Allostratigraphy of the U.S. Middle Atlantic Continental Margin—Characteristics, Distribution, and Depositional History of Principal Unconformity-Bounded Upper Cretaceous and Cenozoic Sedimentary Units

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1542

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Allostratigraphy of the U.S. Middle Atlantic Continental Margin—Characteristics, Distribution, and Depositional History of Principal Unconformity-Bounded Upper Cretaceous and Cenozoic Sedimentary Units

By C. Wylie Poag and Lauck W. Ward

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1542

Descriptions, maps, and names for 12 alloformations and designations of their offshore stratotype sections and onshore supplementary reference sections

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	0.5400	nautical mile
	Area	
square kilometer (km^2)	0.3861	square mile

Allostratigraphy of the U.S. Middle Atlantic Continental Margin—Characteristics, Distribution, and Depositional History of Principal Unconformity-Bounded Upper Cretaceous and Cenozoic Sedimentary Units

By C. Wylie Poag[1] and Lauck W. Ward[2]

ABSTRACT

Publication of Volumes 93 and 95 ("The New Jersey Transect") of the Deep Sea Drilling Project's *Initial Reports* completed a major phase of geological and geophysical research along the middle segment of the U.S. Atlantic continental margin. Relying heavily on data from these and related published records, we have integrated outcrop, borehole, and seismic-reflection data from this large area (~500,000 km^2) to define the regional allostratigraphic framework for Upper Cretaceous and Cenozoic sedimentary rocks. The framework consists of 12 alloformations, which record the Late Cretaceous and Cenozoic depositional history of the contiguous Baltimore Canyon trough (including its onshore margin) and Hatteras basin (northern part). We propose stratotype sections for each alloformation and present a regional allostratigraphic reference section, which crosses these basins from the inner edge of the coastal plain to the inner edge of the abyssal plain. Selected supplementary reference sections on the coastal plain allow observation of the alloformations and their bounding unconformities in outcrop.

Our analyses show that sediment supply and its initial dispersal on the middle segment of the U.S. Atlantic margin have been governed, in large part, by hinterland tectonism and subsequently have been modified by paleoclimate, sea-level changes, and oceanic current systems. Notable events in the Late Cretaceous to Holocene sedimentary evolution of this margin include (1) development of continental-rise depocenters in the northern part of the Hatteras basin during the Late Cretaceous; (2) the appearance of a dual shelf-edge system, a marked decline in siliciclastic sediment accumulation rates, and widespread acceleration of carbonate production during high sea levels of the Paleogene; (3) rapid deposition and progradation of thick terrigenous delta complexes and development of abyssal depocenters during the middle Miocene to Quaternary interval; and (4) deep incision of the shelf edge by submarine canyons, especially during the Pleistocene.

Massive downslope gravity flows have dominated both the depositional and erosional history of the middle segment of the U.S. Atlantic Continental Slope and Rise during most of the last 84 million years. The importance of periodic widespread erosion is recorded by well-documented unconformities, many of which can be traced from coastal-plain outcrops to coreholes on the continental slope and lower continental rise. These unconformities form the boundaries of the 12 allostratigraphic units we formally propose herein. Seven of the unconformities correlate with supercycle boundaries (sequence boundaries) that characterize the Exxon sequence-stratigraphy model.

INTRODUCTION

Seismic surveys and exploratory drilling have established the presence off the U.S. Middle Atlantic States of a deep, elongate, sedimentary basin named the Baltimore Canyon trough (Maher, 1965; figs. 1 and 2). Kingston and others (1983) and Emery and Uchupi (1984) classified this feature as a margin sag basin. The Baltimore Canyon trough underlies the coastal plain and the continental shelf and slope for 600 km between Long Island (Long Island platform) and Cape Hatteras (Carolina platform) (fig. 1; Schlee, 1981; Poag, 1985a). The maximum thickness of sedimentary rocks in the trough is about 18 km under the

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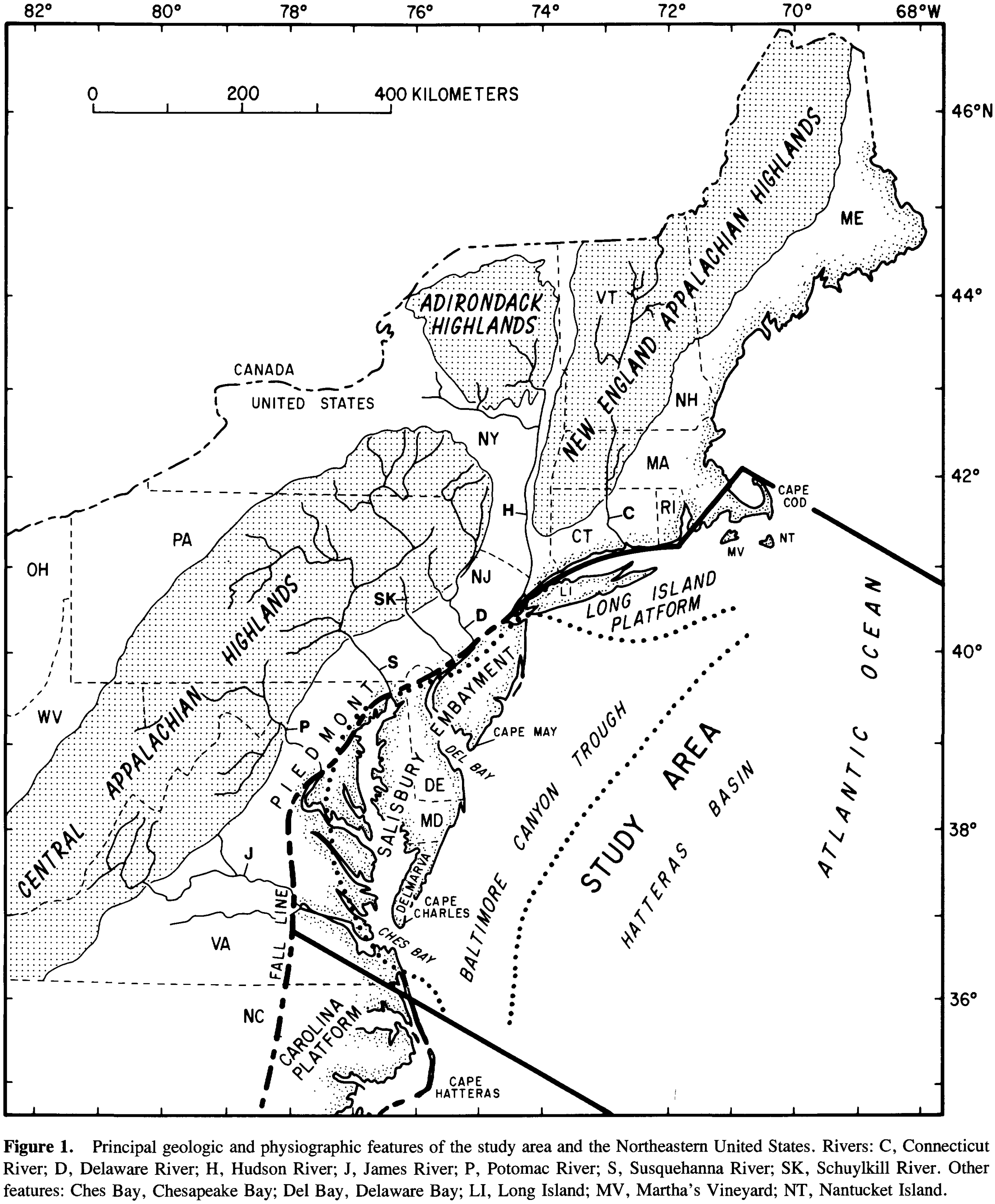

Figure 1. Principal geologic and physiographic features of the study area and the Northeastern United States. Rivers: C, Connecticut River; D, Delaware River; H, Hudson River; J, James River; P, Potomac River; S, Susquehanna River; SK, Schuylkill River. Other features: Ches Bay, Chesapeake Bay; Del Bay, Delaware Bay; LI, Long Island; MV, Martha's Vineyard; NT, Nantucket Island.

New Jersey Shelf. Maximum thickness in the coastal-plain segment of the trough is approximately 2.4 km in eastern Maryland, in a local depocenter known as the Salisbury embayment (fig. 1). Several smaller embayments and intervening arches, which may be structurally controlled (Brown and others, 1972), also are known in the coastal-plain segment of the trough. A structural hingeline (fig. 2) separates the more rapidly subsiding offshore part of the

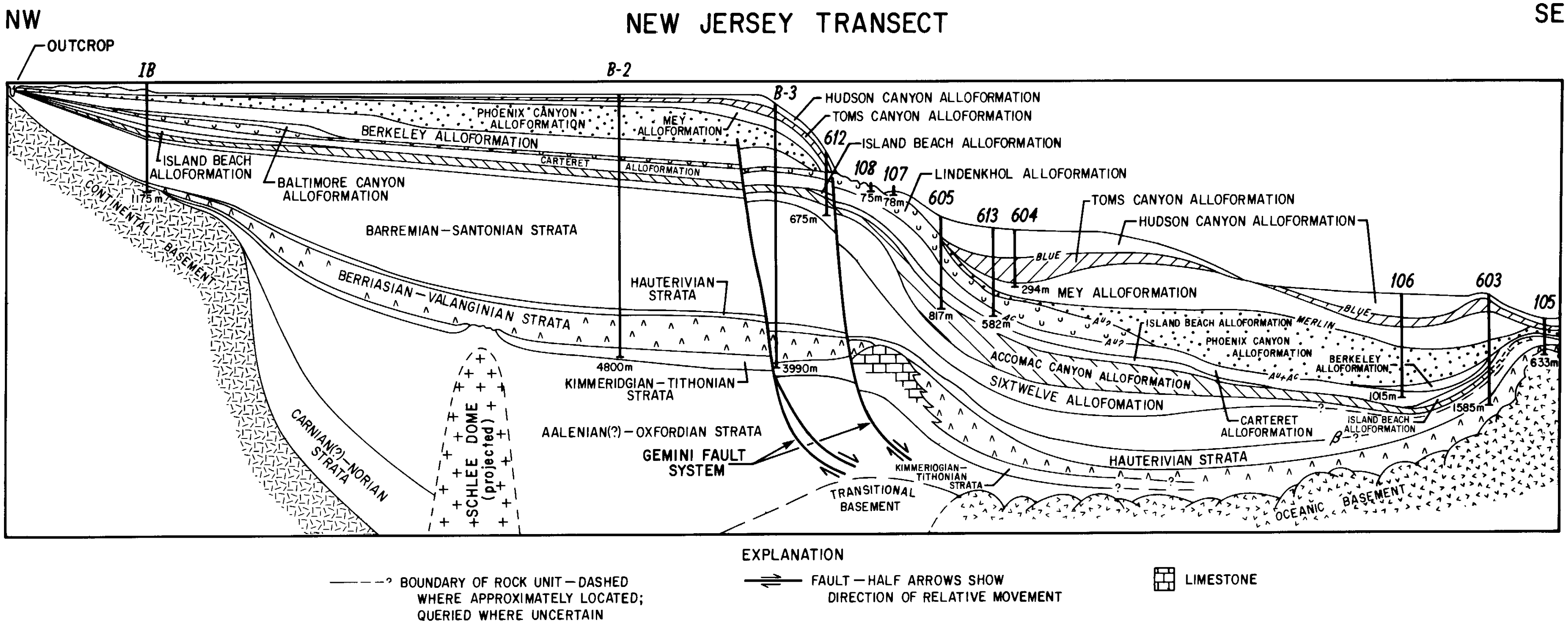

Figure 2. The New Jersey Transect, a diagrammatic cross section (exaggerated scale) that extends about 700 km from outcrops on the New Jersey Coastal Plain to the northern Hatteras basin. Transect is along two multichannel seismic-reflection profiles—U.S. Geological Survey profile 25 crossing the deepest part of the Baltimore Canyon trough and part of Lamont-Doherty Geological Observatory profile *Conrad* 21 (segments 75–77) crossing the lower continental rise of the Hatteras basin (see fig. 3 for transect location). Boreholes shown are discussed in text (see table 1 and figs. 3 and 4 for explanation of boreholes); some boreholes are projected onto the transect. Cross section shows stratigraphic relations and approximate relative thicknesses of alloformations proposed herein. The Babylon Alloformation, which is too thin to show at the scale of this diagram, is present on the continental shelf and slope between the Baltimore Canyon Alloformation and the Berkeley Alloformation. The Baltimore Canyon Alloformation also is too thin to show at this scale, except in the landward part of the Baltimore Canyon trough. Older depositional units (stages) were discussed by Poag (1985a, 1991) and Poag and Sevon (1989). A^u, A^c, β, Merlin, and Blue are deep-sea seismic boundaries (queried where uncertain; Mountain and Tucholke, 1985; Poag and Mountain, 1987).

trough (which consequently has the thickest sediment column) from the onshore part (present coastal plain), which has undergone partially compensating uplift (Hack, 1982; Watts, 1982; Watts and Swift, 1988; Poag and Sevon, 1989).

The Baltimore Canyon trough is bounded on the west by the uplifted rocks of the central Appalachian Highlands (including the Piedmont and the Blue Ridge Mountains), on the north by the Adirondack Highlands of New York, and on the northeast by the New England Appalachian Highlands (fig. 1). The seaward (southeast) margin of the Baltimore Canyon trough is marked by a buried, reef-supported shelf edge, which formed a steep reef-front slope during the Late Jurassic (fig. 2). Seaward of this boundary is the northern part of the Hatteras basin (figs. 1 and 2), which encompasses the continental rise and abyssal plain (Emery and Uchupi, 1984). The total area studied for this report encompasses about 500,000 km^2.

PREVIOUS WORK

Stratigraphic, sedimentological, and paleontological studies of the U.S. Atlantic Coastal Plain north of Cape Hatteras (fig. 1) have a long history (for example, Richards, 1945; Anderson and others, 1948; Murray, 1961; Olsson, 1964, 1970, 1975; Brown and others, 1972; Perry and others, 1975; Owens and others, 1977; Hazel and others, 1984; Ward and Krafft, 1984; Mixon, 1989; Benson, 1990a,b; Poag, in press). Regional summaries that include the continental shelf began to appear in the early 1970's (Maher, 1971; Emery and Uchupi, 1972). Soon thereafter, petroleum exploration began in the offshore region of New Jersey and gave impetus to important research papers describing and interpreting the sedimentary sequences of the continental shelf (Mattick and others, 1974; Minard and others, 1974; Sheridan, 1974; Schlee and others, 1976; Scholle, 1977, 1980; Poag, 1978, 1979, 1980, 1985a, 1991; Hathaway and others, 1979; Mattick and Hennessy, 1980; Libby-French, 1981, 1984, 1986; Robb and others, 1981, 1983; Robb, Hampson, and Twichell, 1981; Schlee, 1981; Poag and Schlee, 1984; Bayer and Milici, 1987; Sheridan and Grow, 1988; Meyer, 1989; Poag and Sevon, 1989; Poag and others, 1990).

Knowledge of the continental slope and rise off the Middle Atlantic States has also increased significantly in the last 15 years. The principal deep-sea geologic data have been collected by the Deep Sea Drilling Project (DSDP), which drilled several sites on the eastern edge of the Baltimore Canyon trough and in the northern part of the Hatteras basin during Leg 11 (Hollister, Ewing, and others, 1972), Leg 43 (Tucholke, Vogt, and others, 1979), Leg 93 (Van Hinte, Wise, and others, 1987), and Leg 95 (Poag, Watts, and others, 1987). In addition to the DSDP reports, important discussions of relevant deep-sea data were provided by Jansa and others (1979), Tucholke and Mountain (1979, 1986), Tucholke and Laine (1982), Tucholke and others (1982), Emery and Uchupi (1984), Ewing and Rabinowitz (1984), Mountain and Tucholke (1985), Poag (1985b, 1991, 1992), Schlee and others (1985), Vogt and Tucholke (1986), Wise and others (1986), Mountain (1987), Schlee and Hinz (1987), O'Leary (1988), McMaster and others (1989), Pratson and Laine (1989), Danforth and Schwab (1990), and Locker and Laine (1992).

A geological and geophysical transect, known as the New Jersey Transect, was originally conceived as a standard reference section for an Atlantic-type passive margin, to extend from the inner edge of the coastal plain, across the thick sedimentary prism of the Baltimore Canyon trough, to the outer edge of the continental rise in the Hatteras basin (Poag, Watts, and others, 1987). The landward segment of the New Jersey Transect includes outcrops and subsurface borings on the coastal plain, a series of boreholes on the continental shelf and upper continental slope (total of 88 boreholes), and more than 20,000 line-km of multichannel (fig. 3) and single-channel (fig. 4) seismic-reflection lines (Poag, 1985a; Poag and Mountain, 1987; Poag and Valentine, 1988). The middle and seaward segments of the New Jersey Transect include sites on the lower continental slope and on the upper and lower continental rise cored during DSDP Legs 93 (Van Hinte, Wise, and others, 1985a,b; 1987) and 95 (Poag, 1985b; Poag, Watts, and others, 1987; fig. 2).

U.S. Geological Survey (USGS) multichannel seismic-reflection profile 25, which crosses the deepest part of the Baltimore Canyon trough, is the standard reference profile (Poag, 1985a) along which the four key updip DSDP sites (Sites 604, 605, 612, and 613) were placed (figs. 2–4). A second multichannel seismic-reflection profile, *Conrad* 21 (obtained by scientists of the Lamont-Doherty Geological Observatory), intersects the seaward end of USGS profile 25 (fig. 3, segments 75–77) and crosses the lower continental rise, eventually reaching DSDP Sites 603 and 105, the distal coreholes on the New Jersey Transect. At this writing, the New Jersey Transect is unique; we know of no comparable publicly available geological and geophysical data set for any other continental margin.

Prior to DSDP Leg 93, investigations of the Atlantic Coastal Plain (Hazel and others, 1984; Kidwell, 1984; Owens and Gohn, 1985; Ward and Strickland, 1985; Poag, in press) and Continental Shelf (Schlee, 1981; Poag and Schlee, 1984; Poag, 1985a; Poag and Ward, 1987) indicated that a series of widespread depositional sequences, bounded by erosional unconformities, could be traced throughout the Baltimore Canyon trough and even 400 km northeastward into the adjacent Georges Bank basin and 1,000 km southwestward into the Blake Plateau basin (Poag and Hall, 1979; Poag, 1982, 1991; Schlee and Fritsch, 1982; Schlee and others, 1985). Along the lower slope and upper rise, USGS seismic profile 25 showed that several of

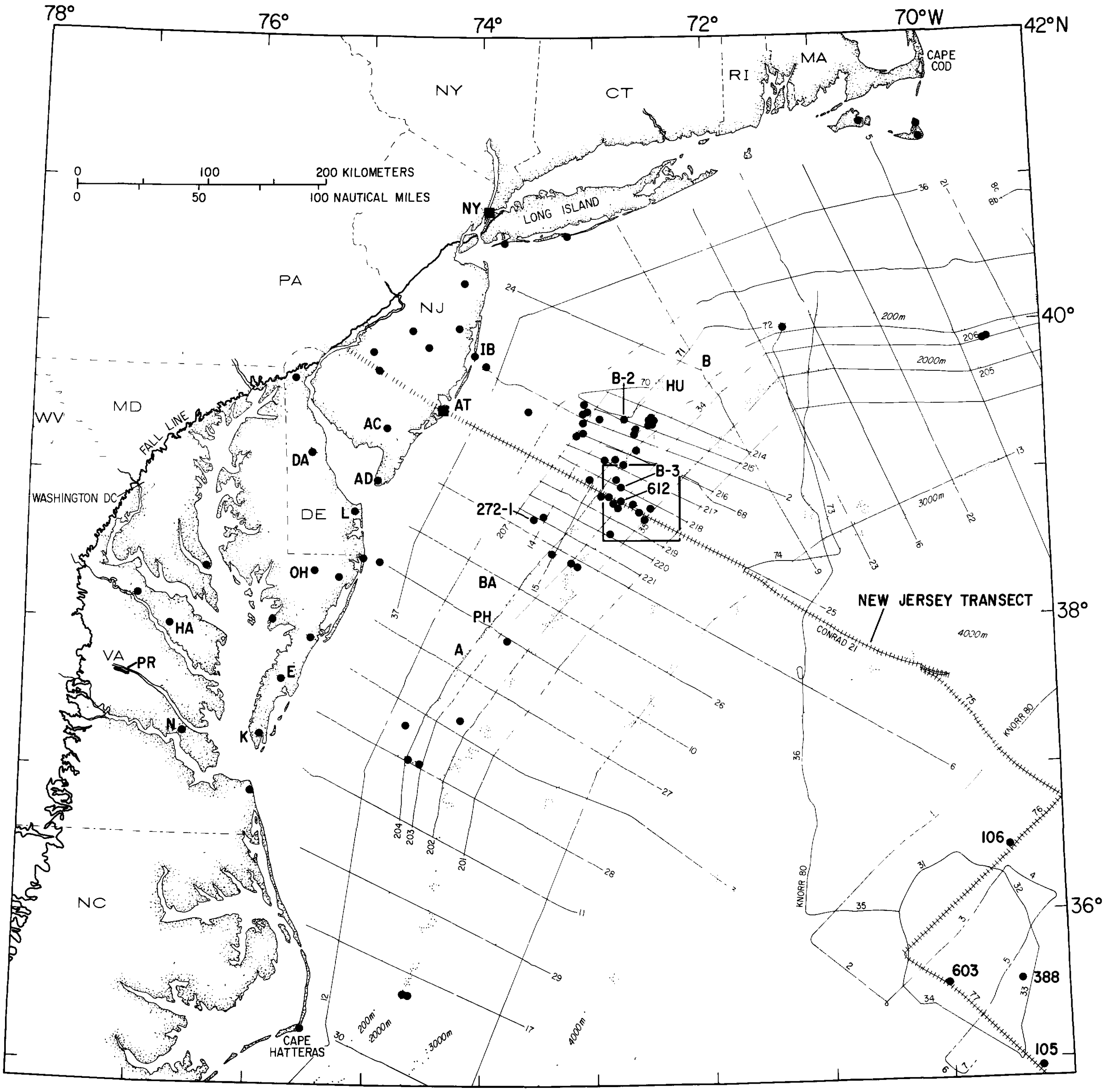

Figure 3. Locations of selected boreholes (solid circles) and tracklines (numbered lines) along which multichannel seismic-reflection profiles (table 2) were collected in the study area. Boreholes discussed in text (also see table 1): AC, ACGS-4 corehole; AD, Anchor-Dickinson No. 1 well; B-2 and B-3, COST (Continental Offshore Stratigraphic Test) wells; DA, Dover Air Force Base well; E, Exmore corehole; HA, Haynesville corehole; IB, Island Beach No. 1 borehole; K, Kiptopeke corehole; L, Lewes, Del., borehole; N, Newport News, Va., corehole; OH, Ohio Oil-Hammond No. 1 well; 272-1, Shell 272-1 well; and 105, 106, 388, 603, and 612, DSDP (Deep Sea Drilling Project) Sites. Data from some of the key boreholes were projected to two seismic profiles as shown in New Jersey Transect (fig. 2): U.S. Geological Survey profile 25 and segments 75–77 of Lamont-Doherty Geological Observatory profile *Conrad* 21, which consists of five continuous segments (segments 73–77). Box shows area of figure 4, which is a more detailed map of vicinity of DSDP Site 612. AT, Atlantic City, N.J.; NY, New York City, N.Y.; PR, Pamunkey River outcrops. Labeled submarine canyons: A, Accomac; B, Babylon; BA, Baltimore; HU, Hudson; and PH, Phoenix. Lindenkohl, Carteret, Berkeley, Toms, and Mey Canyons are not labeled here because of close spacing of seismic lines near Site 612; these canyons are labeled on figure 50. Bathymetry shown by dotted lines.

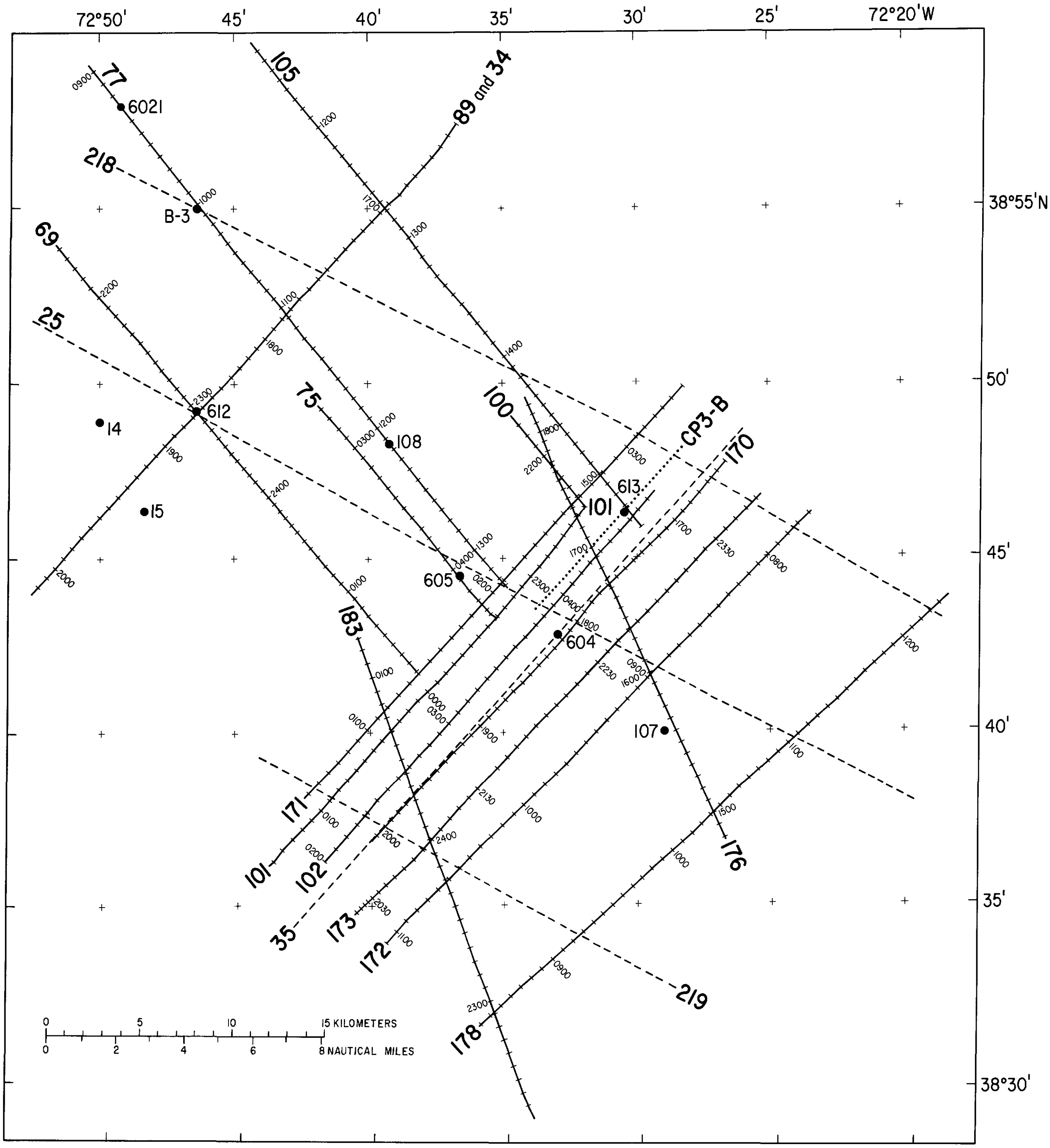

Figure 4. Locations of tracklines, along which single-channel (solid or dotted lines) and multichannel (dashed lines) seismic-reflection profiles (table 2) were collected, and selected boreholes (solid circles) in vicinity of DSDP (Deep Sea Drilling Project) Site 612 (see fig. 3 for location). Multichannel line 34 is approximately coincident with single-channel line 89. Boreholes discussed in text (also see table 1): 6021, AMCOR (Atlantic Margin Coring Project) corehole; 14 and 15, ASP (Atlantic Slope Project) boreholes; B–3, COST (Continental Offshore Stratigraphic Test) well; and 107, 108, 604, 605, 612, and 613, DSDP Sites. Hours (military time) adjacent to tracklines are navigational correlation points.

these depositional units, some as old as Late Cretaceous, were within reach of the *Glomar Challenger*'s drill string. The boundaries of these units produce high-amplitude reflections that truncate underlying reflections and commonly are onlapped by younger reflections, relations that are the chief criteria for recognizing "seismic" unconformities (Vail and others, 1977a). Thus, six sites along profile 25 (Sites 107, 108, 604, 605, 612, and 613) (figs. 2–5; Hollister, Ewing, and others, 1972; Poag, 1985b; Van Hinte, Wise, and others, 1985a, 1987; Poag, Watts, and others, 1987) were chosen to sample these strata and to document the middle segment of the New Jersey Transect. Three sites (Sites 105, 106, and 603; Hollister, Ewing, and others, 1972; Van Hinte, Wise, and others, 1985b, 1987) were selected on the lower continental rise near the extreme end of profile *Conrad* 21 (segment 77; figs. 2, 3, and 5).

At each site, the scientific party attempted to core the sedimentary section as completely as deadlines and equipment durability allowed. Modern Schlumberger logging equipment provided downhole geophysical logs at Sites 612 and 613. Extensive analyses and interpretations of lithologic, sedimentologic, paleontologic, and geochemical data were discussed in detail by Poag, Watts, and others (1987) and by Van Hinte, Wise, and others (1987).

SCOPE OF THIS REPORT

Because allostratigraphy is a relatively new concept in geological thinking, we begin this report with a discussion of allostratigraphic principles. Then, on the basis of available geological and geophysical data, both onshore and offshore, we construct a regional allostratigraphic framework for the U.S. Middle Atlantic margin. We formally propose, define, describe, and map the distribution and thickness of 10 Cenozoic alloformations and 2 Upper Cretaceous alloformations, whose stratotypes are mainly offshore. We also recommend and illustrate previously studied outcrops and boreholes onshore as supplementary reference sections for each alloformation. We conclude with discussions of (1) the allostratigraphic relations between seismostratigraphic sequences and borehole stratigraphy in the study area; (2) the proximate causes of the unconformities that bound the proposed alloformations; (3) depositional regimes and the provenance and dispersal of sediments in the study area; (4) the implications of our study regarding sequence-stratigraphy models; and (5) the intrinsic advantages of applying an allostratigraphic framework, particularly in our study area.

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PRINCIPLES OF ALLOSTRATIGRAPHY

In this report, we propose a formal nomenclature for the principal unconformity-bounded units identified (figs. 2 and 5). We do this in the belief that "unconformity-bounded units can become invaluable stratigraphic units, almost 'natural' units, which the stratigrapher may be able to use. . .for a better, more descriptive, and more lucid interpretation of geologic history" (International Subcommission on Stratigraphic Classification, 1987, p. 234).

We emphasize that ". . .Unconformity-bounded units . . .are not lithostratigraphic, biostratigraphic, or chronostratigraphic units. They are what their name indicates—unconformity-bounded units, a distinct and separate kind of stratigraphic unit that requires separate recognition." (International Subcommission on Stratigraphic Classification, 1987, p. 232).

Some authors have tried to extrapolate the formations of the Scotian basin to the Baltimore Canyon trough (Libby-French, 1981, 1984; Poag, 1985a), but uncertainties in long-distance seismic correlations and inevitable lithofacies changes between basins make such extrapolations unsatisfactory. More recently, Poag (1987, 1991, 1992), Poag and Mountain (1987), and Poag and Sevon (1989) treated the unconformity-bounded stratigraphic units of the study area as "depositional sequences" in the sense of Vail and others (1977a, p. 53), "stratigraphic unit(s) composed of . . .relatively conformable succession(s) of genetically related strata and bounded at. . .[the] top and base by unconformities. . . ." The term "sequence" has serious disadvantages, however, having been applied in various contexts to many different geological features (see International Subcommission on Stratigraphic Classification (1987) for further discussion).

Two influential commissions on stratigraphic nomenclature have suggested new stratigraphic terminology specifically for unconformity-bounded units. In 1983, the latest version of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, p. 865) introduced the allostratigraphic unit, defined as "a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities." In this definition, the term "discontinuities" includes unconformities but is not limited to them; it also

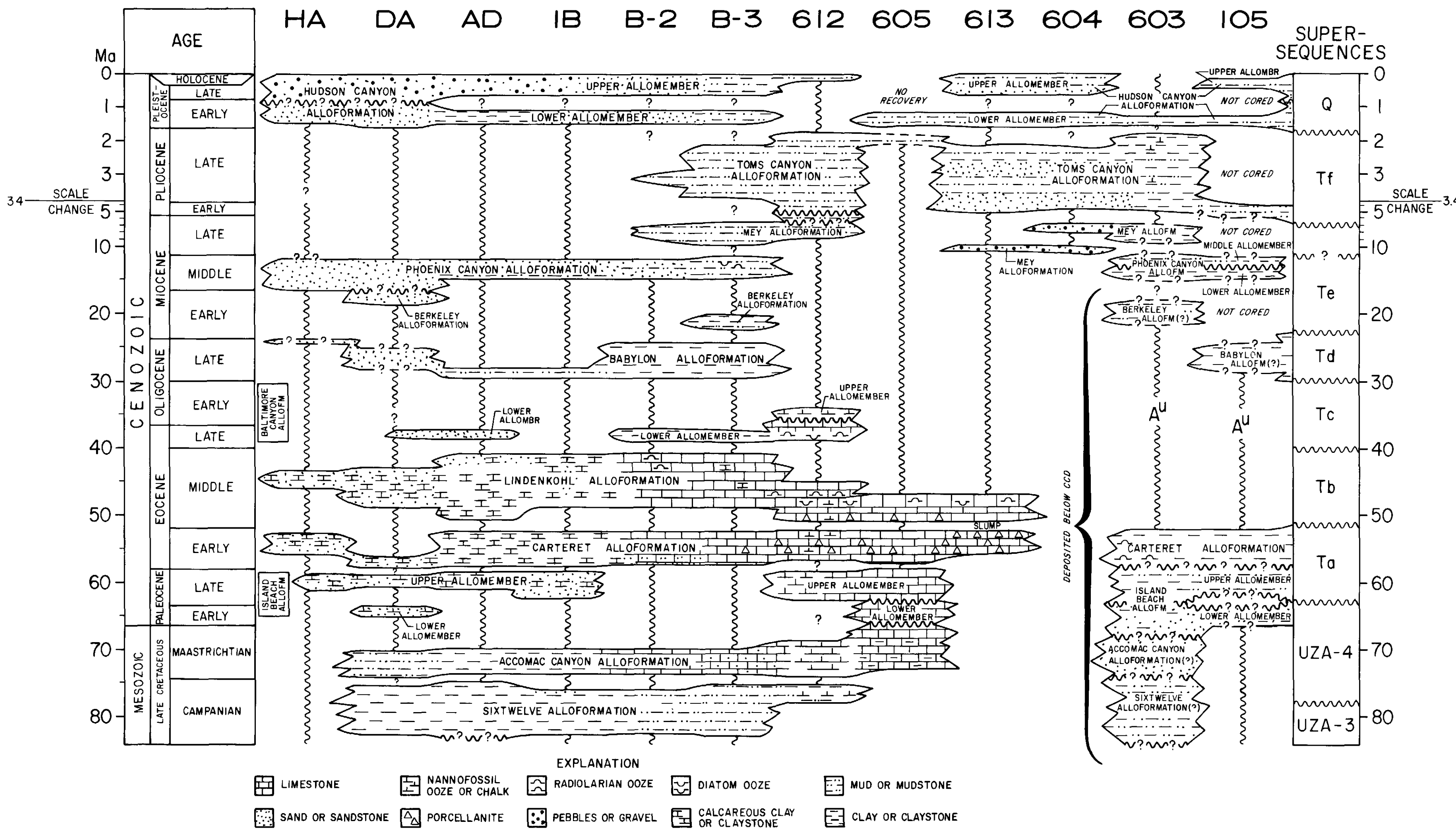


Figure 5. Summary chart showing geographic and stratigraphic distribution of alloformations proposed herein. Vertical scale is time; note change in scale at late Pliocene to show detail. Boreholes: AD, Anchor-Dickinson No. 1 well; B–2 and B–3, COST (Continental Offshore Stratigraphic Test) wells; DA, Dover Air Force Base well; HA, Haynesville corehole; IB, Island Beach No. 1 borehole; other numbers indicate DSDP (Deep Sea Drilling Project) coreholes. Hiatuses indicated by vertical and horizontal wavy lines. Note correlation of alloformations with supersequences of the Exxon sequence-stratigraphy model discussed in text (Vail and Mitchum, 1979, Ta to Q; Haq and others, 1987, UZA–3,4). Note that sections on continental slope (COST B–3, DSDP 612) are most complete; duration of hiatuses increases toward shore and into deep sea. A^u, deep-sea seismic boundary (Mountain and Tucholke, 1985; Poag and Mountain, 1987); CCD, carbonate compensation depth; ?, uncertain.

includes such discontinuities as diagenetic boundaries or soil horizons. Thus, all unconformity-bounded units are allostratigraphic units, though not all allostratigraphic units are unconformity-bounded units. The basic allostratigraphic unit is the alloformation; allomembers and allogroups are finer and coarser divisions, respectively.

Four years later, the International Subcommission on Stratigraphic Classification (1987, p. 233) noted the North American Stratigraphic Code's terminology but curiously declined to comment on it; instead, the Subcommission recommended a different series of names, centered around synthem, proposed on p. 236 and defined on p. 233 as "a body of rock bounded above and below by specifically designated, significant, and demonstrable discontinuities in the stratigraphic succession (angular unconformities, disconformities, etc.), preferably of regional or interregional extent." Synthems may be divided into subsynthems or grouped as supersynthems.

Because the allostratigraphic terminology was proposed specifically for sedimentary strata, and because it was published first, and because the U.S. Geological Survey recommends following the North American Stratigraphic Code, we have adopted this system. The characteristics of the alloformations we propose are those recommended by the North American Stratigraphic Code (p. 865–867): (1) Physical, chemical, and paleontological characteristics may vary horizontally and vertically throughout the units; (2) Boundaries of the allostratigraphic units are laterally traceable discontinuities; (3) The units are mappable at the scale practiced in the study area; (4) Inferred time spans are not used to define the allostratigraphic units, but most units have characteristic time spans within the study area; (5) The allostratigraphic units can be extended from their stratotypes by tracing the boundary discontinuities and by tracing the deposits between the discontinuities; and (6) Names of the proposed allostratigraphic units are derived from permanent natural or artificial geographic features in the study area. Relatively few named geographic features are present in the offshore region (principally submarine canyons), and so we have used, in one instance, the name of a Deep Sea Drilling Project site.

We concede that the concept of a widespread (200,000–500,000 km^2) allostratigraphic unit bounded everywhere by unconformities is somewhat idealistic and probably is not applicable in its purest sense. That is, there are places where the contacts between successive allostratigraphic units become conformable, especially in the Hatteras basin. But even where conformable, the allostratigraphic boundaries are marked by significant discontinuities, whose acoustic impedance contrasts cause distinct, traceable seismic reflections.

In its explanation of allostratigraphic units, the North American Stratigraphic Code contains what appears to be a serious contradiction, or ambiguity. Article 58(e) appears to prohibit the use of formal allostratigraphic nomenclature in areas where lithostratigraphic units have been formalized. Yet the example illustrated in the code's Fig. 7 (p. 866) implies that formations and allostratigraphic units can be recognized in identical rocks at the same locality. If article 58(e) were adhered to, we would be required to erect artificial vertical cutoffs between offshore alloformations and equivalent onshore formations, as if their mutual presence would defy some stratigraphic principle.

We argue that such cutoffs are indefensible, both conceptually and in the field. As a conceptual argument, we cite the relation between lithostratigraphic units and biostratigraphic units. It is normal for these two types of units to overlap or embrace one another in the field. But the code recognizes the individuality of each type of unit, even though the upper and (or) lower boundaries of the units might coincide. Both types of unit are recognized because each type is defined by separate, easily distinguished criteria. So too, are lithostratigraphic and allostratigraphic units defined by separate, easily distinguished criteria.

From the perspective of field relations, we contend that the unconformities that bound the alloformations offshore do not stop at the coastline, but extend across much of the coastal plain and may be observed in outcrop. Some authors, in fact (for example, Vail and others, 1977b; Haq and others, 1987), would go so far as to claim that these unconformities are globally distributed. Moreover, the stratigraphic and geographic relations between the allostratigraphic and lithostratigraphic units are complex. For example, for every alloformation proposed herein, the designated unconformable boundaries encompass more than one formal onshore formation. Each formation has its own separate distribution pattern and correlates with its encompassing alloformation at a different stratigraphic level.

We believe that to erect artificial cutoffs between offshore alloformations and onshore formations implies paradoxically that the two types of units are inherently the same; that the presence of one excludes the other. This practice is scientifically unacceptable. Our viewpoint coincides, rather, with that of the International Subcommission on Stratigraphic Classification (1987), which specifies that (p. 234):

> Unconformity-bounded units may include any number of other kinds of stratigraphic units (lithostratigraphic, biostratigraphic, chronostratigraphic, magnetostratigraphic, and so on), from a few to scores, both in vertical and/or lateral succession. . . . The beds they contain may range widely in age, from a substage or chronozone to one or more systems. In certain cases, in a certain locality, or even over a certain area, a rock body bounded by unconformities may have an over-all uniform lithology or may represent a single biostratigraphic unit. The unconformity-bounded unit will then be essentially equivalent to a given lithostratigraphic or biostratigraphic unit.

