositional basin, the terms, "transgression" (onlap) and "regression" (offlap), refer, in a broad sense, to the relative lateral displacement of successive depositional sequences in either the upbasin (landward) or downbasin (seaward) direction. Herein, these terms are used in a more restrictive sense to refer to the lateral migration of depositional sequences that accompanies the realinement of structural troughs, and, also, to refer to the lateral migration of depositional sequences that takes place within a structural trough.

The lateral migration of depositional sequences, that accompanies a realinement of structural troughs, forms an arcuate pattern. The depositional sequences migrate across the angles formed by the sides of two troughs, one of which is superimposed on the other and whose long axes intersect. The migration takes place when there is a shift from a first-order to a second-order tectonic stage and conversely. Following trough realinement, the lateral migration of depositional sequences that takes place within a trough is basically linear in nature. The depositional sequences migrate either away from or toward the sides of a trough and either away from or toward the head and the foot of a trough respectively.

In order to develop a valid quantification of the distribution of various types of sediments mapped in the region, it is important to have some understanding of the manner in which the migration of depositional sequences and of strandline segments took place during deposition.

ARCUATE-TYPE TRANSGRESSION AND REGRESSION

In the following discussion, we will consider and illustrate (fig. 10) two general cases for the arcuate-type of transgression and regression. In both cases, the migration of depositional sequences, from a trough with one alinement toward a trough with a different alinement, takes place across angles of about 45° and across their supplements. These angles are formed by intersecting hinge zones (axes of tilt) which strike northeast and north, respectively, and which bound the respective sides of differently alined structural troughs that are established during successive tectonic stages.

In the first case (fig. 10*A*), we will consider the migration of depositional sequences that takes place when there is a transition from a first-order to a second-order tectonic stage. As a result of this transition, a graben, whose long axis is alined north-south, is superimposed athwart a pair of half grabens, whose respective long axes are alined northeast-southwest. The sense of trough realinement is clockwise; from a northeast-southwest trough alinement toward a north-south trough alinement.

In the second case (fig. 10*B*), we will consider the migration of depositional sequences that takes place when there is a transition from a second-order to a first-order tectonic stage. As a result of this transition, a pair of half grabens, whose respective long axes are alined northeast-southwest, are superimposed athwart a graben whose long axis is alined north-south. The sense of trough realinement is counterclockwise; from a north-south trough alinement toward a northeast-southwest trough alinement.

The hingebelt pattern illustrated in figure 10 comprises a set of northeast-striking parallel lines (X–X', Y–Y', and Z–Z') that intersect a set of north-striking parallel lines (U–U' and V–V'). The transverse hinge zone U–U' forms 12 angles with the three hinge zones that it intersects. Similarly, the transverse hinge zone V–V' forms eight angles with the two hinge zones that it intersects.

Within 12 of the chronostratigraphic units mapped, facies-distribution and depositional-thickening patterns indicate that their lateral depositional boundaries were accordant with northeast-striking hinge zones. These are the units that belong to a first-order tectonic

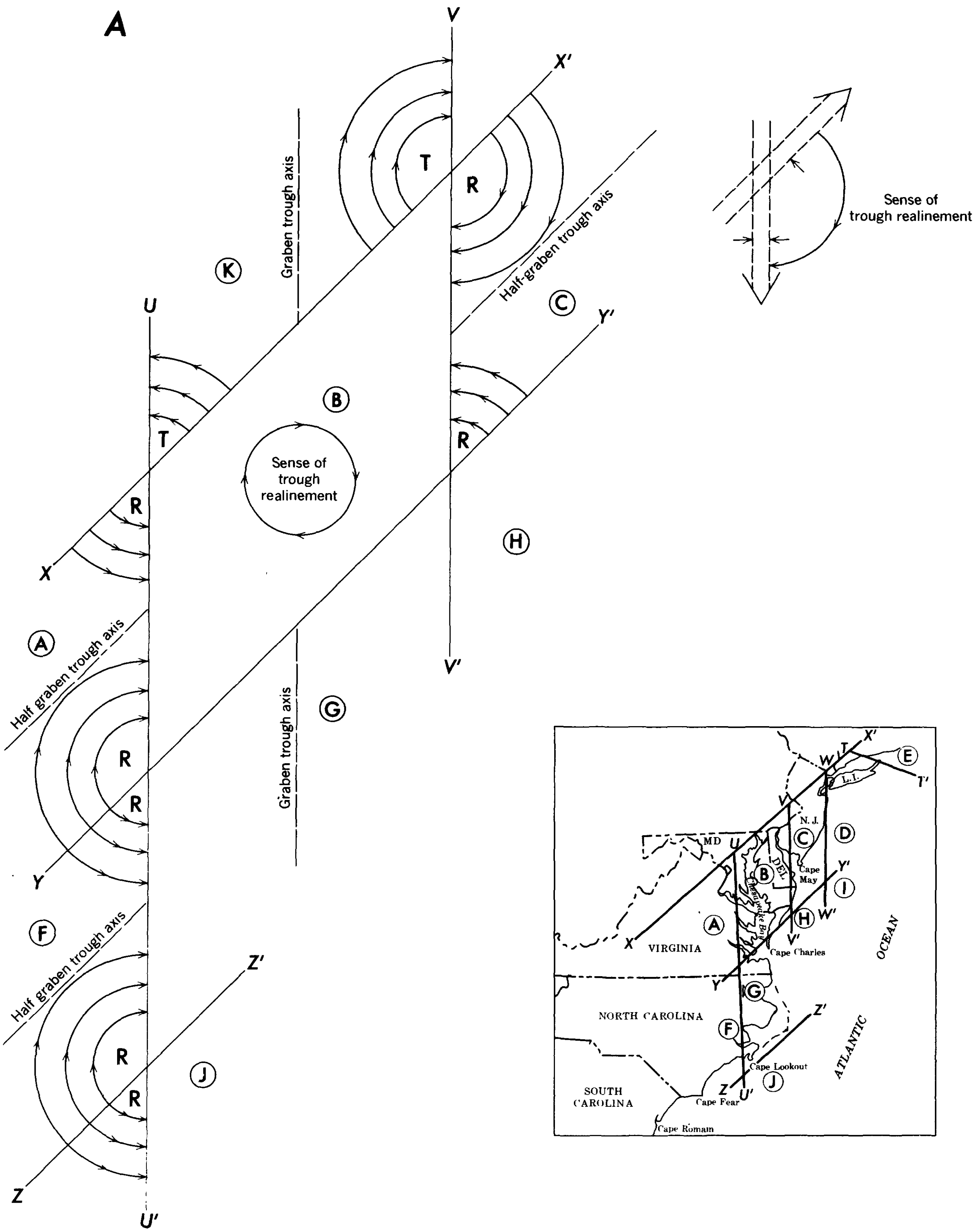

FIGURE 10.—Patterns of arcuate regression and transgression in the central part of the report area.

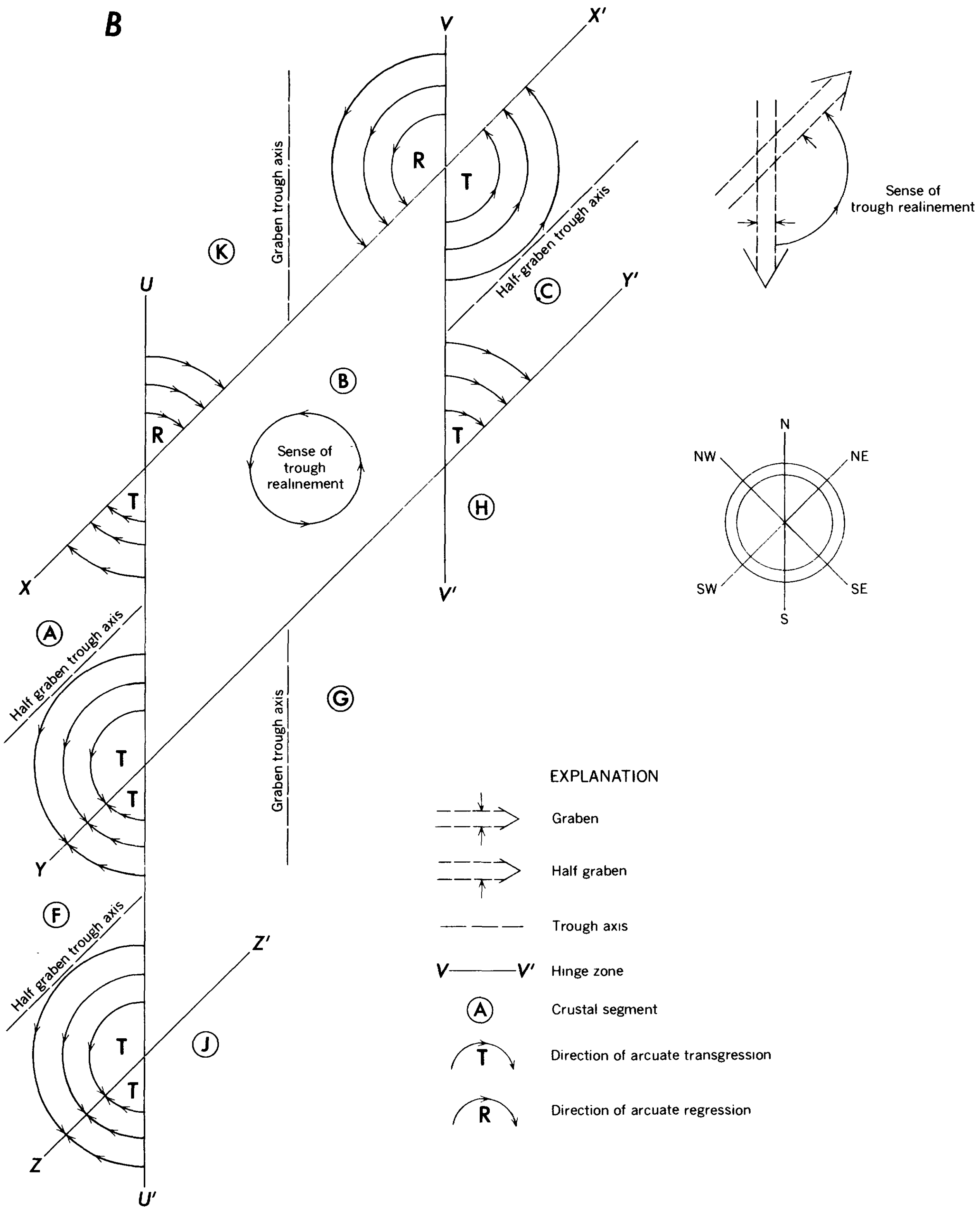

FIGURE 10.—Continued.

stage. Within five of the chronostratigraphic units mapped, facies-distribution and depositional-thickening patterns indicate that their lateral depositional boundaries were accordant with north-striking hinge zones. These are the units that belong to a second-order tectonic stage.

Inasmuch as the lateral depositional boundaries (northeast-southwest) of one group of chronostratigraphic units lie at an angle to the lateral depositional boundaries (N.-S.) of the other group, the transition from one tectonic stage to the other stage must have been accompanied by the migration of depositional sequences through some of the angles formed by intersecting hinge zones.

This type of intertrough migration of depositional sequences is designated an arcuate type of transgression and regression. It occurred at the time of tectonic stage transition and it accompanied the encroachment of the sea upon or the withdrawal of the sea from crustal segments bounded by hinge zones in the Middle Atlantic States. For the purpose of discussing specific examples of arcuate transgression and regression, we will limit the discussion to that part of the report area designated by crustal segments A, B, C, F, G, and K (fig. 10).

The sense of trough realinement that takes place when there is a transition from a first-order to a second-order tectonic stage and the clockwise or counterclockwise sense of migration for transgressive and regressive depositional sequences through the angles formed by the sides of intersecting troughs are shown in figure 10*A*. In conjunction with trough realinement, the sea withdraws from segments A and C in the direction of segment B; it withdraws from segment F in the direction of segment G; and it encroaches upon segment K from the direction of segment B. Regressive depositional sequences develop on crustal blocks A, C, and F, whereas a transgressive depositional sequence is established on block K. As illustrated in figure 10*A*, arcuate regression takes place across six of the angles of intersection and arcuate transgression takes place across two of the angles of intersection.

The sense of trough realinement that takes place when there is a transition from a second-order to a first-order tectonic stage and the clockwise or counterclockwise sense of migration for transgressive and regressive depositional sequences through the angles formed by the sides of intersecting troughs are shown in figure 10*B*. In conjunction with trough realinement, the sea withdraws from block K in the direction of block B; it encroaches upon blocks A and C from the direction of block B; and it encroaches upon block F from the direction of block G. A regressive depositional sequence develops on block K, and transgressive depositional sequences are established on blocks A, C, and F. As illustrated in figure 10*B*, arcuate transgression takes place across six of the angles of intersection and arcuate regression takes place across two of the angles of intersection.

As indicated by angular discordance between layers within the sediment mass, a transition from one tectonic stage to the other tectonic stage took place seven times during its deposition. The times at which transition took place are given as follows in terms of the chronostratigraphic sequences that were deposited immediately before and after a transition.

Transition from a first-order to a second-order tectonic stage, transition being accompanied by a clockwise realinement of depositional troughs:

Tectonic-stage transition

- Between deposition of Unit I and Unit H.
- Between deposition of the Claibornian unit and the Jacksonian unit.
- Between deposition of the Oligocene unit and the middle Miocene unit.
- Between deposition of the late Miocene unit and the Post Miocene unit.

Transition from a second-order to a first-order tectonic stage, transition being accompanied by a counterclockwise realinement of depositional troughs:

Tectonic-stage transition

- Between deposition of Unit G and Unit F.
- Between deposition of the Jacksonian unit and the Oligocene unit.
- Between deposition of the middle Miocene unit and the late Miocene unit.

From the foregoing relations it may be inferred that the period of elapsed time between tectonic-stage transitions has decreased from Early Jurassic(?) time to the present and, correspondingly, that the frequency of regional mobility has increased from Jurassic(?) time to the present.

In the mobile system characterized by semiperiodic realinement of depositional troughs, the linear measurement of the distances, that are involved in the cyclic migration of depositional sequences through angles of about 45° and their supplements, varies proportionately with the length of chords subtending "transgressive or regressive arcs" of unequal length and which intersect the angles that are illustrated in figure 10. Inasmuch as time is a constant factor in the distance-rate-time relation, the rates at which the depositional sequences migrate along arcs of equal radius are much greater through the 135° angles than through the 45° angles. For any given angle, the rate of migration for depositional sequences increases as the radius of an arc through the angle increases. It follows that regresson and transgression of depositional sequences take place simultaneously in different areas in conjunction with a realinement of depositional troughs, but neither takes place at rates which are uniform.

Although the external and internal geometry exhibited by contemporaneous sediments laid down during a trough realinement appears to be quite complex, several broad generalizations that influence the hydrologic capability of the sediments can be made with respect to their geometry. In segments of the system that at any one time are characterized by the arcuate type of transgression, the sediments that are deposited within the acute angles are relatively thick and have a more uniform texture when compared with the contemporaneous sheetlike texturally heterogeneous sediments that are deposited within the obtuse angles (fig. 10) of the system. If and when they develop, basal transgressive sands or conglomerates appear to be confined to the acute angles of the system. In segments of the system that at any one time are characterized by the arcuate type of regression, the sediments that are deposited within the acute angles are relatively thicker and are better sorted in comparison with the contemporaneous more sheetlike and texturally heterogeneous sediments that are deposited within the obtuse angles (fig. 10).

In a related sense, the different rates of intertrough migration for depositional sequences, that takes place during trough realinement, may also be considered to represent different rates of environment change. When trough realinement takes place, the pivot points for the intertrough migration of depositional sequences are at the points where hinge zones intersect. These pivot points determine the location of areas of maximum environmental stability during tectonic-stage transition. As areas of maximum environmental stability, they serve as "seed" areas where faunal elements are relatively protected, environmentwise, during a period of trough realinement and from which faunal elements migrate outward once a new trough-realinement cycle has been established. For many faunal elements reccognized in the region, their vertical range in the area of the pivot points is greater than at other locales where they occur. Where hinge zones intersect, successive chronostratigraphic units that are associated genetically with different tectonic stages show the least faunal diversity, the greatest lithologic similarity, and the greatest degree of hydrologic continuity in vertical sections. Where the hinge zones *U–U′* and *Z–Z′* intersect (fig. 10), specific examples of lithologic similarity between successive sets of strata, that are associated genetically with different trough alinements (the strata of Unit G and Unit F and the strata of the middle Miocene and late Miocene units), are illustrated on section *D–D′* (pl. 26) and on section *E–E′* (pl. 27). It is the paradox of these locales where hinge zones intersect that, because they are locales of maximum environmental stability when trough realinement takes place, they are locales where it is most difficult to establish stratigraphic and hydrologic separation between successively deposited chronostratigraphic units that are associated genetically with different tectonic stages. Generally, regional rather than local criteria must be used to make the separation in these areas.

When trough realinement ceases and a new trough alinement is established, the intertrough arcuate regression and transgression ceases. It is succeeded by intratrough linear regression and transgression.

LINEAR-TYPE TRANSGRESSION AND REGRESSION

During linear regression and transgression, a migration of contemporaneous environments occurs predominantly within the structural-sedimentary troughs. To a lesser degree it also takes place relative to positive intertrough areas, and it takes place in a direction that is either away from or toward regional hinge zones of fixed position. Figure 11 is a structural-sedimentary model constructed to illustrate the directional nature of linear regression and transgression relative to the hinge zones in the report area. Generally, the local migration of environments is accompanied by a shift in the position of a strandline. Quite commonly, however, the migration occurs in conjunction with differential thallatogenic movement. This movement causes either a shallowing or a deepening of the water above a segment of the sea floor, but does not involve the repositioning of a strandline (beach) as such.

The migration of contemporaneous marine environments, either away from or toward a specific hinge zone, is not generally associated with eustatic changes in sea level. This is indicated by the fact that regressive and transgressive movement of contemporaneous marine environments was predominantly local and not regional in extent. Commonly, encroachment of the sea across one segment of the Coastal Plain was coupled with withdrawal of the sea from an adjacent or nearby segment of the Coastal Plain, indicating that regression and transgression occurred simultaneously. This suggests that the migration of local marine environments and accompanying shifts in the position of local strandline segments within the structural-sedimentary troughs, or relative to intertrough areas, reflected states of imbalance between variable rates of sedimentation and variable rates of subsidence which characterized different segments of the Coastal Plain at different times. This relation between rates of sedimentation and rates of subsidence, particularly as it applied to deltaic deposition in a subsiding, marginal-sea basin, was indicated by Rainwater (1964) to have been the principal cause of the regional and local migration of strandlines in the Tertiary of the Gulf region.

At any one time, the relation that existed between rates of crustal subsidence, or coastal downbuilding, and rates of sedimentation was complex. It was com-

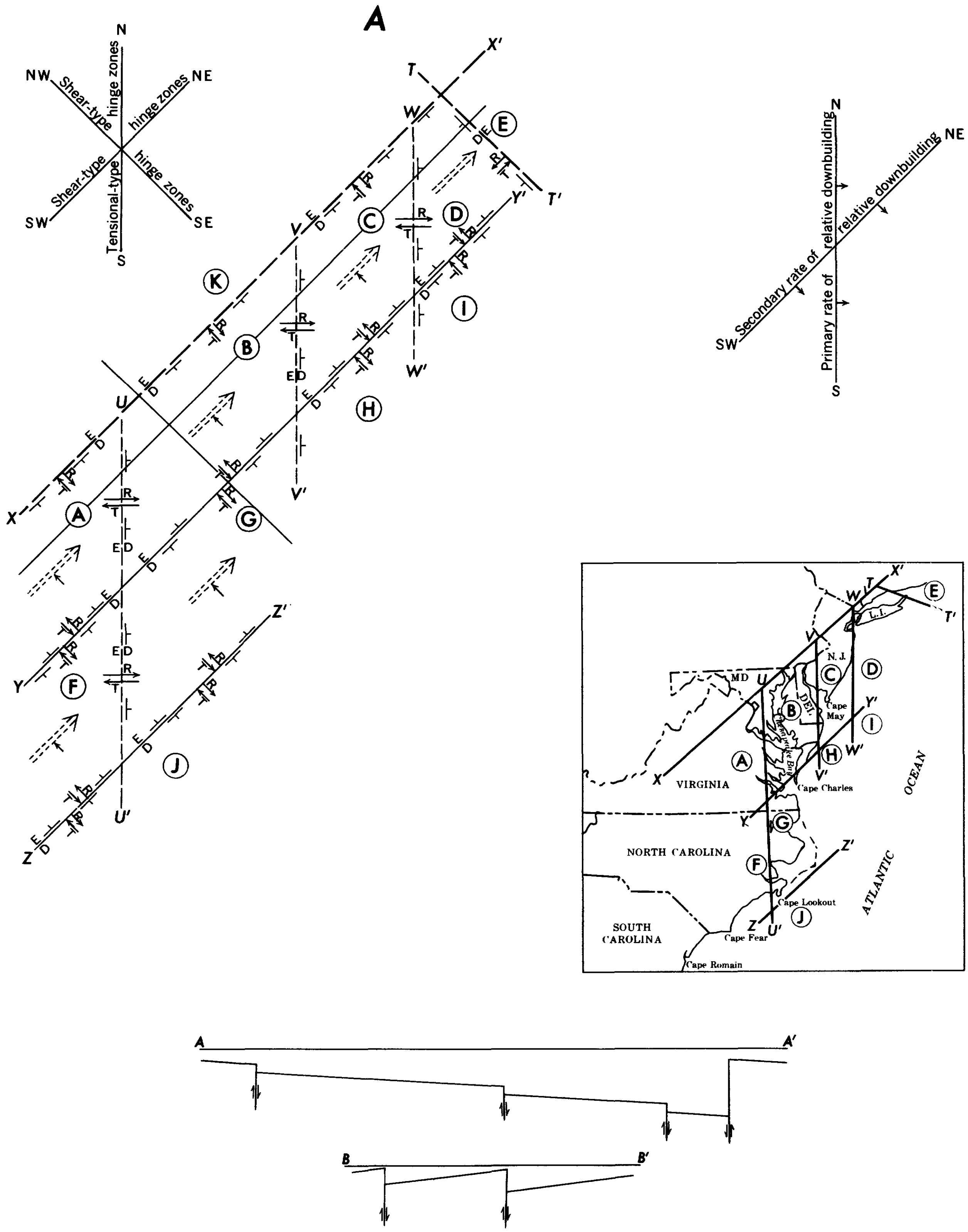

FIGURE 11.—Combined structural-sedimentary models of the report area. *A*. First-order tectonic stage. *B*. Second-order tectonic stage.