Thus, we recognize the presence of the formalized alloformations onshore and have recommended onshore supplementary reference sections where the alloformations and their bounding unconformities may be observed and studied.

In extending the proposed allostratigraphic units to the coastal plain, we are cognizant that interpretations of lithologic, biostratigraphic, and chronostratigraphic relations vary, and sometimes conflict, from State to State. We have not attempted to resolve these conflicts, but have tried to accommodate as many viewpoints as possible in our synthesis.

DATA USED IN THIS STUDY

BOREHOLES AND SEISMIC DATA

We agree with A.D. Miall (1984, p. 3) that "Stratigraphic units ideally should be established on the basis of a basin-wide perspective. . . ." The stratigraphic data available to us from the U.S. Middle Atlantic continental margin provide just such a perspective.

Key boreholes used in this study are listed in table 1 and are plotted in figures 3 and 4. We used lithologic, microfossil, and geophysical-log analyses of these boreholes to document the allostratigraphic framework along the New Jersey Transect. The results also provided a positive test of the coarse (second-order) framework of the Exxon sequence-stratigraphy model (Vail and others, 1977b; Vail and Mitchum, 1979; Vail and others, 1984; Haq and others, 1987, 1988; Van Wagoner and others, 1988). The model postulates that nine Upper Cretaceous and Cenozoic depositional supersequences are separated by widespread (major or global) unconformities. The stratigraphic positions of the unconformities are fixed by microfossil biozonation and then correlated with a paleomagnetic and radiometric time scale. Coring on the continental slope and upper rise sampled supersequences UZA–3 through TB3 of Haq and others (1987) and found erosional unconformities or slump zones (biostratigraphic and (or) lithic discontinuities) at all supersequence contacts (fig. 5). Geophysical logging at Sites 612 and 613 (Poag, Watts, and others, 1987) showed that physical discontinuities correlate with impedance contrasts on seismic-reflection profiles and sonic velocity changes in the boreholes, confirming that seismostratigraphic sequence analysis is applicable in the study area. Thus, a reliable basis in ground truth was established for extrapolating the allostratigraphic framework across the Baltimore Canyon trough and the Hatteras basin along the grid of seismic-reflection profiles (table 2). The close correspondence of these alloformations and supersequences (fig. 5) refutes the claim of Thorne and Watts (1984) that seismic-sequence analysis is useless in predicting the stratigraphic succession of continental shelves and slopes.

A multichannel seismic-reflection grid (fig. 3; table 2) provides the principal network from which isochron maps were constructed for the 12 allostratigraphic units (equivalent, in part, to the depositional sequences of Poag, 1987, and Poag and Mountain, 1987; see also Poag, 1992). Poag and Sevon (1989) published simplified versions of these maps. An additional 15 high-resolution, single-channel profiles provide more detailed stratigraphic and thickness data in the vicinity of the updip DSDP boreholes (fig. 4, Sites 604, 605, 612, 613; Poag and Mountain, 1987). These isochron maps help to demonstrate the chief attributes of depositional style and fabric and the regional aspects of depositional history. In particular, the maps indicate the location of principal depocenters and allow calculation of sediment volumes and net accumulation rates. Generalized sets of isopach maps (isochrons converted to depth), most of which combine several of the proposed alloformations, have been published by Tucholke and Mountain (1979, 1986), Schlee (1981), Emery and Uchupi (1984), Ewing and Rabinowitz (1984), Mountain and Tucholke (1985), Schlee and Hinz (1987), and McMaster and others (1989). The general stratigraphic relations and depositional characteristics of the mapped alloformations have been tabulated and discussed by Poag (1987, 1992).

A KEY ALLOSTRATIGRAPHIC STRATOTYPE: DSDP SITE 612

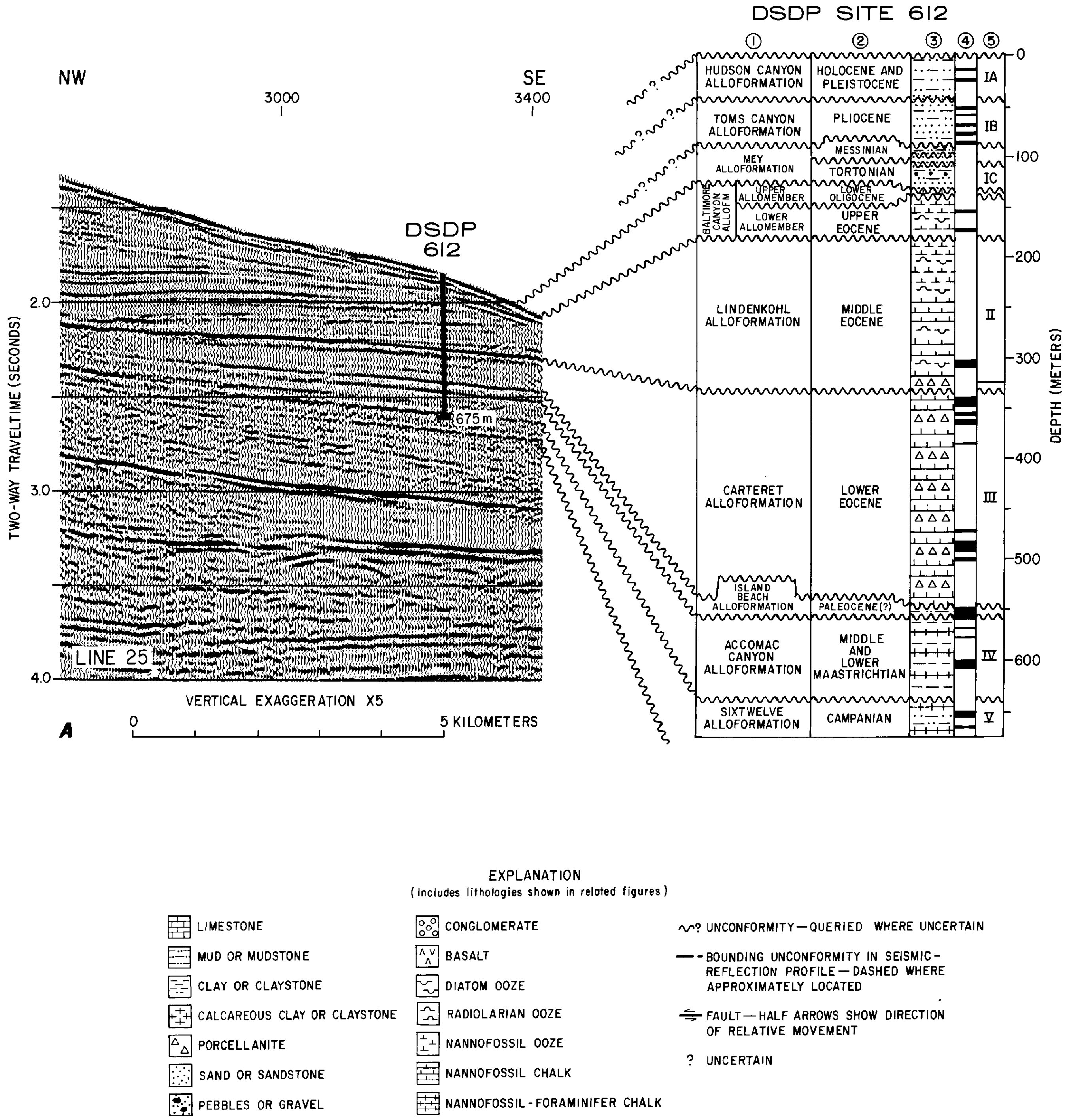
The most landward DSDP drilling on the U.S. Middle Atlantic margin was carried out on the lower continental slope at Site 612 (figs. 2–7). Its position, ~0.7 km northwest of the intersection of USGS multichannel seismic profiles 25 and 34 (figs. 3 and 4), affords an excellent correlation with most of the Upper Cretaceous and Cenozoic sedimentary sequences previously identified on the continental shelf and upper continental slope (Schlee, 1981; Poag and Schlee, 1984; Poag, 1985a, 1992; Poag, Watts, and others, 1987) and those of the continental rise (Van Hinte, Wise, and others, 1987; McMaster and others, 1989; Locker and Laine, 1992). Site 612 is located in 1,404 m of water, 5 km updip of a broad submarine outcrop of middle Eocene biosiliceous chalk and limestone (Hollister, Ewing, and others, 1972; Robb and others, 1983). The hole is the stratigraphic link between the COST B–3 well (12 km north on the upper continental slope (figs. 2–5) and Site 605 (17 km southeast on the uppermost continental rise). Hole 612 was continuously cored to 675.3 m below the sea floor and was logged; core recovery was 86 percent complete. Nine of the 12 proposed alloformations are represented in Hole 612 (figs. 4–7; see Poag, 1987, and Poag and Low, 1987, for further details of allostratigraphic units and unconformities documented at Site 612). For these reasons, we chose Site 612 as the stratotype for 6 of the 12 alloformations we propose herein (table 3).

The oldest alloformation continuously cored at DSDP Site 612 is of Campanian age and is the oldest unit we discuss. Eleven pre-Campanian allostratigraphic units

Table 1. Locations and primary references for key boreholes used in this study.

[Boreholes plotted in figures 3 and 4. ACGS–4 was named for the Atlantic County Girl Scout Council Camp 4. AMCOR, Atlantic Margin Coring Project; ASP, Atlantic Slope Project; COST, Continental Offshore Stratigraphic Test; DSDP, Deep Sea Drilling Project]

Borehole name	Latitude (N.), longitude (W.)	Location	Year drilled	Primary reference
ACGS–4 corehole	39°29′ 74°46′	Atlantic County, N.J. (fig. 3)	1984	Owens and others, 1988.
AMCOR corehole 6021	38°57.92′ 72°49.20′	Outer Continental Shelf 135 km southeast of Atlantic City, N.J. (fig. 4).	1976	Hathaway and others, 1979.
Anchor-Dickinson No. 1 well.	38°57′ 74°57′	Cape May County, N.J. (fig. 3)	1963	Poag, 1985a.
ASP borehole 14	38°48′ 72°50′	Lower continental slope 150 km southeast of Atlantic City, N.J. (fig. 4).	1967	Poag, 1985a.
ASP borehole 15	38°46′ 72°48′	Lower continental slope 150 km southeast of Atlantic City, N.J. (fig. 4).	1967	Poag, 1985a.
COST B–2 well	39°22.5′ 72°44′	Outer Continental Shelf 146 km east of Atlantic City, N.J. (fig. 3).	1976	Poag, 1985a.
COST B–3 well	38°55′ 72°46.4′	Upper continental slope 150 km southeast of Atlantic City, N.J. (figs. 3, 4).	1979	Poag, 1985a.
Dover Air Force Base well	39°7.60′ 75°28.98′	Kent County, Del. (fig. 3)	1970	Benson and others, 1985.
DSDP Site 105	34°53.72′ 69°10.40′	Lower continental rise 575 km east of Cape Hatteras, N.C. (fig. 3).	1970	Hollister, Ewing, and others, 1972.
DSDP Site 106	36°26.01′ 69°27.69′	Lower continental rise 555 km northeast of Cape Hatteras, N.C. (fig. 3).	1970	Hollister, Ewing, and others, 1972.
DSDP Site 107	38°39.59′ 72°28.52′	Upper continental rise 180 km southeast of Atlantic City, N.J. (fig. 4).	1970	Hollister, Ewing, and others, 1972.
DSDP Site 108	38°48.27′ 72°39.21′	Upper continental rise 160 km southeast of Atlantic City, N.J. (fig. 4).	1970	Hollister, Ewing, and others, 1972.
DSDP Site 603	35°29.66′ 70°01.70′	Lower continental rise 500 km east of Cape Hatteras, N.C. (fig. 3).	1983	Van Hinte, Wise, and others, 1987.
DSDP Site 604	38°42.79′ 72°32.95′	Upper continental rise 170 km southeast of Atlantic City, N.J. (fig. 4).	1983	Van Hinte, Wise, and others, 1987.
DSDP Site 605	38°44.5′ 72°36.6′	Upper continental rise 165 km southeast of Atlantic City, N.J. (fig. 4).	1983	Van Hinte, Wise, and others, 1987.
DSDP Site 612	38°49.21′ 72°46.43′	Lower continental slope 150 km southeast of Atlantic City, N.J. (fig. 4).	1983	Poag, Watts, and others, 1987.
DSDP Site 613	38°46.25′ 72°30.43′	Upper continental rise 165 km southeast of Atlantic City, N.J. (fig. 4).	1983	Poag, Watts, and others, 1987.
Exmore corehole	37°35.13′ 75°49.15′	Accomack County, Va. (fig. 3)	1986	Powars and others, 1992.
Haynesville corehole	37°57.22′ 76°40.43′	Richmond County, Va. (fig. 3)	1985	Mixon, 1989.
Island Beach No. 1 borehole.	39°48′ 74°06′	Ocean County, N.J. (fig. 3)	1962	Poag, 1985a.
Kiptopeke corehole	37°08.11′ 75°57.13′	Northampton County, Va. (fig. 3)	1989	Powars and others, 1992.
Lewes, Del., borehole	38°43.98′ 75°10.22′	Sussex County, Del. (fig. 3)	1986	Benson, 1990a.
Newport News, Va., corehole.	37°12.22′ 76°34.23′	York County, Va. (fig. 3)	1990	Poag, unpub. data, 1993.
Ohio Oil-Hammond No. 1 well.	38°18.75′ 75°29.50′	Wicomico County, Md. (fig. 3)	1944	Anderson and others, 1948.
Shell 272–1 well	38°42.10′ 73°32.50′	Middle continental shelf 120 km southeast of Atlantic City, N.J. (fig. 3).	1978	Poag, 1985a.


DSDP SITE 612
① ② ③ ④ ⑤
NW
SE
3000
3400
DSDP 612
675 m
LINE 25
TWO-WAY TRAVELTIME (SECONDS)
2.0
3.0
4.0
VERTICAL EXAGGERATION X5
A
0
5 KILOMETERS
HUDSON CANYON ALLOFORMATION
HOLOCENE AND PLEISTOCENE
TOMS CANYON ALLOFORMATION
PLIOCENE
MEY ALLOFORMATION
MESSINIAN
TORTONIAN
BALTIMORE CANYON ALLOFM
UPPER ALLOMEMBER
LOWER OLIGOCENE
LOWER ALLOMEMBER
UPPER EOCENE
LINDENKOHL ALLOFORMATION
MIDDLE EOCENE
CARTERET ALLOFORMATION
LOWER EOCENE
ISLAND BEACH ALLOFORMATION
PALEOCENE(?)
ACCOMAC CANYON ALLOFORMATION
MIDDLE AND LOWER MAASTRICHTIAN
SIXTWELVE ALLOFORMATION
CAMPANIAN
IA
IB
IC
II
III
IV
V
0
100
200
300
400
500
600
DEPTH (METERS)
EXPLANATION
(Includes lithologies shown in related figures)
LIMESTONE
MUD OR MUDSTONE
CLAY OR CLAYSTONE
CALCAREOUS CLAY OR CLAYSTONE
PORCELLANITE
SAND OR SANDSTONE
PEBBLES OR GRAVEL
CONGLOMERATE
BASALT
DIATOM OOZE
RADIOLARIAN OOZE
NANNOFOSSIL OOZE
NANNOFOSSIL CHALK
NANNOFOSSIL-FORAMINIFER CHALK
UNCONFORMITY—QUERIED WHERE UNCERTAIN
BOUNDING UNCONFORMITY IN SEISMIC-REFLECTION PROFILE—DASHED WHERE APPROXIMATELY LOCATED
FAULT—HALF ARROWS SHOW DIRECTION OF RELATIVE MOVEMENT
? UNCERTAIN

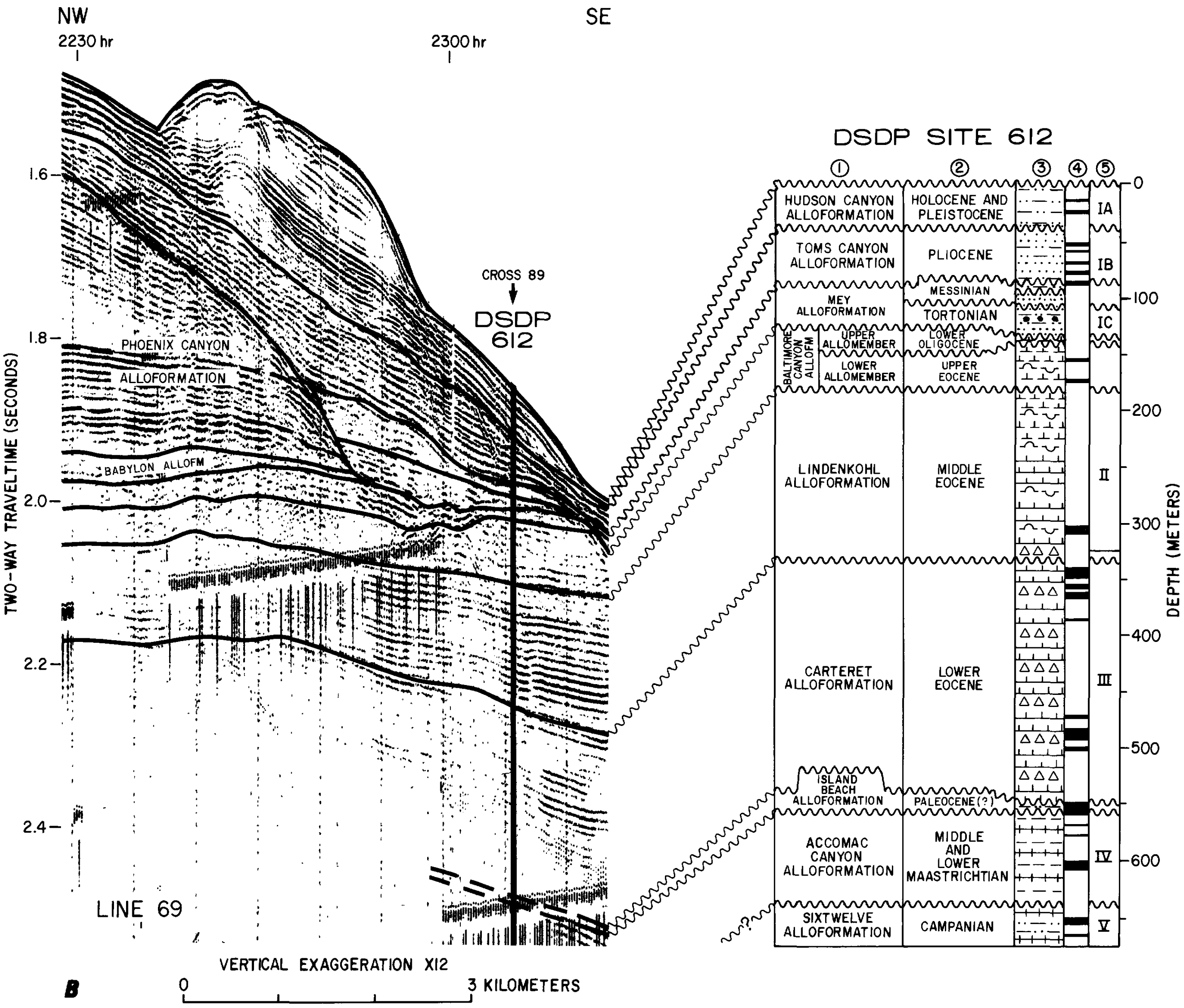


Figure 6. Stratigraphic section at DSDP Site 612 and extrapolation along seismic-reflection profiles 25 and 69 (see fig. 4 for profile locations). Site 612, located on profile 69, but 0.2 km northeast of profile 25, is stratotype for Sixtwelve, Accomac Canyon, Carteret, Lindenkohl, Baltimore Canyon (lower and upper allomembers), and Toms Canyon Alloformations. Column 1 shows allostratigraphic nomenclature proposed herein; column 2 indicates chronostratigraphic position of strata; column 3 shows simplified lithology; column 4 shows position of coring gaps (black rectangles); column 5 shows numbered lithologic units used by Poag, Watts, and others (1987). Intersecting seismic profiles are indicated by arrows (for example, Cross 89). *A*, Dip segment of multichannel seismic-reflection profile 25. Profile 25 is typical profile for Sixtwelve, Accomac Canyon, and Island Beach Alloformations; that is, it shows typical seismic expression of these alloformations. Shotpoints along top of profile provide correlation with navigation tracklines. *B*, Dip segment of single-channel seismic-reflection profile 69, which is typical profile for the Carteret, Lindenkohl, Baltimore Canyon, and Toms Canyon Alloformations. Hour designations along top of profile (for example, 2230 hr) provide correlation with navigation tracklines. Note that Phoenix Canyon Alloformation thickens dramatically to northwest but has been truncated by erosion before reaching Site 612. A thin section of Babylon Alloformation is also truncated by local channel just updip from Site 612.

Table 2. Primary references for seismic-survey tracklines and seismic-reflection profiles used in this study.

[Seismic-reflection profiles: Mcs, multichannel; Scs, single channel. USGS, U.S. Geological Survey]

Trackline and profile no. (this report)	Figure (this report)	Type of profile	Trackline and profile no. (primary reference)	Primary reference	Collected by
68, 69, 75, 77, 89, 100, 101, 102, 105, 170, 171, 172, 173, 176, 178, 183	4	Scs	Same numbers	Robb and others, 1981; Poag and Mountain, 1987.	USGS.
2, 3, 5, 6, 8b, 8c, 9, 10, 11, 12, 13, 14, 15, 16, 17, 21, 22, 23, 24, 25,* 26, 27, 28, 29, 30, 34,* 35,* 36, 37	3	Mcs	Same numbers prefaced by USGS.	Sheridan and others, 1988, and references therein.	USGS.
201, 202, 203, 204, 205, 206, 207, 214, 215, 216, 217, 218,* 219,* 220, 221	3	Mcs	Same numbers prefaced by 79–.	Poag and Mountain, 1987.	USGS and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).
70, 71, 72, 73, 74, 75, 76, 77	3	Mcs	Same numbers prefaced by *Conrad* 21–.	Poag and Mountain, 1987.	Lamont-Doherty Geological Observatory.
1, 2, 3, 4, 5, 6, 7, 31, 32, 33, 34, 35, 36	3†	Mcs	Same numbers prefaced by *Knorr* 80–.	Poag and Mountain, 1987.	Woods Hole Oceanographic Institution.
CP3–B	4	Scs	CP3–B	Poag and Mountain, 1987.	Deep Sea Drilling Project, Leg 95.

* Trackline also shown on figure 4.

† Trackline numbers on figure 3 are prefixed by Knorr 80; tracklines are shown in lower right corner.

Table 3. Stratotypes and typical profiles of the 12 alloformations proposed in this report.

[Stratotypes are plotted in figures 3 and 4. DSDP, Deep Sea Drilling Project; COST, Continental Offshore Stratigraphic Test]

Alloformation	Age	Stratotype	Typical profile
Hudson Canyon	Quaternary	DSDP Site 613	105 (fig. 28).
Toms Canyon	Pliocene (Tabianian and Piacenzian)	DSDP Site 612	69 (fig. 6*B*).
Mey	Late Miocene (Tortonian and Messinian)	DSDP Site 603	*Conrad* 21, segment 77 (fig. 15).
Phoenix Canyon	Middle Miocene (Langhian and Serravalian)	DSDP Site 603	*Conrad* 21, segment 77 (fig. 15).
Berkeley	Early Miocene (Aquitanian and Burdigalian)	COST B–3 well	218 (fig. 8).
Babylon	Late Oligocene (Chattian)	COST B–3 well	218 (fig. 8).
Baltimore Canyon	Late Eocene (Priabonian) and late early Oligocene (Rupelian).	DSDP Site 612	69 (fig. 6*B*).
Lindenkohl	Middle Eocene (Lutetian and Bartonian)	DSDP Site 612	69 (fig. 6*B*).
Carteret	Early Eocene (Ypresian)	DSDP Site 612	69 (fig. 6*B*).
Island Beach	Paleocene (Danian and Thanetian)	DSDP Site 605	25 (fig. 6*A*).
Accomac Canyon	Late Cretaceous (Maastrichtian)	DSDP Site 612	25 (fig. 6*A*).
Sixtwelve	Late Cretaceous (Campanian)	DSDP Site 612	25 (fig. 6*A*).

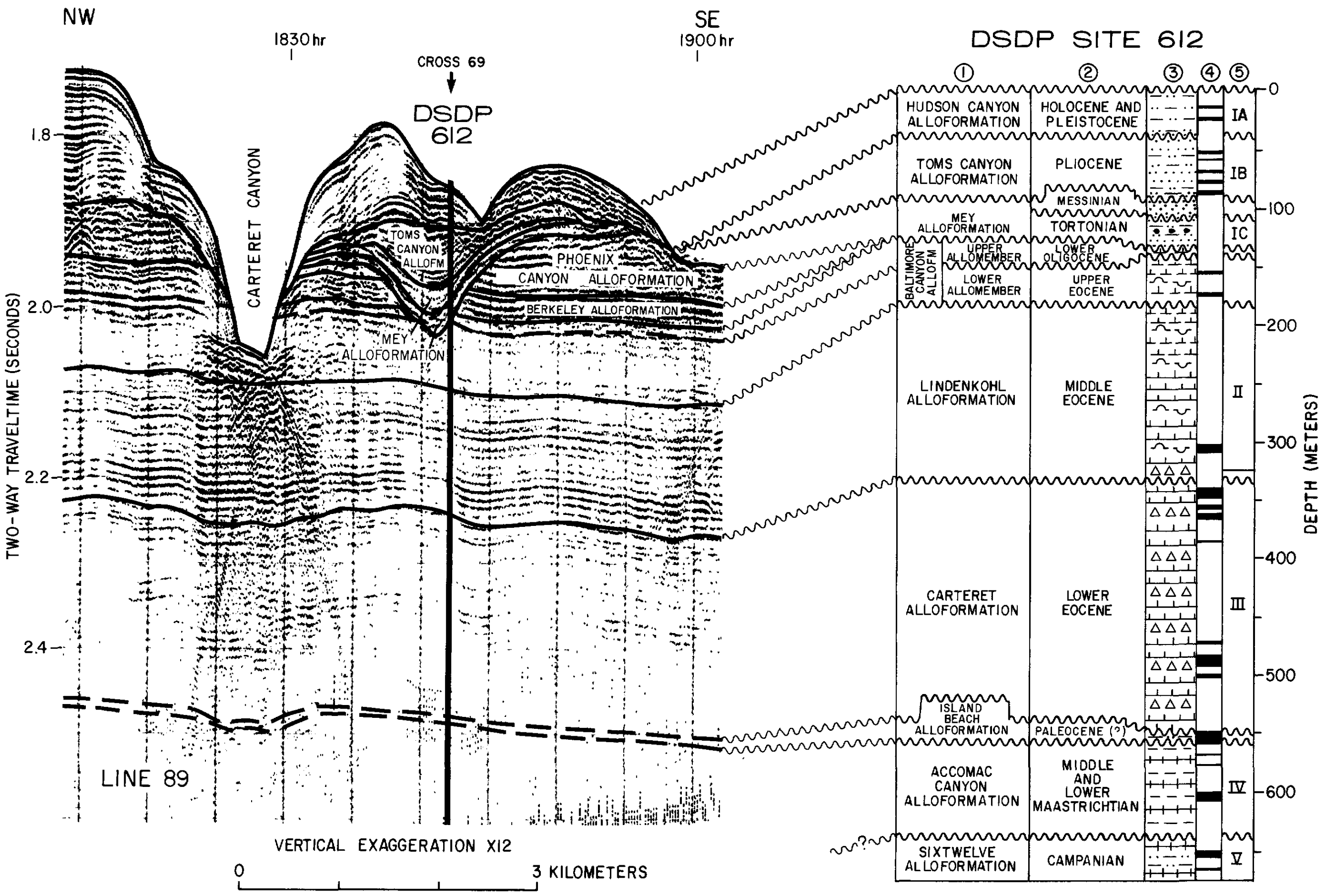


Figure 7. Stratigraphic section at DSDP Site 612 and extrapolation along strike segment of single-channel seismic-reflection profile 89 (see fig. 4 for profile location). Note local erosional channel penetrated by Hole 612. As a result, Babylon, Berkeley, and Phoenix Canyon Alloformations are missing at corehole. Baltimore Canyon Alloformation appears to crop out in walls of Carteret Canyon. See figure 6 for explanation of geology, profile reference points, and columns 1–5.

(eight drilled at Sites 603 and 105) have been discussed by Poag (1987, 1991, 1992), but data are presently inadequate to formalize an allostratigraphic nomenclature for them.

SIXTWELVE ALLOFORMATION

DEFINITION

We propose the name Sixtwelve Alloformation (figs. 5–7) for unconformity-bounded, outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), the submerged continental shelf and slope (Baltimore Canyon trough), and the continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Campanian (Upper Cretaceous strata) in this region. The Sixtwelve Alloformation is named after its stratotype, DSDP Site 612, on the lower continental slope, 150 km southeast of Atlantic City, N.J., at lat 38°49.21′ N., long 72°46.43′ W. (figs. 3 and 4). At the stratotype, the alloformation is approximately 200 m thick and consists of gray to black chalk and mudstone (figs. 6 and 7).

BOUNDING UNCONFORMITIES

The lower bounding unconformity has not yet been cored offshore, but it was drilled at the COST B–3 site, and its seismic expression can be seen on USGS multichannel seismic-reflection profile 25, which passes 0.2 km southwest of the stratotype (fig. 6*A*). This unconformity is also expressed on profile 218 (fig. 8), which passes ~10 km north of the stratotype and through the COST B–3 site (fig. 4). On profiles 25 and 218, the unconformity truncates reflections within the underlying Santonian depositional unit; reflections in the lower part of the Sixtwelve Alloformation onlap the lower unconformity. The lower unconformity can be traced widely in the northern part of the

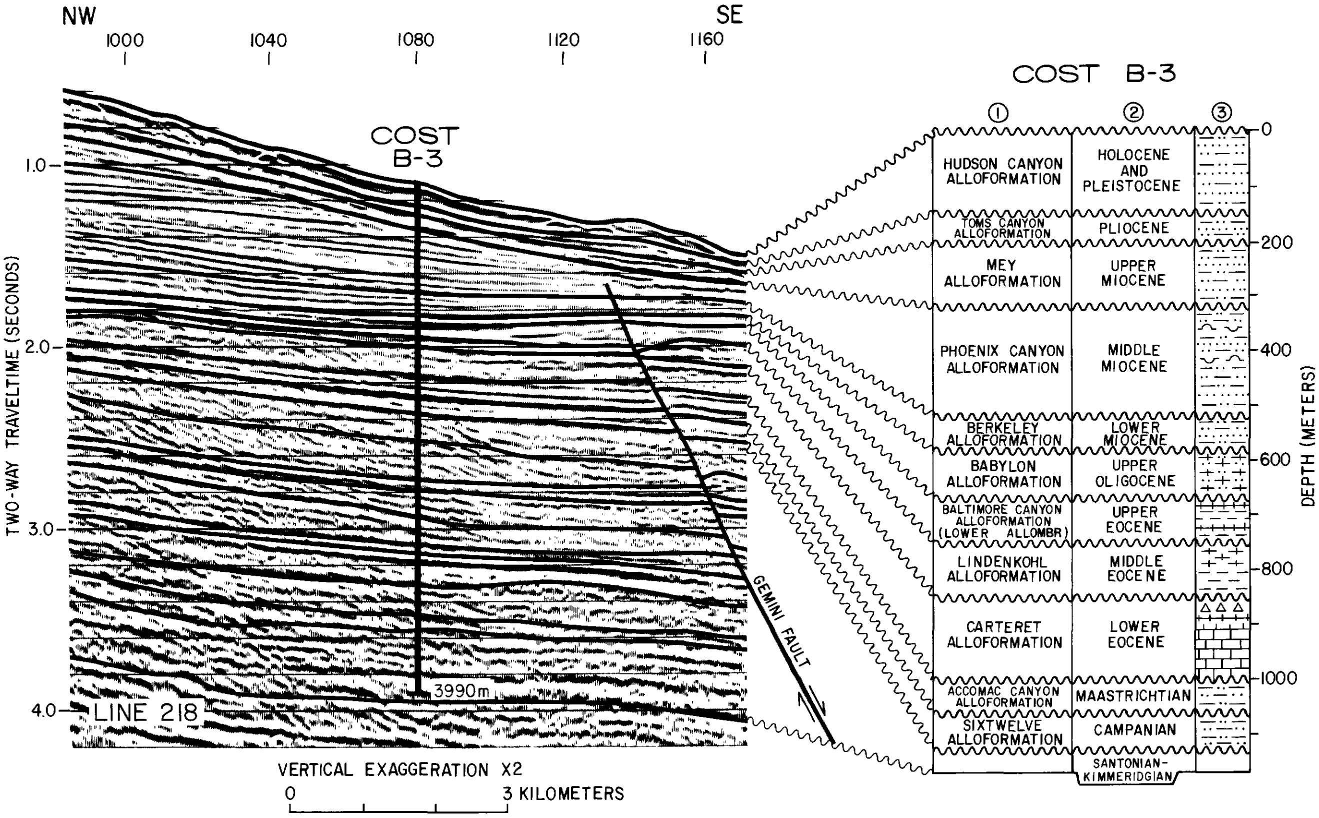


Figure 8. Stratigraphic section at COST B–3 well and extrapolation along a dip segment of multichannel seismic-reflection profile 218 (see fig. 4 for profile location). COST B–3 well is stratotype for Babylon and Berkeley Alloformations; profile 218 is typical profile for these units. Stratigraphic column derived principally from analysis of rotary cuttings; only a few scattered cores were taken (see Scholle, 1980). Shotpoints indicated at top of profile. See figure 6 for explanation of geology, profile reference points, and columns 1–3.

Hatteras basin and the Baltimore Canyon trough, including parts of the Salisbury embayment, where it generally is above Upper Cretaceous beds of the Santonian Stage.

The upper bounding unconformity of the Sixtwelve Alloformation (figs. 6*A* and 9) has been cored at the stratotype, 639.6 m below the sea floor (8 cm below the top of section 3, core 69 (fig. 6*A*; see Poag and Low, 1987). The unconformity appears as a concave scour surface that separates Campanian dark-gray to black, fissile, finely glauconitic, pyritic, laminated mudstone and chalk (below) from Maastrichtian light-gray, coarsely glauconitic, pyritic, marly, foraminifer- and nannofossil-bearing chalk (above). Horizontal burrows filled with light-gray Maastrichtian sediment extend as deep as 10 cm below the unconformity. The upper unconformity can be traced widely in the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, where it is generally overlain by strata of Maastrichtian, Paleocene, or Eocene age.

On seismic-reflection profiles, the bounding unconformities of the Sixtwelve Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections at the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Sixtwelve Alloformation extends in the subsurface from DSDP Site 603, on the lower continental rise, to ~50 km landward of the Dover Air Force Base well, ~700 km updip in the Salisbury embayment (fig. 10; Benson and others, 1985). Along depositional strike, it extends ~750 km from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras). The alloformation is generally thinner than 100 m in the Salisbury embayment and in the southern part of the Baltimore Canyon trough; it thickens gradually seaward to about 350 m at the Campanian shelf edge off Delaware. Its thickness on the shelf is maximum (~500 m) in a small shelf-edge delta southeast of Cape Cod. The main depocenters, however, occupy the upper continental rise and slope aprons along the base of the Long Island platform, which contain gravity-flow deposits as thick as 1,200 m (Poag and Sevon, 1989; Poag, 1992).

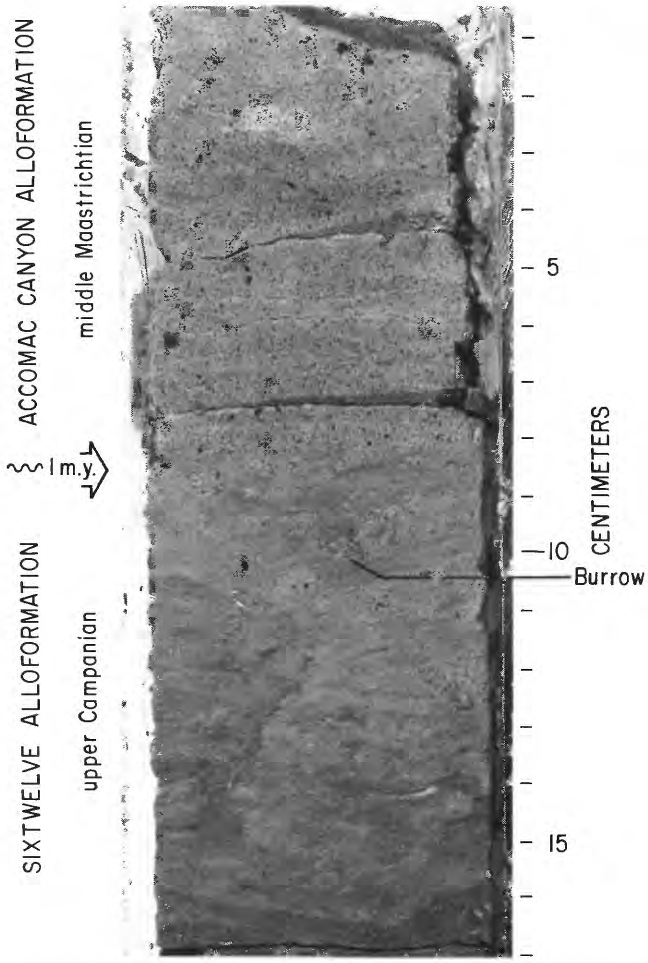


Figure 9. Unconformity separating Sixtwelve Alloformation from Accomac Canyon Alloformation at DSDP Site 612. Unconformity is 639.6 m below sea floor and is 8 cm below top of section 3, core 69 (Poag and Low, 1987). Hiatus is approximately 1 m.y.

Several large submarine fans contain as much as 250 m of deep-sea sediments on the lower continental rise.

In the outer part of the Baltimore Canyon trough and in the Hatteras basin, the Sixtwelve Alloformation is equivalent to the lower part of seismic unit D_1 of Schlee and others (1985); the lower part of seismic unit C of Schlee and Hinz (1987), and the Maastrichtian seismic unit of Mountain and Tucholke (1985) (fig. 11). The Sixtwelve Alloformation thins to less than 100 m in the deepest parts of the Hatteras basin, where it is equivalent to the lower part of the deep-sea Plantagenet Formation (fig. 11).

In the coastal plain of New Jersey, Delaware, and Maryland, the Sixtwelve Alloformation encompasses the Merchantville Formation, Woodbury Clay, Englishtown Formation, Matawan Group, Marshalltown Formation, Wenonah Formation, and Mount Laurel Sand, all of which can be seen at numerous outcropping sections in those States. The lower bounding unconformity of this alloformation (separating the Merchantville Formation (Campanian) from the underlying Magothy Formation (Santonian)) can be seen at Cliffwood Beach on Raritan Bay, N.J. (fig. 10), as described by Owens and others (1977, p. 98). We have selected this section as the onshore supplementary reference section for the lower part of the Sixtwelve Alloformation and its lower bounding unconformity (fig. 12).

The other lithostratigraphic units encompassed by the Sixtwelve Alloformation can be seen in a series of outcrops also described by Owens and others (1977), but no single exposure exhibits all of the included formations. We have selected the relatively complete section at Elk Neck State Park, Md. (fig. 10; Owens and others, 1977, p. 109), as the onshore supplementary reference section for the nearly complete Sixtwelve Alloformation (fig. 13). At this exposure, the Campanian Merchantville Formation overlies deltaic deposits of the Santonian Potomac Group and is overlain, in turn, by the Englishtown Formation, Marshalltown Formation, and Mount Laurel Sand.

The upper bounding unconformity of the Sixtwelve Alloformation can be seen at Irish Hill, near Runnemede, Camden County, N.J. (figs. 10 and 14), another of the exposures described by Owens and others (1977, p. 107). At Irish Hill, the upper bounding unconformity separates the Campanian Mount Laurel Sand from the Maastrichtian Navesink Formation (which constitutes the lower part of the Accomac Canyon Alloformation, as defined herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

Relatively thin strata (<100 m) of the Sixtwelve Alloformation on the coastal plain of New Jersey, Delaware, and Maryland thicken seaward and to the northeast across the broad (~250-km-wide), gently sloping, Campanian shelf. The alloformation reaches ~500 m thickness on the outer shelf southeast of Cape Cod and >1,200 m in the slope apron south of New England (fig. 10; see Poag and Sevon, 1989; Poag, 1992). The buried Campanian shelf break is almost directly beneath the Holocene shelf break and is associated along the Middle Atlantic States with a pair of parallel regional growth faults, the Gemini fault system of Poag (1987; fig. 2), which rims the outer margin of the Baltimore Canyon trough (fig. 1). On the inner part of the Campanian shelf, at the Island Beach No. 1 borehole (fig. 10; Poag, 1985a), a 165-m section of the Sixtwelve Alloformation includes dark-greenish-gray to black, calcareous, fossiliferous, lignitic, pyritic, micaceous clay and silty clay of the Marshalltown Formation, which are topped by calcareous, glauconitic, clayey, quartzose sand and glauconitic clay interbeds of the Wenonah Formation and Mount Laurel Sand (Petters, 1976). Diverse and abundant microfaunas indicate deposition in middle to outer sublit-

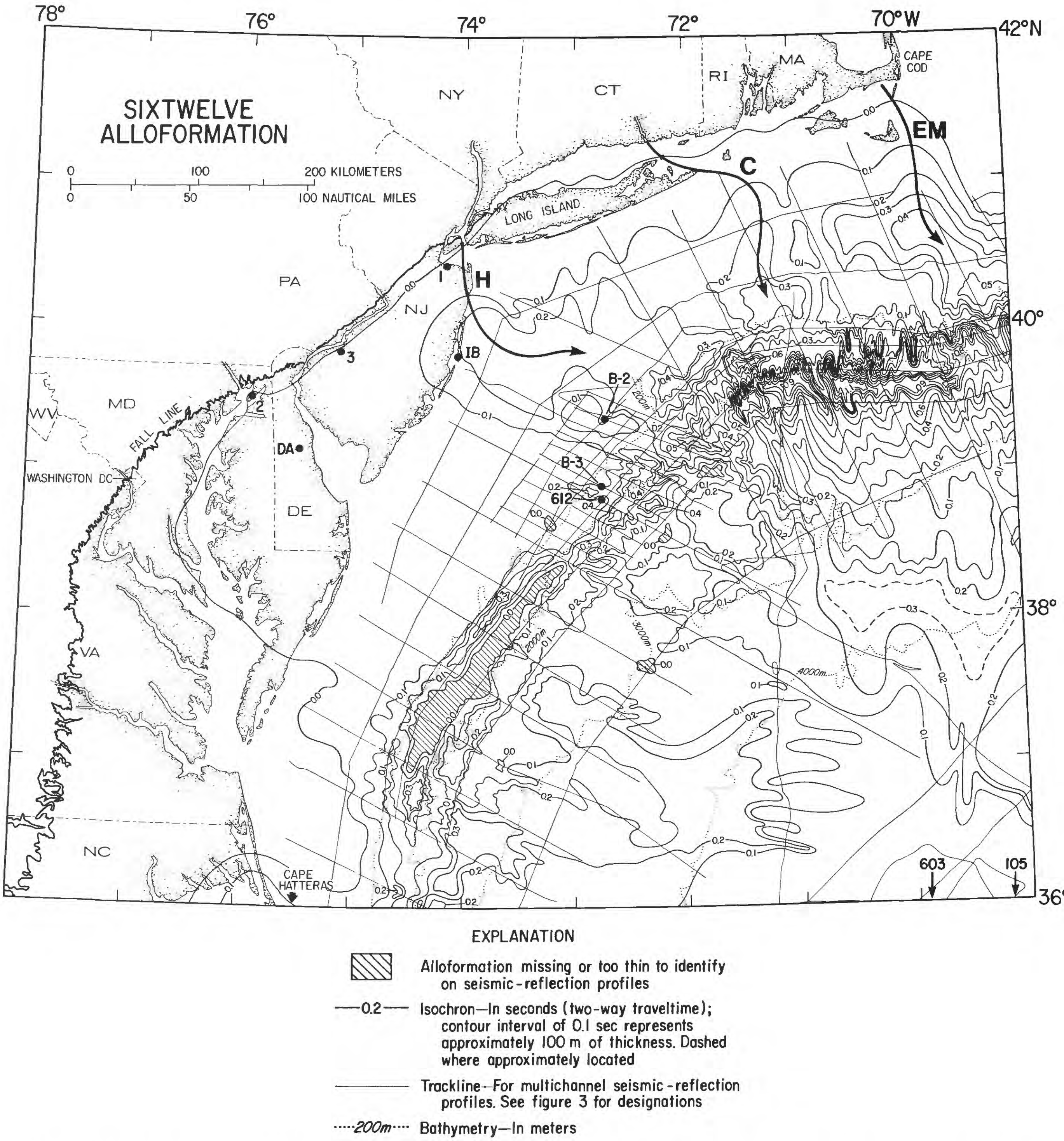


Figure 10. Isochron map of Sixtwelve Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: C, ancient Connecticut River; EM, unspecified ancient rivers in eastern Massachusetts; H, ancient Hudson River. Boreholes: DA, Dover Air Force Base well; IB, Island Beach No. 1 borehole; other labeled boreholes identified in text. Onshore reference sections: 1, Cliffwood Beach, N.J.; 2, Elk Neck State Park, Md.; 3, Irish Hill, N.J. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

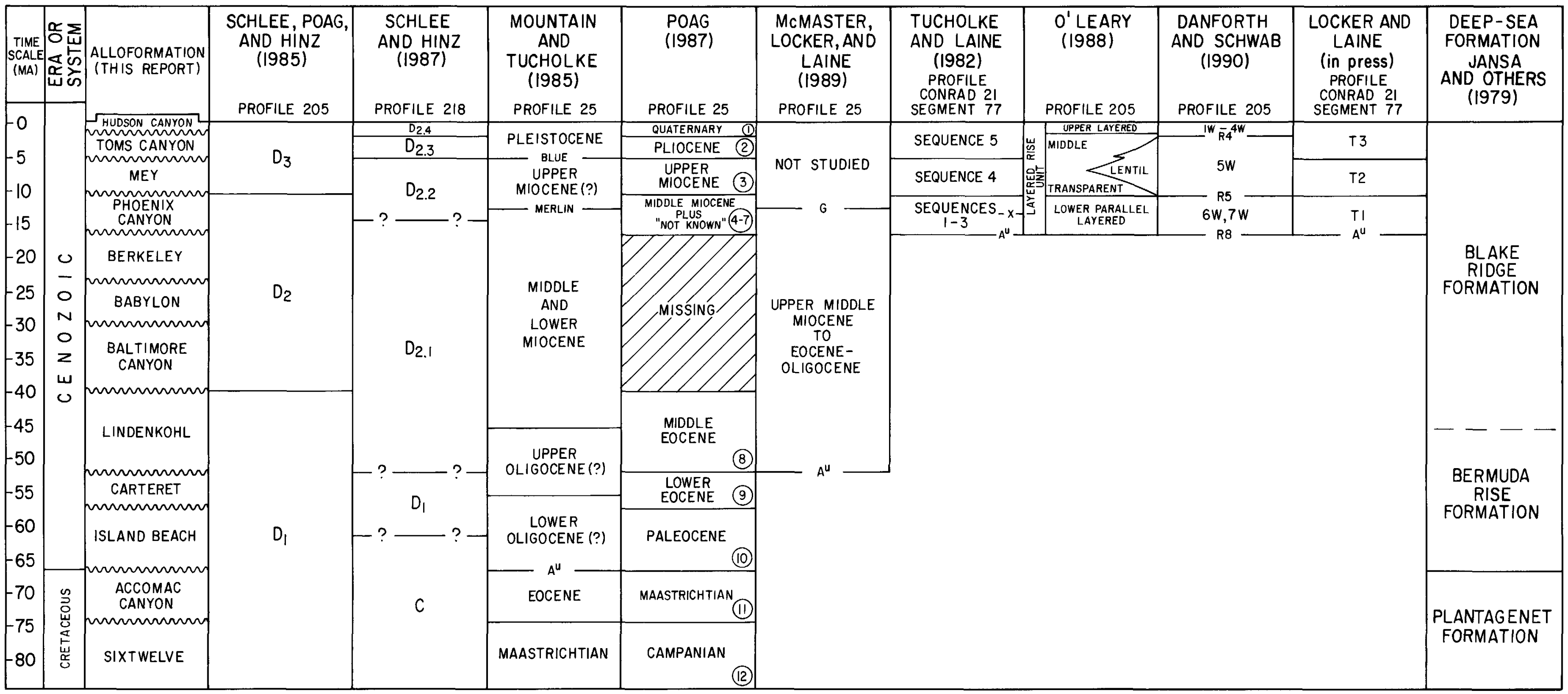


Figure 11. Correlation chart comparing stratigraphic positions of alloformations and previously published depositional units of offshore segment of U.S. Middle Atlantic margin. Profile numbers on column headings (for example, "Profile 205") indicate profiles on which Poag (1992) directly compared positions of cited authors' seismic boundaries with Poag's allostratigraphic boundaries. Dashed lines are approximate; queried lines are uncertain. A^u, G, X, Blue, and Merlin are seismic-reflection boundaries used for regional correlation. R4, R5, and R8 are local seismic unconformities. Circled numerals in column for Poag (1987) indicate depositional-unit designations.

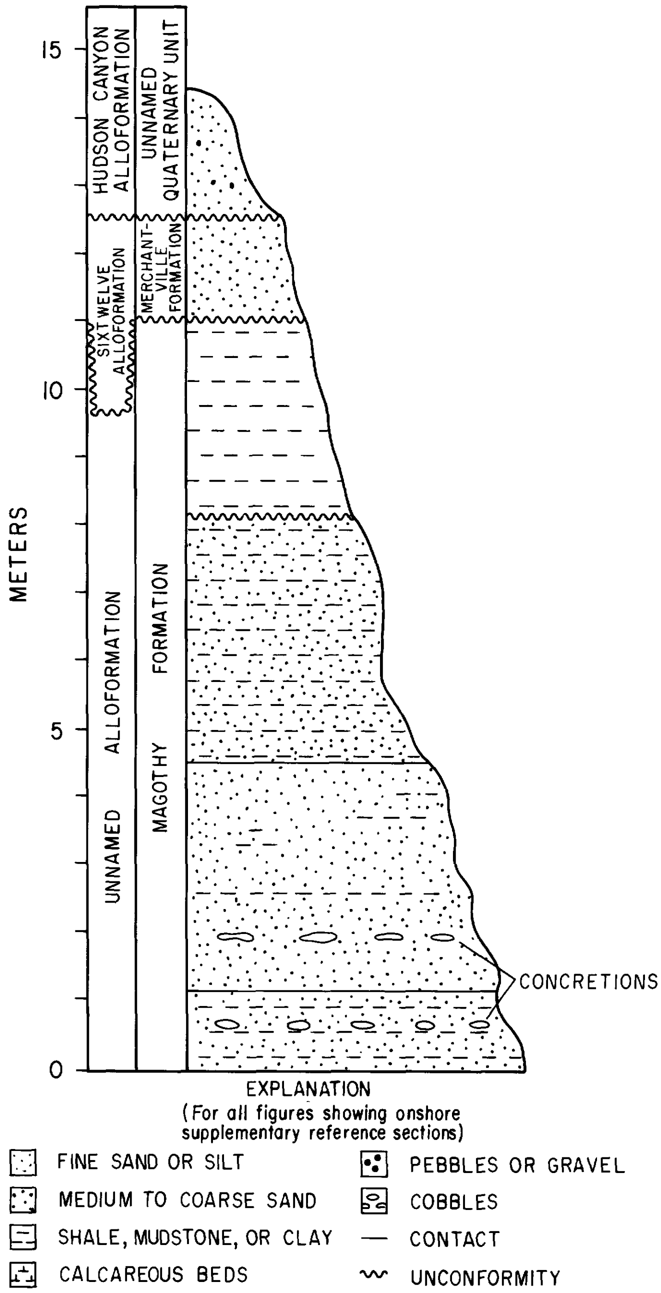


Figure 12. Onshore supplementary reference section for lower part of Sixtwelve Alloformation and its lower bounding unconformity exposed at Cliffwood Beach, N.J. (modified from Owens and others, 1977, fig. 88). Subdivisions within Magothy Formation are shown lithologically but are not labeled because they are not the focus of this report. See figure 10 for location.

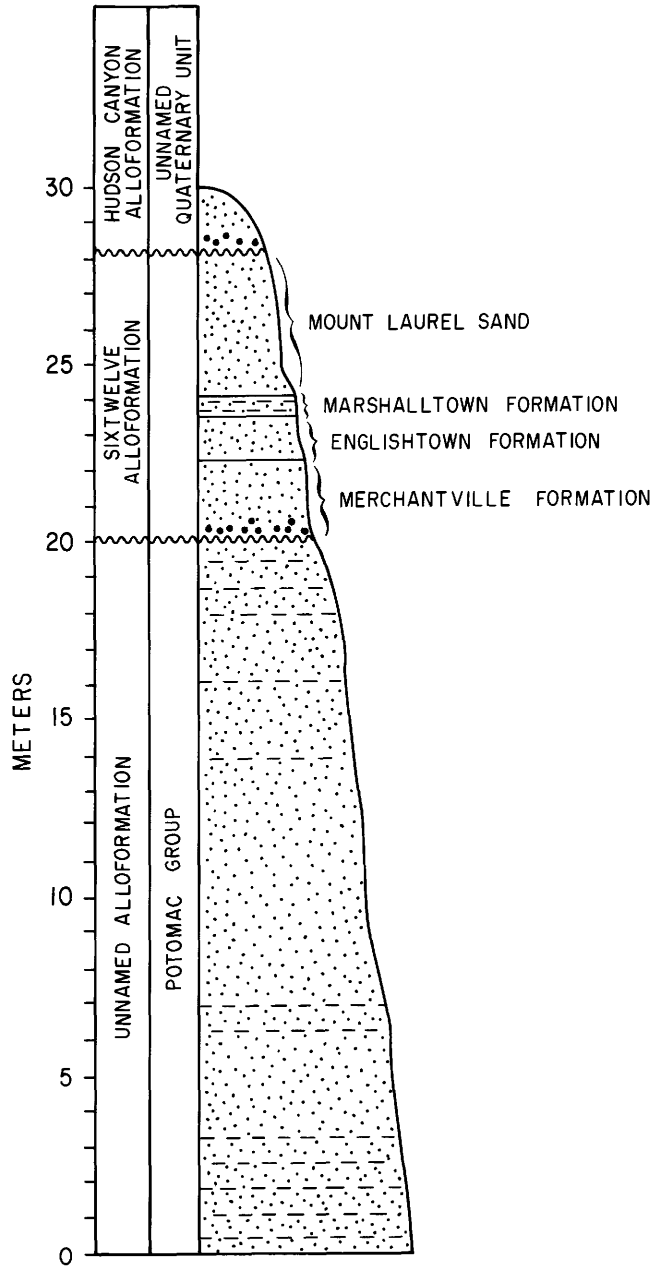


Figure 13. Onshore supplementary reference section for nearly complete exposure of Sixtwelve Alloformation at Elk Neck State Park, Md. (modified from Owens and others, 1977, fig. 95). See figure 10 for location and figure 12 for lithologic explanation.

toral environments (100–200 m). If the paleoslope was uniform, then the Campanian shoreline was at least 50 km west of the present New Jersey outcrop, which contains microfaunas of 50–100 m paleodepth (Nyong and Olsson, 1984; Olsson and Nyong, 1984).

On the outer shelf, the COST B–2 well (fig. 10; Poag, 1985a) penetrated 120 m of silty, calcareous sandstone and gray to black micaceous siltstone and claystone of the Sixtwelve Alloformation containing outer sublittoral to upper bathyal microfaunas (200–300 m paleodepth). The COST B–3 well, located near the Campanian shelf break, penetrated a Sixtwelve section comprising 95 m of dark-brown to gray, calcareous, silty mudstone containing rich microfaunal assemblages of upper bathyal origin (300–350 m paleodepth) (figs. 2 and 8).

The Campanian shelf break is marked by a rapid seaward thickening of the Sixtwelve section as it crosses the Gemini fault system to form a lenticular slope apron (figs.

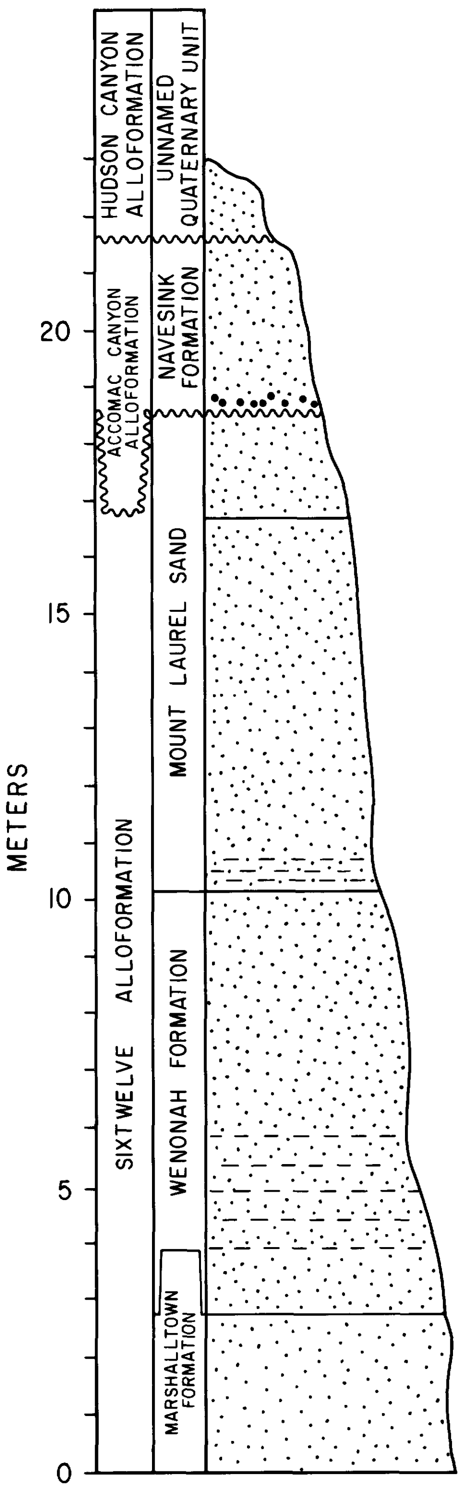


Figure 14. Onshore supplementary reference section for upper part of Sixtwelve Alloformation, lower part of Accomac Canyon Alloformation, and unconformity that separates them exposed at Irish Hill, near Runnemede, Camden County, N.J. (modified from Owens and others, 1977, fig. 93). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 10 for location and figure 12 for lithologic explanation.

2 and 10). DSDP Site 612 (figs. 6 and 7) sampled 28 m of dark-gray to black chalk, shale, and mudstone, which constitutes approximately the upper one-seventh of the Sixtwelve slope apron (total thickness there is ~200 m). The dark, pyritiferous, organic-matter-rich shales near the base of the cored Sixtwelve section are evidence that an oxygen-minimum zone may have impinged upon the sea floor between Site 612 and the COST B–3 well during the late Campanian. Enrichment of the dinoflagellate assemblage and the presence of a low-diversity assemblage of planktonic foraminifers may be further evidence of oxygen depletion (Poag, Watts, and others, 1987).

Northeast of DSDP Site 612, the Sixtwelve slope apron forms a thick, elongate, double lens characterized by chaotic and onlapping seismic reflections; its maximum thickness there is ~1,200 m (fig. 10). Superimposed on the generally longslope-trending lenticular geometry of the Sixtwelve Alloformation is a series of downslope-trending, thickened pods, which alternate across the slope with thinner intervening swaths to produce a "ribbed" downslope fabric. Profiles that parallel the depositional strike (for example, profiles 34 and 35; fig. 3) show that the ribbing is produced both by erosion of deep channels in the upper surface of the alloformation (thinning) and by filling of channels cut into the underlying alloformation (thickening; Poag, 1987). Farther into the Hatteras basin (to the southeast), where the Sixtwelve Alloformation thins to 100 m or less, the principal component of the ribbed fabric is the filling of several broad channels (as wide as 17 km; fig. 10) and one ovate depression where the alloformation is >200 m thick.

Southwest of DSDP Site 612, a different depositional pattern is seen. The Campanian shelf break is farther westward in this area, and the Sixtwelve slope apron is much thinner than that to the northeast (fig. 10). A period (or several periods) of erosion has removed a considerable amount of the Upper Cretaceous to lower Paleocene section over the crest of the buried Jurassic shelf-edge reef, producing an unconformity at which lower Eocene rocks lie directly on Santonian and older rocks. The Sixtwelve section seaward of this erosional scar, except for an elongate, >200-m-thick submarine fan, is relatively thin (~100 m). The strike profiles in this area clearly show that downslope channeling took place here as well.

Evidence of Sixtwelve strata at the seaward end of the New Jersey Transect is scanty. At DSDP Site 603 (figs. 5 and 15), an unfossiliferous series of dark, reddish-gray and brown, terrigenous, silt-rich claystone and glauconite- and mica-rich quartz sand and sandstone (Accomac Canyon Alloformation(?) as defined herein; 34 m total thickness) separates upper Paleocene radiolarian-bearing claystone (Island Beach Alloformation as defined herein) from undifferentiated Cenomanian(?) to Campanian(?) terrigenous claystones. The undifferentiated claystones might contain Sixtwelve strata. At DSDP Site 105 (fig. 16), the Sixtwelve

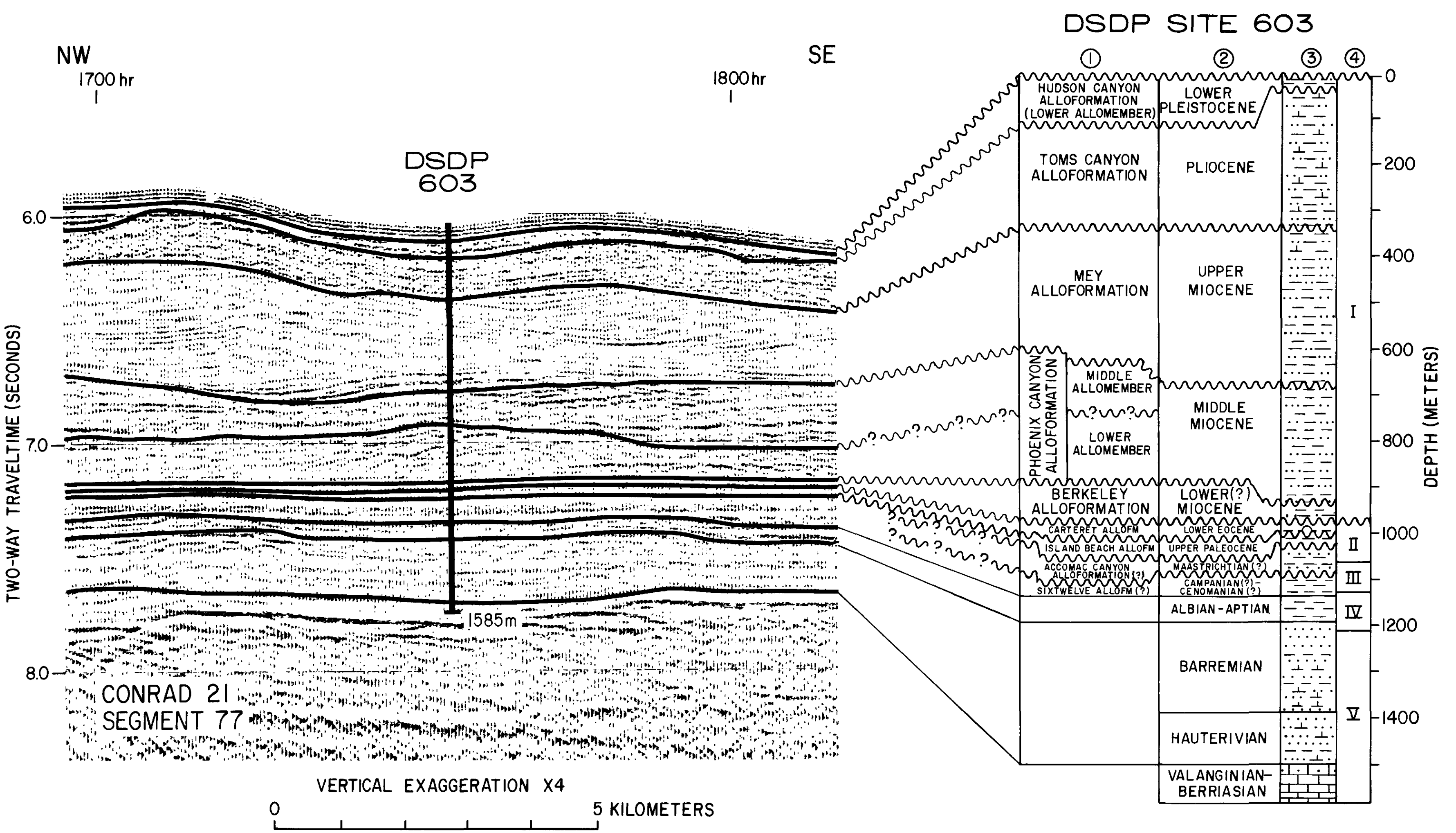


Figure 15. Stratigraphic section at DSDP Site 603 and extrapolation along dip segment 77 of multichannel seismic-reflection profile *Conrad* 21 (see fig. 3 for profile location). Site 603 is stratotype for Mey Alloformation (top in Hole 603C; base in Hole 603) and Phoenix Canyon Alloformation (top in Hole 603; base in Hole 603B); profile *Conrad* 21 (segment 77) is typical profile for both. Seven adjacent holes were drilled at this site (Holes 603, 603A, 603B, 603C, 603D, 603E, and 603F), and combined core recovery constitutes a virtually complete record of stratigraphy at this location. See figure 6 for explanation of geology, profile reference points, and columns 1–4.

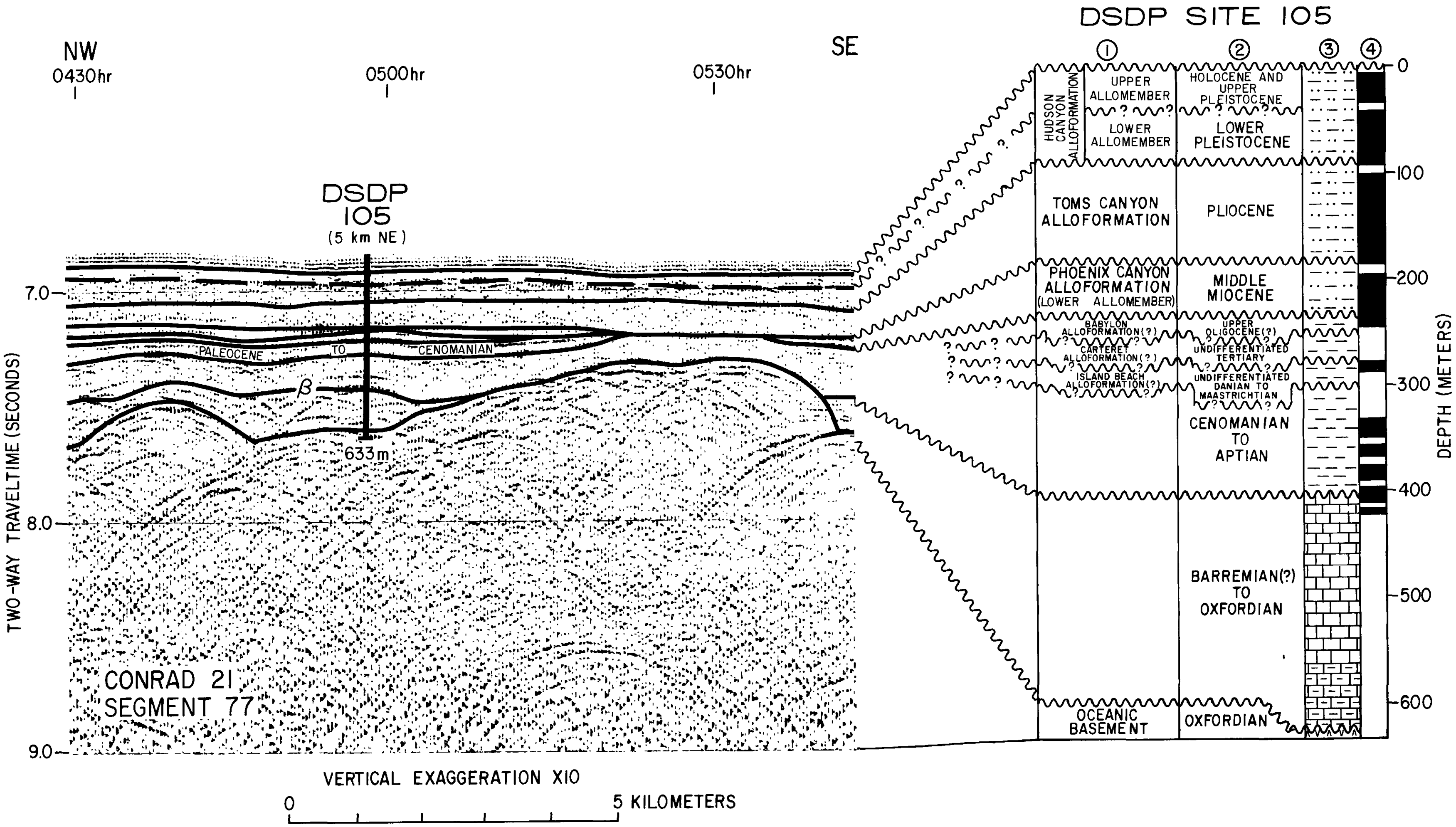


Figure 16. Stratigraphic section at DSDP Site 105 and extrapolation along dip segment 77 of multichannel seismic-reflection profile *Conrad* 21 (see fig. 3 for profile location). β, deep-sea seismic boundary (Mountain and Tucholke, 1985; Poag and Mountain, 1987). Note that core recovery is poor except in Oxfordian-Barremian(?) section. Lithologic units were not numbered by shipboard party (Hollister, Ewing, and others, 1972). See figure 6 for explanation of geology, profile reference points, and columns 1–4.

Alloformation appears to be missing. The section presumed by Tucholke (1979, fig. 1, sheet 2) to represent Campanian deposits at Site 105 (and thus part of the Sixtwelve Alloformation as defined herein) is composed of multicolored (reddish-brown, yellow, orange, olive-green, black), silty, zeolitic, noncalcareous clays (Hollister, Ewing, and others, 1972). However, during and after the original analysis (Leg 11; Hollister, Ewing, and others, 1972), dinoflagellates and ichthyoliths of late Oligocene and undifferentiated Tertiary age were found in this section (cores 105–5 to 105–7; 241–268 m below the sea floor; Kaneps and others, 1981). Below this section, an undifferentiated Maastrichtian to Danian (ichthyolith-dated) section (268–286 m below the sea floor) rests on Aptian to Cenomanian (dinoflagellate-dated) black clay (286–403 m).

On multichannel seismic profiles crossing the outer Baltimore Canyon trough and the Hatteras basin, the Sixtwelve Alloformation comprises broad zones of moderately high amplitude, parallel to subparallel, continuous reflections that are inferred to represent relatively uniform deposits. The zones are interrupted, however, at irregular intervals, by chaotic or poorly defined reflections inferred to represent sediments deposited by downslope mass movement. The latter are particularly prevalent in the slope aprons (fig. 10).

The persistence of the upper bounding unconformity of the Sixtwelve Alloformation in much of the present coastal plain and continental shelf, slope, and rise of the study area is evidence that it was caused, in large part, by a relative sea-level fall (Poag and Schlee, 1984; Poag, 1985a, 1987; Poag and Low, 1987). Olsson (1978) and Nyong and Olsson (1984) have noted that the basal part of the overlying Accomac Canyon Alloformation (Maastrichtian section; new allostratigraphic unit, herein described) beneath the New Jersey Coastal Plain was deposited during a sea-level low. Owens and Gohn (1985) have shown that regressive facies at the Sixtwelve-Accomac Canyon contact (Campanian-Maastrichtian boundary) can be traced from the Southeast Georgia embayment, located beneath the continental shelf and coastal plain of Georgia, to the Long Island platform.

ACCOMAC CANYON ALLOFORMATION

DEFINITION

We propose the name Accomac Canyon Alloformation for unconformity-bounded, outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), the submerged continental shelf and slope (Baltimore Canyon trough), and the continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Maastrichtian (Upper Cretaceous) strata in this region.

The Accomac Canyon Alloformation is named after Accomac Canyon, which incises the present continental slope and shelf edge 160 km southwest of the alloformation's stratotype, DSDP Site 612 (figs. 3, 6, and 7). At the stratotype (lat 38°49.21′ N.; long 72°46.43′ W.), the alloformation is 80.2 m thick and consists of light- and dark-gray, marly, foraminifer- and nannofossil-bearing chalk containing occasional thin layers of lithified limestone.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Accomac Canyon Alloformation has been cored at the stratotype, 639.6 m below the sea floor (8 cm below the top of section 3, core 69; figs. 6*A*, 7, and 9; see Poag and Low, 1987). The unconformity appears as a concave scour surface that separates Maastrichtian light-gray, coarsely glauconitic, pyritic, marly, foraminifer- and nannofossil-bearing chalk (above) from Campanian dark-gray to black, fissile, finely glauconitic, pyritic, laminated shale and chalk (below). Horizontal burrows filled with light-gray Maastrichtian sediment extend as deep as 10 cm below the unconformity. The lower unconformity can be traced widely in the northern part of the Hatteras basin and in the Baltimore Canyon trough, including the Salisbury embayment, where it generally is above Upper Cretaceous beds of the Sixtwelve Alloformation.

The upper bounding unconformity of the Accomac Canyon Alloformation was not cored (core was attempted, but not recovered) at the stratotype, but it was cored at DSDP Site 605, 17 km downdip from Site 612 (figs. 4 and 17). At DSDP Site 605, the unconformity is present at ~778.73 m below the sea floor, in a 30-cm-thick disturbed zone of broken core fragments, which obscures the contact (fig. 18; Poag, 1985b; Lang and Wise, 1987; Smit and Van Kempen, 1987). The unconformity separates Maastrichtian light-gray, argillaceous, foraminifer- and nannofossil-bearing limestone (below) from Paleocene light-blue-gray, slightly laminated, foraminifer-bearing mudstone (above). The upper unconformity can be traced widely in the northern part of the Hatteras basin and in the Baltimore Canyon trough, including the Salisbury embayment, and generally is overlain by strata of either Paleocene or Eocene age (fig. 6*A*).

On seismic-reflection profiles, the bounding unconformities of the Accomac Canyon Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections at the contacts (Poag and Schlee, 1984; Poag, 1985a, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

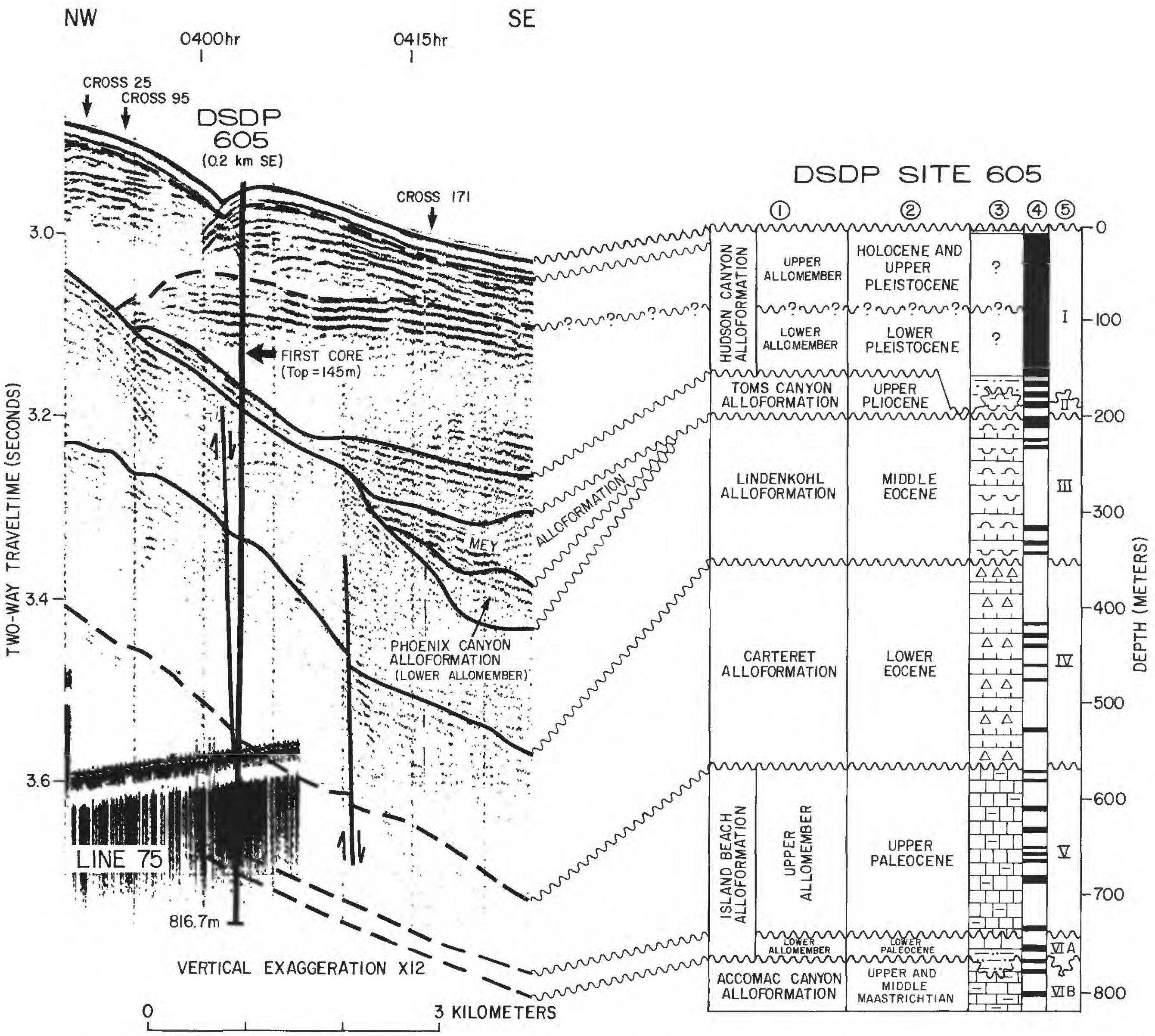


Figure 17. Stratigraphic section at DSDP Site 605 and extrapolation along dip segment of single-channel seismic-reflection profile 75 (see fig. 4 for profile location). Site 605 is stratotype for Island Beach Alloformation. Typical profile is multichannel profile 25 (fig. 6*A*), because profile 75 does not clearly define stratigraphy below 3.5 sec (two-way traveltime). See figure 6 for explanation of geology, profile reference points, and columns 1–5.

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Accomac Canyon Alloformation extends in the subsurface from DSDP Site 603 (on the lower continental rise) to ~45 km landward of the Dover Air Force Base well, ~700 km updip in the Salisbury embayment (fig. 19). Along depositional strike it extends 750 km from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras). The alloformation is generally thinner than 100 m in the Salisbury embayment and across the continental shelf of the Baltimore Canyon trough, where it appears to have been completely eroded in several broad patches. It thickens to >300 m in an outer shelf delta on the Long Island platform and to >500 m in a shelf-edge depocenter seaward of Cape Charles, Va. Thickest depocenters are located along the base of the Long Island platform, where broad channels contain gravity-flow deposits as thick as 600 m. In the outer part of the Baltimore Canyon trough and in the Hatteras basin, the Accomac Canyon Alloformation is equivalent to a lower part of seismic unit D_1 of Schlee and others (1985); the middle part of seismic unit C of Schlee and Hinz (1987); and the Eocene seismic unit of Mountain and Tucholke (1985) (fig. 11). In this part of the Hatteras

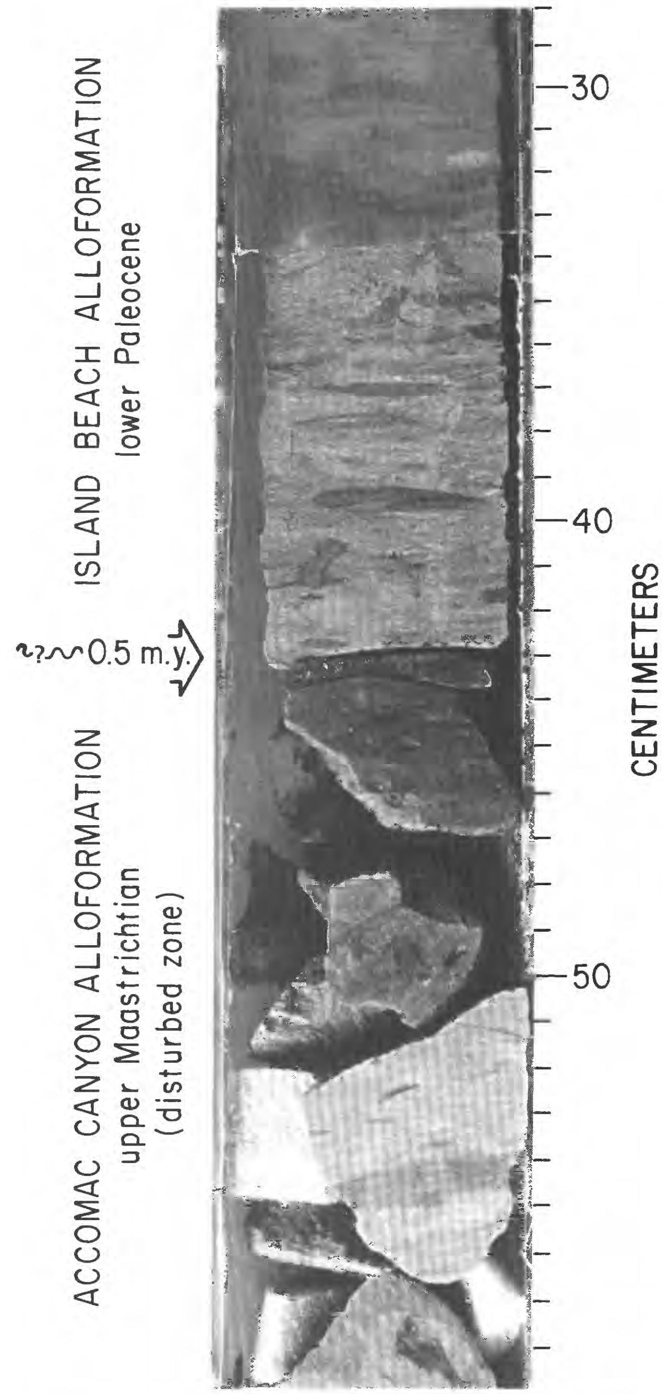


Figure 18. Unconformity separating Accomac Canyon Alloformation from Island Beach Alloformation at DSDP Site 605. Unconformity is 778.73 m below sea floor and is 43 cm below top of section 1, core 66 (Poag and Low, 1987). Hiatus is approximately 0.5 m.y.

basin, the Accomac Canyon Alloformation is equivalent to the upper part of the deep-sea Plantagenet Formation (fig. 11).