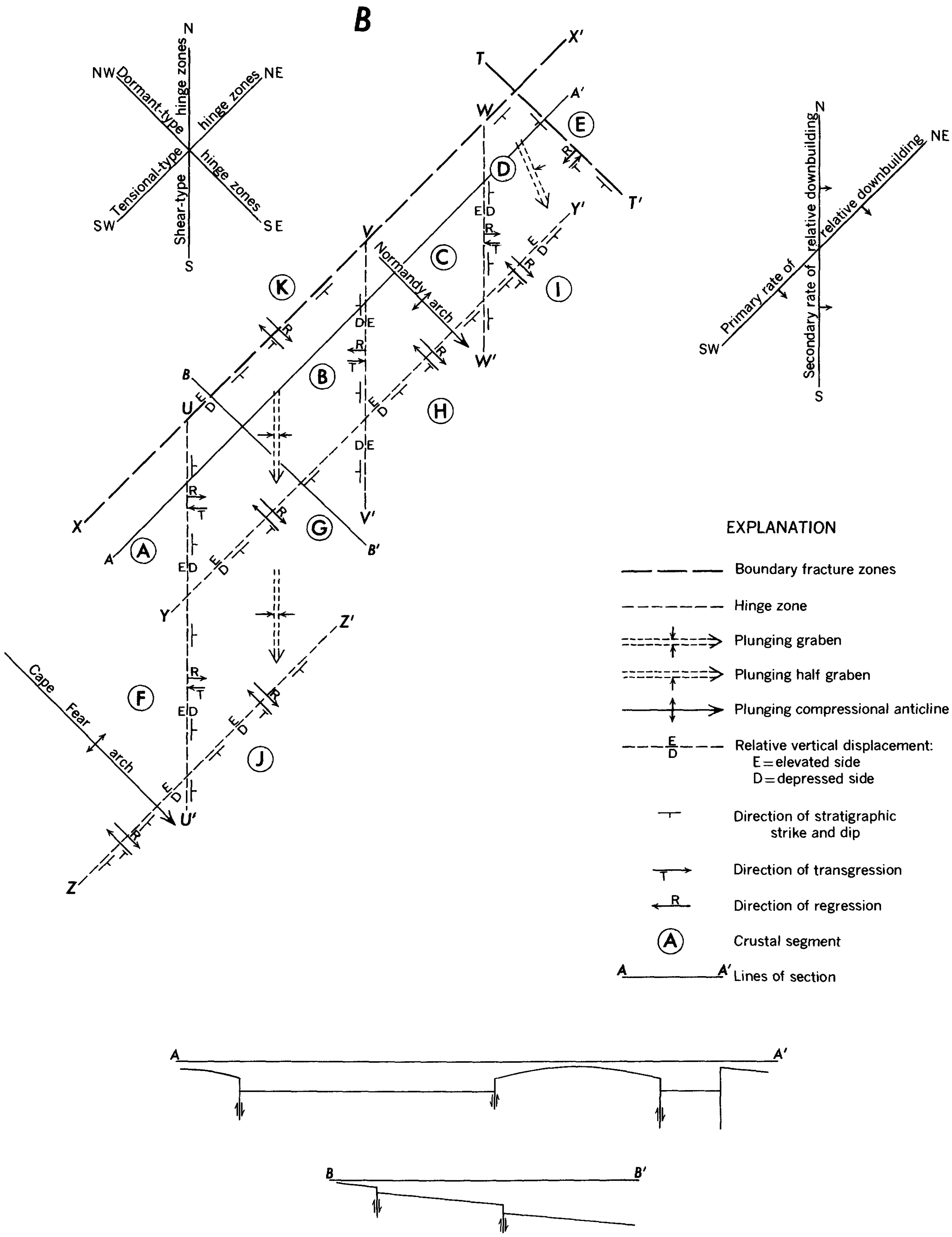

FIGURE 11.—Continued.

plex because it involved simultaneous crustal subsidence that occurred at different rates along intersecting hinge zones, because it involved periodic transposition in the rates of crustal subsidence associated with two different types of hinge lines (tension and shear), and because it involved variable rates of sedimentation relative to the fixed position of each hinge zone. Within the structural-sedimentary troughs, the migration of contemporaneous marine environments took place relative to hinge zones that coincided with the sides of the trough and relative to hinge zones that lay athwart the troughs. The sense of migration was transgressive away from the axis of a trough and it was regressive toward the axis of a trough. With respect to hinge zones that lay athwart the plunging troughs, the sense of migration was transgressive in a general uptrough direction and was regressive in a general downtrough direction (fig. 11).

In discussing the historic nature of the imbalance between rates of subsidence and rates of sedimentation, that existed at different places in the region at different times, we will discuss first the nature and locale of the structural subsidence and secondly the nature of the sedimentation that was associated with the subsidence.

The hinge zones that comprise a regional hingebelt system bound various crustal segments and comprise axes of tilt along which the relative vertical displacement of adjacent crustal segments takes place. The relative vertical displacement is variable as to rate and time along differently alined and different types of hinge zones. Depending upon whether the regional structural architecture is that of a first-order or a second-order tectonic stage, the hinge zones either bound or lie athwart various structures as illustrated in figure 11.

REGIONAL PATTERNS OF SUBSIDENCE AND SEDIMENTATION

According to the theory presented in this report and derived from patterns of discordance within the onshore sediment mass, two types of hinge zone, a tension type and a shear type, are inferred for the region contained within the unit-structural block. These internal hinge zones, that strike either north or northeast, bound the crustal segments that comprise the block. During any one tectonic stage, downbuilding takes place along both types of hinge zones. When any one crustal segment lies on the relatively depressed sides of both tension-type and shear-type hinge zones, the rate of relative subsidence of the crustal segment seems to be about five times greater along a side that lies adjacent to a tension-type hinge zone than it is along a side that lies adjacent to a shear-type hinge zone.

During a first-order tectonic stage, tension-type hinge zones strike north and shear-type hinge zones strike northeast. The strata of the 12 chronostratigraphic units that belong to this tectonic stage attain a thickness about five times as great along the relatively depressed sides of crustal segments that lie adjacent to north-striking hinge zones as they do along the relatively depressed sides of crustal segments that lie adjacent to northeast-striking hinge zones. During a second-order tectonic stage, tension-type hinge zones strike northeast and shear-type hinge zones strike north. The strata of the five chronostratigraphic units that belong to this tectonic stage attain a thickness about five times as great along the relatively depressed sides of crustal segments that lie adjacent to northeast-striking hinge zones as they do along the relatively depressed sides of crustal segments that lie adjacent to north-striking hinge zones. Thus, when tension-type and shear-type hinge zones are transposed as a result of tectonic-stage transition, rates of relative downbuilding associated with each of the two types of hinge zones also are transposed.

Generally, when hinge-zone transposition takes place, the sense of relative vertical displacement for adjacent crustal segments on the opposite sides of a hinge zone remains constant. The transposition is accompanied only by a change in the rate of relative vertical displacement; from a predominant to a subordinate rate, or conversely. Thus, with respect to the hinge zone designated by *U–U′* (fig. 11) for example, the sense of relative vertical displacement for adjacent crustal segments on its opposite sides is the same during both tectonic stages (fig. 11*A* and *B*). Along this hinge zone downbuilding is cumulative, but it occurs more rapidly during a first-order than during a second-order tectonic stage. However, this is not true with respect to the relative vertical displacement of adjacent crustal segments on the opposite sides of the hinge zone designated by *V–V′* (fig. 11). When tectonic-stage transition takes place, the sense of relative vertical displacement is reversed for adjacent crustal segments on the opposite sides of this hinge zone. In a first-order tectonic stage (fig. 11*A*), crustal segments on the east side of the hinge zone are depressed relative to adjacent crustal segments on its west side. In a second-order tectonic stage (fig. 11*B*), crustal segments on its west side are depressed relative to adjacent segments on its east side. Along *U–U′* the direction of depositional thickening remains constant for all the chronostratigraphic units mapped, whereas along *V–V′* the direction of depositional thickening remains constant for the 12 units that belong to the first-order tectonic stage but is reversed for the five units that belong to the second-order tectonic stage.

The geometric relations that are observed for the relative vertical displacement of crustal segments and their overlying sediments in the report area are summarized in the following statements. During any one tectonic stage, each crustal segment bounded by hinge zones is either elevated or depressed relative to crustal segments that lie mutually adjacent to it, and the opposite sides of each crustal segment are either elevated or depressed relative to each other. In a first-order tectonic stage, the relative vertical displacement of crustal segments, that lie on the opposite sides of north-striking tension-type hinge zones, is cumulative toward the northeast boundary shear zone of the unit-structural block. In a second-order tectonic stage, the relative vertical displacement of crustal segments that lie on the opposite sides of northeast-striking tension-type hinge lines is cumulative toward the southeast.

Where crustal segments on the opposite sides of a hinge line are displaced vertically relative to each other, the relatively uplifted segment will constitute a source area for sediments that accumulate on the relatively depressed segment adjacent to it. Where the opposite sides of a crustal segment are displaced vertically relative to each other, the relatively uplifted side will constitute a source area for sediment that accumulates on the relatively depressed side of the same segment. In the report area and so far as the accumulation of sediment on any one crustal segment is concerned, either the source areas that lie on relatively uplifted, mutually adjacent blocks or the source area that lies on the relatively uplifted part of the segment itself may constitute the dominant source of the sediment that accumulates on a crustal segment at any one time.

Across any one crustal segment or group of segments, the direction of migration for contemporaneous depositional sequences is regressive if it is away from source areas, and it is transgressive if it is toward source areas. It follows that an axis of potential regression and transgression will lie essentially normal to each of the source areas that contribute sediments to any one crustal segment or group of segments at any one time. Thus, for example, if the sediment that accumulates on a crustal segment at any time is derived from three different source areas, regression or transgression of depositional sequences, relative to these source areas, may take place, either simultaneously or alternately, along as many as three different axes or along any resultant combination of axes.

In figure 11 these statements are illustrated by symbols which show:

1. The directions of and the sense of migration (transgressive or regressive) for depositional sequences across the crustal segments, labeled A–K, relative to their mutual boundary hinge zones.
2. The rates of relative downbuilding that characterized the internal hinge zones during each tectonic stage.
3. The directions of stratigraphic strike and dip that develop in response to the relative vertical displacement of adjacent crustal segments that lie on the opposite sides of a hinge zone.
4. The directions of stratigraphic strike and dip that develop in response to the relative vertical displacement of opposite sides of the same crustal segment.

Commonly, a state of imbalance exists between the rate at which a crustal segment subsides, relative to an adjacent source area, and the rate at which sediments are being supplied to it from an adjacent source area. The nature of the state of imbalance may be complex, particularly as is the case in the report area, where a crustal segment, or a part of a segment, subsides at different rates relative to different source areas and where it accumulates sediments at different rates from more than one source area, either simultaneously or alternately. Across any one crustal segment, the incidence of and the actual rate of migration for contemporaneous depositional sequences and for strandline segments is controlled by many factors, some of which are more dominant than others in a gain-loss sediment system wherein each crustal segment, or a part of a segment, gains sediment from several adjacent and relatively uplifted segments and, in turn, is a source area for sediments that accumulate on other relatively depressed segments adjacent to it. For example, consider crustal segment B. During a first-order tectonic stage (fig. 11*A*), segment B receives sediment from segments A and K, the southeast flank of segment B is a source for sediment that accumulates on its northwest flank, and segment B is a source area for sediment that accumulates on crustal segments C and G. A dominant and complex factor that exerts control on the migration of depositional sequences and of strandline segments in this gain-loss sediment system is the relation that exists between sediment supply and subsidence—the variable amounts and rates of sediment supply from multiple source areas relative to the rate of and the amount of subsidence for a receiving crustal segment. A less dominant factor might be the effect of littoral drift or other action of the sea upon sediment redistribution between areas of sediment accumulation.

At any one time, the position of a strandline reflects a state of imbalance between sediment supply and subsidence, and it represents the sum of the regression or transgression of its component segments relative to several source areas that border the area of sediment accumulation. If the rate of subsidence is increased or if the sediment supply is decreased, a strandline segment will migrate toward a source area (transgression). If the rate of subsidence decreases or if the sediment supply is increased, a strandline segment will migrate away from a source area (regression). Inasmuch as each crustal segment in the system under discussion has several source areas and subsides at a different rate relative to each source area, one strandline segment may be migrating away from a source area at the same time that another segment is migrating toward a source area. The strandline that is a composite of its segments may assume many different positions on any one crustal segment. In figure 12, using crustal segment B as an example, several of these average positions for a composite strandline are illustrated. During a first-order tectonic stage, the approximate position for a Midwayan strandline and for a strandline of Unit C are shown in A1 and A2. During a second-order tectonic stage, the approximate position for a middle Miocene strandline and for a strandline of Unit H are shown in B1 and B2.

The variable positions that a strandline may assume on any one crustal segment illustrate the fact that sediments deposited on any one crustal segment may have a complex depositional history. Moreover, the depositional history may be quite different for sediments deposited on adjacent crustal segments. Inasmuch as certain combinations of crustal segments in the report area constitute parts of structural-sedimentary troughs or adjacent source areas, it is convenient to discuss the regional depositional system in terms of sediment input versus trough subsidence.

SEDIMENT INPUT VERSUS TROUGH SUBSIDENCE

Because each structural-sedimentary trough in the report area has several source areas, subsides at different rates relative to each source area, and receives sediment at different rates from each of its source areas, the nature of sediment input versus trough subsidence is complex and constitutes an interplay of factors that can best be evaluated in terms of some "typical" proportionate relations.

The subsidence of a trough relative to any one source area and to the amount of sediment derived from a source area is reflected as an imbalance between trough subsidence and sediment input. When imbalance favors sediment input, regression away from a source area occurs. Where the imbalance favors trough subsidence, transgression toward a source area takes place. In the report area and with respect to tension-type and shear-type hinge zones, that strike either northeast or north, the degree of imbalance associated with tension-type hinge zones seems to be about five times greater than the degree of imbalance associated with shear-type hinge zones. The relation between these degrees of imbalance may be expressed as the ratio 5:1. This ratio is approximate and represents a regional average based upon comparison of depositional thickening trends, judged to be essentially contemporaneous, which have been observed in different parts of the project area and which represent different intervals of geologic time. Although the ratio is approximate, it is a useful guide in evaluating the nature of the relation between the rates of sediment input from different source areas and the rates of trough subsidence relative to these source areas. For illustrative purposes and because they are based primarily upon comparative thickness of sediments, degrees of imbalance associated with north or northeast-striking hinge zones are here considered as proportional to rates of relative subsidence.

For any one crustal segment that lies on the relatively depressed side of both tension-type and shear-type hinge zones, its rate of relative subsidence is about five times greater along a side that lies adjacent to a tension-type hinge zone than along a side that lies adjacent to a shear-type hinge zone. For example. and with reference to figure 11*A*, the rate of subsidence for segment G relative to segment F is about five times greater than the rate of subsidence for segment G relative to segment B. With reference to figure 11*B*, the rate of subsidence for segment G relative to segment B is about five times greater than the rate of subsidence for segment G relative to segment F. We refer to these greater and lesser rates of relative subsidence as primary and secondary rates of relative downbuilding respectively (fig. 11).

During regression and for the general case, a primary rate of downbuilding, relative to an adjacent source area, is associated with a comparatively slow rate of progradation and with the accumulation of comparatively thick, narrow, wedge-shaped lenses of sediment. A secondary rate of downbuilding, relative to an adjacent source area, is associated with a comparatively rapid rate of progradation and with the accumulation of comparatively thin, wide, sheetlike lenses of sediment. The ratio of thickness to width may be about 5:1 for the wedge-shaped lenses and about 1:5 for the sheetlike lenses during a given interval of geologic time.

Preferential geographic locations for the accumulation of these types of lenses during a first-order tectonic stage are shown in figure 11*A*. Wedge-shaped lenses of sediment accumulate, preferentially, on the relatively depressed side of north-striking hinge zones and sheetlike lenses on the relatively depressed side of northeast-striking hinge zones. Preferential geographic locations for the accumulation of these two types of lenses during a second-order tectonic stage are shown in figure 11*B*. Wedge-shaped lenses of sediment accumulate, preferentially, on the relatively depressed side of northeast-striking hinge zones and the sheetlike

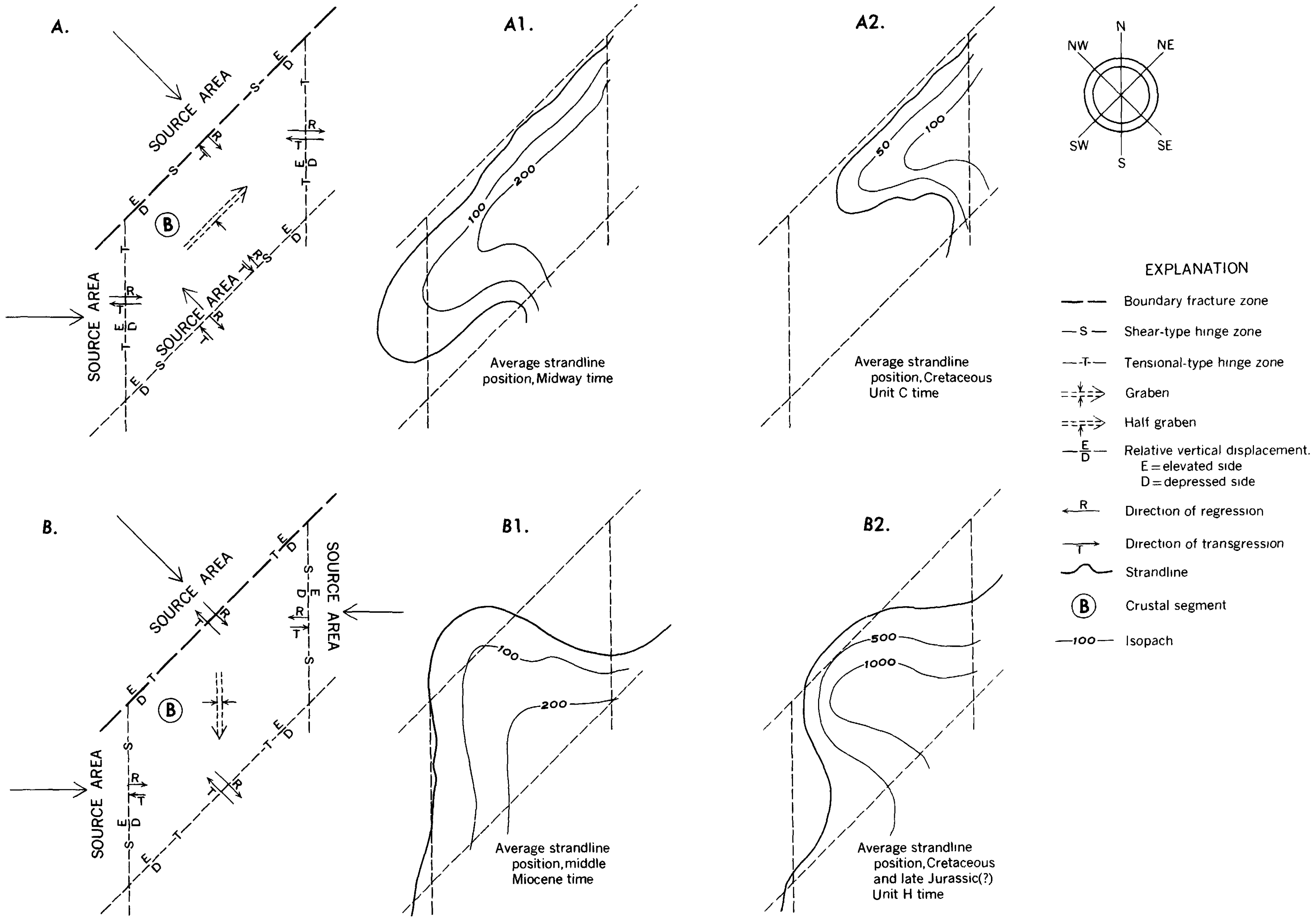

FIGURE 12.—Comparative average strandline positions for some stratigraphic intervals in the central part of the report area that are associated genetically with the first-order tectonic stage and with the second-order tectonic stage, respectively. *A1* and *A2*. First-order tectonic stage *B1* and *B2*. Second-order tectonic stage.

lenses on the relatively depressed side of north-striking hinge zones.

A similar type of proportional relation may be derived for the comparative geometry shown by sediment lenses that accumulate in response to transgression. Comparatively rapid migration of depositional sequences toward a source area is associated with the development of thin sheetlike lenses and with tension-type hinge zones. Comparatively slow migration of depositional sequences toward a source area is associated with the development of relatively thick wedgelike lenses and with shear-type hinge zones.