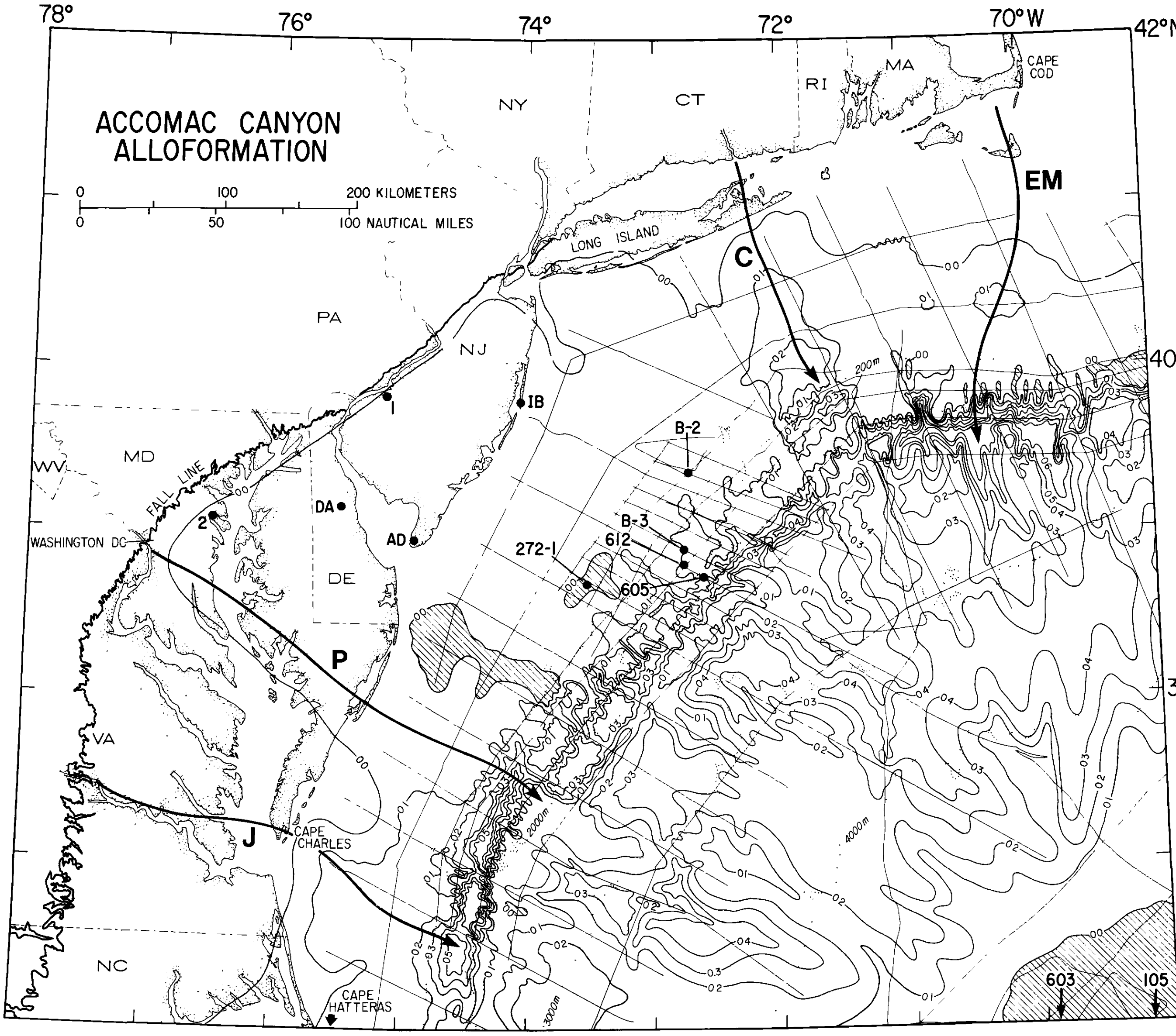
In the coastal plain of New Jersey, Delaware, and Maryland, the Accomac Canyon Alloformation encompasses the Navesink Formation, Redbank Sand, Tinton Sand, and Severn Formation, which can be seen at numerous outcropping sections in these States. No single coastal-plain exposure, however, exhibits all the lithostratigraphic units encompassed by the Accomac Canyon Alloformation. The lower bounding unconformity of the Accomac Canyon Alloformation may be seen at Irish Hill, near Runnemede, Camden County, N.J. (fig. 19), a section described by Owens and others (1977, p. 107). We have, therefore, selected the exposure at Irish Hill as the onshore supplementary reference section for the lower part of the alloformation and its lower bounding unconformity (fig. 14). At this exposure, the lower bounding unconformity separates the Campanian Mount Laurel Sand (upper part of Sixtwelve Alloformation) from the Maastrichtian Navesink Formation (lower part of Accomac Canyon Alloformation).

The upper bounding unconformity (as well as the lower) of the Accomac Canyon Alloformation is exposed at Round Bay, on the Severn River, near Annapolis, Md. (fig. 19; Owens and others, 1977, p. 113). Thus, we have selected the Round Bay exposure as the supplementary reference section for the upper part of the Accomac Canyon Alloformation and its upper bounding unconformity (fig. 20). At Round Bay, the upper bounding unconformity separates the Maastrichtian Severn Formation (Accomac Canyon Alloformation) from the Paleocene Brightseat Formation (lower part of the Island Beach Alloformation, as defined herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The distribution and depositional fabric of the Accomac Canyon Alloformation are similar to those of the Sixtwelve Alloformation, but the Accomac Canyon section is thicker throughout most of the northern Hatteras basin (fig. 19; see Poag and Sevon, 1989; Poag, 1992). A broad Maastrichtian shelf, like that of the Campanian, was covered by a thin blanket of contemporaneous sediments (generally <100 m thick), but, in several broad patches, Accomac Canyon strata appear to be entirely missing due to subsequent erosion. The Maastrichtian shelf break had prograded southeastward about 10 km (along profile 25) relative to the Campanian shelf break (fig. 2).

The ribbed (cut-and-fill) downslope fabric characteristic of the Sixtwelve Alloformation is also widely distributed within the Accomac Canyon slope aprons (fig. 19). This fabric is evidence of the continued dominance of downslope mass sediment dispersal. Even as far as 100 km downdip from Site 612, the middle-rise deposits are marked by broad (20-km-wide) southeast-trending erosional swaths and intervening linear thickenings (Poag, 1987). The persistence of terrigenous components at DSDP Sites 603 (fig.



EXPLANATION

Alloformation missing or too thin to identify on seismic-reflection profiles

—0.2— Isochron—In seconds (two-way traveltime); contour interval of 0.1 sec represents approximately 100 m of thickness. Dashed where approximately located

——— Trackline—For multichannel seismic-reflection profiles. See figure 3 for designations

·····200m····· Bathymetry—In meters

Figure 19. Isochron map of Accomac Canyon Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: C, ancient Connecticut River; EM, unspecified ancient rivers in eastern Massachusetts; J, ancient James River; P, ancient Potomac River. Boreholes: AD, Anchor-Dickinson No. 1 well; DA, Dover Air Force Base well; IB, Island Beach No. 1 borehole; other labeled boreholes identified in text. Onshore reference sections: 1, Irish Hill, N.J.; 2, Round Bay, Md. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

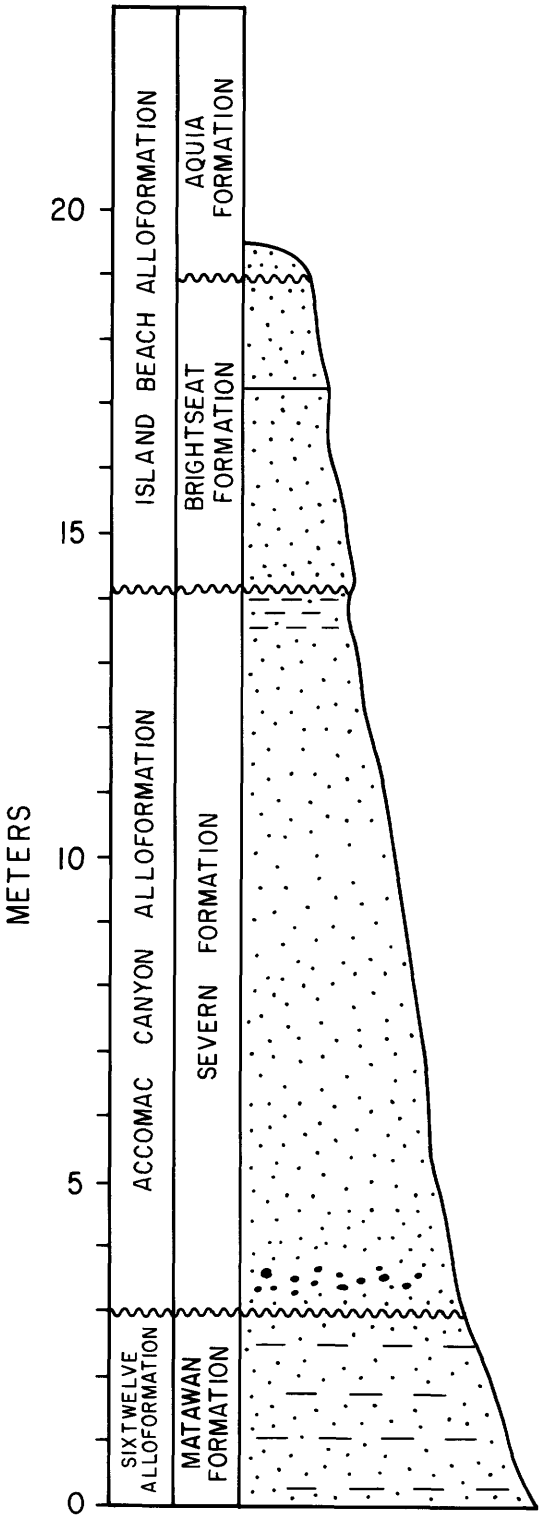


Figure 20. Onshore supplementary reference section for upper part of Accomac Canyon Alloformation, lower part of Island Beach Alloformation, and unconformity that separates them, exposed at Round Bay, on Severn River, near Annapolis, Md. (modified from Owens and others, 1977, fig. 100). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 19 for location.

15) and 105 (fig. 16) attests to continued long-distance (~500 km) dispersal of sediment from the continental shelf.

The erosional unconformity bounding the top of the Accomac Canyon Alloformation has been sampled widely from coastal-plain outcrops to the deep sea and can be traced on seismic profiles throughout the study area. There is a consensus (Owens and Gohn, 1985) that on the coastal plain an unconformity separates the Accomac Canyon (Maastrichtian) and Island Beach (Danian) Alloformations, although parts of the uppermost Maastrichtian planktonic foraminiferal zone have been reported at scattered localities (Olsson, 1964; Koch and Olsson, 1977; Hazel and Brouwers, 1982). Only lower Accomac Canyon strata are present in the Anchor-Dickinson, Island Beach, and COST B–2 and B–3 wells (Poag, 1985a), and the entire Accomac Canyon (Maastrichtian) section is missing at the Shell 272–1 well (fig. 19; Poag, 1987). Early and middle Maastrichtian microfaunas were recovered in the Accomac Canyon section at DSDP Site 612 (figs. 6 and 7). At DSDP Site 605 (fig. 17), the Accomac Canyon Alloformation contains a nearly complete Maastrichtian succession, but the incomplete nannoplankton and planktonic foraminifer biozonations indicate that a short hiatus is represented at the Cretaceous-Tertiary boundary (Van Hinte, Wise, and others, 1987). At DSDP Site 105, the Accomac Canyon unit appears to be missing (fig. 16). At DSDP Site 603 (fig. 15), late Paleocene radiolarian assemblages of the Island Beach Alloformation (defined below) unconformably overlie an unfossiliferous Accomac Canyon(?) section of turbiditic sandstone.

The Accomac Canyon Alloformation displays chiefly onlap-fill and chaotic-fill seismic facies within the slope-apron deposits; these facies result from the mass transport of sediment downslope.

ISLAND BEACH ALLOFORMATION

DEFINITION

We propose the name Island Beach Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), the submerged continental shelf and slope (Baltimore Canyon trough), and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Paleocene (Danian and Thanetian) strata in this region. The Island Beach Alloformation is named after the Island Beach No. 1 borehole, Ocean County, N.J., at lat 39°48′ N., long 74°06′ W. (fig. 3). The stratotype is DSDP Site 605, on the upper continental rise, 165 km southeast of Atlantic City, N.J., at lat 38°44.52′

N., long 72°36.55′ W. (figs. 4 and 17). At the stratotype, the alloformation is 214.8 m thick and consists mainly of dark-greenish-gray, clay-rich or silty, nannofossil-bearing limestone.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Island Beach Alloformation has been cored at DSDP Site 605 (figs. 17 and 18) at ~778.73 m below the sea floor. Poag (1985b) placed the unconformity at 43 cm below the top of section 1, core 66; Smit and Van Kempen (1987) and Lang and Wise (1987) placed the unconformity ~30 cm lower. The unconformity occurs within a disturbed zone of broken core fragments, which obscures the precise position of the contact. The unconformity separates Paleocene light-blue-gray, slightly laminated, foraminifer-bearing mudstone (above) from Maastrichtian light-gray, argillaceous, foraminifer- and nannofossil-bearing limestone (below). The lower bounding unconformity can be traced widely in the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, where it generally truncates Upper Cretaceous beds of either the Sixtwelve or Accomac Canyon Alloformation.

The upper bounding unconformity of the Island Beach Alloformation (fig. 21) has been cored at DSDP Site 605 (fig. 17), 563.83 m below the sea floor (33 cm below the top of section 5, core 44; see Poag, 1985b; Lang and Wise, 1987). The unconformity separates upper Paleocene dark-blue-gray, densely burrowed, marly, foraminifer- and nannofossil-bearing limestone (below) from lower Eocene light-green-gray, lightly burrowed, argillaceous, porcelaneous, foraminifer- and nannofossil-bearing limestone (above). The contact lies in a 4-cm section disturbed by expansion cracks in the Paleocene sediments. The upper bounding unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, and is directly overlain by lower Eocene beds of the Carteret Alloformation (defined herein).

On seismic-reflection profiles, the unconformities bounding the Island Beach Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections at the contacts (Poag and Schlee, 1984; Poag, 1985a,b, in press; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Island Beach Alloformation extends discontinuously in the subsurface from DSDP Site 603 (and possibly Site 105) (on the lower continental rise) to ~40 km landward of the Dover Air Force Base well, ~700 km updip in the Salisbury embayment (fig. 22; see Poag and Sevon, 1989; Poag, 1992). Along depositional strike, the alloformation extends as scattered patches on the continental shelf and nearly continuously on the continental slope and rise ~750 km from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras) (fig. 22). The alloformation is generally thin (<100 m) in the Salisbury embayment, but it thickens to >100 m in a narrow depocenter a few kilometers seaward of Cape May, N.J.

The alloformation is missing (or too thin to identify on seismic-reflection profiles) beneath much of the continental shelf; it thickens to >200 m in slope aprons off New Jersey and Long Island and reaches a maximum of >300 m in an elongate submarine fan seaward of Cape Henry, Va. (Poag and Sevon, 1989; Poag, 1992). In the outer part of the Baltimore Canyon trough and in the Hatteras basin, the Island Beach Alloformation is equivalent to the middle part of seismic unit D_1 of Schlee and others (1985); the upper

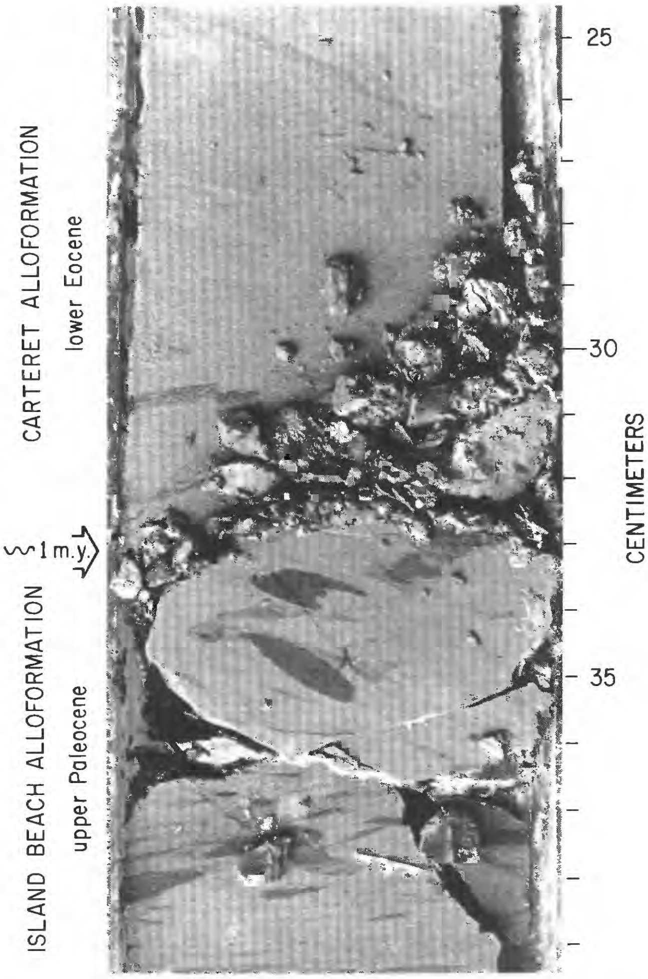


Figure 21. Unconformity separating Island Beach Alloformation and Carteret Alloformation at DSDP Site 605. Unconformity is 563.83 m below sea floor and is 33 cm below top of section 5, core 44 (Poag, 1985b). Hiatus is approximately 1 m.y.

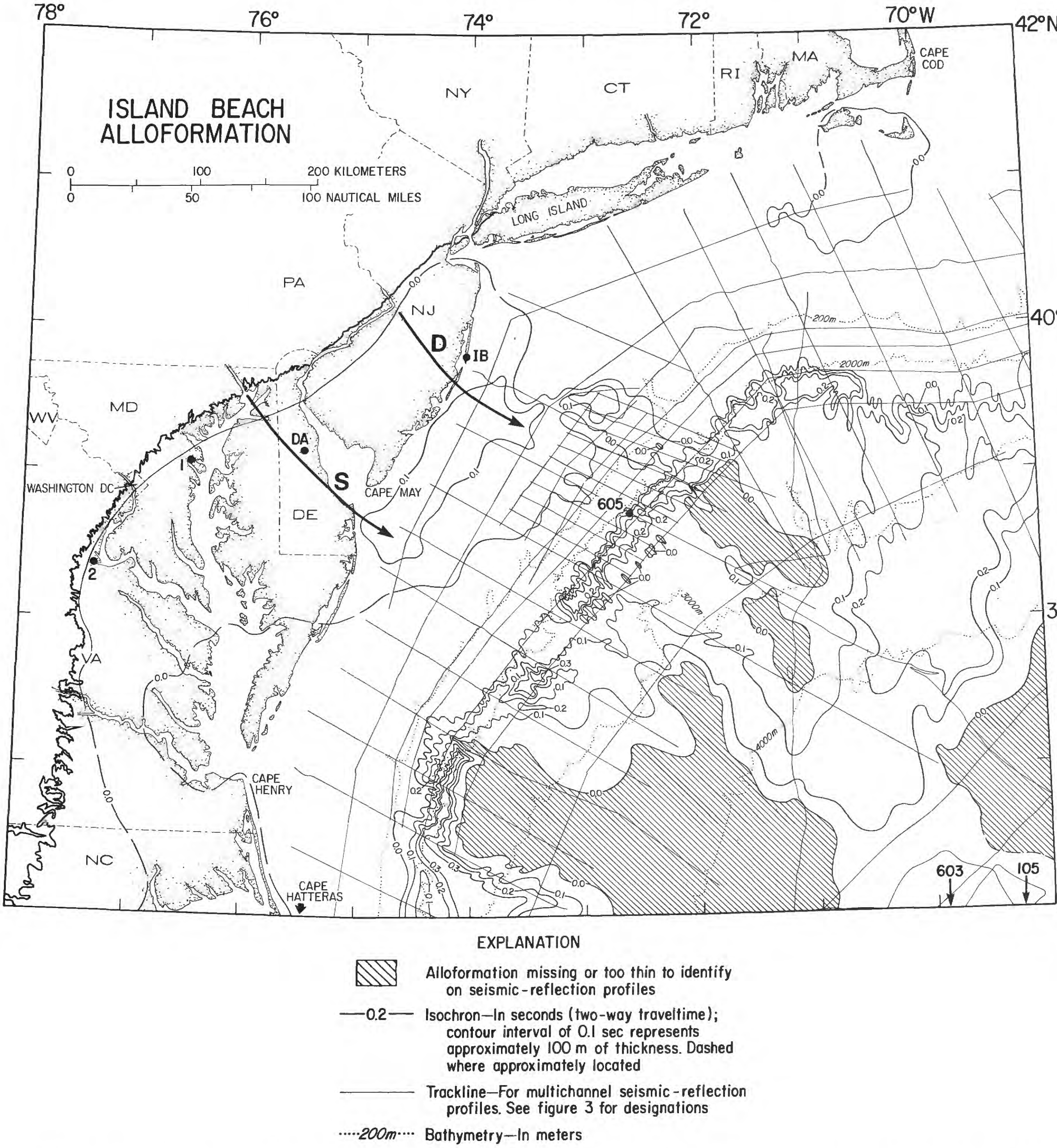


Figure 22. Isochron map of Island Beach Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: D, ancient Delaware River; S, ancient Susquehanna River. Boreholes: DA, Dover Air Force Base well; IB, Island Beach No. 1 borehole; other labeled boreholes identified in text. Onshore reference sections: 1, Round Bay, Md.; 2, USGS loc. 26332 on Potomac River near Aquia Creek, Va. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

part of seismic unit C and the lower part of unit D_1 of Schlee and Hinz (1987); and most of the lower Oligocene(?) seismic unit of Mountain and Tucholke (1985) (fig. 11).

The Island Beach Alloformation is quite thin (<100 m) or missing beneath most of the rest of the continental rise. Where present in the northern part of the Hatteras basin, the alloformation is equivalent to the lower part of the deep-sea Bermuda Rise Formation (fig. 11).

In the coastal plain of New Jersey, Delaware, Maryland, and Virginia, the Island Beach Alloformation encompasses the Brightseat Formation, Hornerstown Sand, Aquia Formation, Vincentown Formation, and Marlboro Clay, which may be seen at numerous outcropping sections in those States. One of the best exposures of the lower bounding unconformity, which separates the Maastrichtian Severn Formation (Accomac Canyon Alloformation) from the Paleocene Brightseat Formation (Island Beach Alloformation), is at Round Bay, Md. (Owens and others, 1977, p. 113). This is the same outcrop selected above as the onshore supplementary reference section for the upper part of the Accomac Canyon Alloformation (fig. 20). We designate this exposure also as the onshore supplementary reference section for the lower part of the Island Beach Alloformation and its lower bounding unconformity.

The upper part of the Island Beach Alloformation (Aquia Formation) is best exposed along the Potomac River in the vicinity of Aquia Creek, Stafford County, Va. We designate the exposure described by Ward (1985, p. 62, loc. 3, USGS loc. 26332) as the supplementary reference section for the upper part of the Island Beach Alloformation and its upper bounding unconformity (figs. 22 and 23). At this locality, the upper bounding unconformity separates the Paleocene Marlboro Clay from the lower Eocene Nanjemoy Formation. The upper bounding unconformity of the alloformation also may be seen at numerous other outcrops in southeastern Virginia, where the unconformity separates the overlying Nanjemoy Formation from either the Marlboro Clay, or where the Marlboro is absent, from the Aquia Formation.

In the Island Beach No. 1 borehole, from which the name of this unit was taken, the Island Beach Alloformation consists of 47 m of light- to dark-greenish-gray, calcareous, glauconitic, lignitic, micaceous clay interbedded with olive- to greenish-gray, calcareous, lignitic, micaceous, pyritic, glauconitic sandy silt (Seaber and Vecchioli, 1963; Poag, 1985a).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The striking feature of the Island Beach Alloformation's distribution pattern (fig. 22) is the unit's widespread absence (or thinness) compared to the distribution of the underlying Sixtwelve and Accomac Canyon Alloformations. The general pattern of a broad, thinly covered continental shelf, whose shelf break is marked by a thickened slope apron, persisted, however, during deposition of the Island Beach Alloformation. The position of the shelf break remained about the same as during Accomac Canyon deposition. On the inner to middle shelf, a thin (~100 m),

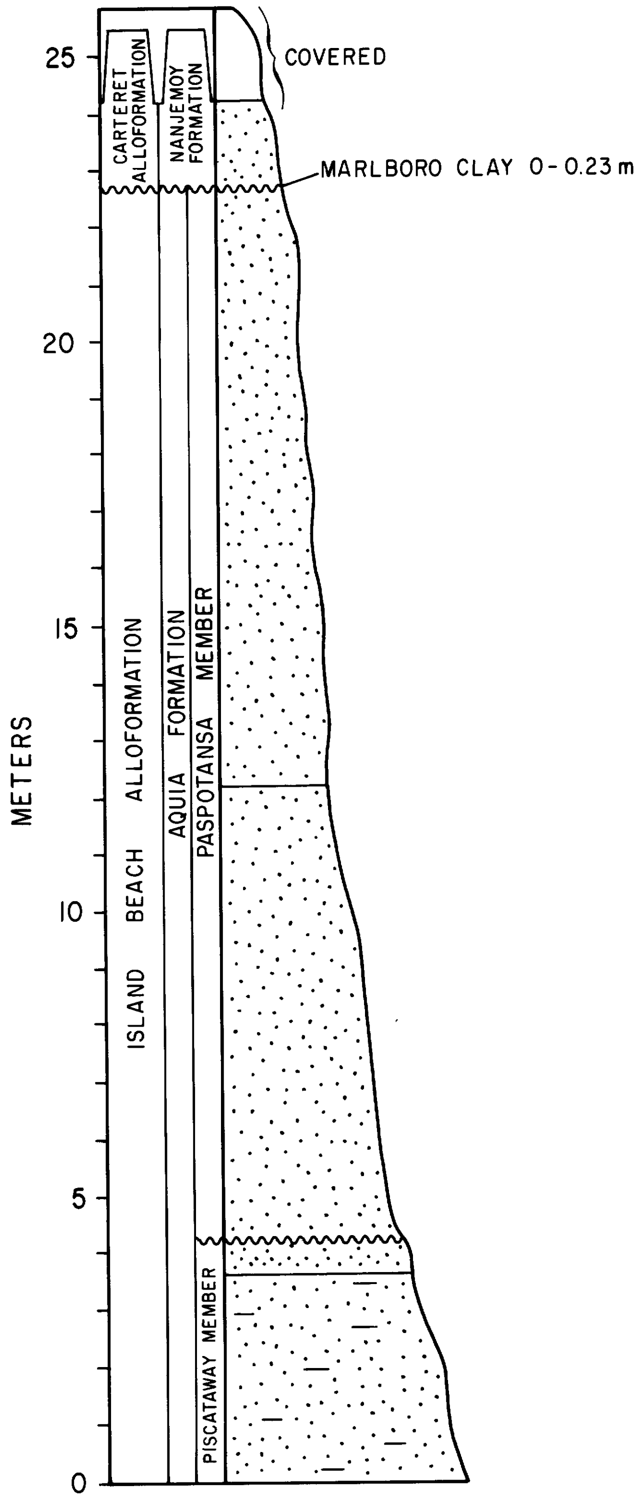


Figure 23. Onshore supplementary reference section for upper part of Island Beach Alloformation and its upper bounding unconformity, exposed near Aquia Creek, along Potomac River, Stafford County, Va. (Ward, 1985, p. 62, loc. 3, USGS loc. 26332). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 22 for location.

elongate delta built out, extended a few broad lobes onto the outer shelf, and fed narrow slope aprons (~200 m thick). The Island Beach Alloformation gradually thins downdip to a featheredge before pinching out on the underlying surface of the Accomac Canyon Alloformation.

Strata of the Island Beach Alloformation are missing from wide swaths on the outer shelf and upper slope northeast and southwest of New Jersey. A distinct submarine fan (200–300 m thick) developed in the Hatteras basin downdip from each of those erosional swaths. The thickness of the slope aprons and the obvious upslope origin of their sedimentary components (channel fill, as inferred from chaotic seismic reflections and from the terrigenous detritus cored at Site 605) are evidence that some of the updip erosion was contemporaneous with downdip deposition, which redistributed outer shelf sediments to the continental slope and rise. Elongate patches of thin or missing Island Beach deposits extend from the base of the slope aprons and appear to be additional erosional swaths created by downslope channeling.

At DSDP Site 603 (figs. 5 and 15), a 20-m section of the Island Beach Alloformation contains dark-greenish-gray, zeolitic, silt-bearing, radiolarian-rich claystone having minor amounts of quartz and mica. Obviously, long-distance dispersal of shelf-derived detritus continued in the northern Hatteras basin during the late Paleocene.

Thin deposits of the Island Beach Alloformation beneath the continental shelf and at DSDP Site 603 contain chiefly late Paleocene fossils, indicating that erosion was dominant in the early Paleocene history of this region. At DSDP Site 605 (figs. 5 and 17), the Island Beach section is thicker and more complete, but a sharp intraformational contact between glauconitic silty strata and overlying argillaceous nannofossil-bearing limestone (53 cm below the top of section 1, core 64; Van Hinte, Wise, and others, 1987) represents an important early Paleocene erosional event. This event may be used to divide the Island Beach Alloformation informally into an upper and a lower allomember.

Approximately 14 m of multicolored zeolitic clay at DSDP Site 105 contains ichthyoliths of Maastrichtian to Danian age and might represent the Island Beach Alloformation (fig. 16).

CARTERET ALLOFORMATION

DEFINITION

We propose the name Carteret Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), submerged continental shelf and slope (Baltimore Canyon trough), and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Ypresian (lower Eocene) strata in this region. The Carteret Alloformation is named after Carteret Canyon, which incises the present continental slope and shelf edge ~150 km southeast of Atlantic City, N.J. (fig. 3). The stratotype of the alloformation is DSDP Site 612 (figs. 6 and 7), on the lower continental slope, 2 km southwest of Carteret Canyon, at lat 38°49.21′ N., long 72°46.43′ W. At the stratotype, the Carteret Alloformation is 227.5 m thick and consists of light-greenish-gray to olive-gray porcellanite and porcelaneous, nannofossil-bearing chalk.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Carteret Alloformation (fig. 21) has been cored at DSDP Site 605 (17 km downslope from Site 612), 563.83 m below the sea floor (33 cm below the top of section 5, core 44; see Poag, 1985b; Lang and Wise, 1987). The unconformity (fig. 17) separates lower Eocene light-green-gray, lightly burrowed, argillaceous, porcelaneous, foraminifer- and nannofossil-bearing limestone (above) from upper Paleocene dark-blue-gray, densely burrowed, marly, foraminifer- and nannofossil-bearing limestone (below). The contact lies in a 4-cm section disturbed by expansion cracks in the Paleocene sediments. The lower unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, and truncates upper Paleocene beds (Island Beach Alloformation), Upper Cretaceous beds (Accomac Canyon and Sixtwelve Alloformations), or older beds.

The upper bounding unconformity of the Carteret Alloformation (fig. 24) has been cored at DSDP Site 612 (figs. 6 and 7), 331.90 m below the sea floor (80 cm below the top of section 3, core 37; see Poag and Low, 1987). The unconformity separates lower Eocene dark-yellowish-brown, horizontally burrowed, biosiliceous, foraminifer- and nannofossil-bearing chalk (below) from middle Eocene, light-greenish-gray, coarsely glauconitic, thinly laminated, biosiliceous, foraminifer- and nannofossil-bearing chalk containing clasts of dark-gray, Upper Cretaceous chalk (above). The upper bounding unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, and is generally overlain by middle Eocene beds of the Lindenkohl Alloformation (defined herein).

On seismic-reflection profiles, the bounding unconformities of the Carteret Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections at the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

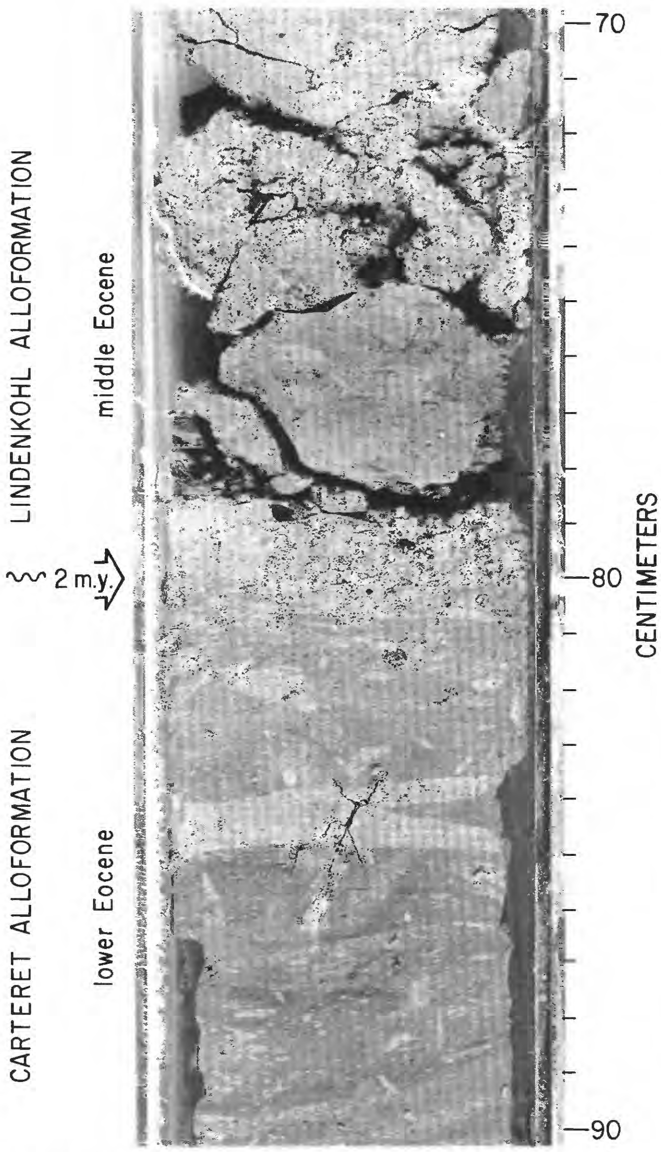


Figure 24. Unconformity separating Carteret Alloformation from Lindenkohl Alloformation at DSDP Site 612. Unconformity is 331.90 m below sea floor and is 80 cm below top of section 3, core 37 (Poag and Low, 1987). Hiatus is approximately 2 m.y.

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Carteret Alloformation extends nearly continuously in the subsurface from DSDP Site 603 (and possibly Site 105) (on the lower continental rise) to ~30 km landward of the Dover Air Force Base well, ~700 km updip in the Salisbury embayment (fig. 25). Along depositional strike, the alloformation extends ~750 km along the outer shelf from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras). It is generally thinner than 100 m in the Baltimore Canyon trough, including the Salisbury embayment, and is missing from much of this area. Its distribution in the northern Hatteras basin is even more scattered; the unit principally forms an elongate series of slope aprons and two associated large submarine fans seaward of New Jersey and Long Island, where thickness reaches >200 m (see Poag and Sevon, 1989; Poag, 1992). In this area, the alloformation is correlative with the upper part of seismic unit D_1 of Schlee and others (1985); the upper part of seismic unit D_1 of Schlee and Hinz (1987); the uppermost part of the lower Oligocene(?) seismic unit and the lower part of the upper Oligocene(?) seismic unit of Mountain and Tucholke (1985); and the middle part of the deep-sea Bermuda Rise Formation (fig. 11).

In the coastal plain of New Jersey, Delaware, Maryland, and Virginia, the Carteret Alloformation encompasses the Nanjemoy and Manasquan Formations, which may be seen in numerous outcrops in those States. No single locality, however, exhibits both the upper and lower bounding unconformities of the Carteret Alloformation. We have selected Bull Bluff on the Potomac River, just downstream from Potomac Creek, Stafford County, Va. (fig. 25), as the supplementary reference section for the lower part of the alloformation and its lower bounding unconformity (Ward, 1985, p. 63, loc. 11, USGS loc. 26340). At Bull Bluff, the lower bounding unconformity separates the lower Eocene Nanjemoy Formation (Carteret Alloformation) from the Paleocene Marlboro Clay (Island Beach Alloformation; fig. 26).

The upper bounding unconformity of the Carteret Alloformation has been cored in several places in the Virginia-New Jersey Coastal Plain, including the Haynesville corehole, Va. (Mixon, 1989). The only sections where this unconformity may be viewed in outcrop, however, are along the Pamunkey and James Rivers in Virginia; the best exposures are along the Pamunkey River in Hanover County. We have selected the Pamunkey River section described by Ward (1985, p. 73, loc. 74, USGS loc. 26403) as the onshore supplementary reference section for the upper part of the Carteret Alloformation and its upper bounding unconformity (figs. 25 and 27). At this locality, the upper bounding unconformity is an irregular, deeply burrowed surface that separates the lower Eocene Nanjemoy Formation (Carteret Alloformation) from the overlying middle Eocene Piney Point Formation (Lindenkohl Alloformation as designated herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The Carteret Alloformation was deposited under an elevated early Eocene sea level, which allowed several depocenters to develop on the continental shelf (figs. 2 and 25; see Poag and Sevon, 1989; Poag, 1992). Along the middle and outer shelf, the Carteret Alloformation is generally 100–250 m thick. A seaward-thickening slope apron is present seaward of New Jersey. Downslope cutting, filling, and slumping have produced a ribbed isochron

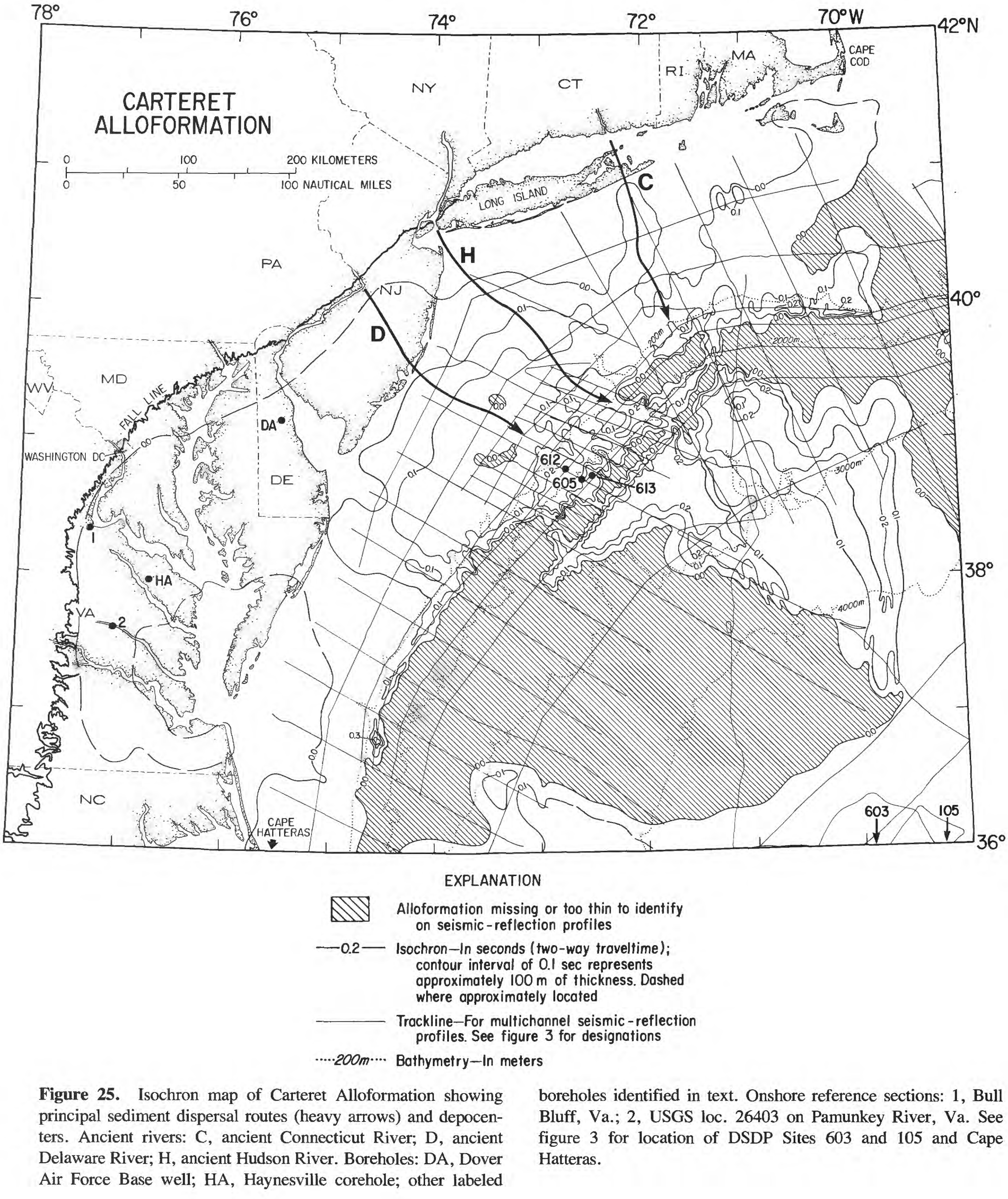


Figure 25. Isochron map of Carteret Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: C, ancient Connecticut River; D, ancient Delaware River; H, ancient Hudson River. Boreholes: DA, Dover Air Force Base well; HA, Haynesville corehole; other labeled boreholes identified in text. Onshore reference sections: 1, Bull Bluff, Va.; 2, USGS loc. 26403 on Pamunkey River, Va. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

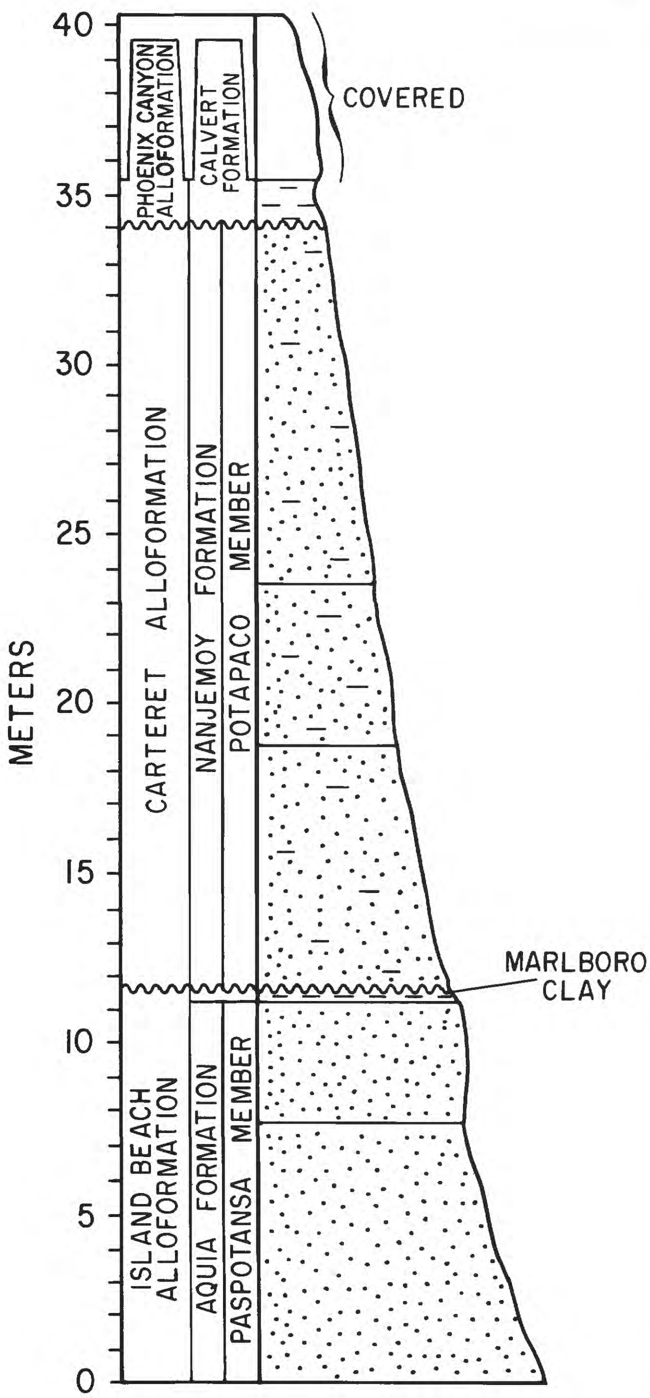


Figure 26. Onshore supplementary reference section for lower part of Carteret Alloformation and its lower bounding unconformity, exposed at Bull Bluff on Potomac River, just downstream from Potomac Creek, Stafford County, Va. (Ward, 1985, p. 63, loc. 11, USGS loc. 26340). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 25 for location.