FIRST-ORDER TECTONIC STAGE

Two structural-sedimentary troughs and their component crustal segments are illustrated in figure 11*A*. These troughs are present during a first-order tectonic stage. The trough which contains the crustal segments labeled A, B, C, and D is a half graben whose long axis is alined northeast-southwest and whose northwest flank is depressed relative to its southeast flank. The trough is tilted toward the northeast; its upper end (head) lies to the southwest of segment A, and its lower end (foot) terminates where segment D abuts on segment E along the northeast border of the unit-structural block. For purposes of discussion it is designated the inner trough. The trough which contains the crustal segments labeled F, G, H, and I is a similar half graben. It is designated the outer trough.

The structural sides of the two troughs coincide with northeast-striking shear-type hinge zones, designated by X–X', by Y–Y', and by Z–Z' if extended. The hinge zone X–X' coincides with the northwest boundary of the unit-structural block. The hinge zone Y–Y' forms a structural boundary common to both troughs. The relative vertical displacement of adjacent crustal segments on the opposite sides of these hinge zones is expressed topographically as fault-block anticlines, asymmetrical flexures having a relatively steep southeast flank, or as monoclinal flexures. The lower ends of both troughs abut against segment E, which lies on the relatively uplifted side of the unit-structural block's northeast boundary shear, designated by T–T'. Topographically, the relative vertical displacement of adjacent crustal segments on the opposite sides of this boundary zone is expressed as a monoclinal flexure that lies adjacent and parallel to the trend of the boundary shear zone. North-striking tension-type hinge zones, designated by U–U', and by V–V' and W–W' if extended, lie athwart and are common to both troughs. Topographically, the relative vertical displacement of adjacent crustal segments on the opposite sides of these hinge zones is expressed as flexures or faults.

At any one time, the sediment that accumulates in each asymmetrical trough may be derived from as many as four source areas. For any one trough, two of its source areas are internal and two are external. The upper end of a trough constitutes an internal source area for sediment that accumulates at its lower end, and its relatively uplifted southeast flank constitutes an internal source area for sediment that accumulates on its relatively depressed northwest flank. The two external source areas are adjacent to a trough's northwest flank and adjacent to its lower end, respectively.

With respect to the inner trough, one of its internal source areas lies to the southwest of segment A, and its other internal source area lies along the southeast margin of segments A through D. The inner trough's external source areas lie on segment K and on segment E, respectively (fig. 11*A*). With respect to the outer trough, one of its internal source areas lies to the southwest of segment F, and the other internal source area lies along the southeast margin of segments F through I. The outer trough's external source areas lie on segments A through D, and on segment E, respectively (fig. 11*A*).

As shown in figure 11*A*, and as indicated by the respective directions shown for regression and transgression, the relatively elevated southeast margins of segments A through D comprise either a fault-block anticline or an asymmetrical flexure that has a gently dipping northwest flank and a relatively steeply dipping southeast flank. This relatively positive feature is an internal source area for sediment that accumulates in the inner trough and, at the same time, is an external source area for the sediment that accumulates in the outer trough. The relatively elevated southeast margins of segments F and G constitute part of a similar northeast-striking fault-block anticline or asymmetrical flexure. Judging from the composition and depositional thickness of sediments that were deposited on the flanks or athwart these relatively positive features, they probably constituted elongated landmasses of variable width which, in a northeast direction, were transitional to island-type areas of low relief, to bars, and to ridges on the ocean floor. They thus became more sill-like in a northeast direction.

Certain comparative generalizations may be made about the structures, the textures, and the detrital and chemical components of sediments which accumulated in each trough and which were derived, preferentially, from each of a trough's four source areas. The sediment that accumulated in the inner trough consists predominantly of arenaceous and argillaceous clastics.

The sediments which were derived from segment E (an external source area), and which accumulated primarily at the foot of the trough adjacent to the northeast boundary of the unit-structural block, comprise relatively thick wedge-shaped lenses in which quartz sand and lignitic clay are dominant. In general, the sand is coarse, arkosic, and more dominant than clay in the overall sand-clay section. Hematite and marcasite, that occur in minor to trace amounts, are the chief chemical components of these sediment lenses.

The sediments which were derived from segment K (the other external source area), and which accumulated principally along the northwest flank of the trough, consist of thin to moderately thin sheetlike lenses in which clay and sand are dominant. The sand is medium to coarse, rarely arkosic, and less common than clay in the overall clay-sand section. Siderite occurs commonly in the sediments, together with moderate amounts of glauconite, minor amounts of hematite, and trace amounts of marcasite and gypsum.

The sediments which were derived from the southwest end or head of the trough (an internal source area), and which accumulated downtrough, particularly on the relatively depressed side of north-striking hinge zones that lay athwart the trough, form thick to moderately thick wedge-shaped lenses. These lenses consist chiefly of lignitic, micaceous clay and recycled sand. The sand, that is poorly sorted, ranges from fine to medium to coarse, is rarely arkosic, and, with the exception of its occurrence in the upper part of Unit F, is not dominant in the overall clay-sand section. Glauconite is the dominant chemical component in the sediment. It occurs together with moderate amounts of siderite and hematite and with trace amounts of marcasite, dolomite, and gypsum. During certain geologic epochs that were associated genetically with a first-order tectonic stage (the Late Cretaceous, the Paleocene, and the Eocene, in part), glauconite was the dominant component in sediment that was derived from the source area at the head of the trough. Apparently, thick massive beds of glauconite, formed in a reducing environment, accumulated in situ adjacent to the trough's southwest source area. Much of the glauconite now recognized within the sediments in various parts of the trough has been recycled in a downtrough direction from the primary in situ deposits.

The sediments which were derived from the southeast flank of the trough (the other internal source area), and which accumulated principally adjacent to or along the trough's southeast rim, form relatively thin sheetlike lenses. The thickness attained by the lenses at any one time was governed to a large extent by the moderate degree of structural dip toward the northwest coupled with plunge toward the northeast. Clay and intercalated calcareous quartz sand are the dominant components of the sediment. Minor components consist of pelagic limestone (chalk) and glauconite that occur with trace amounts of dolomite and collophane.

Except in that part of the trough in North Carolina, the outer trough lies offshore, and little direct information is available concerning the nature of its sedimentary fill, much of which represents a spillover of sediment from the inner trough. The following discussion deals with that part of the outer trough which lies onshore in North Carolina.

The sediment consists predominantly of argillaceous clastics, moderate amounts of arenaceous clastics, and lesser amounts of carbonate clastics. Periodically, sedentary limestones, both biostromal and biohermal in character, developed along the southeast rim of the plunging trough. These sedentary limestones are the source of the carbonate clastics that accumulated in different parts of the outer trough. During middle Eocene and Oligocene times, the sedentary limestones comprised relatively massive bryozoan limestones and molluscan limestones. These limestone units, that developed preferentially along the southeast rim of the outer trough and adjacent to hinge zone $Z-Z'$, in some places migrated across the trough and encroached upon its northwest margin, adjacent to hinge zone $Y-Y'$.

The sediments in the outer trough which were derived from segments A–D (an external source area), and which accumulated principally on the northwest flank of the trough, form thin to moderately thin sheetlike lenses. The sediments consist chiefly of sandy clay that contains intercalations of fine to medium quartz sand. Sandy clay is dominant in the section. Siderite is the dominant chemical component of the sediment. It occurs with moderate amounts of hematite, minor amounts of glauconite, and trace amounts of marcasite and dolomite.

The sediments which were derived from the southwest end or head of the trough (an internal source area), and which accumulated downtrough, particularly on the relatively depressed side of the north-striking hinge zone $U-U'$, form thick to moderately thick wedge-shaped lenses. The sediments consist of lignitic, micaceous clay and recycled quartz sand. The quartz sand, which ranges from fine to medium to coarse, is poorly sorted and is less prevalent than micaceous clay in the overall clay-sand section. Hematite is a dominant chemical component of the sediment. Siderite and glauconite occur in moderate amounts. Marcasite, dolomite, and chalcedony usually occur in trace amounts but may occur in moderate amounts locally. During the Paleocene Epoch, glauconite was the dominant component in sediment derived from the head of the trough.

The sediments which were derived from the southeast flank of the trough (an internal source area), and which accumulated principally adjacent to or along the trough's southeast rim, form relatively thin sheetlike lenses whose sediment consists chiefly of bioclastic carbonates that contain minor intercalations of clay and sand. The chemical component of the sediment, that is predominantly sedentary carbonate, includes minor amounts of collophane.

Regionally, the distribution pattern for sediment lenses in Unit F and, locally, their distribution patterns in Unit B and Unit A in certain areas seem to be somewhat anomalous when compared with the distribution patterns of sediment lenses in other units that belong to a first-order tectonic stage. Within Unit F and apparently in accordance with a southeast component of regional tilt, thick wedge-shaped lenses of sediment, rather than thin sheetlike lenses, formed on the relatively depressed sides of the hinge zones X–X' and Y–Y' during at least part of the time when the unit was being deposited. In effect, a regional component of downbuilding seems to have been superimposed on or to have supplanted the local components of downbuilding generally associated with a first-order tectonic stage along segments of the hinge-zone system. This resulted in an influx of arenaceous and argillaceous clastics from external source areas adjacent to the unit-structural block and into the northeast-trending troughs developed on the block. A clastic front, first developed adjacent to crustal segment K, migrated southeastward across the inner trough and advanced into the outer trough.

Within Unit B and Unit A locally, thick wedge-shaped lenses of sediment formed on the relatively depressed sides of the hinge zones Y–Y' and Z–Z' where they border crustal segment F. As indicated by the internal geometry of these two chronostratigraphic units where they overlie segment F, a clastic front, predominantly argillaceous and first developed on segment F adjacent to the hinge zone Y–Y', advanced southeastward across segment F, encroached upon and then overrode the margin of the segment before spilling over into the adjacent trough that lay to the southeast of the hinge zone Z–Z'. In effect, a regional component of downbuilding seems to have been manifest locally rather than the local components of downbuilding generally associated with a first-order tectonic stage along some segments of the hinge-zone system.

An explanation of the anomalous distribution of thick wedge-shaped lenses of sediment, recognized in some chronostratigraphic units of the first-order tectonic stage, may be found in and adopted from Moody's (1966, p. 505–507) discussion of a crustal model. A reasonable explanation for the anomaly is that a crustal segment or group of crustal segments, within a unit-structural block under lateral compression and freed from such compression when it is absorbed by other segments within the block, react to the sum of vertical forces to which they are subjected.

For the 12 chronostratigraphic units that belong to a first-order tectonic stage, isopach and lithofacies maps and geologic cross sections show the structural, textural, and compositional contrasts in sediments that are present in different parts of the structural-sedimentary trough system. The maps and cross sections reflect the proportionate nature of sediment input from different source areas versus trough subsidence as well as the quantitative nature of the overall sediment input versus trough subsidence during a first-order tectonic stage.

SECOND-ORDER TECTONIC STAGE

Presently available sediment data for chronostratigraphic units associated genetically with a second-order tectonic stage are insufficient for purposes of differentiating the control that each phase exerts on sediment distribution and sediment type.

The following discussion will be limited to the subsequent or rupture phase of deformation in a second-order tectonic stage.

In this tectonic stage the crustal segments labeled B, G, and J (fig. 11*B*), together with their overlying sediments, lie within a graben whose long axis is alined north-south and whose plunge is southward. The upper end (head) of the graben abuts segment K and its lower end (foot) lies south of segment J. The respective sides of the graben stand tangential to southeast-plunging compressional anticlines, the Cape Fear arch and the Normandy arch, whose geographic positions are shown in figure 11*B*.

Crustal segments D and I, together with their overlying sediments, are part of a triangular-shaped trough whose long axis is alined north-northwest to south-southeast and whose plunge is toward the south-southeast. The upper end of the trough terminates at the point where crustal segments K, D, and E meet. The lower end of the trough lies south-southeast of segment I. One side of the trough lies adjacent to the southeast-plunging Normandy arch, whereas the other side lies adjacent to the northeast boundary of the unit-structural block (fig. 11*B*).

The structural sides of the graben coincide with north-striking shear-type hinge zones, designated by U–U' and by V–V' if extended. The upper end of the graben is bounded by a segment of the hinge zone X–X' which coincides with a segment of the northwest boundary of the unit-structural block. The graben is open faced to the south. Segments of northeast-striking tension-type hinge zones, designated by Y–Y' and by Z–Z' if extended, lie athwart the graben and intersect its sides at an angle of about 45°.

Overall, the sediments that have accumulated in the graben are predominantly clastic. Clays are far more prevalent than detrital sands or gravels. Except in the post-Miocene unit, sand, and less commonly gravel, are confined chiefly to local areas that lie along the sides or at the head of the graben. The nonclastics consist chiefly of carbonate, diatomite, radiolarite, and phosphorite. The latter three occur chiefly in rocks of Tertiary age. In terms of their preferential geographic occurrence, the nonclastic facies developed chiefly on the relatively depressed side of the hinge line U–U' and extended outward into the graben from its western flank. During middle Miocene time, the diatomite facies and, to a lesser extent, the radiolarite facies developed preferentially along the northern half of U–U' (between X–X' and Y–Y') whereas the phosphorite facies and the carbonate facies developed preferentially along the southern half of U–U' (between Y–Y' and Z–Z'). In part, the development of these chemical facies was controlled by the residual structural effect, during a second-order tectonic stage, of northeast-striking positive features that developed during a first-order tectonic stage. The effect of the residual structures was to localize environmentally restrictive conditions of water depth and water temperature within the graben, which in turn led to certain geographic restrictions in facies development.

The sediment that accumulated in the graben was derived principally from three source areas, all of which lay external to the graben. These three source areas (fig. 11*B*) were segment K, adjacent to the head of the graben; segments C and H and their overlying sediments, adjacent to the eastern flank of the graben; and segments A and F and their overlying sediments, adjacent to the western flank of the graben. An overall evaluation of the sediment that accumulated in the graben reflects the relative order of dominance of these three source areas. Segment K, adjacent to the head of the graben, was the dominant source area. Segments C and H and segments A and F, adjacent to the sides of the graben, were subordinate source areas. Because of the position of the graben relative to southeast-plunging positive areas, segments C and H provided more of its sediment than segments A and F.

The sediment derived from segment K, adjacent to the head of the graben, comprises comparatively thick wedge-shaped lenses. In this area, downbuilding of the section was more dominant than outbuilding. The sediment consists chiefly of micaceous clay interbedded with minor amounts of gravel. In any chronostratigraphic unit that belongs to a second-order tectonic stage, the percentage of clay increases and the percentage of sand decreases in a southeast direction. The chemical component of the sediment includes siderite, hematite, limonite, and marcasite, all of which occur in moderate to trace amounts and which become less abundant toward the southeast.

The sediments which were derived from segments C and H, and which accumulated chiefly along the graben's eastern flank, form comparatively thin tabular or sheetlike lenses. In this area outbuilding of the section was more dominant than downbuilding. The sediments derived from segments C and H, chiefly recycled sediments that show a high degree of compositional homogeneity, consist chiefly of micaceous and lignitic clay, together with lesser amounts of intercalated fine to medium quartz sand. The percentage of clay in the section increases southward and westward with respect to the hinge zone V–V'. The chemical component of the sediments consists chiefly of hematite, marcasite, glauconite, and gypsum, all of which occur in moderate to trace amounts.

The sediments which were derived from segments A and F, and which accumulated chiefly on the graben's western flank, form comparatively thin sheetlike lenses. In this area outbuilding of the section was more dominant than downbuilding. The sediment derived from segments A and F consists chiefly of micaceous and lignitic clay that contains intercalations of fine to medium water-polished quartz sand. These are predominantly recycled sediments that show a marked degree of maturity and compositional homogeneity. The chemical component of sediment that accumulated along and adjacent to the western flank of the graben consists chiefly of carbonate, phosphorite, and the opaline tests of diatoms and radiolaria.

The foregoing descriptions represent generalizations with respect to the shapes, textures, and compositions of sediments that are illustrated on the regional geologic cross sections. The generalizations are useful in making an overall appraisal of some of the factors that influence the types and amounts of sediment deposited in the graben during a second-order tectonic stage.

During a second-order tectonic stage, the trough that develops adjacent to the northeast boundary of the unit-structural block (fig. 11*B*) probably is a minor depocenter. This trough lies chiefly offshore and few data are available on the amount or nature of the sediment that may have been deposited in it. Several chronostratigraphic units that belong to this tectonic stage are shown (section *EE*–*EE*′, pl. 57) as projecting into the trough from the area adjacent to its western flank. Other than glacial and interglacial deposits and deposits of post-Miocene age, no rocks of those stratigraphic units that are included in a second-order tectonic stage are recognized in wells on Long Island, along the northeast margin of the trough.

REGIONAL DISTRIBUTION FRAMEWORK OF INTRINSIC PERMEABILITY

GENERAL DISCUSSION

The permeability of a rock is a measure of the relative ease with which it transmits fluid through its interconnected pores. The nature of the rock, the nature of the fluid, and the magnitude of the potential gradient on the fluid determine the relative ease with which a unit cross section of rock will transmit fluid, as well as the relative volume of fluid that it will transmit during a finite period of time. Some rocks are less permeable than others, but it is probable that all rocks are permeable if the potential gradient on the fluid is of sufficient magnitude (Fraser, 1935). According to Meinzer (1936, p. 710), laboratory tests of the comparative permeability of natural clastic materials, such as those in the project area, indicate that the most permeable material tested (a gravel) transmitted water through its pore spaces at a rate of about 90,000,000 times that of the least permeable material tested (a silt).

Intrinsic permeability, like porosity, is a mass property that depends only on the nature of the rock itself. Inasmuch as the intrinsic permeability of a rock is dependent upon the interconnected pore spaces or voids, it is dependent upon the rock's effective porosity, which is the percentage of the total pore spaces that are interconnected. Although dependent upon effective porosity, the intrinsic permeability is not quantitatively related thereto; instead it is quantitatively related to the size and shape of the voids. Therefore, intrinsic permeability is influenced by geologically important characteristics or attributes of a rock that govern the dimension and shape of its pore spaces and their degree of interconnection.

The geologically important attributes of a sediment that exert an influence on the geometry of its pore spaces have been investigated and summarized by many workers (by Slichter, 1899; Meinzer, 1923 and 1936; Stearns, 1927; Graton and Fraser, 1935; Fraser, 1935; Krumbein and Monk, 1942; Pettijohn, 1957; and numerous others). The main geologically important attributes include grain size, grain shape, surface texture of the grains, the uniformity of grain size, and the geometry of grain packing. They also include various physical and chemical changes associated with stratification, compaction, cementation, and solution that tend to decrease or increase the effective porosity of a sediment either during or after its deposition.

Among these geologic attributes, grain size and, to a lesser extent, uniformity of grain size (sorting) have been considered the most important factors governing the intrinsic permeability of clastic rocks (Fraser, 1935). Other influencing factors being equal, intrinsic permeability usually increases with an increase in grain diameter because the size of the voids between grains is greater in coarse material than in fine. Other influencing factors being equal, the intrinsic permeability of well-sorted clastics usually is greater than that of poorly sorted clastics because the average void size decreases as the nonuniformity of grain size increases.

THE NONUNIFORM NATURE OF INTRINSIC PERMEABILITY IN THE REPORT AREA

The distribution of intrinsic permeability is not uniform in the report area. Lateral and vertical changes, commonly abrupt, take place in response to changes in lithologic character. In order to establish a hierarchy and a pattern of distribution for intrinsic permeability, either within a stratigraphic interval or between intervals, it is necessary to establish empirical relationships between change in lithologic character and change in intrinsic permeability. Then, because change in intrinsic permeability accompanies a change in lithologic character, the spatial arrangement of lithologic character, expressed on isopach maps by the distribution of contrasting lithofacies, may be used to predict the spatial arrangement of intrinsic permeabilities in a regional or a local area of study.

For sediments in the report area, the textural grain size and uniformity of grain size, together with the physical and chemical effects of compaction, intrastratal solution, precipitation, and recrystallization, seem to be the factors that have exerted a dominant and selective influence in determining the nonuniformity of intrinsic permeability.

In the absence of any widespread effect upon pore geometry resulting from intrastratal solution, precipitation, or recrystallization, it appears that grain size, uniformity of grain size, and compaction are the dominant factors in determining the size and shape of the voids in the clastic sediments, in the sediment mixtures that are dominantly clastic, and in the fine-textured sediment mixtures that contain either a proportionately significant or a dominant nonclastic fraction. The latter group of mixtures would include fine to medium calcareous sand, chalk, diatomaceous shale, radiolarian shale, and phosphatic shale. The effective porosity of the shale has been reduced somewhat with time as a result of compaction by overlying sediments. With local exceptions, the fine to medium sand and the chalk have not been lithified or compacted and their effective porosity has not altered appreciably since they were deposited. For any given stratigraphic interval in which clastics, mixtures of clastic and fine-textured nonclastics, and fine-textured nonclastics comprise the interval, the intrinsic permeability varies chiefly with grain size and, to a lesser extent, with uniformity of grain size. In this group of sediments, the intrinsic permeability is greater for those intervals that contain the highest percentage of sand, and undergoes a relative decrease as the percentage of sand decreases and as the percentage of shale or of fine-textured nonclastics within the stratigraphic interval increases.