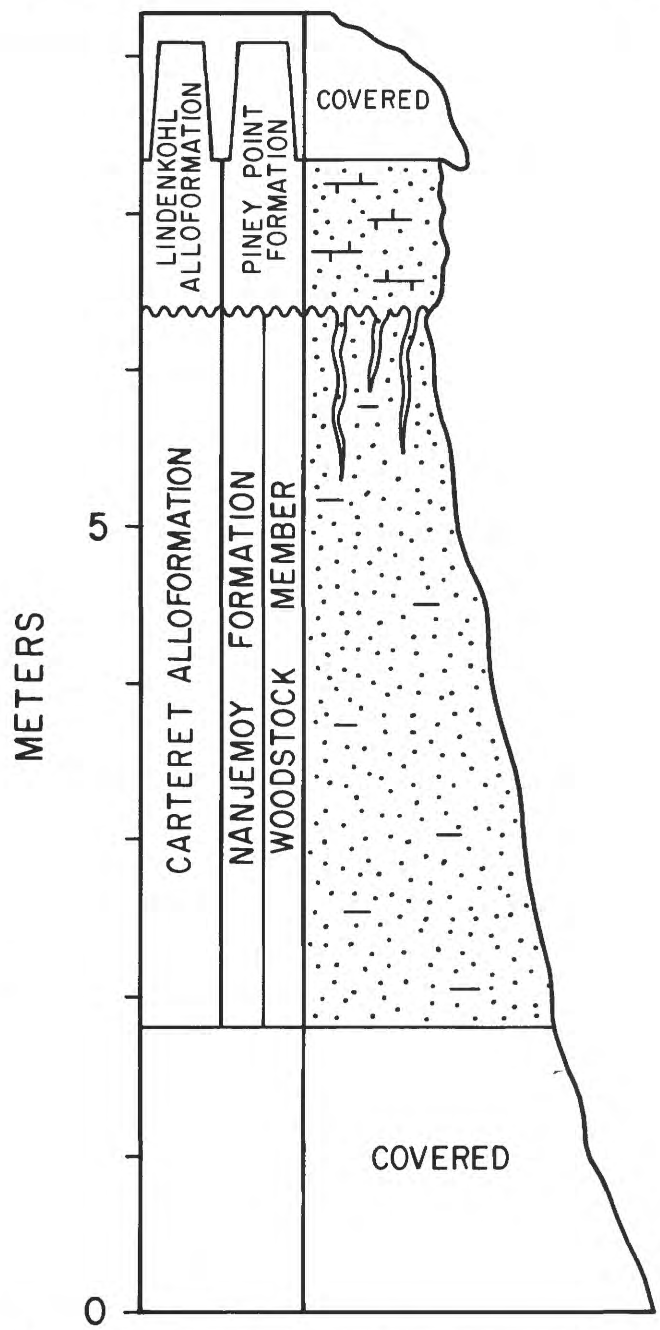


Figure 27. Onshore supplementary reference section for upper part of Carteret Alloformation, lower part of Lindenkohl Alloformation, and unconformity that separates them, exposed along Pamunkey River, Hanover County, Va. (Ward, 1985, p. 73, loc. 74, USGS loc. 26403). See figure 12 for lithologic explanation and figure 25 for location.

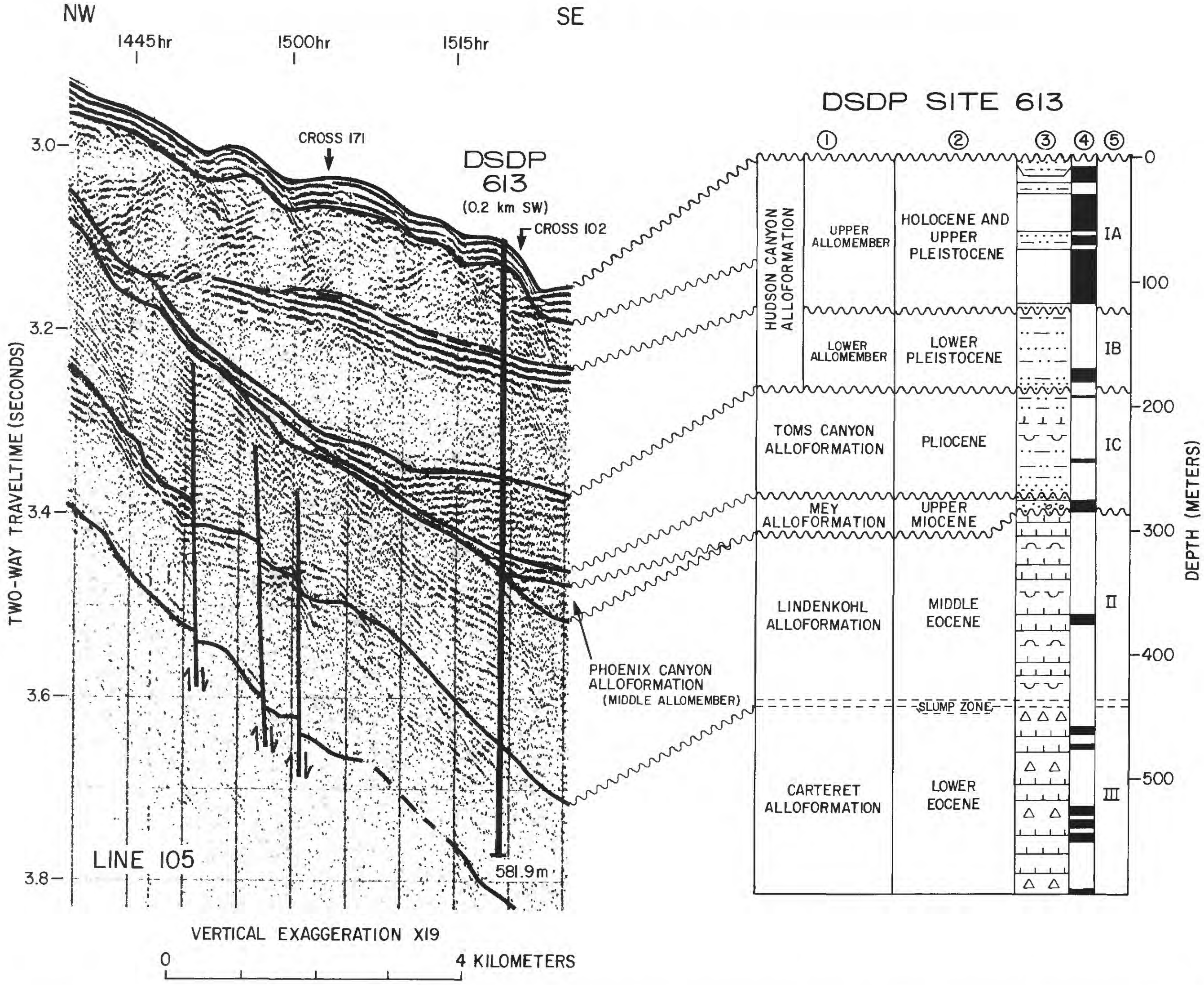


Figure 28. Stratigraphic section at DSDP Site 613 and extrapolation along dip segment of single-channel seismic-reflection profile 105 (see fig. 4 for profile location). Site 613 is stratotype for Hudson Canyon Alloformation; profile 105 is typical profile. See figure 6 for explanation of geology, profile reference points, and columns 1–5.

pattern. The most distinctive component of the depositional fabric in the slope apron is a series of deep channels cut into the upper surface of the Carteret Alloformation. Farther downdip, most of the thickened pods are caused by filling of channels in the underlying Island Beach Alloformation.

The borehole at DSDP Site 612 (figs. 6 and 7) was drilled through the thickest part of the Carteret slope apron, where it penetrated 227.5 m of bathyal, light-gray, biosiliceous, nannofossil- and foraminifer-bearing chalk and limestone, which had been partly silicified during diagenesis by conversion of radiolarian skeletons to silica cements (Wilkens and others, 1987).

Downdip at DSDP Sites 605 and 613 (figs. 17, 25, and 28), the Carteret Alloformation thins (214 m at 605; ~142 m at 613), but lithic and paleontologic characteristics are similar to those at Site 612. The depositional regime at Site 613, however, included slumping on the flank of an erosional channel. Broad erosional swaths flank two 200-m-thick submarine fans in the northern Hatteras basin.

At DSDP Site 603 (fig. 15), the Carteret Alloformation is only 36 m thick and consists of multicolored radiolarian claystones; silica diagenesis is believed to have been retarded here by the enriched clay content (Van Hinte, Wise, and others, 1987). Calcareous microfossils are present in only trace amounts, probably as a result of deposition below the carbonate compensation depth.

At DSDP Site 105, approximately 23 m of multicolored zeolitic clay contains ichthyoliths and dinoflagellates of undifferentiated Tertiary age and might represent the Carteret Alloformation (fig. 16).

Onlap-fill and chaotic-fill facies are abundant in the lower part of the Carteret slope apron (DSDP Site 613; fig. 28). Updip at Sites 612 (figs. 6 and 7) and 605 (fig. 17), seismic reflections are chiefly subparallel and subcontinuous or they are lacking; such reflections indicate relatively uniform lithology.

An erosional surface equivalent to that at the top of the Carteret Alloformation has been reported widely outside the western North Atlantic (Steele, 1976; McGowran, 1979; Quilty, 1980; Barr and Berggren, 1980; Loutit and Kennett, 1981; Berggren and Aubert, 1983; Aubry, 1985). At Site 612, nannofossil biozonation indicates that the erosional hiatus is about 2 m.y. long.

LINDENKOHL ALLOFORMATION

DEFINITION

We propose the name Lindenkohl Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), the submerged continental shelf and slope (Baltimore Canyon trough), and the continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Lutetian and Bartonian (middle Eocene) strata in this region. The Lindenkohl Alloformation is named after Lindenkohl Canyon, which incises the present continental slope and shelf edge ~160 km southeast of Atlantic City, N.J. (fig. 3). The stratotype is DSDP Site 612 (figs. 6 and 7) on the lower continental slope, ~15 km northeast of Lindenkohl Canyon, at lat 38°49.21′ N., long 72°46.43′ W. At the stratotype, the alloformation is 150.6 m thick and consists of pervasively bioturbated, light-greenish-gray to grayish-yellow-green, biosiliceous, foraminifer- and nannofossil-bearing ooze and chalk or biosiliceous nannofossil-bearing ooze and chalk.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Lindenkohl Alloformation (fig. 24) has been cored at DSDP Site 612 (figs. 6 and 7), 331.90 m below the sea floor (80 cm below the top of section 3, core 37; see Poag and Low, 1987). The unconformity separates middle Eocene light-greenish-gray, coarsely glauconitic, thinly laminated, biosiliceous, foraminifer- and nannofossil-bearing chalk (above) from lower Eocene dark-yellowish-brown, horizontally burrowed, biosiliceous, foraminifer- and nannofossil-bearing chalk (below). The lower unconformity can be traced widely throughout the northern part of the Hatteras basin

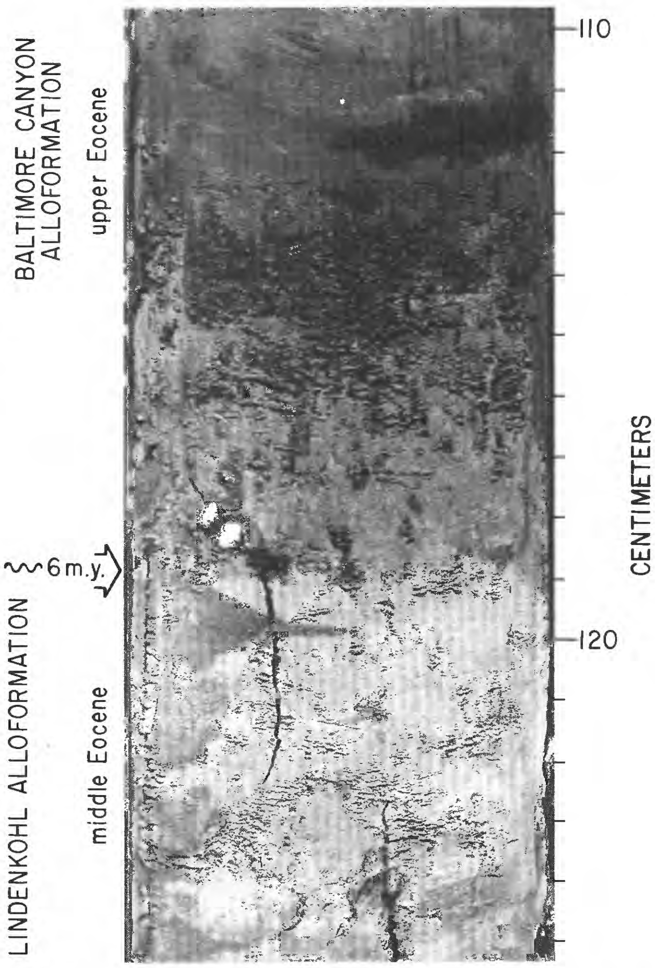


Figure 29. Unconformity separating Lindenkohl Alloformation from Baltimore Canyon Alloformation at DSDP Site 612. Unconformity is 181.35 m below sea floor and is 119 cm below top of section 5, core 21 (Miller and others, 1991). Hiatus is approximately 6 m.y.

and the Baltimore Canyon trough, including the Salisbury embayment, and generally truncates beds of Paleocene (Island Beach Alloformation) or Late Cretaceous (Sixtwelve and Accomac Canyon Alloformations) age.

The upper bounding unconformity of the Lindenkohl Alloformation (fig. 29) has been cored at DSDP Site 612 (figs. 6 and 7), 181.35 m below the sea floor (119 cm below the top of section 5, core 21; Miller and others, 1991). The unconformity is an irregular scour surface that separates middle Eocene medium-gray, biosiliceous, sparsely burrowed, nannofossil-bearing ooze (below) from upper Eocene, dark-greenish-gray, glauconitic clayey sand (above) containing tektite fragments, microtektites, microkrystites, coesite, stishovite, and shocked rock fragments and mineral grains (Cousin and Thein, 1987; Keller and others, 1987; Thein, 1987; Glass, 1989). The upper bounding unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore

Canyon trough, including the Salisbury embayment, and truncates beds of middle Eocene (Lindenkohl Alloformation) to early Eocene (Carteret Alloformation) age.

On seismic-reflection profiles, the bounding unconformities of the Lindenkohl Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Lindenkohl Alloformation extends in the subsurface continuously from the middle part of the continental rise to ~25 km landward of the Dover Air Force Base well, ~400 km updip in the Salisbury embayment (fig. 30). Along depositional strike, the alloformation extends ~750 km from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras). The alloformation is generally thinner than 100 m in the Salisbury embayment and in the continental-shelf segment of the Baltimore Canyon trough, but it reaches a maximum shelf thickness of >400 m in a large mid-shelf delta off Delaware Bay. Several small slope aprons and submarine fans are present in the Hatteras basin, but most of the upper and middle continental rise contains a layer <100 m thick. In this region, the Lindenkohl Alloformation is equivalent to the uppermost part of seismic unit D_1 of Schlee and others (1985); the lower part of seismic unit $D_{2.1}$ of Schlee and Hinz (1987); the upper part of the upper Oligocene(?) seismic unit and the lower part of the lower and middle Miocene unit of Mountain and Tucholke (1985); the middle Eocene of Poag (1987); and the lower part of the Eocene-Oligocene to upper middle Miocene unit of McMaster and others (1989) (fig. 11). The alloformation is notable for its broad swath of outcrops along the base of the continental slope and a parallel downslope swath (5–20 km wide) where the alloformation is absent (fig. 30). The Lindenkohl Alloformation also appears to be missing in the southeastern corner of the study area, but where present in the Hatteras basin, it is correlative with the upper part of the deep-sea Bermuda Rise Formation and the lower part of the Blake Ridge Formation (fig. 11).

In the coastal plain of New Jersey, Delaware, Maryland, and Virginia, the Lindenkohl Alloformation encompasses the Shark River and Piney Point Formations. The Lindenkohl Alloformation crops out only along the Pamunkey and James Rivers in Virginia, where it is represented by the Piney Point Formation. The Shark River is an equivalent in the subsurface of New Jersey (Olsson and Wise, 1987). No single Pamunkey River outcrop, however, exhibits the entire lithostratigraphic succession of the Lindenkohl Alloformation. We have selected the Pamunkey River section described by Ward (1985, p. 73, loc. 74, USGS loc. 26403) as the onshore supplementary reference section for the lower part of the Lindenkohl Alloformation and its lower bounding unconformity (fig. 27). This is the same locality selected as the onshore supplementary reference section for the upper part of the Carteret Alloformation. The sediments of the Lindenkohl Alloformation are best represented, however, on the Pamunkey River at Horseshoe, Hanover County, Va. (Ward, 1985, p. 74, loc. 83, USGS loc. 26412) (fig. 31). At this locality, the upper part of the alloformation is exposed along with the upper bounding unconformity. We have chosen this locality as the onshore supplementary reference section for the upper part of the Lindenkohl Alloformation and its upper bounding unconformity. The upper bounding unconformity here is a deeply burrowed erosional surface that separates the middle Eocene Piney Point Formation (Lindenkohl Alloformation) from the Old Church Formation (upper Oligocene; Babylon Alloformation as designated herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The middle Eocene was a time of considerable change in the depositional patterns in and near the Baltimore Canyon trough, as relative sea level reached maximum heights for the Cenozoic, and carbonate-enriched sediments of the Lindenkohl Alloformation are widespread. The most notable change is the development of a large (>400 m thick), elongate, middle-shelf delta complex (fig. 30; see Poag and Sevon, 1989; Poag, 1992). The front of this delta complex formed a second ("hinter") shelf break, marked by a relatively thick, prograded wedge of sediments yielding clinoform reflections along the inshore segments of the dip profiles. The chief source of sediments for this delta appears to have been northwest of the Dover Air Force Base well (Benson and others, 1985). The Lindenkohl sediments presumably were dispersed by a precursor of the Susquehanna River system (Poag and Sevon, 1989; Poag, 1992), which constructed a thick subaqueous delta complex (chiefly marine sediments where drilled). The preserved delta stretches for 250 km along the Maryland-New Jersey coast and resembles the subaqueous delta of the modern Amazon Shelf (Nittrouer and others, 1986). A secondary, more northerly sediment source, presumably the ancient Hudson River system (Poag and Sevon, 1989; Poag, 1992), built a smaller elongate, lobate delta complex seaward of what is now Long Island.

From the hintershelf break (the delta front), the Lindenkohl Alloformation thins significantly (to <100 m) seaward across a broad foreshelf, before thickening again in small slope aprons (200–500 m thick) that built out in the vicinity of the earlier Late Cretaceous and Paleocene shelf break (figs. 2 and 30). About 60 km southwest of DSDP

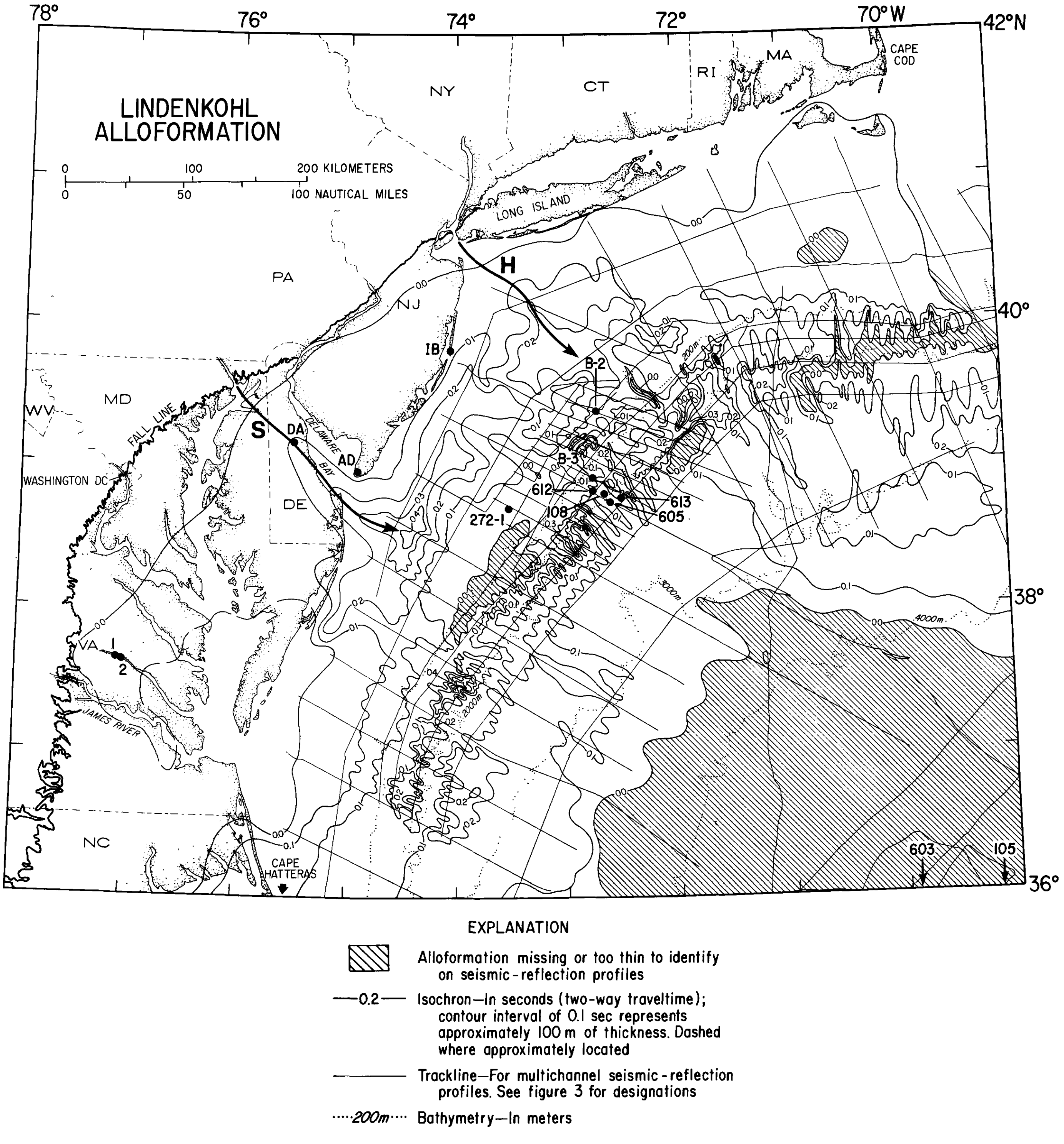


Figure 30. Isochron map of Lindenkohl Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Note two large deltas built out on middle continental shelf (hinter shelf); coalescing debris piles form slope aprons. Ancient rivers: H, ancient Hudson River; S, ancient Susquehanna River. Boreholes: AD, Anchor-Dickinson No. 1 well; DA, Dover Air Force Base well; IB, Island Beach No. 1 borehole; other labeled boreholes identified in text. Onshore reference sections: 1, USGS loc. 26403 on Pamunkey River, Va.; 2, USGS loc. 26412 on Pamunkey River at Horseshoe, Va. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

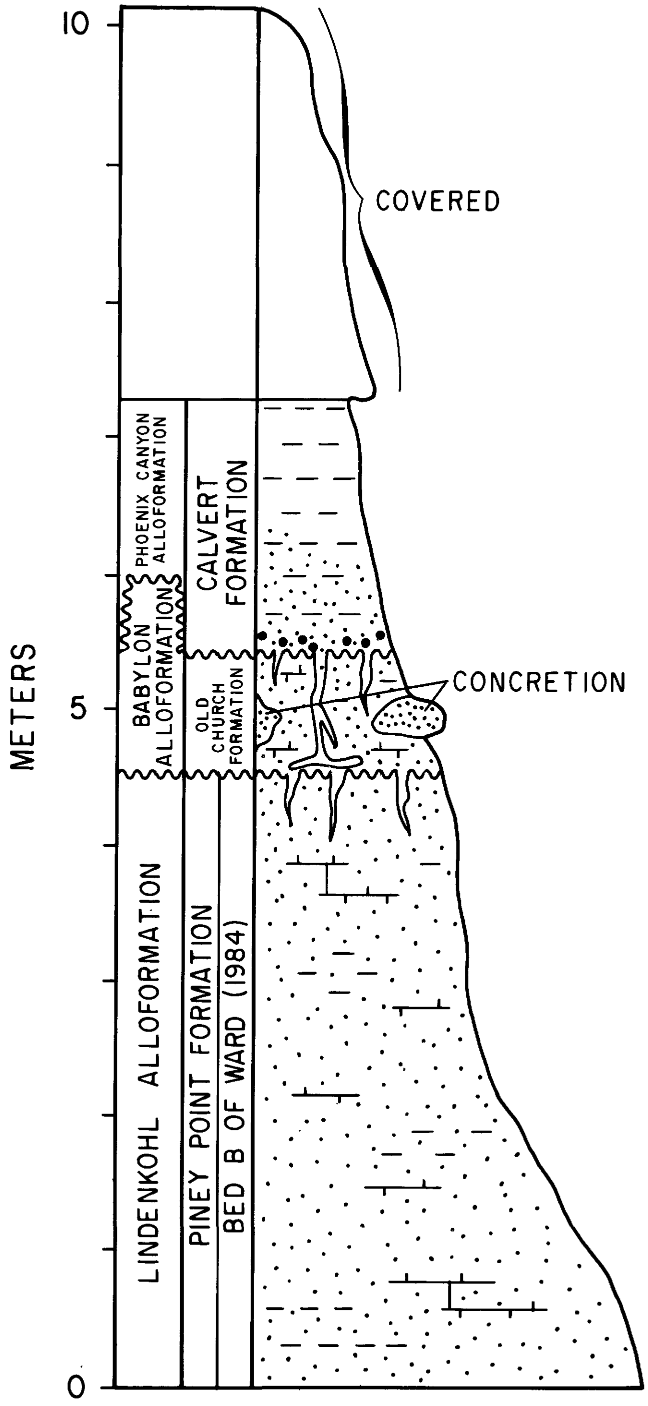


Figure 31. Onshore supplementary reference section for upper part of Lindenkohl Alloformation, upper part of Babylon Alloformation, and unconformity that separates them, exposed at Horseshoe, on Pamunkey River, Hanover County, Va. (Ward, 1985, p. 74, loc. 83, USGS loc. 26412). Upper bounding unconformity of Babylon Alloformation also exposed at this locality. See figure 12 for lithologic explanation and figure 30 for location.

Site 612, however, an elongate, narrow, erosional swath is present on the outer foreshelf, and another parallel swath was formed about 70 km northeast of Site 612 on the middle to lower continental slope. These erosional swaths apparently were scoured by turbidity currents and debris flows that radiated from the deltas. A downslope, ribbed, depositional fabric is obvious along all the strike profiles southeast of the foreshelf edge, where numerous channels and lobate fans protrude onto the continental rise.

Strata of the Lindenkohl Alloformation throughout the Baltimore Canyon trough and vicinity are characterized by an enrichment in calcium carbonate, which accumulated in a warm, moist, tropical, maritime climate (Wolfe, 1978; Frederiksen, 1984b). At updip locations in New Jersey, Lindenkohl strata include glauconitic sands and clays characterized by inner to middle sublittoral (10–50 m) microfossil assemblages (Charletta, 1980). Similar assemblages and lithologies characterize the Lindenkohl Alloformation in Virginia (Ward, 1984). The most carefully studied well in the updip axis of the subaqueous delta is the Dover Air Force Base well (fig. 30; Benson and others, 1985). There the Lindenkohl section consists of 37 m of silty sediments overlain by 74 m of glauconitic quartz sand. Calcareous clay becomes a more significant component in deeper water facies near the delta margin (for example, in the Anchor-Dickinson well).

At the Island Beach No. 1 borehole, located 40 km shoreward from the edge of the middle Eocene hintershelf (figs. 2 and 30; Poag, 1985a), the Lindenkohl Alloformation consists of 34 m of sandy, shelly, calcareous clay topped by a 9-m gypsiferous section.

At the COST B–2 well, located between two delta lobes on the outer part of the gently sloping middle Eocene foreshelf (fig. 30; Poag, 1985a), the Lindenkohl Alloformation consists of 135 m of buff to light-gray, dense, argillaceous micrite containing bathyal (500–600 m) microfossil assemblages. Radiolarians are noticeably more abundant at this location than updip, and they increase even more at downdip sites. In contrast, at the Shell 272–1 well, located approximately on depositional strike with the B–2 well, but directly in front of the principal lobe of the southern delta, the Lindenkohl Alloformation consists mainly of mudstones (~50 m thick; Poag, 1985a).

At the COST B–3 site (figs. 8 and 30), located on the middle Eocene continental slope, the Lindenkohl section consists of 90 m of light-gray to white calcareous claystone and fossiliferous limestone. Rich microfossil assemblages, including abundant radiolarians, indicate bathyal paleodepths of ~1,000 m.

Farther downslope at DSDP Site 612 (figs. 6 and 7), the Lindenkohl section thickens to 151.6 m and changes to light-greenish-gray, biosiliceous, nannofossil-bearing chalk; radiolarian and diatom abundances continue to increase, and terrigenous lithic components drop out. The upper 42 m of the section constitutes a soft ooze, but the constituents are the same as those of the indurated lower section. The porcelaneous interval of the diagenetic front makes up the basal 8 m of the Lindenkohl Alloformation (Wilkens and others, 1987).

The Lindenkohl Alloformation changes little in composition downdip at DSDP Sites 605 and 613 (figs. 17 and 28), but it thickens gradually (to 145 and 173 m, respectively). Considerably thicker sections (300–400 m) are present in some of the slope-apron deposits (fig. 30). One notable lithologic change is the presence of a thin (2–5 cm) layer of unaltered rhyodacitic ash, 9 m above the base of the Lindenkohl Alloformation at DSDP Site 605 and 37 m above its base at Site 613. Von Rad and Kreuzer (1987) assumed that these ash layers were deposited simultaneously, but the higher relative stratigraphic position and the 5-m.y. younger K-Ar age of ash at Site 613 are evidence that the two layers represent two different events. Schlee (1977), in fact, reported as many as nine different ash layers in the Eocene and Oligocene sections of JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) coreholes 3, 4, and 6 on the nearby continental margin of Florida. Presumably wind and (or) surface currents (such as the proto-Gulf Stream) transported the ash to the New Jersey margin from active centers of volcanism in the Caribbean Island Arc.

No Lindenkohl strata were identified at DSDP Sites 603 and 105 (figs. 15 and 16). These results confirm the limited deep-sea distribution of the Lindenkohl Alloformation, which pinches out (is truncated) about 200 km from the foreshelf edge.

The seismic-reflection characteristics of the Lindenkohl Alloformation indicate that onlap-fill, slope-front fill, and chaotic-fill facies are abundant in the thickened slope aprons. Updip and downdip from these slope aprons, however, broad reflection-free intervals (on multichannel profiles) and parallel, subcontinuous, high-amplitude reflections (on single-channel profiles) are evidence for uniform, low-energy depositional environments. Coring confirmed the depositional environments deduced from seismic-reflection profiles. The Lindenkohl Alloformation is now exposed on the sea floor at the base of the continental slope (for example, between Sites 612 and 605; fig. 30; Robb and others, 1983; Hampson and Robb, 1984; Farre, 1985; Farre and Ryan, 1985, 1987; Poag, 1985a), where it was drilled during DSDP Leg 11 at Site 108 (Hollister, Ewing, and others, 1972). Farther seaward, at DSDP Sites 605, 613, and vicinity (figs. 17 and 28), the upper erosion surface of the Lindenkohl is onlapped by Tertiary and Quaternary sequences of the upper continental rise (Tucholke and Mountain, 1979, 1986; Mountain and Tucholke, 1985; Poag, 1985b), but its precise relation to the deep-sea erosion surface known as A^u is not yet determined (Poag, 1987).

A significant positive deflection in the gamma-ray log at DSDP Site 612 is associated with the basal sand of the overlying Baltimore Canyon Alloformation; sparse to moderate amounts of glauconite and volcanic glass keep the gamma-ray values consistently higher in the Baltimore Canyon Alloformation section than in the Lindenkohl section. This gamma-ray characteristic is also seen on the COST B–3 well log (Poag, 1985b), which suggests a similar change in lithology at the Lindenkohl-Baltimore Canyon contact there. Sediments from the B–3 well have not yet been studied in detail (Pollack, 1980), but we can confirm that volcanic glass shards are present within the Baltimore Canyon Alloformation at this site.

BALTIMORE CANYON ALLOFORMATION

DEFINITION

We propose the name Baltimore Canyon Alloformation for unconformity-bounded subsurface beds of the exposed coastal plain (Salisbury embayment) and the submerged continental shelf and slope (Baltimore Canyon trough) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the base of the Priabonian (upper Eocene) strata and the top of the Rupelian (lower Oligocene) strata in this region. The Baltimore Canyon Alloformation is named after the Baltimore Canyon trough, which underlies the coastal plain and continental shelf and slope of the Middle Atlantic States, southern New England, and New York (fig. 1). The stratotype of the Baltimore Canyon Alloformation is DSDP Site 612 (figs. 6 and 7), on the lower continental slope of the Baltimore Canyon trough, 150 km southeast of Atlantic City, N.J., at lat 38°49.21′ N., long 72°46.43′ W. (fig. 3). At the stratotype, the alloformation is 46 m thick and consists of light-greenish-gray to yellow-green, biosiliceous, pervasively bioturbated, foraminifer- and nannofossil-bearing ooze and chalk.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Baltimore Canyon Alloformation (fig. 29) has been cored at DSDP Site 612 (figs. 6 and 7), 181.35 m below the sea floor (119 cm below the top of section 5, core 21; Miller and others, 1991). The unconformity is an irregular scour surface that separates upper Eocene dark-greenish-gray, glauconitic clayey sand (above) containing tektite fragments, microtektites, microkrystites, coesite, stishovite, and shocked rock fragments and mineral grains from middle Eocene medium-gray, biosiliceous, sparsely burrowed, nannofossil-bearing

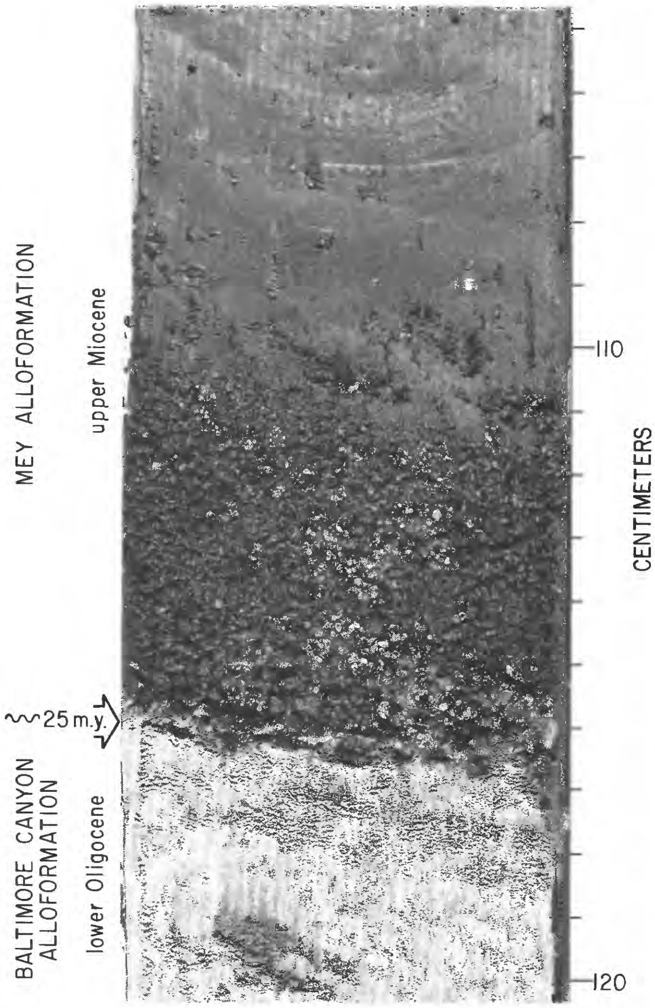


Figure 32. Unconformity separating Baltimore Canyon Alloformation from Mey Alloformation at DSDP Site 612. Unconformity is 135.36 m below sea floor and is 116 cm below top of section 6, core 16 (Poag and Low, 1987). Hiatus is approximately 25 m.y.

ooze (below). The lower bounding unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, where it truncates beds of middle Eocene (Lindenkohl Alloformation) and lower Eocene (Carteret Alloformation) age.

The upper bounding unconformity of the Baltimore Canyon Alloformation (fig. 32) has been cored at DSDP Site 612 (figs. 6 and 7), 135.36 m below the sea floor (116 cm below the top of section 6, core 16; see Poag and Low, 1987). The unconformity is a sharply defined scour surface that separates lower Oligocene light-gray microfossil-bearing ooze (below) from upper Miocene dark-gray, well-sorted, coarse, glauconitic, quartzose, turbidite sand (above). The upper bounding unconformity can be traced widely throughout the northern part of the Hatteras basin and the Baltimore Canyon trough, including the Salisbury embayment, where it truncates beds of late Eocene (Baltimore Canyon Alloformation), middle Eocene (Lindenkohl Alloformation), and early Eocene (Carteret Alloformation) age.

On seismic-reflection profiles, the bounding unconformities of the Baltimore Canyon Alloformation can be traced throughout the Baltimore Canyon trough by means of truncated, overlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Baltimore Canyon Alloformation extends in the subsurface discontinuously from near DSDP Site 612 to landward of the Ohio Oil-Hammond No. 1 well in the Salisbury embayment, ~250 km updip (fig. 33). Along depositional strike, the alloformation extends discontinuously along the continental shelf and coastal plain ~450 km between the Long Island platform (northern tip of New Jersey) and the Carolina platform (Cape Hatteras). The principal depocenter is a small bilobate prism <200 m thick, centered about 60 km offshore from Cape May, N.J. The alloformation is missing or too thin to identify on seismic profiles of the rest of the offshore region, except for an elongate wedge (~170 km long) along the continental slope and upper rise (see Poag and Sevon, 1989; Poag, 1992). In this region, the Baltimore Canyon Alloformation is equivalent to the lower third of seismic unit D_2 of Schlee and others (1985); the middle part of seismic unit $D_{2.1}$ of Schlee and Hinz (1987); the middle part of the lower and middle Miocene seismic unit of Mountain and Tucholke (1985); the middle part of the Eocene-Oligocene to upper middle Miocene seismic unit of McMaster and others (1989); and the lower part of the deep-sea Blake Ridge Formation (fig. 11).

The Baltimore Canyon Alloformation does not crop out in the coastal plain, but it is exposed along the base of the continental slope and in the walls of some submarine canyons. In the subsurface of the coastal plain, the Baltimore Canyon Alloformation encompasses the Chickahominy Formation and informally named sedimentary units in Virginia (Exmore and Delmarva beds of Powars and others, 1991, 1992; Poag and others, 1991; Poag, in press) and unnamed equivalents in Maryland and Delaware (Benson, 1990a). In southeastern New Jersey, it is represented by the ACGS Alpha unit and Mays Landing unit of Owens and others (1988), Poore and Bybell (1988), and Miller and others (1990).

Because the Baltimore Canyon Alloformation does not crop out in the coastal plain, no exposure is available as a supplementary reference section. The upper bounding unconformity of the Baltimore Canyon Alloformation can be observed, however, in continuous cores taken from

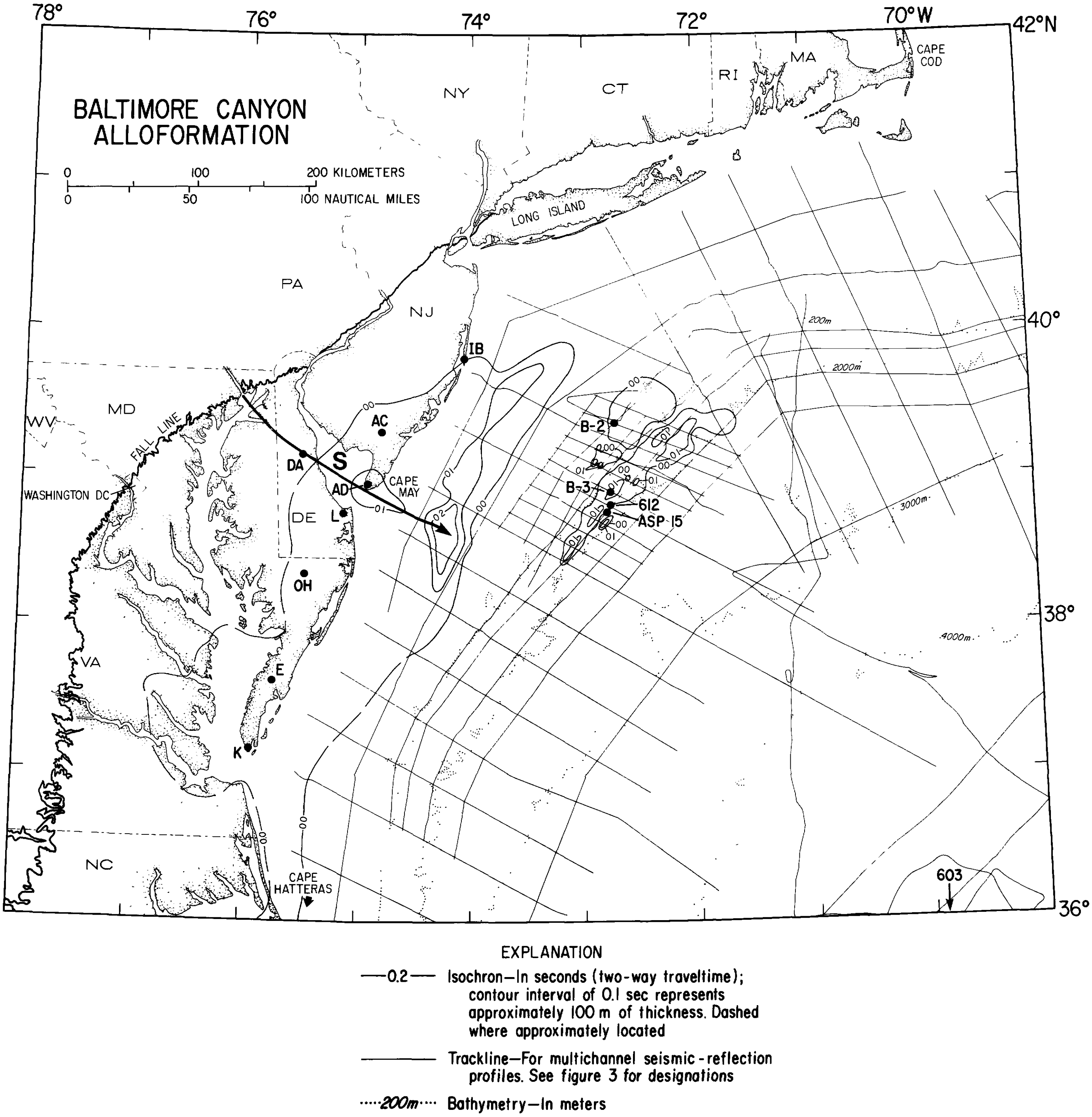


Figure 33. Isochron map of Baltimore Canyon Alloformation showing principal sediment dispersal route (heavy arrow) and depocenters. Alloformation is missing or too thin to identify on seismic profiles (outside of 0.0 contour) throughout most of the study area. Ancient river: S, ancient Susquehanna River. Boreholes: AC, ACGS-4 corehole; AD, Anchor-Dickinson No. 1 well; DA, Dover Air Force Base well; E, Exmore corehole; IB, Island Beach No. 1 borehole; K, Kiptopeke corehole; L, Lewes, Del., borehole; OH, Ohio Oil-Hammond No. 1 well; other labeled boreholes identified in text. Onshore reference section is Exmore corehole. See figure 3 for location of DSDP Site 603 and Cape Hatteras.

coreholes near Exmore and Kiptopeke on Cape Charles, Va. (the lower bounding unconformity was not recovered). At these sites (fig. 33), the upper bounding unconformity is a burrowed erosion surface between the lower Oligocene Delmarva beds (below) and the upper Oligocene Old Church Formation (above) (Babylon Alloformation of this report). We have chosen the Exmore corehole (table 1; Poag and others, 1992; Powars and others, 1992) as the onshore supplementary reference section for the Baltimore Canyon Alloformation and its upper bounding unconformity (fig. 34).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The Baltimore Canyon Alloformation is much more limited in its distribution than many of the other allostratigraphic units (fig. 33; see Poag and Sevon, 1989; Poag, 1992). It has been sampled at DSDP Site 612 (figs. 6 and 7), the Anchor-Dickinson No. 1 well, the COST B–2 and B–3 wells (figs. 5 and 8), and ASP (Atlantic Slope Project) borehole 15 (Poag, 1978) and at a few additional boreholes in the Salisbury embayment (fig. 33, Ohio Oil-Hammond No. 1 well, Dover Air Force Base well, ACGS–4 corehole, Lewes, Del., borehole, Exmore corehole, Kiptopeke corehole; Brown and others, 1972; Ward and Strickland, 1985; Benson, 1990a; Powars and others, 1992; Poag, in press). The alloformation does not crop out in the coastal plain and is missing in much of the subsurface of the Salisbury embayment. The alloformation is thin at most sites (45–65 m at COST B–2 and B–3 and DSDP 612) but thickens in the Anchor-Dickinson well to ~120 m (Poag, 1985a). In the subsurface of Virginia, the Baltimore Canyon Alloformation is represented by the Exmore beds (upper Eocene), the Chickahominy Formation (upper Eocene), and the Delmarva beds (lower Oligocene), and it reaches a thickness as great as 100 m (Cushman and Cederstrom, 1945; R.B. Mixon, written commun., 1989; Powars and others, 1991; Poag, in press). The combined thickness of the ACGS Alpha unit and the Mays Landing unit in New Jersey is ~55 m (Owens and others, 1988; Poore and Bybell, 1988; Miller and others, 1990). The alloformation is either missing or too thin to be traced on seismic profiles over much of the upper Eocene continental shelf (figs. 2 and 33). A long, narrow, prograded wedge of Baltimore Canyon strata appears to have created an inner shelf depocenter (~100–200 m thick) seaward of the Anchor-Dickinson and Island Beach wells (fig. 33). Sediments of the Baltimore Canyon Alloformation have not yet been positively identified from the continental rise between DSDP Sites 612 and 603 (fig. 3).

Where present in Virginia, the Baltimore Canyon Alloformation contains widely variable lithologies. The lower part (Exmore beds) is an unusual deposit of chaoti-

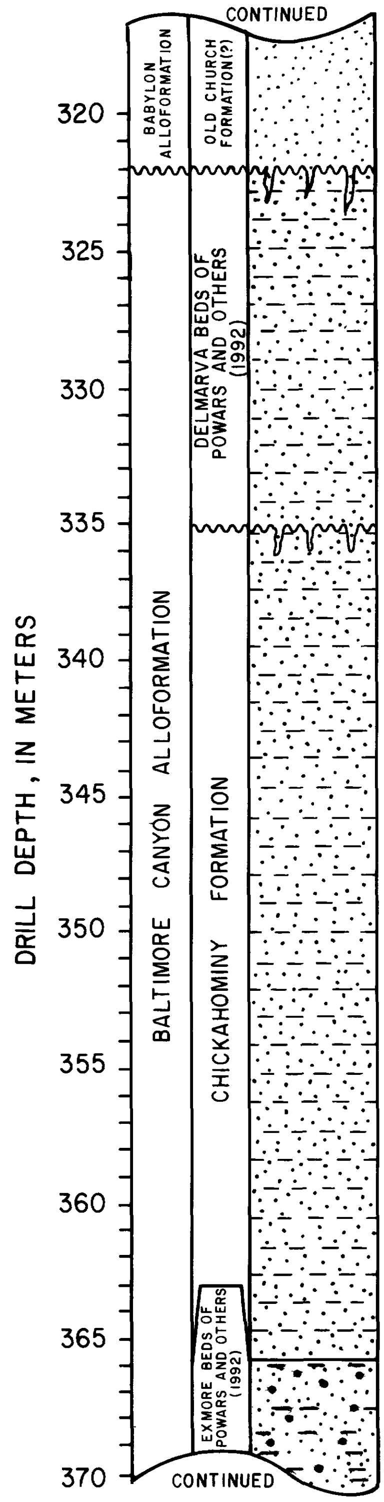


Figure 34. Stratigraphic column for part of the Exmore corehole, drilled by the U.S. Geological Survey near Exmore, Accomack County, Va., showing the Baltimore Canyon Alloformation and its upper bounding unconformity (modified from Powars and others, 1992, fig. 18.7). This section is designated as onshore supplementary reference section for Baltimore Canyon Alloformation. Corehole recorded in feet; total depth is 1,396 ft (425.5 m). See figure 12 for lithologic explanation and figure 33 for location.

cally mixed sedimentary clasts (pebbles, cobbles, and boulders) ranging in age from Early Cretaceous to middle Eocene and enclosed in a glauconitic, sandy matrix of early late Eocene age (Powars and others, 1990, 1991, 1992; Poag and others, 1992; Poag, in press). Their chaotic nature, their content of shocked quartz and tektite(?) glass, and their biostratigraphic equivalence to the microtektite-bearing layer at DSDP Site 612 caused Poag and others (1991, 1992) to conclude that the Exmore beds represent an impact-wave deposit produced by a bolide impact nearby on the New Jersey Continental Shelf. The overlying Chickahominy Formation is mainly a deep-water silty clay (contains bathyal foraminifers; Poag and others, 1991); the succeeding Delmarva beds are much sandier and contain neritic foraminiferal assemblages (Powars and others, 1992; Poag, in press).

In the subsurface of New Jersey, the ACGS Alpha unit consists mainly of brownish silty clay, medium to coarse glauconitic sand, olive-black silty clay, and medium glauconitic quartz sand (Owens and others, 1988); the Mays Landing unit ranges from massive to laminated, fine, micaceous sand, to dark-greenish-gray, silty clay, to fine to medium glauconitic quartz sand. At the Anchor-Dickinson No. 1 well, the Baltimore Canyon Alloformation consists of mainly glauconitic sand, with minor amounts of silty clay and calcareous clay, containing neritic microfauna. At the Lewes, Del., borehole (Benson, 1990a), the alloformation is mainly a bathyal(?) glauconitic silt. At the COST B–2 and B–3 wells, the alloformation is mainly silty clay of outer neritic to bathyal origin. At DSDP Site 612 (figs. 6 and 7), the 45-m-thick Baltimore Canyon section is principally light-greenish-gray, bathyal, biosiliceous, nannofossil-bearing ooze, similar to the softer upper strata of the Lindenkohl Alloformation, but a ~10-cm- thick zone at its base contains a small amount of glauconite, along with tektite glass, microtektites, microkrystites, and shocked quartz and rock fragments (Glass, 1989). The lower Oligocene part of the alloformation at Site 612 and at COST B–3 (as confirmed herein) contains trace amounts of volcanic glass shards.

BABYLON ALLOFORMATION

DEFINITION

We propose the name Babylon Alloformation for unconformity-bounded beds on the submerged continental shelf and slope (Baltimore Canyon trough) and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York and equivalent outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment) (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Chattian (upper Oligocene) strata in this region. The Babylon Alloformation is named after Babylon Canyon, which incises the present continental slope and shelf edge ~130 km south of the eastern tip of Long Island (fig. 3). The stratotype of the Babylon Alloformation is the COST B–3 well (fig. 8) on the upper continental slope, ~150 km southeast of Atlantic City, N.J., and ~97 km southwest of Babylon Canyon, at lat 38°55.0′ N., long 72°46.4′ W. (fig. 3). At the stratotype, the alloformation is 91 m thick and consists of light-olive-gray, glauconitic, microfossiliferous, calcareous clay.

BOUNDING UNCONFORMITIES

The bounding unconformities of the Babylon Alloformation were drilled, but not cored, at the stratotype. They can be discerned between shotpoints 840 and 1250 on seismic-reflection profile 218 (fig. 8), which crosses the stratotype COST B–3 well site. The lower bounding unconformity is present at 1.89 sec (two-way traveltime) where profile 218 crosses the COST B–3 site. The unconformity truncates reflections from the underlying upper Eocene section (Baltimore Canyon Alloformation). The upper bounding unconformity is present at 1.85 sec (two-way traveltime) where profile 218 crosses the COST B–3 site; the unconformity is downlapped by reflections from the overlying lower Miocene section (Berkeley Alloformation as designated herein; fig. 8).

On other seismic-reflection profiles, the bounding unconformities of the Babylon Alloformation can be traced throughout the offshore region (where present) by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Babylon Alloformation extends in the subsurface continuously from ~30 km east of the COST B–3 well to the Haynesville corehole in southeastern Virginia, and possibly to the Dover Air Force Base well (fig. 35). The Babylon Alloformation also appears to be present at one location, DSDP Site 105, on the lower continental rise (fig. 16). Along depositional strike, the alloformation extends continuously along the continental shelf from the Long Island platform (eastern tip of Long Island) ~550 km southwestward toward the Carolina platform (southeast of Chesapeake Bay) (fig. 1).

The Babylon Alloformation is thinner than 100 m throughout its extent, except for an elongate outer shelf delta complex seaward of the Middle Atlantic States, where

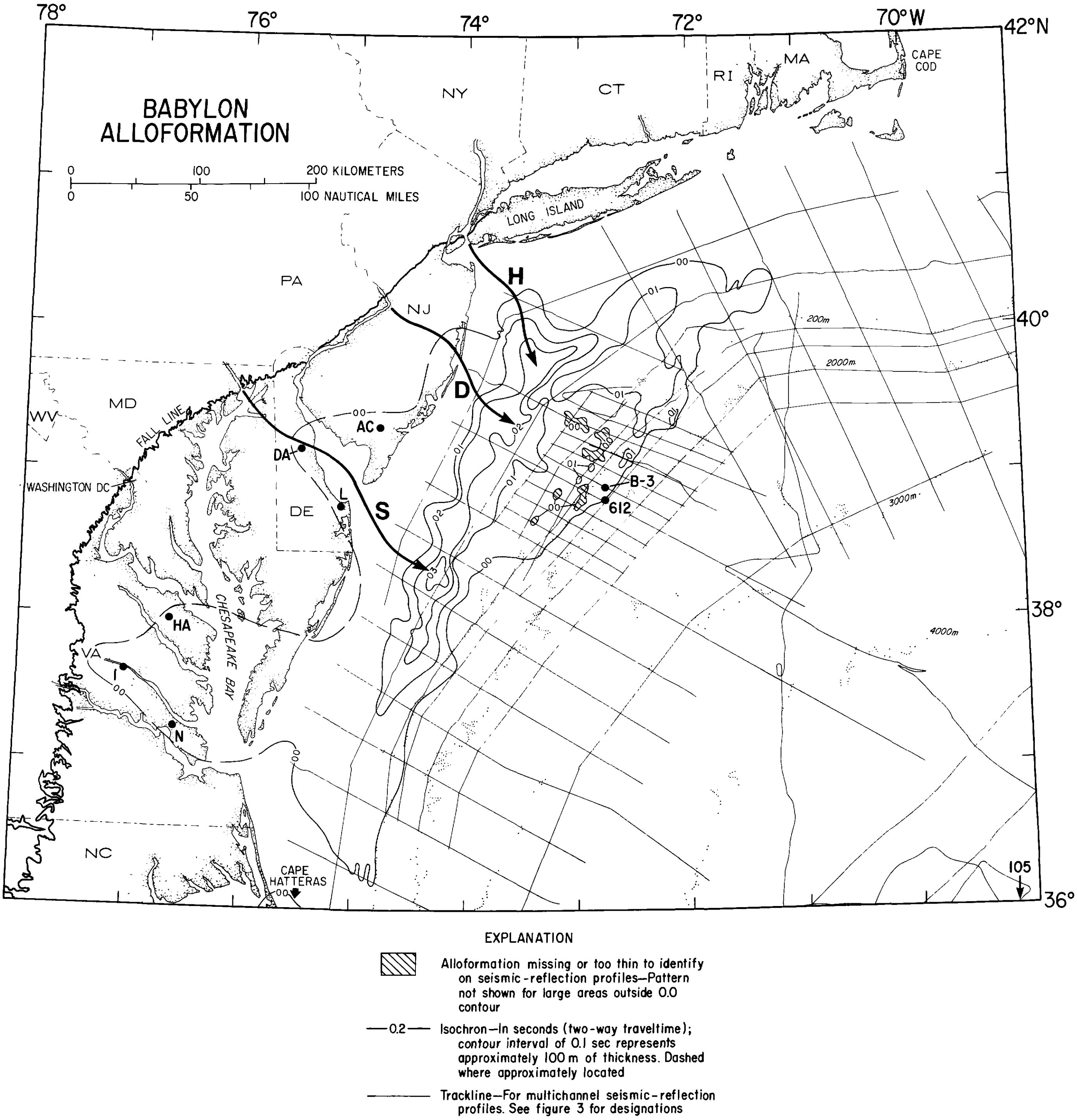


Figure 35. Isochron map of Babylon Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: D, ancient Delaware River; H, ancient Hudson River; S, ancient Susquehanna River. Boreholes: AC, ACGS–4 corehole; DA, Dover Air Force Base well; HA, Haynesville corehole; L, Lewes, Del., borehole; N, Newport News, Va., corehole; other labeled boreholes identified in text. Onshore reference section: 1, USGS loc. 26412 on Pamunkey River at Horseshoe, Va. See figure 3 for location of DSDP Site 105 and Cape Hatteras.

its maximum thickness is ~300 m. Seismic profiles indicate that the alloformation is missing or too thin to identify throughout most of the Hatteras basin (see Poag and Sevon, 1989; Poag, 1992). Figure 11 shows how the Babylon Alloformation correlates with units described in other reports.

The Babylon Alloformation is sparsely represented in the coastal plain, both in the subsurface and in outcrop. The best microfaunally documented sections are of the Old Church Formation cored near Haynesville and Newport News, Va., which contain moderately to well-developed late Oligocene foraminiferal assemblages (Zone P 22; Poag, 1989, and unpub. data, 1993). Outcropping sections of the Old Church Formation in southeastern Virginia (Pamunkey River outcrops) also have been assigned to the upper Oligocene (or lower Miocene; Edwards, 1984, 1989; Frederiksen, 1984a; Ward, 1984; Poag, 1989) on the basis of mollusks, dinoflagellates, sporomorphs, and planktonic foraminifers.

Informally named beds in the subsurface of New Jersey (ACGS Beta unit of Owens and others, 1988; Poore and Bybell, 1988) may belong in the Babylon Alloformation. Miller and others (1990) assigned this unit to the upper Oligocene on the basis of four divergent Sr-isotope dates (ranging from 34.5 Ma to 27.6 Ma; early to late Oligocene). Planktonic microfossils are virtually absent from this unit, and the predominant benthic foraminifers *(Pseudononion pizzarensis* and *Caucasina elongata)* are characteristic of Miocene strata in other coastal-plain localities (Gibson, 1983; Poag, 1989).

Autochthonous late Oligocene foraminiferal assemblages in rotary cuttings from the Lewes borehole (Benson, 1990a) represent the Babylon Alloformation in southeastern Delaware. In northeastern Delaware, an upper Oligocene foraminiferal assemblage possibly assignable to the Babylon Alloformation was reported from the Dover Air Force Base well (Benson and others, 1985). The depositional age of this assemblage is equivocal, however, because it is a mixture of Eocene, Oligocene, and Miocene taxa.

We have chosen the type section of the Old Church Formation on the Pamunkey River at Horseshoe, Hanover County, Va. (Ward, 1985, p. 74, loc. 83, USGS loc. 26412), as the onshore supplementary reference section for the upper part of the Babylon Alloformation and its lower and upper bounding unconformities (fig. 31). At this reference section, 0.9 m of grayish-olive, clayey sand of the Old Church Formation (Babylon Alloformation) unconformably overlies the middle Eocene Piney Point Formation (Lindenkohl Alloformation) and is unconformably overlain by the middle Miocene part of the Calvert Formation (part of the Phoenix Canyon Alloformation as defined herein). Both the lower and upper bounding unconformities are deeply burrowed marine erosion surfaces.

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The Babylon Alloformation, as presently known, is chiefly an upper Oligocene shelf deposit (fig. 35; see Poag and Sevon, 1989; Poag, 1992). Like the middle Eocene Lindenkohl Alloformation, the prograded strata of the Babylon Alloformation created a double shelf. Sediments of the hintershelf are thickest (~300 m) southeast of the present entrance of Delaware Bay. Principal sediment sources appear to have been the same as those that built the Lindenkohl hintershelf.

Strata of the Babylon Alloformation extend downdip to within a few hundred meters of DSDP Site 612 before the section is truncated by erosion (figs. 5–7 and 35). The original edge of the Oligocene foreshelf appears to have been completely eroded in the study area, and its former position can only be grossly estimated to have been somewhere near the edge of the middle Eocene foreshelf. It is possible that a thin deposit of Babylon strata is present in the northern Hatteras basin (Mountain and Tucholke, 1985; Poag, 1985a), but its presence is not obvious on seismic profiles, and it has not yet been identified by drilling.

A thin sedimentary section probably belonging to the Babylon Alloformation was drilled near the outer end of the New Jersey Transect at DSDP Site 105 (fig. 16). There, a 4-m interval in core 105–5 contains noncalcareous, multicolored, zeolitic clays and silts and an ichthyolith assemblage of possibly late Oligocene age (Kaneps and others, 1981).

BERKELEY ALLOFORMATION

DEFINITION

We propose the name Berkeley Alloformation for unconformity-bounded subsurface beds of the exposed coastal plain (Salisbury embayment), the submerged continental shelf and slope (Baltimore Canyon trough), and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Aquitanian and Burdigalian (lower Miocene) strata in this region. The Berkeley Alloformation is named after Berkeley Canyon, which incises the present continental slope and shelf edge ~150 km southeast of Atlantic City, N.J. (fig. 3). The stratotype of the Berkeley Alloformation is the COST B–3 well (figs. 3 and 8), 2 km southwest of Berkeley Canyon at lat 38°55.0′ N., long 72°46.4′ W. At the stratotype, the alloformation is ~96 m thick and consists of glauconitic, micaceous, organic-matter-rich, silty clay containing thin glauconitic sandstone beds.

BOUNDING UNCONFORMITIES

The bounding unconformities of the Berkeley Alloformation were drilled, but not cored, at the stratotype. The lower bounding unconformity is present at 1.85 sec (two-way traveltime) where seismic-reflection profile 218 crosses the stratotype COST B–3 well site (fig. 8, shotpoint 1080). Reflections at the base of the Berkeley Alloformation onlap and downlap the underlying upper Oligocene surface (Babylon Alloformation).

The upper bounding unconformity can be seen at 1.80 sec (two-way traveltime) where profile 218 crosses the stratotype COST B–3 well site. Reflections in the upper part of the alloformation are truncated along the unconformable contact.

On other seismic-reflection profiles, the bounding unconformities of the Berkeley Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Berkeley Alloformation extends in the subsurface nearly continuously from the COST B–3 well to ~30 km northwest of the Dover Air Force Base well, ~300 km updip (fig. 36). Along depositional strike, it extends nearly continuously along the Outer Continental Shelf ~600 km from the Long Island platform (eastern tip of Long Island) to near Cape Hatteras. The alloformation is generally thinner than 100 m in the Salisbury embayment and the inner shelf part of the Baltimore Canyon trough, but it reaches a maximum of >500 m in an elongate delta complex on the middle shelf seaward of New Jersey. The alloformation is missing or too thin to be identified on seismic profiles throughout most of the Hatteras basin (Poag and Sevon, 1989; Poag, 1992), but, where present, it is equivalent to a portion of the upper part of seismic unit D_2 of Schlee and others (1985); the upper part of seismic unit $D_{2.1}$ of Schlee and Hinz (1987); the upper part of the lower and middle Miocene seismic unit of Mountain and Tucholke (1985); the upper part of the Eocene-Oligocene to upper middle Miocene seismic unit of McMaster and others (1989); and the middle part of the deep-sea Blake Ridge Formation (fig. 11).

On the coastal plain of New Jersey, Delaware, Maryland, and Virginia, the Berkeley Alloformation encompasses an informally named lithostratigraphic unit (ACGS Beta unit of Owens and others, 1988) below the Calvert Formation, the lower part of the Calvert Formation in some localities, and probably most of the Kirkwood Formation. In Maryland, the Berkeley Alloformation encompasses the Fairhaven Member of the Calvert Formation, which crops out at numerous localities. The best exposures, however, are along the western shore of the Chesapeake Bay in Calvert County, Md. We have chosen the bluffs exposed at Fairhaven Bay, Anne Arundel County, type section for the Fairhaven Member (Shattuck, 1904, p. lxxxvi, sec. II), as the onshore supplementary reference section for the Berkeley Alloformation (fig. 37). The lower bounding unconformity of the Berkeley Alloformation may be observed along a branch of Lyons Creek, Calvert County, Md., where it separates the Fairhaven Member of the Calvert Formation from strata of Eocene age (Shattuck, 1904, sec. I).

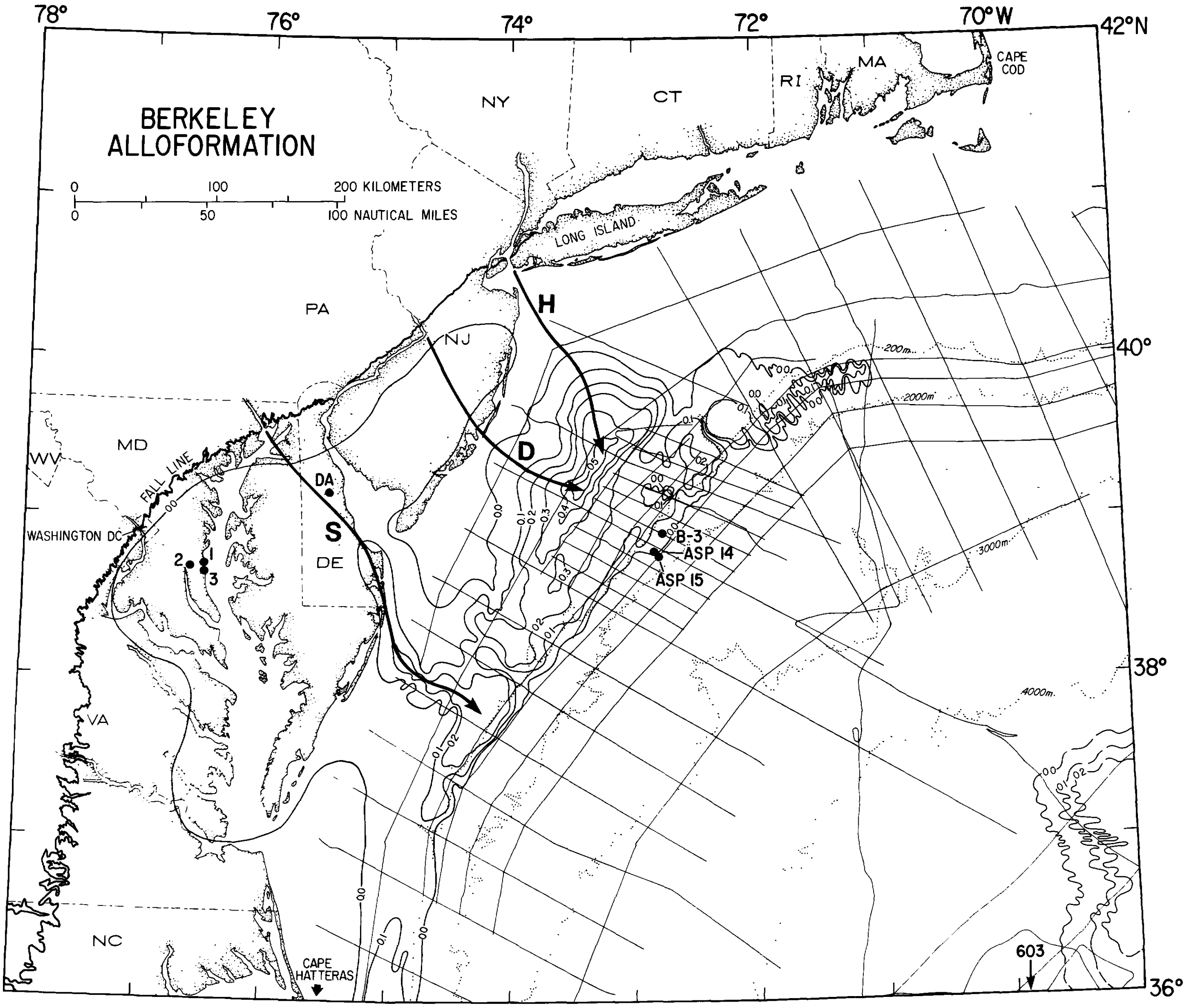
The top of the Berkeley Alloformation is not exposed at Fairhaven Bay but can be seen at the high bluffs south of Chesapeake Beach and north of Randle Cliff, also in Calvert County, Md. (Shattuck, 1904, p. lxxxvii, sec. IV; Ward, 1992, loc. 26). There the upper bounding unconformity separates the lower Miocene Fairhaven Member from the middle Miocene Plum Point Marl Member of the Calvert Formation (fig. 38). The Plum Point Marl Member is encompassed by the Phoenix Canyon Alloformation as defined herein.

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The Berkeley Alloformation is distributed in two widely separated swaths: one in the deep sea near DSDP Site 603, and the other on the continental shelf and coastal plain (see Poag and Sevon, 1989; Poag, 1992). The latter swath extends ~250 km from the shelf edge to ~40 km northwest of the Dover Air Force Base well in Delaware, and ~600 km along strike between the eastern end of Long Island and Cape Hatteras (fig. 36).

During the early Miocene, the double-shelf physiography of the New Jersey margin was maintained (figs. 2 and 36), but the edge of the hintershelf prograded ~40–60 km to the southeast as the Baltimore Canyon trough entered a phase of accelerated terrigenous deposition (Poag and Sevon, 1989; Poag, 1992). The main source of clastic detritus of the Berkeley Alloformation appears to have been north and northwest of the study area (dispersed by the ancient Hudson, Delaware, and Susquehanna Rivers), as the thickest accumulation (>500 m) lies off central New Jersey.

The Berkeley Alloformation is represented on the coastal plain by very silty and sandy paralic and inner sublittoral beds. On the inner part of the coastal plain, such as in the Dover Air Force Base well (figs. 5 and 36), the



EXPLANATION

—0.2— Isochron—In seconds (two-way traveltime); contour interval of 0.1 sec represents approximately 100 m of thickness. Dashed where approximately located

——— Trackline—For multichannel seismic-reflection profiles. See figure 3 for designations

·····200m····· Bathymetry—In meters

Figure 36. Isochron map of Berkeley Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Alloformation is missing or too thin to identify on seismic profiles (outside the 0.0 contour) over most of continental slope and rise. Ancient rivers: D, ancient Delaware River; H, ancient Hudson River; S, ancient Susquehanna River. Boreholes: DA, Dover Air Force Base well; other labeled boreholes identified in text. Onshore reference sections: 1, Fairhaven Bay, Md.; 2, Lyons Creek, Md.; 3, high bluffs between Chesapeake Beach and Randle Cliff, Md. See figure 3 for location of DSDP Site 603 and Cape Hatteras.

alloformation becomes increasingly fine grained and enriched with diatoms. Besides its stratotype at the COST B–3 well, the best documentation of the Berkeley Alloformation on the early Miocene foreshelf comes from the ASP 14 and 15 coreholes (figs. 4 and 36; Poag 1985a), where it consists of glauconitic, micaceous, silty clays.

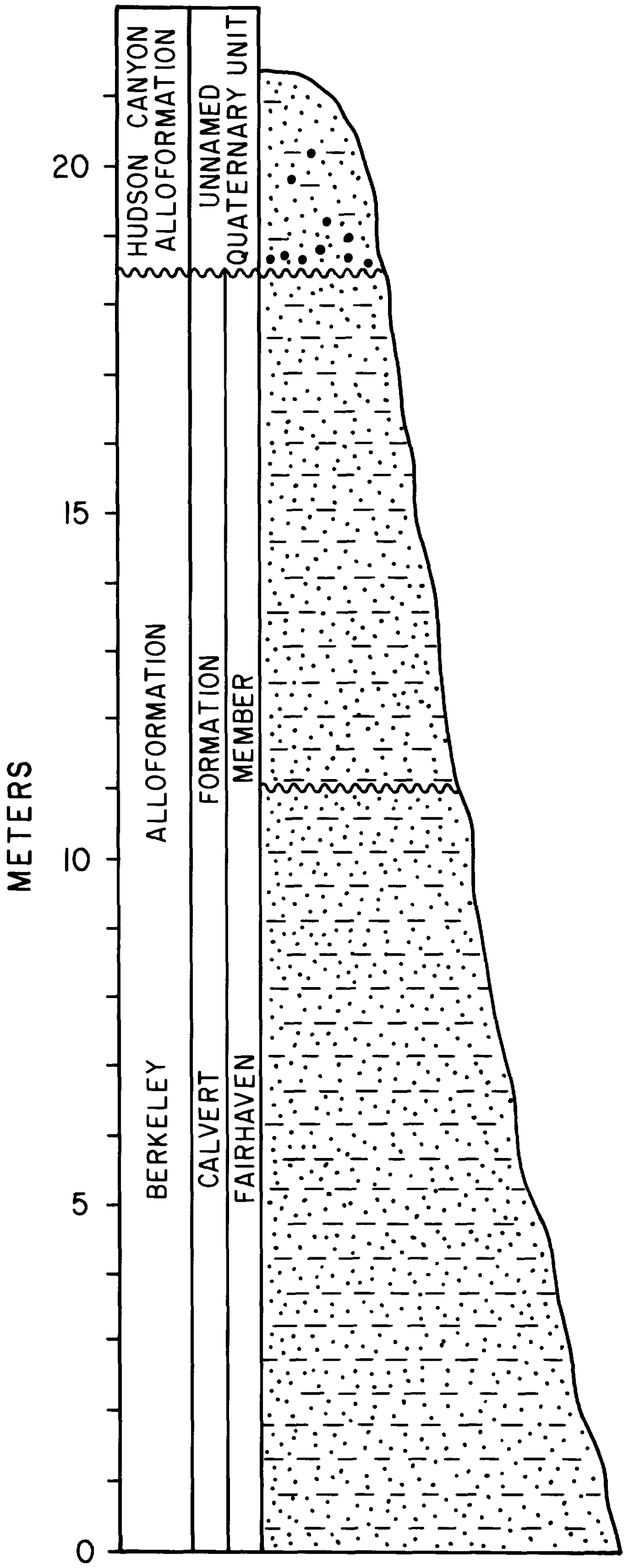


Figure 37. Onshore supplementary reference section for Berkeley Alloformation, exposed at Fairhaven Bay, Anne Arundel County, Md. (Shattuck, 1904, sec. II). See figure 12 for lithologic explanation and figure 36 for location.

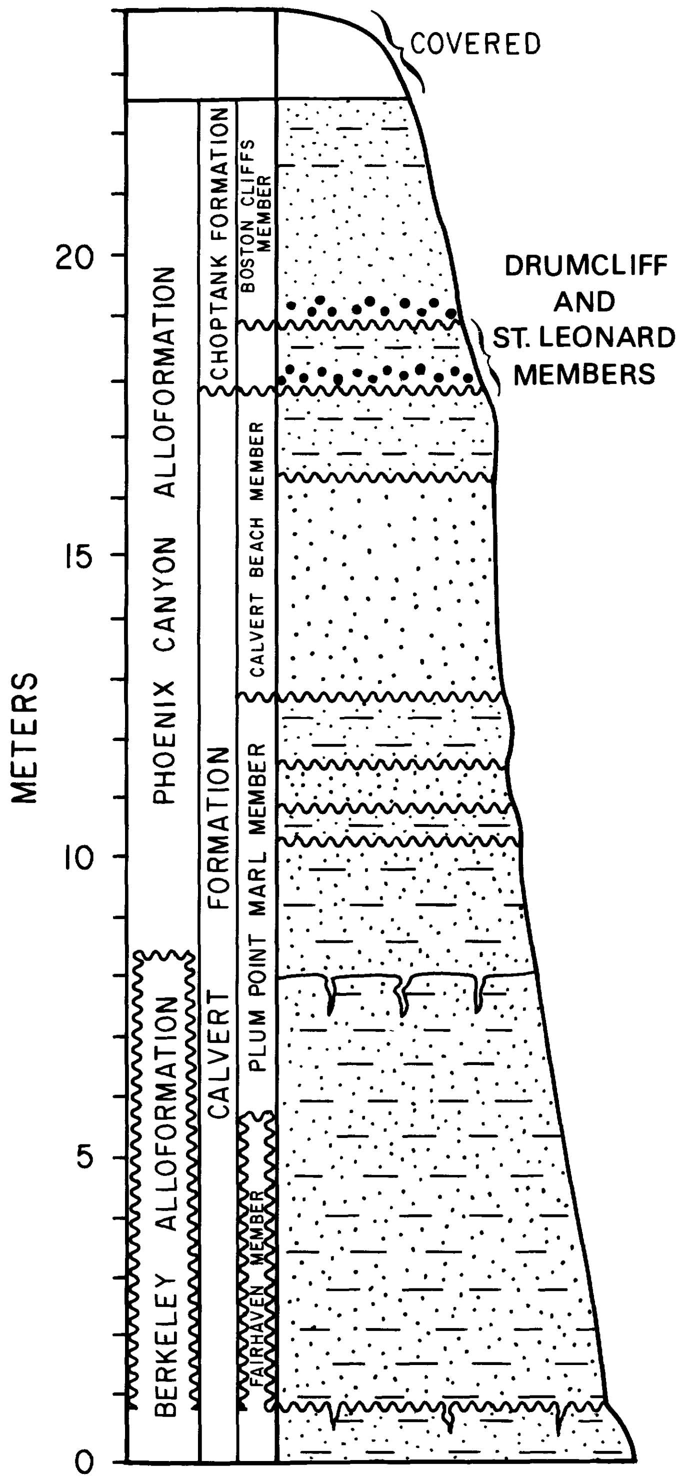


Figure 38. Onshore supplementary reference section for upper part of Berkeley Alloformation, lower part of Phoenix Canyon Alloformation, and unconformity that separates them, exposed south of Chesapeake Beach and north of Randle Cliff, Calvert County, Md. (Shattuck, 1904, sec. IV; Ward, 1992, loc. 26). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 36 for location.