Original particle size and the combined effects of material loss and material gain associated with intrastratal solution, precipitation, and recrystallization have been the dominant influences in determining the current intrinsic permeability of the moderately coarse to coarse-textured sediment mixtures in which carbonate is either a dominant or a proportionately significant fraction (>25 percent). Arranged according to ascending particle size, these mixtures include coarse to moderately coarse calcareous sand, sandy oolitic limestone, sandy bryozoan limestone, sandy coquina, and sandy molluscan limestone. When they are considered in aggregate, these sediment mixtures have suffered a net loss of material with time as a result of the combined loss-gain effects associated with the processes of leaching, precipitation or reprecipitation, and recrystallization. The intrinsic permeability of these mixtures depends partly on their original effective porosity and partly on their secondary effective porosity. In general, overall enlargement of their interconnected voids has occurred with time and they have developed a secondary effective porosity that is greater than their original effective porosity. The tendency of these sediment mixtures toward the development of secondary effective porosity has been roughly proportional to their original texture. Secondary effective porosity is more highly developed in the coarse-textured mixtures and is less well developed as the particle size of the mixtures decreases. Overall, the greatest enlargement of voids and the maximum development of secondary effective porosity is in the relatively coarse textured molluscan limestone, whereas the least enlargement of voids and the minimum development of secondary effective porosity is in the relatively finer textured coarse to moderately coarse calcareous sand.

In the molluscan limestone that is both biostromal and biohermal in character the original shell material has been almost entirely removed by solution, and the resulting rock is little more than a honeycomb of lithified solid material and voids. The mollusk casts represent the lithified solid material, and the mollusk molds, that are lined with a filigreed mosaic of calcite, represent the dominant voids.

The coarse to moderately coarse textured calcareous sand, that is both wedgelike and sheetlike, reflects variable degrees of lithification. In part, the degree of lithification seems to be associated with the development of secondary porosity. The unconsolidated or weakly consolidated calcareous sands are relatively unaffected by solution and show almost no development of secondary porosity. The indurated calcareous sands have had a great deal of original material removed by solution and generally have a well developed to moderately well developed secondary porosity parallel to the bedding.

When observed in outcrop in North Carolina, and depending upon their degree of structural rigidity and numerous other factors, some lithified limestone and other indurated sediments that contain a significant amount of carbonate, show the probable influence of regional fracture systems upon the development of directional intrinsic permeability. Where large, virtually horizontal solution channels have developed and also where a group of vertical sinks have developed, these solution features most generally have either a northeast-southwest trend or a north-south trend, with the northeast-southwest trend being dominant regionally. It is a reasonable inference that the prefferential trends observed for these solution features are related to northeast-striking and north-striking fracture systems and that these preferential trends observed for the solution openings in outcrop also characterize subsurface sections in some areas.

In the report area, the intrinsic permeability, that is associated with either dominantly monomineralic sediments or multimineralic sediments, is of two main types. One type, primary intrinsic permeability, is linked to primary effective porosity. It depends chiefly upon the size and shape of interconnected voids that were formed during deposition of the sediments, and it increases as the size of the grains and voids increases. Quantitatively, it is linked to the texture of the sediments, but is largely independent of their chemical composition. This type of intrinsic permeability is characteristic of the clastic sediments, the dominantly clastic sediment mixtures, and the fine sediment mixtures that contain a significant nonclastic fraction. For this group of sediments, the primary intrinsic permeability increases with increase in grain size, and a sequential order of relative intrinsic permeability may be established that is based primarily upon contrasts in grain size. An example is the contrast in grain size between sand and shale or between sand and chalk.

Secondary intrinsic permeability is linked to the development of secondary effective porosity. It depends on the enlargement of original voids and (or) upon the development of new voids. These processes, which operate after deposition of the sediments, cause permeability to increase as the size of the voids increases. Quantitatively, secondary permeability is linked to both the textural and chemical composition of the sediments. Characteristically, this type of intrinsic permeability is developed in coarse to moderately coarse textured calcareous sand, in sandy oolitic limestone, in sandy bryozoan limestone, in sandy coquina, and in sandy molluscan limestone. For this group of sediments, no inflexible regionally applicable sequential order of relative intrinsic permeability can be established, because of the total number of complex factors that are involved in the development of secondary effective porosity. Among these complex factors, however, the original texture of the carbonate sediments seems to be significant. When these sediments are arranged according to ascending particle size, their secondary intrinsic permeabilities exhibit a general increase from the coarse to moderately coarse calcareous sand at the lower end of the textural scale toward the sandy molluscan limestone at the upper end. During the present study differentiation as to the types of limestone present in local carbonate sequences, such as in the Castle Hayne Limestone of North Carolina, has been used to establish the distribution of intrinsic permeability locally. These local variances were then averaged for inclusion on the regional permeability-distribution maps.

CONSTRUCTION OF THE REGIONAL LITHOFACIES MAPS

Three types of stratigraphic maps were constructed to provide a framework for the illustration and discussion of regional intrinsic permeability distribution. Structure-contour maps were drawn to show the configuration of the surface for 17 chronostratigraphic units and for bedrock. Isopach maps were drawn to show the distribution and the thickness of the 17 chronostratigraphic units. Lithofacies maps were drawn to show the areal variation in sediment character within the mapped units. In order that the percentage thicknesses of different sediment mixtures may be compared to the total thickness of a stratigraphic interval in which they occur, the base maps for lithofacies variation are isopach maps. Depending upon the density of data, both equal-spacing contouring and interpretive contouring methods were used in drawing the structure-contour and isopach maps.

For the purpose of establishing a hierarchy for relative intrinsic permeability—based upon differences in both the textural and chemical composition of sediments—sand, shale, and carbonate were selected as the individual lithologic components most useful and most readily differentiated. Statistically and with respect to either the thickness of individual beds or to the total number of beds, the gravels and the evaporites are negligible lithologic components of the sediments. Statistically, the areal distribution and thickness of gravel is included in the areal distribution and thickness established for sand. Statistically, the areal distribution and thickness of the evaporites is included in the areal distribution and thickness established for carbonate.

The 209 individual wells that appear on the geologic cross sections, together with the 371 additional wells, constitute the basic wells in a group of some 2,200 wells from which cuttings were examined to determine the aggregate thickness of sand, shale, and carbonate within stratigraphic intervals at specific points in the report area. At each of the cross-section wells and for each stratigraphic interval completely penetrated, the thickness of individual beds of sand, shale, and carbonate were determined. The determinations were made from strip logs, prepared after microscopic examination of cuttings and cores, and in conjunction with the interpretation of the curves of various borehole geophysical logs. The curves were interpreted in terms of bed composition and bed thickness, using standard interpretive procedures. The measured aggregate thickness for beds of sand, shale, and carbonate was computed as percentages of the total thickness of the stratigraphic interval in which they occur as is shown in the following example :

	Thickness (ft)	*Percent*
Sand	300	50
Shale	200	33 1/3
Carbonate	100	16 2/3
Total for stratigraphic interval	600	100

Depending upon the location of available wells that completely penetrate individual stratigraphic intervals, the aggregate thickness for beds of sand, shale, and carbonate was measured in wells comprising the key-well network as well as in other wells in the report area.

These and other basic geologic data used in the preparation of this report are available in automated form. Requests for these data should be sent to the Chief Hydrologist, U.S. Geological Survey, Washington, D. C. 20242. Each request should specify whether the data are desired in the form of printed tables, magnetic tape, or punch cards.

Following an overall evaluation of the percentage occurrence of sand, shale, and carbonate in vertical section at specific control points, seven lithologic percentage categories (lithofacies), based upon textural and chemical composition, were established. They encompass the observed percentage variability. These are as follows:

1. Sand 75–100 percent
2. Sand 50–75 percent
   Shale 25–50 percent
3. Shale 50–75 percent
   Sand 25–50 percent
4. Shale 75–100 percent

5. Carbonate 25–50 percent
   Clastics 50–75 percent
6. Carbonate 50–75 percent
   Clastics 25–50 percent
7. Carbonate 75–100 percent

For any of the chronostratigraphic units and at any control point, the lithology of a measured section is within the percentage limits of one of the seven categories. After a specific lithologic category was determined at several control points for each mapped chronostratigraphic unit, areas characterized by the same category were delineated from areas of a different category by means of boundary lines and patterns on the isopach map, yielding a qualitative lithofacies map for each chronostratigraphic unit.

In order to compare the areal extent of the different lithofacies within any chronostratigraphic unit, the area of each of the different lithofacies was measured by planimeter and its percentage was computed. These percentages are presented in graphic form on the individual lithofacies maps. The individual graphs are reproduced in figure 13, where they permit an overall comparison of the areal extent of the seven lithofacies within the several chronostratigraphic units. These comparative percentages are useful in appraising the need for quantitative stratigraphic maps and in determining the kinds of maps needed to expedite the optimum development of ground-water supplies in specific areas and within specific stratigraphic intervals. The comparative percentages are useful also in selecting exploration methods for ground-water development programs and in estimating their cost.

The vertical distribution of sediment character cannot be shown on regional facies maps of the type contained in this report. However, by selecting one or more typical reference sections for each of the lithofacies of each chronostratigraphic unit, the relation between vertical and areal distribution of lithologies may be shown. Such a relation is established on plate 3. With reference to the geologic cross sections, a series of designated reference sections is listed in columns to the right of each chronostratigraphic unit. Listed in the first column are the designated reference sections that typify the overall vertical distribution of sediment character within each chronostratigraphic unit. Listed in successive columns are the designated reference sections, associated with either marine, marginal-marine, or nonmarine deposition that typify the vertical distribution of sediment character at those control points used to establish the areal distribution of a particular lithofacies for each chronostratigraphic unit. The various lithofacies maps used in conjunction with the various designated reference sections present a three-dimensional view of sediment character in the report area.

It should be emphasized that regional lithofacies maps of this type reflect a considerable degree of subjectivity, so far as drawing the boundaries of the lithofacies is concerned, because relatively few control points generally are available for each chronostratigraphic unit. For this reason, their accuracy in depicting the areal distribution of lithologic variance depends to a large extent upon the preestablishment of valid empirical relationships between a tectonic framework, a structural framework, and sediment distribution patterns in the area being mapped. These empirical relationships, which were used in constructing the lithofacies maps, have been discussed in detail in previous sections of this report.

In mapping subsurface geohydrology on a regional scale, the density of control points usually is such that the data never demand interpretation. Instead they permit more than one interpretation, the validity of any one of which depends, in part, on the experienced judgment of those doing the mapping. The well-control data must be supplemented by an understanding of the geohydrologic habit of the region.

CONSTRUCTION OF THE RELATIVE INTRINSIC-PERMEABILITY NETWORKS

Following construction of the lithofacies maps, each map was used to construct a permeability-distribution network for each of the chronostratigraphic units mapped.

The dimensions and shapes of pore spaces and their degree of interconnection vary in accordance with the textural and compositional character of rocks in the region as discussed previously. Therefore, a scale of relative intrinsic permeability may be established that is quantitatively related to rock lithology. Using available well-control points, one or more vertical sections within the boundary of each areally-segregated lithofacies were evaluated in terms of the lithologies present and in terms of the proportionate percentage thickness of each lithology to the total thickness of the stratigraphic unit at the control point. Each lithology with a significant thickness was assigned a number, ranging from one to seven, indicative of its position on a scale of relative intrinsic permeability. The scale follows:

1. Very high intrinsic permeability
2. High intrinsic permeability
3. Moderately high intrinsic permeability
4. Moderate intrinsic permeability
5. Moderately low intrinsic permeability
6. Low intrinsic permeability
7. Very low intrinsic permeability

The numbers, assigned to each lithology of significant thickness, were averaged according to the proportionate percentage thickness of lithologies having any one number to the total thickness of the stratigraphic unit

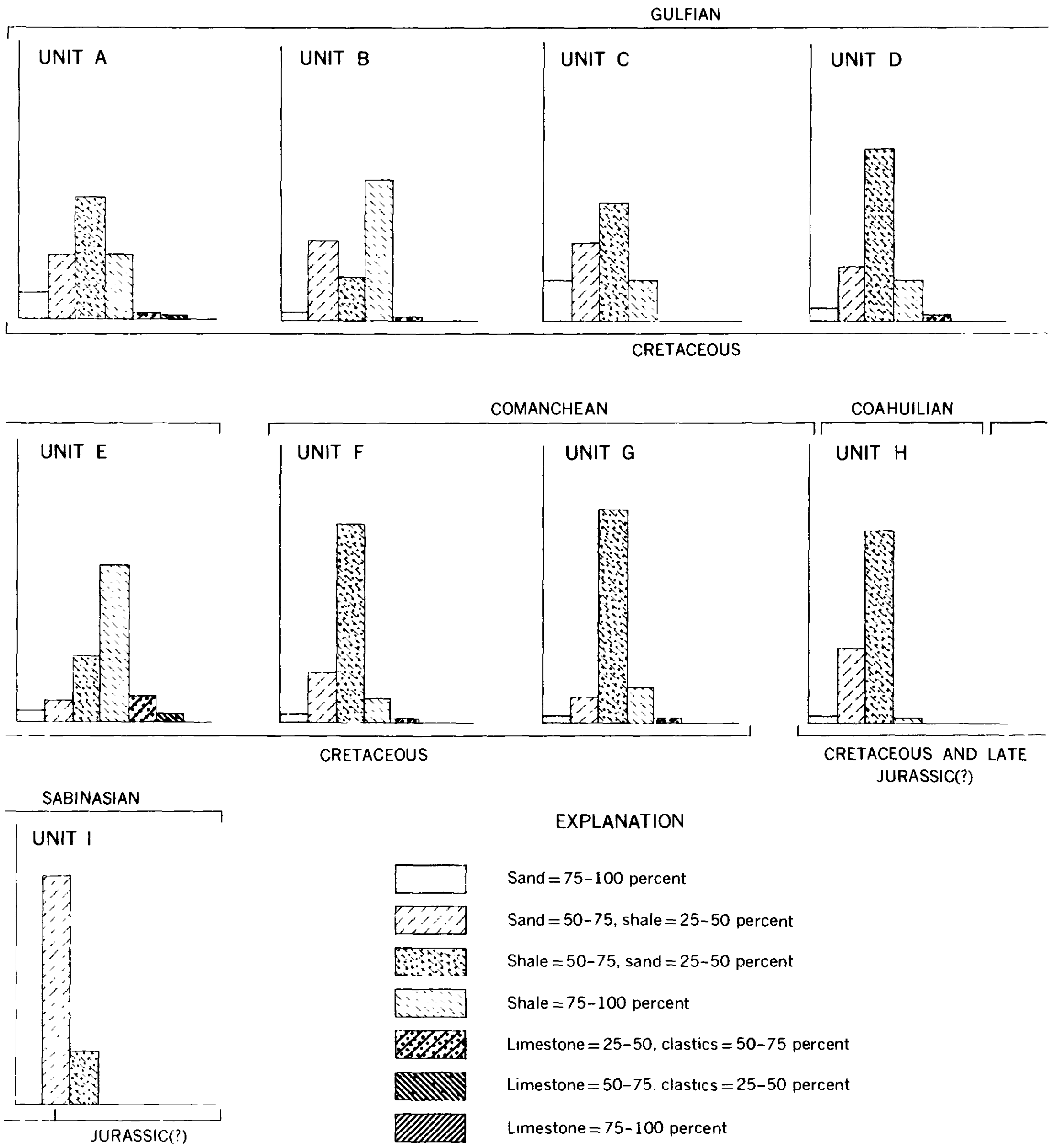

FIGURE 13.—Bar graphs of the areal distribution (percent) of lithofacies mapped in each of the seventeen stratigraphic intervals delineated in the report area.

in the well. The resulting average number was rounded off to the nearest whole number and assigned to the areally restricted lithofacies on the isopach-lithofacies map.

For certain areally segregated lithofacies, no wells were within their boundaries and hence no sections could be evaluated in terms of a relative intrinsic-permeability lithology. For this group of lithofacies, judgment as to their comparative position on the permeability scale and the assignment of a number to designate that position could not be made directly. Instead, the judgment and the assignment of a number were based upon the assumption that their comparative position on the scale of relative intrinsic permeability would be the same as that determined for like lithofacies which were similarly located structurally, with respect to the margins of a contemporaneous depositional area, and for which sections were available for evaluation.

Using either direct or indirect methods of lithologic evaluation, a comparative position on the scale was determined for each lithofacies mapped in the project area and a number was assigned to each lithofacies indicating its position on the permeability scale. The result of the evaluation is presented as a series of per-

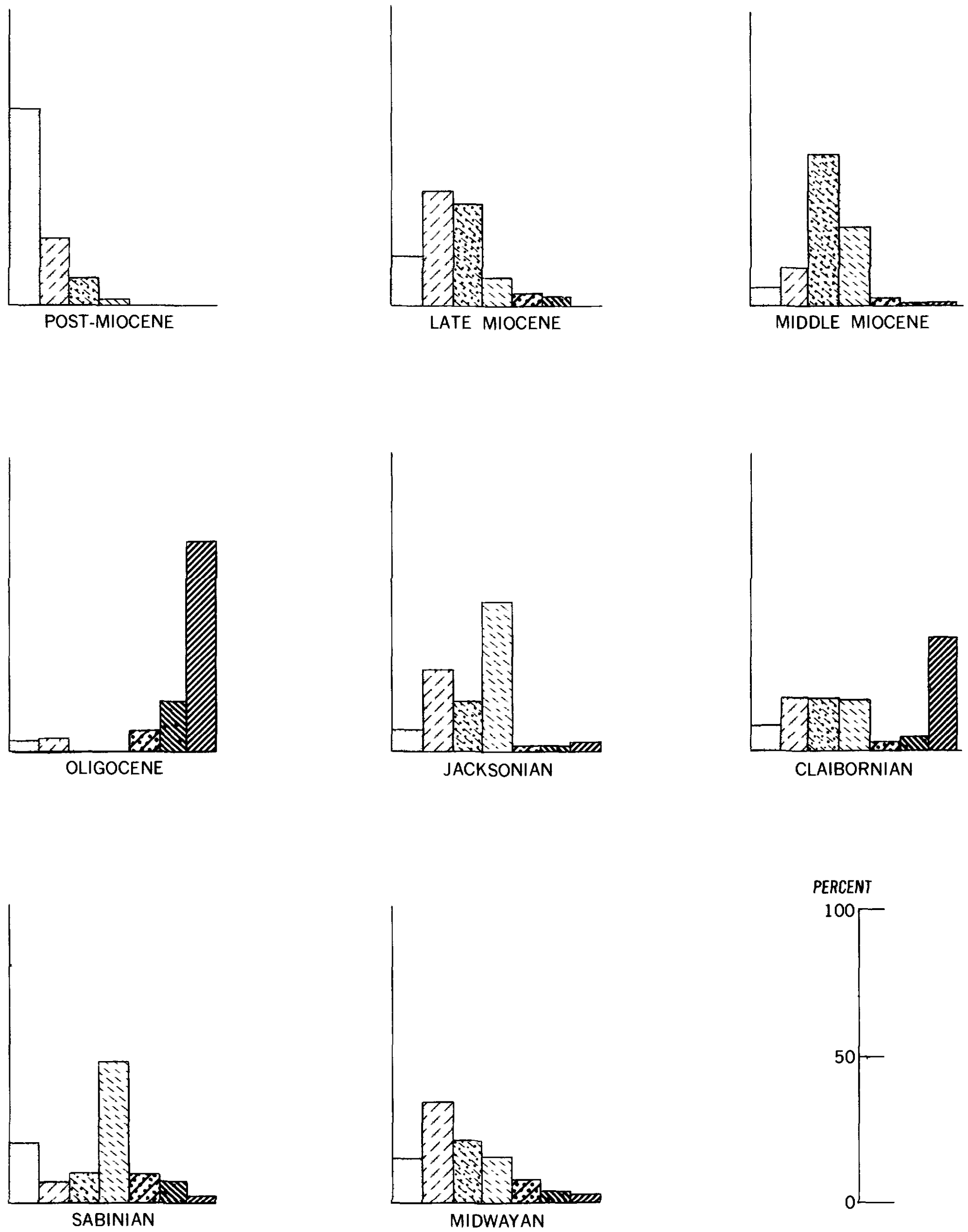

FIGURE 13.—Continued.

meability-distribution networks superimposed on isopach-lithofacies maps. Each network illustrates the regional distribution of intrinsic permeability within a chronostratigraphic unit. The series of isopach-lithofacies-permeability-distribution maps, together with the series of structure-contour maps that were drawn to show the configuration of the surface of each of the various stratigraphic intervals mapped, comprise a three-dimensional geohydrologic model that illustrates the distribution of intrinsic permeability in that part of the Atlantic Coastal Plain extending from North Carolina to Long Island, N. Y.

SUMMARY

Chronostratigraphic units mapped in the subsurface record a structural history dominated by the alternate presence of two discordant structural systems and by a system of intersecting hingebelt segments. Taphrogeny, related to transcurrent faulting and induced by both rotational and irrotational stress acting in a horizontal plane, was the dominant type of deformation that controlled the areal distribution and thicknesses of the sediments mapped. The vertical forces that have been operative in the region since at least Jurassic time are "basically" resultants of horizontal ("compressional") forces. The horizontal forces may be derived from the rotation and precession of the earth.

Historically, the region is characterized by a semi-periodic realinement of positive and negative structural features. Within the sediment mass, regional chronostratigraphic units that have no genetic roots in the present-day configuration of the basement surface are interlayered with chronostratigraphic units that have genetic roots in that surface. This relation suggests that two different types of deformation, each with its own characteristic structural alinements, are established alternately in the area covered by the report. Using the internal and external geometries of the rocks mapped, as a starting point, structural models were derived that satisfy the internal geometry of the regional sediment mass and satisfy the alinement of structures inferred to have been present during the deposition of both the rooted and unrooted chronostratigraphic units. Similarly, tectonic models were derived that satisfy the structural models.

Lithologic variance, both areally and vertically, was used to map the distribution of permeability in each of the chronostratigraphic units delineated in the subsurface. Lithofacies, based on percentage composition of sand, shale, and carbonate, when combined with an adequate recognition of the role exerted by structure in controlling the areal distribution and thicknesses of sediments, provide the best means for constructing regional permeability-distribution networks; networks which can be used in evaluating the ground-water potential of a coastal region such as that of the Middle Atlantic States.

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