At DSDP Site 603 (figs. 5 and 15), part of a 14-m section of gray, brown, and yellow, silty, sideritic, gas-emitting claystones may belong to the Berkeley Alloformation. This claystone section contains early to middle Miocene ichthyoliths in an otherwise nonfossiliferous interval (Van Hinte, Wise, and others, 1987) resting on lower Eocene radiolarian-bearing claystones. Seismic extrapolation of this thin claystone section updip across the continental rise shows that it pinches out ~400 km southeast of the base of the continental slope.

PHOENIX CANYON ALLOFORMATION

DEFINITION

We propose the name Phoenix Canyon Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury Embayment) and the submerged continental shelf and slope (Baltimore Canyon trough) and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Langhian and Serravalian (middle Miocene) strata in this region. The Phoenix Canyon Alloformation is named after Phoenix Canyon, which incises the present continental slope and shelf edge ~150 km southeast of Atlantic City, N.J. (fig. 3). The stratotype of the Phoenix Canyon Alloformation is DSDP Site 603 (fig. 15) on the lower continental rise, at lat 35°29.66′ N., long 70°01.70′ W. At the stratotype, the alloformation is 258.9 m thick and consists of dark-greenish-gray, silty, micaceous, commonly sideritic, organic-matter-rich, turbiditic claystone.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Phoenix Canyon Alloformation has been cored at DSDP Site 603 (Hole 603B; Poag, 1987). The unconformity occurs, however, in a section whose stratification has been disrupted by the coring process, thus obscuring the precise position of the contact (Van Hinte, Wise, and others, 1987). The estimated position is at 928.37 m below the sea floor (1.37 m below the top of section 1, core 12). At this level, a 15-cm gap in the core separates dark-grayish-green claystone (below) from grayish-green, silt-rich, micaceous, quartzose claystone (above).

On seismic profile *Conrad* 21 (segment 77, 1700 to 1800 hr), which crosses DSDP Site 603 (fig. 15), the lower bounding unconformity can be seen at 7.19 sec (two-way traveltime), where reflections in the lower part of the Phoenix Canyon Alloformation onlap the upper surface of the underlying lower Miocene beds (Berkeley Alloformation).

The upper bounding unconformity of the Phoenix Canyon Alloformation has been cored at DSDP Site 603 (Hole 603), ~669.4 m below the sea floor (top of section 1, core 39; fig. 15; see Poag, 1987; Van Hinte, Wise, and others, 1987). The unconformity separates dark-greenish-gray, mica-rich, silty claystone (below) from dark-greenish-gray, quartz-bearing, silty claystone (above) containing pyritized burrows and siderite nodules. Disturbance of stratification by the coring process obscures the unconformable contact.

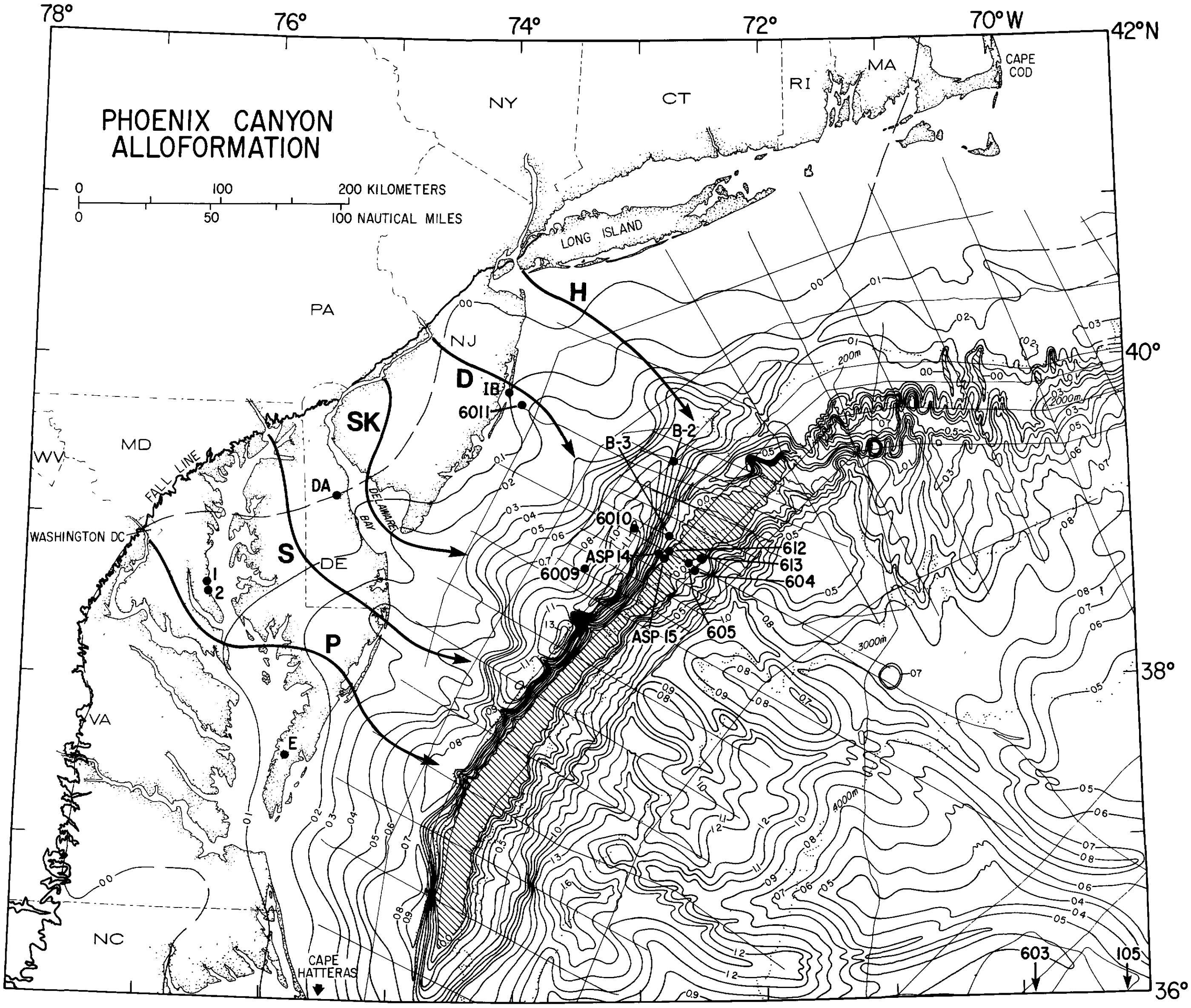
On seismic profile *Conrad* 21 (segment 77, 1700 to 1800 hr), which crosses DSDP Site 603 (fig. 15), the upper bounding unconformity can be seen at 6.79 sec (two-way traveltime), where reflections from the upper part of the alloformation are truncated and onlapped by reflections of the overlying upper Miocene beds.

On other seismic-reflection profiles, the bounding unconformities of the Phoenix Canyon Alloformation can be traced throughout the offshore region by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Phoenix Canyon Alloformation extends continuously from seaward of DSDP Site 603 to ~20 km west of the Dover Air Force Base well, ~750 km updip (fig. 39). Along depositional strike, the alloformation extends continuously over the entire study area, ~900 km from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras).

The Phoenix Canyon Alloformation is generally thinner than 100 m in the Salisbury embayment, but it thickens dramatically to >1,300 m in an enormous complex of deltas on the Miocene outer continental shelf. The alloformation has been eroded along much of the continental slope, but, in the northern Hatteras basin, it comprises large submarine fans and contourite drifts, which reach thicknesses of >1,600 m (McMaster and others, 1989; Poag and Sevon, 1989; Poag, 1992). In the outer part of the Baltimore Canyon trough and in the Hatteras basin, the Phoenix Canyon Alloformation is correlative with the uppermost part of seismic unit D_2 of Schlee and others (1985); the uppermost part of seismic unit $D_{2.1}$ and the lower half of seismic unit $D_{2.2}$ of Schlee and Hinz (1987); the uppermost part of the lower and middle Miocene seismic unit and the lower third of the upper Miocene(?) unit of Mountain and Tucholke (1985); the middle Miocene and "not known"



EXPLANATION

Alloformation missing or too thin to identify on seismic-reflection profiles

—0.2— Isochron—In seconds (two-way traveltime); contour interval of 0.1 sec represents approximately 100 m of thickness. Dashed where approximately located

——— Trackline—For multichannel seismic-reflection profiles. See figure 3 for designations

·····200m····· Bathymetry—In meters

Figure 39. Isochron map of Phoenix Canyon Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Note that main shelf depocenters have moved to edge of single shelf in front of present Delaware Bay. Ancient rivers: D, ancient Delaware River; H, ancient Hudson River; P, ancient Potomac River; S, ancient Susquehanna River; SK, ancient Schuylkill River. Boreholes: 14 and 15, ASP (Atlantic Slope Project) boreholes; B–2 and B–3, COST (Continental Offshore Stratigraphic Test) wells; DA, Dover Air Force Base well; E, Exmore corehole; IB, Island Beach No. 1 borehole; 6009, 6010, and 6011, AMCOR (Atlantic Margin Coring Project) coreholes; other labeled boreholes identified in text. Onshore reference sections: 1, high bluffs between Chesapeake Beach and Randle Cliff, Md.; 2, Parker Creek, Md. See figure 3 for location of DSDP Sites 603 and 105 and Cape Hatteras.

seismic units of Poag (1987); the uppermost part of the Eocene-Oligocene to upper middle Miocene seismic unit of McMaster and others (1989); seismic sequences 1–3 of Tucholke and Laine (1982); the lower parallel layered subunit of the layered rise seismic unit of O'Leary (1988); seismic units 6W and 7W of Danforth and Schwab (1990); seismic unit T1 of Locker and Laine (1992); and some of the upper part of the deep-sea Blake Ridge Formation (fig. 11).

On the coastal plain of Virginia and Maryland, the Phoenix Canyon Alloformation encompasses the upper beds of the Calvert Formation (Plum Point Marl and Calvert Beach Members) and the Choptank Formation (Drumcliff, St. Leonard, and Boston Cliffs Members). Beds encompassed by the Phoenix Canyon Alloformation are best exposed along the major coastal waterways, such as the Chesapeake Bay, and along the Potomac, Rappahannock, Mattaponi, and Pamunkey Rivers in Virginia. The most complete sections including all of the beds composing the Phoenix Canyon Alloformation are present along the western shore of the Chesapeake Bay in Calvert County, Md. No single section, however, exposes all of the beds well. The lower part of the alloformation is exposed in the same locality as the onshore reference section for the Berkeley Alloformation, south of Chesapeake Beach and north of Randle Cliff, Calvert County, Md. (Shattuck, 1904, p. lxxxvii, sec. IV; Ward, 1992, loc. 26). We have chosen this exposure also as the onshore supplementary reference section for the lower part of the Phoenix Canyon Alloformation and its lower bounding unconformity (fig. 38). There the lower bounding unconformity separates the lower Miocene Fairhaven Member of the Calvert Formation from the middle Miocene Plum Point Marl Member of the Calvert Formation.

The upper part of the alloformation, including the Calvert Beach Member of the Calvert and all three members of the Choptank Formation, is exposed just south of the mouth of Parker Creek, Md. (Shattuck, 1904, p. lxxxix, sec. X; Ward, 1992, loc. 18). We have chosen this exposure as the onshore supplementary reference section for the upper part of the Phoenix Canyon Alloformation and its upper bounding unconformity (fig. 40). There the upper bounding unconformity separates the middle Miocene Boston Cliffs Member of the Choptank Formation from the upper Miocene Little Cove Point Member of Ward (1984) of the St. Marys Formation (the latter member is encompassed by the Mey Alloformation as defined herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

During the middle Miocene, accumulation of prograding deltaic detritus accelerated to a maximum for Tertiary

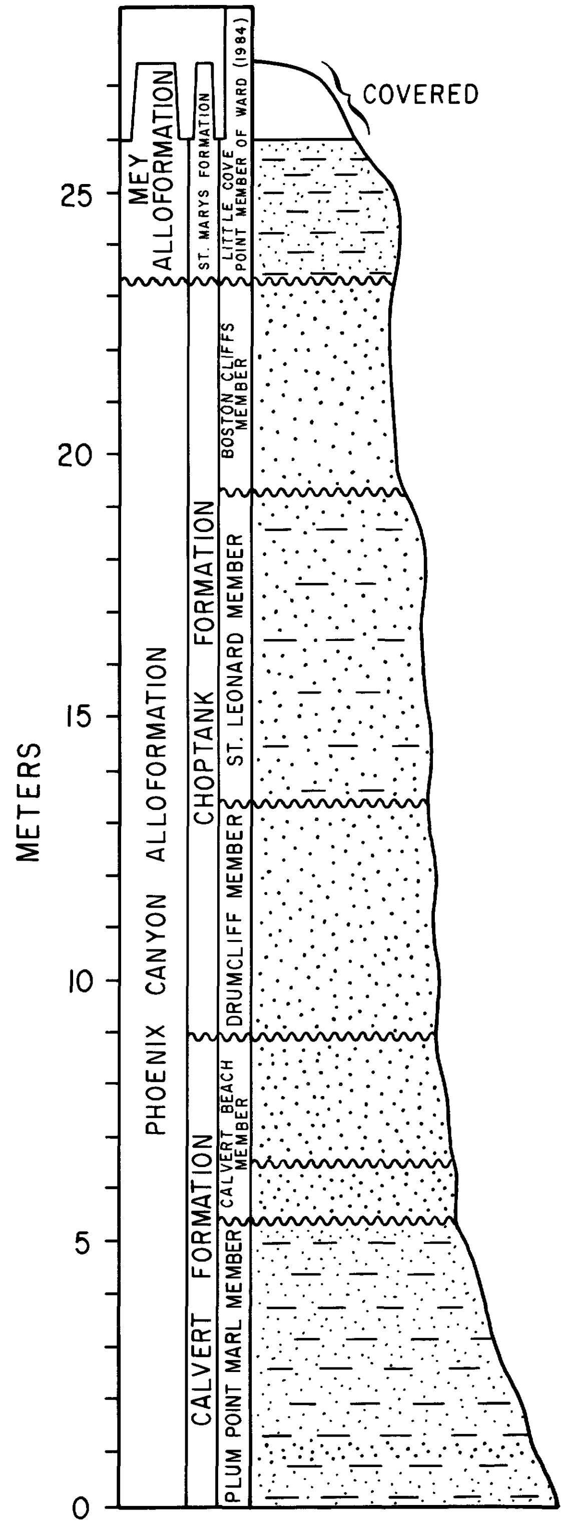


Figure 40. Onshore supplementary reference section for upper part of Phoenix Canyon Alloformation and its upper bounding unconformity, exposed south of Parker Creek, Calvert County, Md. (Shattuck, 1904, sec. X; Ward, 1992, loc. 18). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 39 for location.

deposition in the Baltimore Canyon trough (see Poag and Sevon, 1989; Poag, 1992). Presumably, deep weathering of humic subtropical soils (Frederiksen, 1984b) and tectonic uplift of the central Appalachian Highlands (Hack, 1982; Poag and Sevon, 1989; Poag, 1992) contributed to this rapid accumulation. The main shelf depocenter of the middle Miocene, located off the present mouth of Delaware Bay, collected more than 1,300 m of terrigenous detritus assigned to the Phoenix Canyon Alloformation (figs. 2 and 39). The chief sources for these terrigenous strata appear to have been the Adirondacks and central Appalachian Highlands (Poag and Sevon, 1989; Poag, 1992). The Phoenix Canyon Alloformation of the continental shelf forms the bulk of Schlee's (1981) prograded Unit G. Garrison (1970), writing before borehole data were available, speculated that this wedge prograded during the Oligocene. Several major pulses of seaward progradation took place during the middle Miocene, as shown by the presence of discrete sets of prograding reflections on the shelf segments of the dip profiles (Greenlee and Moore, 1988).

The Phoenix Canyon Alloformation thins to the northeast and southwest and shoreward from the outer shelf depocenter, and its slope apron has been deeply incised by shelf-edge submarine canyons that developed during the Pleistocene (fig. 39). By the end of the middle Miocene, the hintershelf edge had moved seaward ~30–60 km from its early Miocene position and had formed the relatively steep slope face that is the foundation of today's continental slope. At this time, therefore, the New Jersey margin was again characterized by a single shelf break (fig. 2). The Phoenix Canyon Alloformation has been truncated by erosion along much of the lower continental slope, where it borders the submarine outcrop belt of the Lindenkohl Alloformation (diagonal-line pattern on fig. 39). Presumably, Phoenix Canyon strata originally covered this belt and joined the upper rise prism as they presently do along the Long Island platform.

Three unnamed allomembers can be distinguished within the Phoenix Canyon Alloformation (Poag, 1987). The older two allomembers can be traced with confidence all the way to Site 603 along seismic profile *Conrad* 21 (fig. 15), where microfossils document their middle Miocene age. The oldest allomember reaches DSDP Site 105 (fig. 16), but the middle allomember does not. The youngest allomember is limited to a small area southwest of the upper rise drill sites (DSDP Sites 604, 605, 613; figs. 4 and 39) and has not yet been sampled. In composite distribution, these three allomembers are thickest (1,000–1,600 m) in a submarine fan complex southwest of the shelf-edge depocenter (fig. 39); they thin northeastward in concert with the shelf sequences of the Phoenix Canyon Alloformation. They also thin basinward in the direction of DSDP Site 603, where a 258.9-m section was cored (fig. 15). The downslope ribbed fabric, characteristic of older alloformations of the upper rise prism, was maintained and intensified during deposition of the Phoenix Canyon Alloformation, as turbidity currents and debris flows repeatedly cut and filled downslope channels and extended multilobed submarine fans across the continental rise (fig. 39).

The Phoenix Canyon Alloformation is noted on the coastal plain for its content of quartzose, shelly, diatomaceous, sandy beds and gray-green clay (Owens and Minard, 1979; Ward and Strickland, 1985). Paleocurrent directions derived from extensive crossbedding in the fluviatile sands (Owens and Minard, 1979) indicate that a major middle Miocene drainage system (perhaps the ancient Schuylkill River) paralleled the present Delaware River southwestward across New Jersey and turned sharply eastward directly toward the principal outer shelf depocenter of the Phoenix Canyon Alloformation (fig. 39).

In the Island Beach well (fig. 39), 100 m of glauconitic, micaceous, shelly, medium to coarse, quartzose sand and several beds of gray, micaceous, lignitic, silty clay represent the Phoenix Canyon Alloformation (Poag, 1985a). Most samples are barren of microfossils, but diatoms and a few middle Miocene radiolarians have been identified. Paralic and inner and middle sublittoral paleoenvironments are inferred from the lithofacies and biofacies of these strata.

At the COST B–2 well (Poag, 1985a, 1987), along the northeast margin of the depocenter, the Phoenix Canyon Alloformation thickens to 600 m. Here silty, micaceous, organic-matter-rich sands, sandy silts, and silty clays contain abundant diatoms. Foraminifers are sparse and poorly preserved, and radiolarians are few. Middle sublittoral paleoenvironments are inferred from these constituents. Three AMCOR coreholes (6009, 6010, 6011; Poag, 1985a) penetrated part of the Phoenix Canyon Alloformation within 100 km of the COST B–2 well, revealing similar lithofacies and microfaunal assemblages.

At the COST B–3 well, the Phoenix Canyon section thins to 200 m on the lower part of the middle Miocene continental slope (fig. 8). Glauconitic, micaceous, organic-matter-rich, silty clays dominate this site and contain lower bathyal (1,000–1,500 m) microfossil assemblages; radiolarians and diatoms are especially abundant constituents. At nearby ASP borehole 14, 240 m of similar strata were cored, and an abbreviated 24-m section was sampled at ASP borehole 15 (Poag, 1985a). The Phoenix Canyon Alloformation has been completely removed from DSDP Site 612 (figs. 6 and 7) and Site 605 (fig. 17) by local downslope channeling, but seismic-reflection profiles show that the unit is present downdip from Site 613 (fig. 28), which occupies an interchannel ridge.

Within the upper rise prism, seismic facies of the Phoenix Canyon Alloformation include onlap and chaotic fill, which are especially common near the base of the deep downslope channels. Several mounded sedimentary sections represent submarine fan deposits.

At DSDP Site 603 (fig. 15), the Phoenix Canyon Alloformation stratotype consists of 258.9 m of dark-greenish-gray, silty, micaceous, commonly sideritic claystone and is the second thickest alloformation cored at Site 603. Foraminifers are sparse or missing throughout this section, but nannofossils are common, especially in the upper half of the section, and radiolarians are abundant in the lower two-thirds. Siliciclastic turbidites characterize this site, and the emission of gas from many of the cores results from relatively abundant terrigenous organic matter (as much as 1.32 percent total organic carbon).

Phoenix Canyon strata of the continental shelf and slope also are enriched in organic matter (both marine and terrigenous). Poag (1985a) and Palmer (1986) concluded that upwelling combined with the accumulation of organic-matter-rich deltaic sediments created high biologic productivity in the coastal waters in the middle Miocene (see also Snyder, 1982; Riggs, 1984), which accounts for the abundance of diatoms and radiolarians in the shelf sequences.

The contact between the Phoenix Canyon Alloformation and overlying upper Miocene sections has not been cored on the continental shelf, slope, and upper continental rise region off New Jersey, but seismic-reflection profiles (figs. 8, 15, and 17) indicate that it is a widespread erosional surface. The uppermost part of the Phoenix Canyon Alloformation is missing at the most complete stratigraphic sections in Virginia and Maryland (Ward and Strickland, 1985; Olsson and others, 1987). An even longer hiatus seems to be represented in the subsurface of New Jersey and parts of Delaware, where Pleistocene strata of the Hudson Canyon Alloformation rest on the upper surface of the Phoenix Canyon Formation in many places (Owens and Minard, 1979; Benson and others, 1985; Ward and Strickland, 1985). The paralic nature of many of the middle Miocene and younger formations of the coastal plain, however, reduces the accuracy of fossil dating techniques so that most age relations (and the duration of hiatuses) are imprecisely known.

The most severe erosion on the upper surface of the Phoenix Canyon Alloformation took place on the continental slope, as expressed by abrupt truncation of seismic reflections along all the dip profiles (for example, see figs. 8 and 28). Clearly, large volumes of sediment were removed from what is now the submarine outcrop belt of the Lindenkohl Alloformation (middle Eocene) and transferred to the upper rise wedge by downslope gravity flows. The Gemini fault system (fig. 2), which presumably periodically triggered downslope mass movement (Poag, 1987), appears to have become dormant during the late middle Miocene, as seismic reflections are offset along the fault traces only about halfway up through the thick Phoenix Canyon section (fig. 8).

MEY ALLOFORMATION

DEFINITION

We propose the name Mey Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment) and the submerged continental shelf and slope (Baltimore Canyon trough) and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Tortonian and Messinian (upper Miocene) strata in this region. The Mey Alloformation is named after Mey Canyon, which incises the present continental slope and shelf edge ~150 km southeast of Atlantic City, N.J. (fig. 3). The stratotype of the Mey Alloformation is DSDP Site 603 (fig. 15), on the lower continental rise ~420 km southeast of Mey Canyon, at lat 35°29.66′ N., long 70°01.70′ W. At the stratotype, the Mey Alloformation is 341.8 m thick and consists of dark-greenish-gray, micaceous, quartzose, sideritic claystone.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Mey Alloformation has been cored at Site 603 (fig. 15), ~669.4 m below the sea floor (top of section 1, core 39; Poag, 1987; Van Hinte, Wise, and others, 1987). The unconformity separates dark-greenish-gray, mica-rich, silty claystone (below) from dark-greenish-gray, quartz-bearing, silty claystone (above) containing pyritized burrows and siderite nodules. Disturbances of stratification by the coring process obscure the unconformable contact. The contact is exceptionally well preserved, however, at DSDP Site 612 (fig. 32; see Poag and Low, 1987). There, dark-olive-gray, homogeneous mud of the Mey Alloformation is separated from light-gray microfossil-bearing ooze of the Baltimore Canyon Alloformation by a 5-cm section of dark-gray, well-sorted, coarse, quartzose, turbidite sand.

The lower bounding unconformity can be seen on seismic profile *Conrad* 21 (segment 77), which crosses DSDP Site 603 (fig. 15). The unconformity is expressed between the 1700-hr and 1800-hr positions on this profile at 6.79 sec (two-way traveltime). Seismic reflections from the bottom part of the Mey Alloformation onlap and downlap the underlying unconformable surface of the Phoenix Canyon Alloformation at this locality.

The upper bounding unconformity of the Mey Alloformation has been cored at Site 603 (Hole 603C), ~327.6 m below the sea floor (core catcher of core 36; fig. 15; Poag, 1987; Van Hinte, Wise, and others, 1987). The unconformity separates dark-gray to greenish-gray, nannofossil-rich,

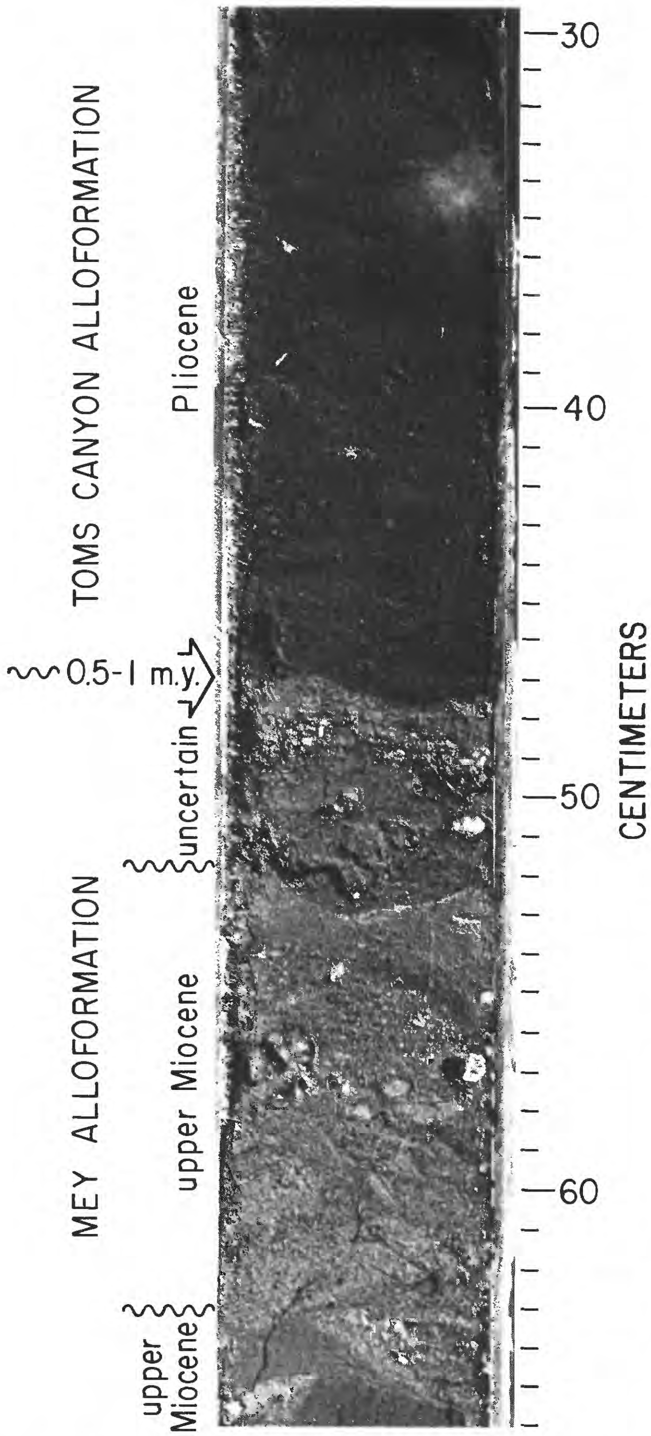


Figure 41. Unconformity separating Mey Alloformation from Toms Canyon Alloformation at DSDP Site 604. Unconformity is 238.97 m below sea floor and is 47 cm below the top of section 2, core 26 (Poag, 1985b). Hiatus is approximately 0.5–1.0 m.y.

sideritic, pyrite-bearing claystone (below) from dark-greenish-gray quartz- and mica-bearing claystone (above). The upper bounding unconformity is more sharply expressed at DSDP Site 604 (figs. 41 and 42; see Poag and Low, 1987). At Site 604, the Mey Alloformation consists of brownish-gray conglomerates, which are separated by a sharp scour surface from dark-olive-green, biosiliceous, glauconitic claystone of the Toms Canyon Alloformation.

The upper bounding unconformity may be seen between the 1700-hr and 1800-hr marks on seismic profile *Conrad* 21 (segment 77) at 6.36 sec (two-way traveltime), where it truncates reflectors in the top part of the Mey Alloformation (fig. 15).

On other seismic-reflection profiles, the bounding unconformities of the Mey Alloformation can be traced throughout the offshore area by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Mey Alloformation extends continuously in the subsurface from the vicinity of DSDP Site 603 to ~750 km updip in the Salisbury embayment (fig. 43), where it crops out in the coastal plain. Along depositional strike, it extends continuously ~900 km along the margin from the Long Island platform (Cape Cod) to the Carolina platform (Cape Hatteras).

The Mey Alloformation is thinner than 100 m in most of the Salisbury embayment, but it reaches 100–300 m along the edge of the upper Miocene continental shelf (outer part of the Baltimore Canyon trough) between the present Cape Charles, Va., and Cape May, N.J. (Andres, 1986; Benson, 1990a), and thickens to as much as 300–500 m in several small shelf-edge depocenters. The alloformation is missing in a broad swath along most of the continental slope but reaches its maximum thickness of >800 m on the lower continental rise (Mountain and Tucholke, 1985; Poag and Sevon, 1989; Poag, 1992). In the northern Hatteras basin, the alloformation is equivalent to the lower third of seismic unit D_3 of Schlee and others (1985); the upper half of seismic unit $D_{2.2}$ of Schlee and Hinz (1987); the upper two-thirds of the upper Miocene(?) seismic unit of Mountain and Tucholke (1985); the upper Miocene seismic unit of Poag (1987); seismic sequence 4 of Tucholke and Laine (1982); the lower part of the middle transparent subunit and of the lentil subunit of the layered rise seismic unit of O'Leary (1988); the lower two-thirds of seismic unit 5W of Danforth and Schwab (1990); seismic unit T2 of Locker and Laine (1992); and some of the upper part of the deep-sea Blake Ridge Formation (fig. 11).

On the coastal plain of Virginia, Maryland, Delaware, and New Jersey, the Mey Alloformation encompasses the St. Marys Formation, Eastover Formation, and Manokin formation of Andres (1986); perhaps the Bethany formation of Andres (1986) and the lower part of the Beaverdam

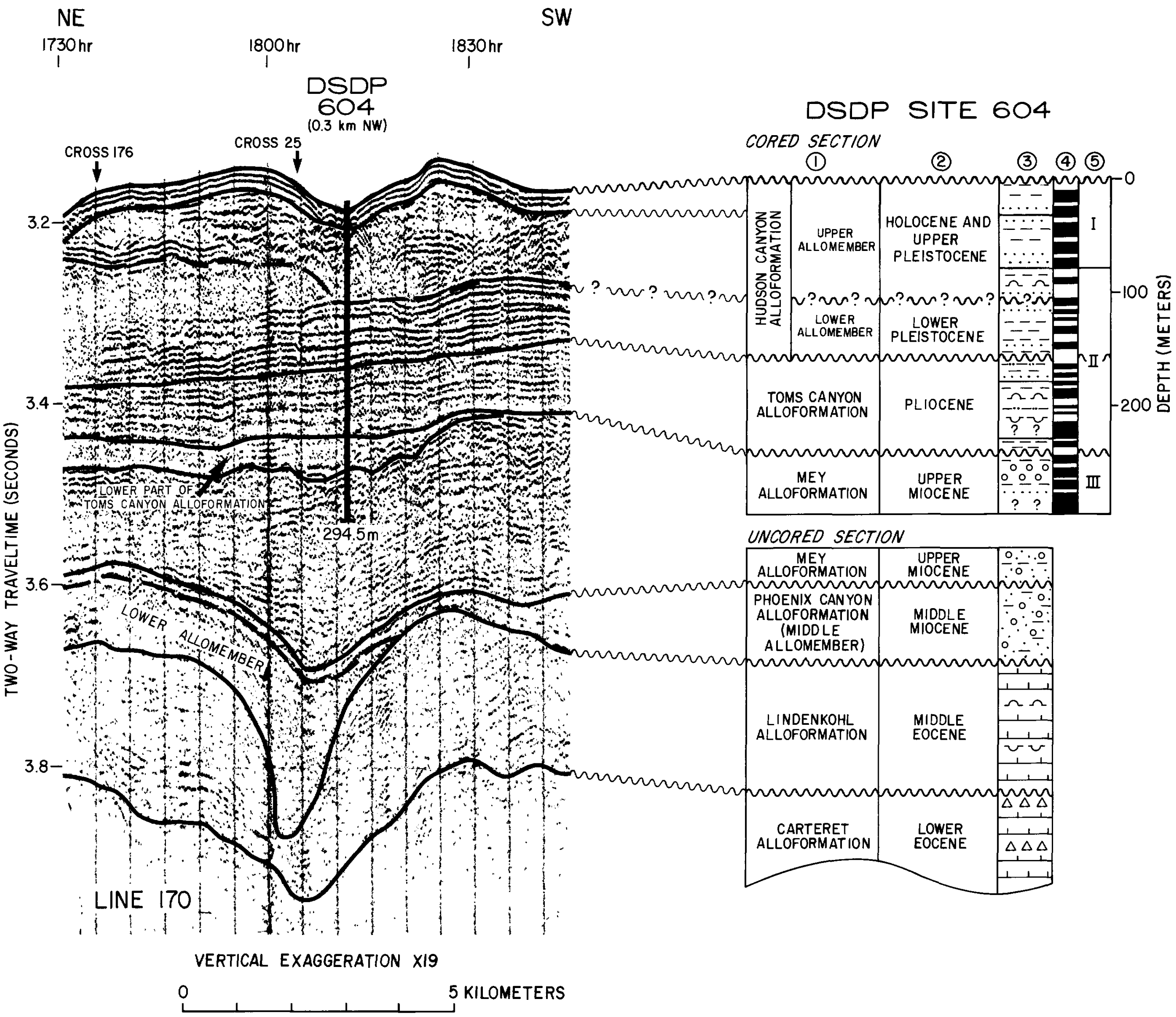


Figure 42. Stratigraphic section at DSDP Site 604 and extrapolation along strike segment of single-channel seismic-reflection profile 170 (see fig. 4 for profile location). Note deep channels cut into Carteret and Lindenkohl Alloformations. See figure 6 for explanation of geology, profile reference points, and columns 1–5.

Formation (Groot and others, 1990); and, possibly, part of the Pensauken Formation. The St. Marys Formation consists of three members whose coastal-plain depocenters migrated progressively farther southward through late Miocene time (Ward, 1984; Ward and Strickland, 1985). The (lower) Conoy Member is confined mostly to southern Maryland. The (middle) Little Cove Point member of Ward (1984) is also present in southeastern Maryland, whereas the (upper) Windmill Point member of Ward (1984) extends from southern Maryland into northeastern Virginia. The Conoy Member can best be seen south of Flag Pond, Calvert County, Md. (Shattuck, 1904, p. xc, sec. XIV; Ward, 1992, loc. 17). We have selected the Flag Pond exposure as the onshore supplementary reference section for the lower part of the Mey Alloformation and its lower bounding unconformity (fig. 44). There the lower bounding unconformity separates the middle Miocene Boston Cliffs Member of the Choptank Formation (upper part of Phoenix Canyon Alloformation) from the upper Miocene Conoy Member of the St. Marys Formation (lower part of Mey Alloformation). The Little Cove Point member of Ward (1984) is best exposed just south of Little Cove Point (Shattuck, 1904, p. xci, sec. XV). The Windmill Point member of Ward (1984) is exposed at Windmill Point on the St. Marys River, Md., but it is best seen across the river from Windmill Point, at Chancellor Point (Shattuck, 1907, p. 80, sec. II; Ward, 1992, loc. 13).

The areal extent of the Eastover Formation includes the coastal plain of Virginia, the southeastern part of Maryland, and northeastern North Carolina. The coastal-plain depo-

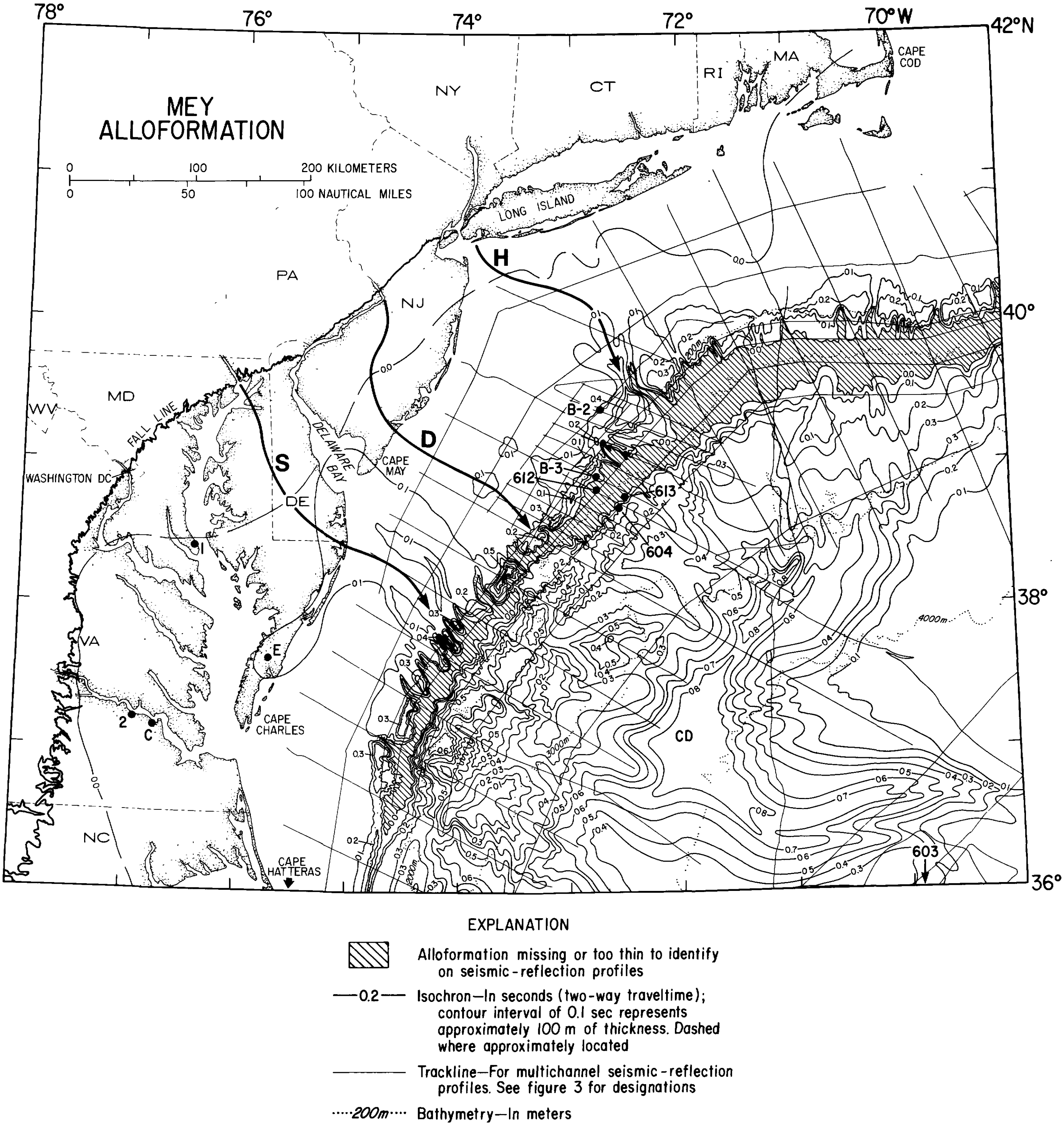


Figure 43. Isochron map of Mey Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: D, ancient Delaware River; H, ancient Hudson River; S, ancient Susquehanna River. Boreholes: E, Exmore corehole; other labeled boreholes identified in text. CD, Chesapeake drift. Onshore reference sections: 1, Flag Pond, Md.; 2, Claremont, Va. Other onshore exposure: C, Cobham Wharf, Va. See figure 3 for location of DSDP Site 603 and Cape Hatteras.

center of the Eastover is in central Virginia, where the formation is 43 m thick in the Exmore corehole (Powars and others, 1992). The (lower) Claremont Manor Member of the Eastover is well exposed in the vicinity of Claremont, on the south bank of the James River, Surry County, Va. (Ward and Blackwelder, 1980, p. 15, loc. 42; Ward, 1992, loc. 7). The (upper) Cobham Bay Member of the Eastover is also present at the Claremont locality but is best exposed in its type area at Cobham Wharf, Surry County, Va. (Ward and Blackwelder, 1980, p. 22, loc. 28). We have chosen the Claremont locality as the onshore supplementary reference section for the upper part of the Mey Alloformation and its upper bounding unconformity (fig. 45). There the upper bounding unconformity separates the upper Miocene Cobham Bay Member of the Eastover Formation (upper part of the Mey Alloformation) from the lower Pliocene Sunken Meadow Member of the Yorktown Formation (lower part of the Toms Canyon Alloformation as defined herein).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The late Miocene was a time when deep-water deposition dominated the middle Atlantic margin, as the shelf break migrated still farther seaward than its middle Miocene position, and the principal depocenters were established on the continental rise (400–800 m thickness; figs. 2 and 43; see Poag and Sevon, 1989; Poag, 1992). Shelf deposition of the Mey Alloformation was relatively sparse (generally <100 m), except at the shelf edge.

In the northern Hatteras basin, the main depocenter for Mey sediments shifted northeastward relative to that of the Phoenix Canyon Alloformation (fig. 43); maximum thickness (>800 m) accumulated on the middle continental rise. There vigorous longslope bottom currents swept the sediments into the elongate, crescentic, contourite mound known as the Chesapeake drift (Tucholke and Laine, 1982; Mountain and Tucholke, 1985; Tucholke and Mountain, 1986; Poag and Sevon, 1989; Poag, 1992).

The upper and middle continental rise are crossed by numerous, broad to narrow, downslope channels filled with chaotic seismic facies of the Mey Alloformation. At DSDP Site 604 on the upper rise (fig. 42), the upper part of the Mey channel fill yielded coarse conglomeratic sands containing large quartz pebbles, igneous and metamorphic clasts, and white chunks of reworked Eocene chalk (Poag, 1985b; Van Hinte, Wise and others, 1987). DSDP Site 613 (fig. 28) is located over a late Miocene interchannel ridge, where the Mey section is much thinner than at Site 604, but even there the strata of the Mey Alloformation are coarse to fine, glauconitic, quartzose sands and conglomeratic sands.

Channel-fill deposits were recovered from the Mey Alloformation also at DSDP Site 612 (figs. 6 and 7). There the sediments are finer grained, chiefly dark-gray, micaceous mud, but chert pebbles, glauconitic quartz sand, and vertebrate fossils are also present. Sediments of the Mey Alloformation have not been documented from any other drill site on the New Jersey margin. Although several exploration wells and the COST B–2 and B–3 (fig. 8) wells

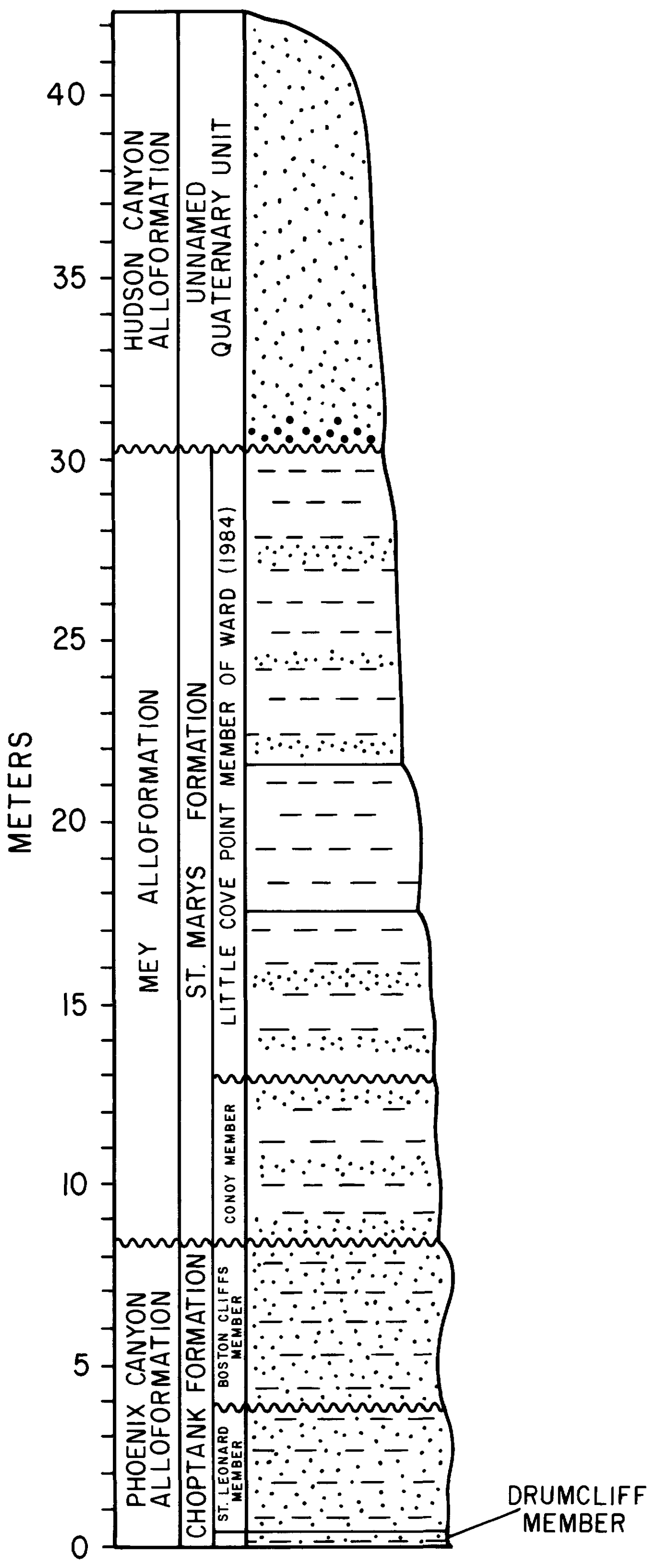


Figure 44. Onshore supplementary reference section for lower part of Mey Alloformation and its lower bounding unconformity, exposed at Flag Pond, Calvert County, Md. (Shattuck, 1904, sec. XIV; Ward, 1992, loc. 17). Subdivisions within units are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 43 for location.

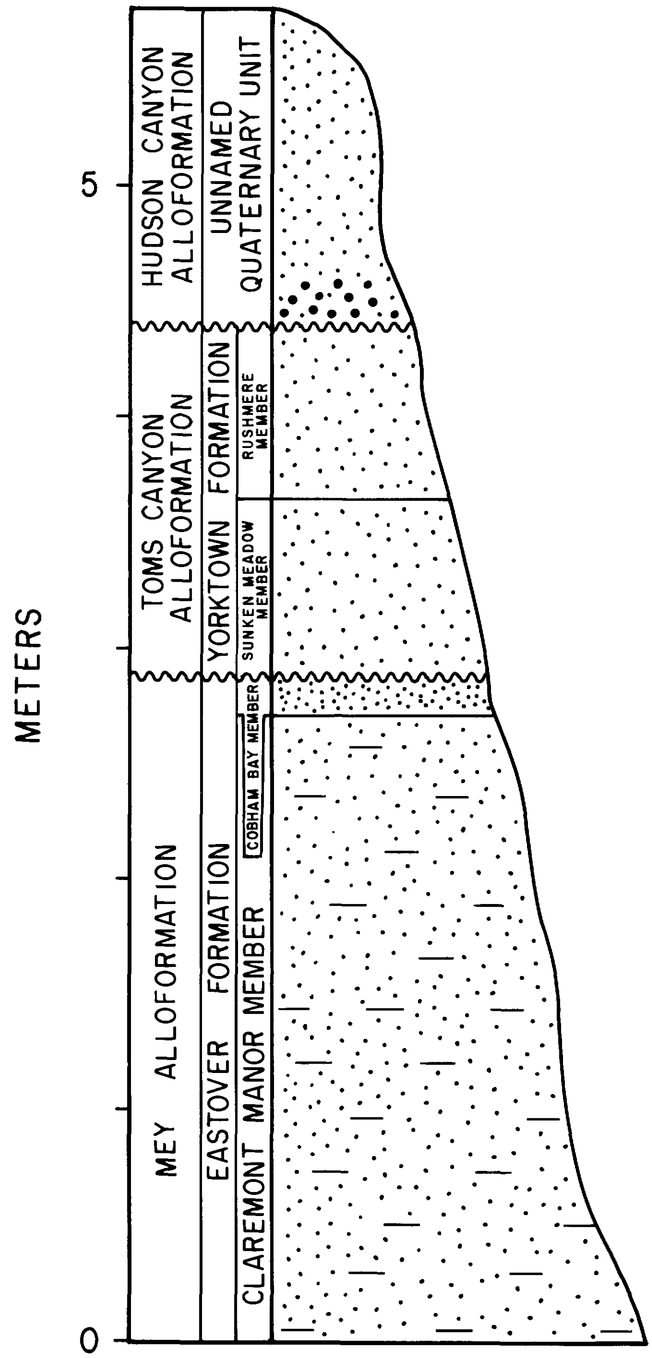


Figure 45. Onshore supplementary reference section for upper part of Mey Alloformation, lower part of Toms Canyon Alloformation, and unconformity that separates them, exposed just east of Claremont, Surry County, Va. (Ward and Blackwelder, 1980, loc. 42; Ward, 1992, loc. 7). See figure 12 for lithologic explanation and figure 43 for location.

penetrated the Mey Alloformation, few samples were collected at these shallow drilling depths.

The downslope ribbed fabric of the Mey Alloformation is due mainly to the filling of channels cut into the surface of the underlying Phoenix Canyon Alloformation. The upper surface of the Mey Alloformation is not as extensively channeled as those of older alloformations, although deep channels incise it at places on the uppermost continental rise (Poag, 1987). Seaward of the continental slope, the upper surface of the Mey Alloformation is relatively smooth over broad areas. In most places, the Mey section is truncated along the edge of the Lindenkohl Alloformation outcrop belt, but seaward of Delaware Bay, Mey strata cross the Lindenkohl erosional surface and spread onto the continental rise. Several of the major submarine canyons that developed during the Pleistocene have cut deeply into the Mey Alloformation, exposing it in the walls of some canyons, including Hudson, Wilmington, and Baltimore Canyons (Hampson and Robb, 1984).

At DSDP Site 603 (fig. 15), Mey strata are 341.8 m thick and constitute the major component of the Hatteras Ridge (Mountain and Tucholke, 1985) and include chiefly dark-greenish-gray, micaceous, sideritic claystone. These distal sections of the Mey Alloformation can be traced updip along the *Conrad* 21 profile to USGS profile 25 (figs. 2 and 3).

TOMS CANYON ALLOFORMATION

DEFINITION

We propose the name Toms Canyon Alloformation for unconformity-bounded, outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), submerged continental shelf and slope (Baltimore Canyon trough), and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), North Carolina, and New York (fig. 1). The alloformation is bounded above and below by unconformities correlative with those bounding the Tabianian and Piacenzian (Pliocene) strata in this region. The Toms Canyon Alloformation is named after Toms Canyon, which incises the present continental slope and shelf edge ~150 km southeast of Atlantic City, N.J. (fig. 3). The stratotype of the Toms Canyon Alloformation is DSDP Site 612 (figs. 6 and 7) on the lower continental slope of New Jersey, ~18 km southwest of Toms Canyon, at lat 38°49.21′ N., long 72°46.43′ W. At the stratotype, the Toms Canyon Alloformation is 51.14 m thick and consists of dark-gray glauconitic mud and interbeds of glauconitic sand.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Toms Canyon Alloformation has been cored at DSDP Site 612 but was recovered in a disturbed condition. It is present at approximately 88.1 m below the sea floor, between the core

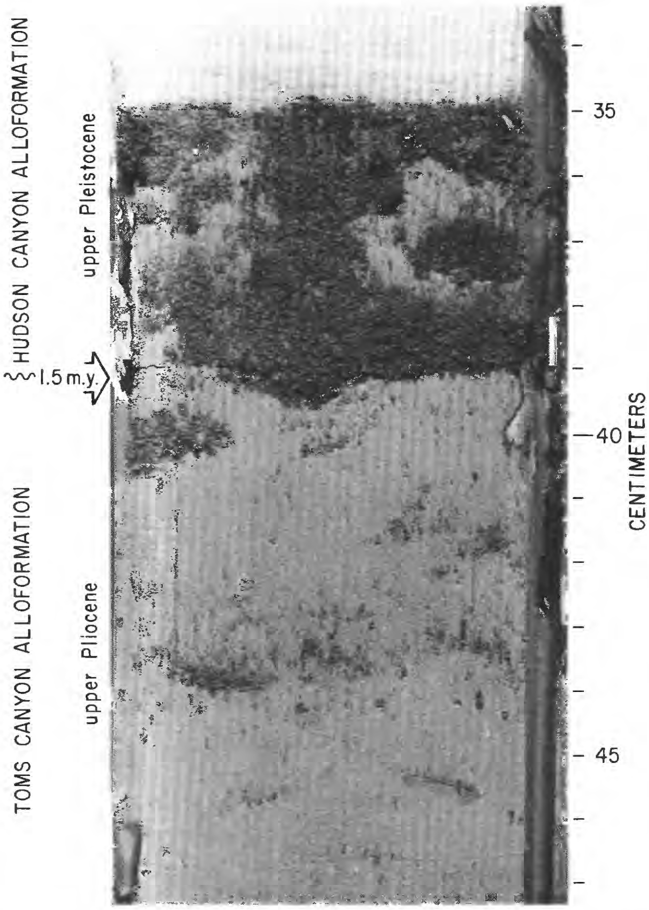


Figure 46. Unconformity separating Toms Canyon Alloformation from Hudson Canyon Alloformation at DSDP Site 612. Unconformity is 36.96 m below sea floor and is 39 cm below top of section 3, core 5 (Poag and Low, 1987). Hiatus is approximately 1.5 m.y.

catcher of core 11 and the top of core 12 (figs. 6 and 7). The unconformity separates similar lithologies of olive-gray, sandy, glauconitic mud containing interbeds of glauconite sand. The lower bounding unconformity is expressed on seismic-reflection profile 69 (Poag, 1987) at 1.98 sec (two-way traveltime), where it crosses DSDP Site 612 (fig. 6). On profile 69, reflections from the lower part of the Toms Canyon Alloformation downlap those from upper Miocene beds of the Mey Alloformation. Reflections from the upper part of the Mey Alloformation are truncated by the unconformity.

The lower bounding unconformity was also cored at DSDP Site 604 (figs. 41 and 42), where a sharp scour surface separates dark-olive-green, biosiliceous, glauconitic claystone of the Toms Canyon Alloformation from the underlying brownish-gray conglomerates of the Mey Alloformation.

The upper bounding unconformity of the Toms Canyon Alloformation (fig. 46) was cored at Site 612 (figs. 6 and 7), 36.96 m below the sea floor (39 cm below the top of section 3, core 5; Poag and Low, 1987). The unconformity is a concave scour surface that separates an upper Pliocene section of homogeneous, dark-gray mud from an upper Pleistocene section of coarse, dark-green to black, glauconitic sand, mixed with clasts of the underlying dark-gray mud. The upper bounding unconformity is expressed on seismic-reflection profile 69 (Poag, 1987) at 1.92 sec (two-way traveltime) where it crosses DSDP Site 612 (fig. 6). Reflections in the upper part of the Toms Canyon Alloformation are truncated by the upper bounding unconformity and are downlapped by reflections in the lower part of the overlying Pleistocene section (Hudson Canyon Alloformation as described herein).

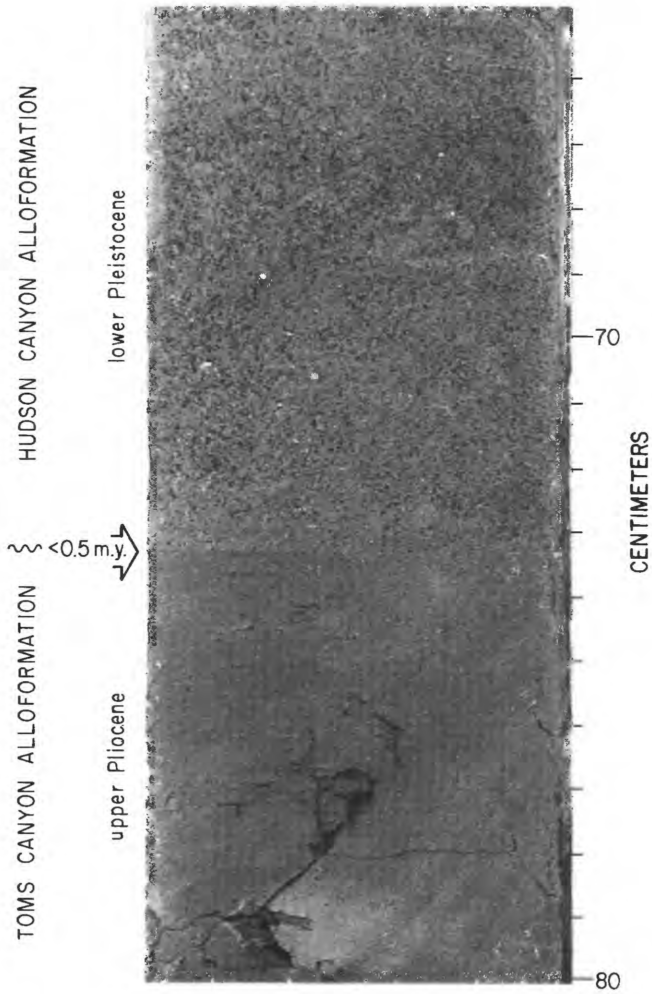


Figure 47. Unconformity separating Toms Canyon Alloformation from Hudson Canyon Alloformation at DSDP Site 613. Unconformity is 186.6 m below sea floor and is 73 cm below top of section 3, core 11 (Poag, 1985b). Hiatus is <0.5 m.y.

The upper bounding unconformity was also cored at DSDP Site 613 (fig. 47) at 186.6 m below the sea floor (73 cm below the top of section 3, core 11). At that location, a sharp lithologic change separates dusky-yellow-green, homogeneous, unbedded, diatomaceous, nannofossil-bearing mud of the Toms Canyon Alloformation from overlying greenish-gray, calcareous, glauconitic mud of the Hudson Canyon Alloformation (as defined herein).

On other seismic-reflection profiles, the bounding unconformities of the Toms Canyon Alloformation can be traced throughout the offshore area by means of truncated, onlapping, and downlapping reflections along the contacts (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Toms Canyon Alloformation extends continuously in the subsurface from DSDP Site 105 to the inner edge of the coastal plain in southeastern Virginia (~750 km updip), and to the middle of the coastal plain in Delaware (Groot and others, 1990), except for a swath (10–60 km wide, ~650 km long) along the continental slope, where the alloformation is missing (fig. 48). In the northern Hatteras basin, the alloformation forms the upper part of the Chesapeake drift (Mountain and Tucholke, 1985). Along depositional strike, the alloformation extends continuously ~900 km from the Long Island platform (Cape Cod) to the inner coastal plain of North Carolina.

The Toms Canyon Alloformation is missing or is <100 m thick on the northern half of the coastal plain and most of the continental shelf, except for a narrow wedge at the New Jersey shelf edge, which reaches ~400 m in thickness. Depocenters in the Hatteras basin, however, are 600–800 m thick (Poag and Sevon, 1989; Poag, 1992). In the northern Hatteras basin, the Toms Canyon Alloformation is correlative with the middle third of seismic unit D_3 of Schlee and others (1985); seismic unit $D_{2.3}$ of Schlee and Hinz (1987); the lower half of the Pleistocene seismic unit of Mountain and Tucholke (1985); the lower two-thirds of seismic sequence 5 of Tucholke and Laine (1982); the upper part of the middle transparent subunit and of the lentil subunit of the layered rise seismic unit of O'Leary (1988); the upper third of seismic unit 5W of Danforth and Schwab (1990); the lower half of seismic unit T3 of Locker and Laine (1992); and some of the upper part of the deep-sea Blake Ridge Formation (fig. 11).

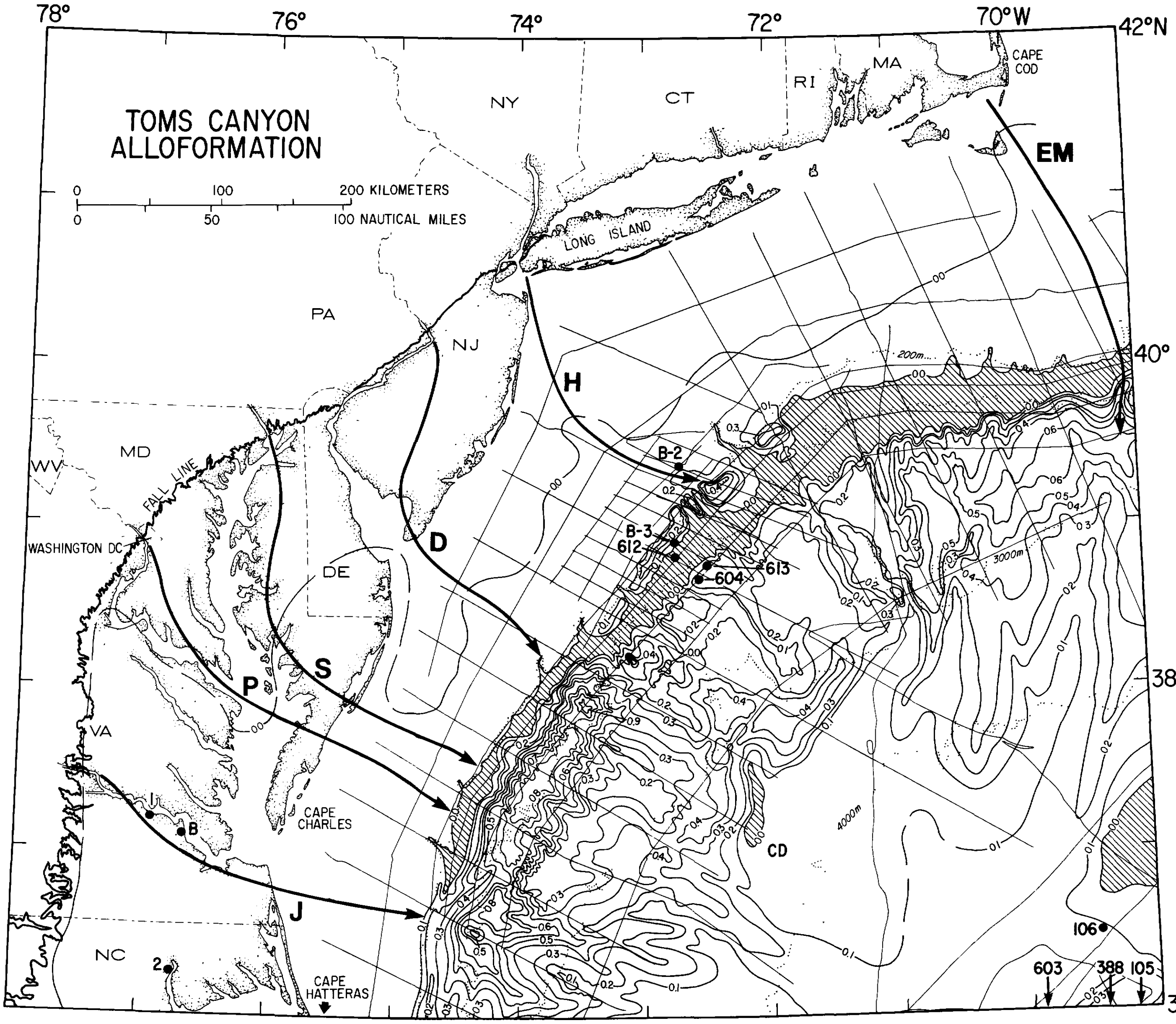
On the coastal plain of Virginia, the Toms Canyon Alloformation encompasses the Bacons Castle, Yorktown, and Chowan River Formations and the Moorings unit of Oaks and Coch (1973). Marginal-marine equivalents of these formations are also present in southeastern Maryland. In Delaware, the Toms Canyon Alloformation comprises the upper part of the Beaverdam Sand and the lower part of the Omar Formation and, perhaps, the lower part of the Beaverdam Sand and the Bethany formation of Andres (1986) (Groot and others, 1990).

The Yorktown Formation consists of four members, which were deposited during three separate marine transgressions (Ward, 1984). The (lower) Sunken Meadow Member is exposed in numerous sections, but the best exposure is its type locality, just east of Claremont, Surry County, Va. (fig. 48; Ward and Blackwelder, 1980, p. 15, loc. 42; Ward, 1992, loc. 7). We have chosen this locality as the onshore supplementary reference section for the lower part of the Toms Canyon Alloformation and its lower bounding unconformity (fig. 45). There the lower bounding unconformity separates the upper Miocene Cobham Bay Member of the Eastover Formation from the lower Pliocene Sunken Meadow Member of the Yorktown Formation. The Rushmere Member, Morgarts Beach Member, and Moore House Member of the Yorktown are excellently exposed in the bluffs of Burwell Bay, just east of Rushmere, Isle of Wight County, Va. (fig. 48; Ward and Blackwelder, 1980, p. 37, loc. 61).

The Chowan River Formation (containing two members) is present in southeastern Virginia but is best exposed in bluffs along the western bank of the Chowan River in Bertie County, N.C., extending from Colerain Landing to Edenhouse Landing. We have chosen the outcrop at Colerain Landing, which exposes both members (Blackwelder, 1981, fig. 2), as the onshore supplementary reference section for the upper part of the Toms Canyon Alloformation and its upper bounding unconformity. There the upper bounding unconformity separates the upper Pliocene Chowan River Formation (upper part of Toms Canyon Alloformation) from unnamed Quaternary strata that constitute part of the Hudson Canyon Alloformation, as defined herein (fig. 49).

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

During the Pliocene, shelf deposition was concentrated even farther seaward than during the late Miocene (fig. 48). Accumulation rates slowed (Poag and Sevon, 1989; Poag, 1992) and maritime climates cooled (Frederiksen, 1984b). The main depocenter for the Toms Canyon Alloformation (800–900 m) was in the northern Hatteras basin, while a narrow, relatively thin, prograded wedge (100–300 m) formed at the shelf break seaward of New Jersey. On the inner and middle continental shelf north of Cape Charles, Va., Toms Canyon strata are missing or are too thin to identify on most multichannel seismic profiles. About 210 km northeast of DSDP Site 612, the Toms Canyon section thickens to >600 m in an upper rise lobe, whose terrigenous source was the New England Appalachian Highlands (fig. 1) (Poag and Sevon, 1989; Poag, 1992). A second major depocenter on the continental rise (800–900 m thick) is present 150 km southwest of DSDP Site 612, indicating a detrital source to the northwest (fig. 1, central Appalachian Highlands).



EXPLANATION

Alloformation missing or too thin to identify on seismic-reflection profiles

—0.2— Isochron—In seconds (two-way traveltime); contour interval of 0.1 sec represents approximately 100 m of thickness. Dashed where approximately located

——— Trackline—For multichannel seismic-reflection profiles. See figure 3 for designations

·····200m····· Bathymetry—In meters

Figure 48. Isochron map of Toms Canyon Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: D, ancient Delaware River; EM, unspecified ancient rivers in eastern Massachusetts; H, ancient Hudson River; J, ancient James River; P, ancient Potomac River; S, ancient Susquehanna River. Labeled boreholes identified in text. CD, Chesapeake drift. Onshore reference sections: 1, Claremont, Va.; 2, Colerain Landing, N.C. Other onshore exposure: B, Burwell Bay, Va. See figure 3 for location of DSDP Sites 603, 388, and 105 and Cape Hatteras.

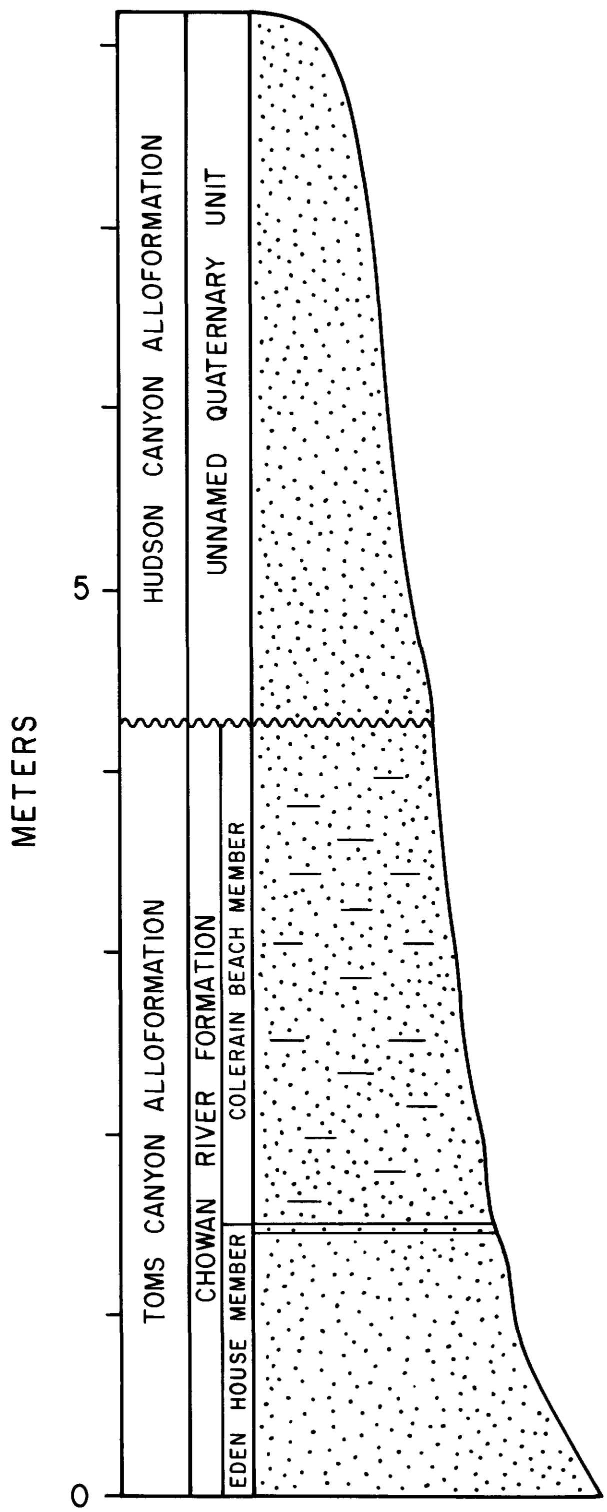


Figure 49. Onshore supplementary reference section for upper part of Toms Canyon Alloformation and its upper bounding unconformity, exposed at Colerain Landing on Chowan River, Bertie County, N.C. (Blackwelder, 1981, fig. 2). Subdivisions within the Eden House Member are shown lithologically but are not labeled because they are not the focus of this report. See figure 12 for lithologic explanation and figure 48 for location.

No beds unequivocally assignable to the Toms Canyon Alloformation have been recognized in New Jersey or most of Maryland (Owens and Minard, 1979; Ward and Strickland, 1985). In Delaware, however, the Toms Canyon Alloformation includes mainly medium to coarse sands and fine to very fine shelly sands of fluvial and estuarine origin (Groot and others, 1990). In Virginia, the Toms Canyon Alloformation contains shelly, phosphatic, and glauconitic sands of paralic to inner sublittoral origin, along with lagoonal clays and lag deposits of coarse sand, gravel, and cobbles (Blackwelder, 1981; Mixon and others, 1989).

At DSDP Site 612 (figs. 6 and 7), the Toms Canyon Alloformation of the Pliocene continental slope consists of 51.14 m of channel-fill deposits, including dark-gray glauconitic mud and distinctive interbeds of glauconitic sand. Samples were not recovered from the COST B–3 well (fig. 8) or the thin Toms Canyon section at the COST B–2 well.

The Toms Canyon Alloformation was sampled in an upper rise setting at DSDP Sites 604 (fig. 42; 84 m thick) and 613 (fig. 28; 77 m thick), where dark-greenish-gray, glauconitic muds contain occasional layers of glauconitic sand and conglomeratic sand and intervals of biosiliceous, nannofossil-rich clay. Reworked Eocene microfossils also are common in the Toms Canyon sediments at these sites.

Farther seaward, cores from DSDP Sites 105 (fig. 16), 106, 388, and 603 (fig. 15) sampled Toms Canyon strata from the flank of the Hatteras Ridge (Mountain and Tucholke, 1985). The most complete and thickest section of Toms Canyon deposits (298 m) was cored at Site 603C, where turbidites consist of greenish-gray, quartzose, micaceous muds, grading downward to micaceous, silty claystone.

The downslope cut-and-fill fabric of the Toms Canyon Alloformation is seen along strike profiles, but channeling is not as extensive as in most older alloformations. Superimposed on the cut-and-fill downslope fabric is a longslope fabric, created by contour-following bottom currents (Mountain and Tucholke, 1985). Seismic reflections from the upper rise sections of the Toms Canyon Alloformation are generally parallel and subcontinuous, except where chaotic channel-fill deposits are present.

HUDSON CANYON ALLOFORMATION

DEFINITION

We propose the name Hudson Canyon Alloformation for unconformity-bounded outcropping and subsurface beds on the exposed coastal plain (Salisbury embayment), submerged continental shelf and slope (Baltimore Canyon trough), and continental rise (Hatteras basin) of the Middle Atlantic States (Virginia, Maryland, Delaware, New Jersey), southern New England (Connecticut, Rhode Island, Massachusetts), and New York (fig. 1). The alloformation is bounded above and below by unconformities bounding the Quaternary strata in this region. The Hudson Canyon Alloformation is named after Hudson Canyon, which incises the present continental slope and shelf edge ~200 km southeast of New York City (fig. 3). The stratotype of the alloformation is DSDP Site 613 (fig. 28), ~50 km southwest of Hudson Canyon, at lat 38°46.25′ N., long 72°30.43′ W. At the stratotype, the alloformation is 186.6 m thick and consists of dark-greenish-gray, homogeneous, gas-emitting, organic-matter-rich, commonly diatomaceous mud and interbeds of quartzose, glauconitic sand and occasional zones of conglomerate.

BOUNDING UNCONFORMITIES

The lower bounding unconformity of the Hudson Canyon Alloformation (fig. 46) was cored at DSDP Site 612 (figs. 6 and 7) at 36.96 m below the sea floor (39 cm below the top of section 3, core 5; Poag and Low, 1987). There the unconformity is a concave scour surface that separates coarse, dark-green to black, glauconitic sand, mixed with clasts of dark-gray mud, of the Hudson Canyon Alloformation from underlying homogeneous, dark-gray mud of the Toms Canyon Alloformation.

The lower bounding unconformity also was cored at DSDP Site 613 (fig. 47), 186.6 m below the sea floor (73 cm below the top of section 3, core 11; Poag, 1987). At Site 613, the unconformity is a sharp lithologic change that separates Pliocene dusky-yellow-green, homogeneous, unbedded, diatomaceous, nannofossil-bearing mud (below) from Quaternary greenish-gray, calcareous, glauconitic mud (above).

The lower bounding unconformity is expressed on single-channel seismic-reflection profile 105 (fig. 28; Poag, 1987) at 3.35 sec (two-way traveltime) where the profile crosses the continental slope and rise (in a dip direction) 0.2 km northeast of DSDP Site 613. Reflections from the lower part of the Hudson Canyon Alloformation onlap the unconformity near Site 613.

On other seismic-reflection profiles, the lower bounding unconformity of the Hudson Canyon Alloformation can be traced throughout the offshore area by means of truncating, onlapping, and downlapping reflections along the contact (Poag and Schlee, 1984; Poag, 1985a,b, 1987, 1992; Poag and Mountain, 1987; Poag and Sevon, 1989).

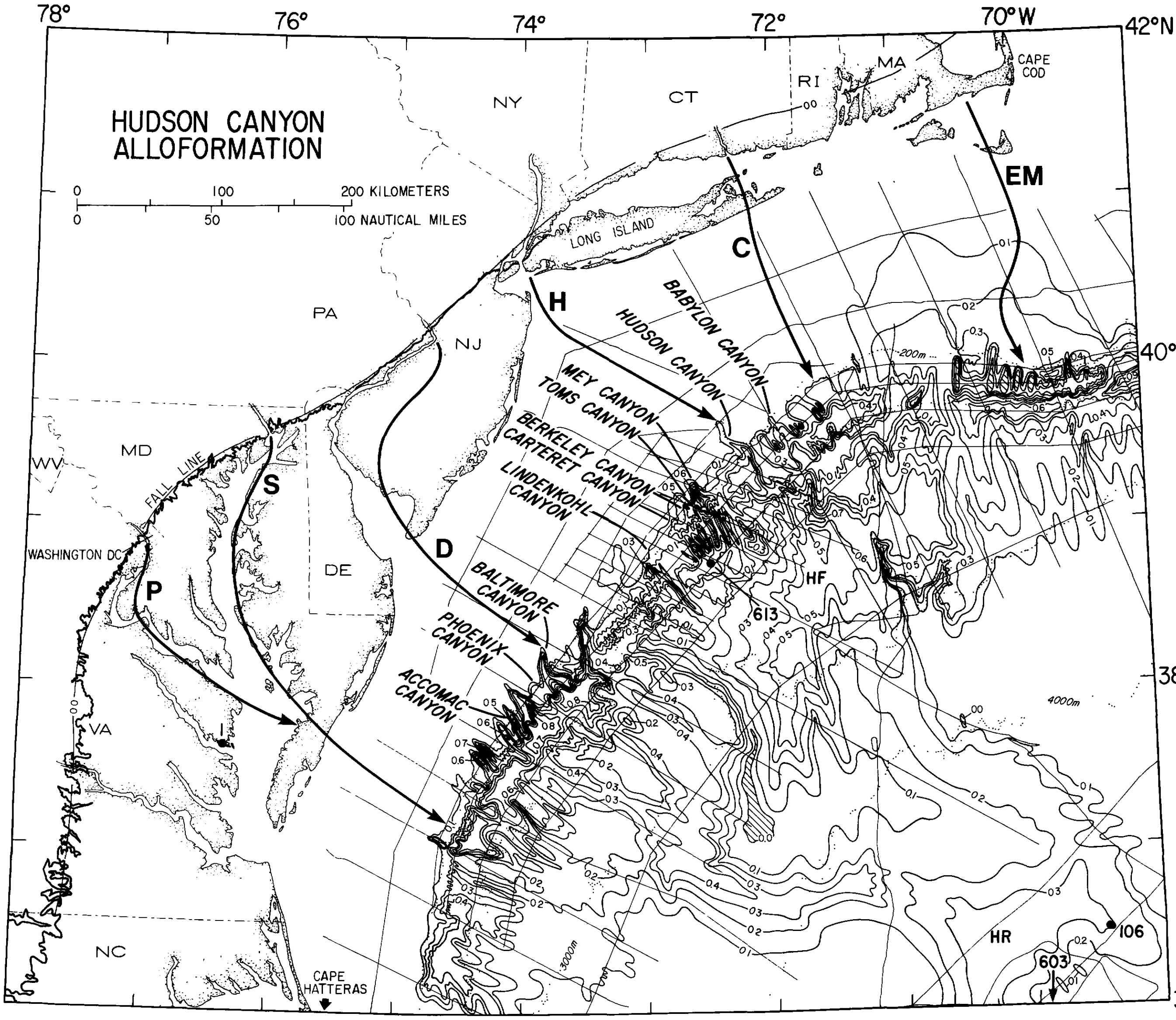
The upper bounding unconformity of the Hudson Canyon Alloformation is the present sea floor, an irregular surface marked by numerous channels (valleys, canyons) and sediment mounds (fans, slumps, drifts; O'Leary, 1988; McMaster and others, 1989; Pratson and Laine, 1989; Poag, 1992; Locker and Laine, 1992). Older beds of Cretaceous to Pliocene age crop out at various places along this surface in the study area (Hampson and Robb, 1984).

DISTRIBUTION AND STRATIGRAPHIC EQUIVALENTS

The Hudson Canyon Alloformation extends from DSDP Site 105 nearly continuously to the inner edge of the coastal plain, ~750 km updip (fig. 50). Along depositional strike, it extends >900 km from the Long Island platform (Cape Cod) to the coastal plain of North Carolina.

The Hudson Canyon Alloformation is generally <100 m thick over the coastal plain and continental shelf, but it is >700 m thick in three depocenters on the continental slope and rise of the northern Hatteras basin (Poag and Sevon, 1989; Poag, 1992). In the Hatteras basin, the alloformation is equivalent to the uppermost part of seismic unit D_3 of Schlee and others (1985); seismic unit $D_{2.4}$ of Schlee and Hinz (1987); the upper half of the Pleistocene seismic unit of Mountain and Tucholke (1985); the Quaternary seismic sequence of Poag (1987); the upper third of seismic sequence 5 of Tucholke and Laine (1982); the upper layered subunit of the layered rise seismic unit of O'Leary (1988); seismic units 1W–4W of Danforth and Schwab (1990); the upper half of seismic unit T3 of Locker and Laine (1992); and the uppermost part of the deep-sea Blake Ridge Formation (fig. 11).

On the coastal plain of New Jersey, Delaware, Maryland, and Virginia, the Hudson Canyon Alloformation encompasses a complex array of lithostratigraphic units, which have been given a host of formation names, including Bridgeton Formation, Pensauken Formation (part), Cape May Formation, Omar Formation, Joynes Neck Sand, Nassawadox Formation, Wachapreague Formation, Kent Island Formation, Windsor Formation, Charles City Formation, Chuckatuck Formation, Shirley Formation, Norfolk Formation, and Tabb Formation (Mixon, 1985; Mixon and others, 1989). These units contain a variety of upper alluvial, estuarine, and back-barrier deposits and include crossbedded sands, gravels, cobbles, silty sands, shelly sands, and organic-matter-rich sands. Good exposures of the units are sparse, except in borrow pits. One of the better natural exposures of this alloformation is on the left bank of the Rappahannock River, just downriver from the Virginia Route 3 bridge, Lancaster County, Va. There beds range from slightly brackish water sands containing *Rangia*, to more brackish shelly sands dominated by *Crassostrea*, to open-bay shelly sands containing a moderately diverse molluscan assemblage, and finally to fine clean sands of nearshore and beach origin. Mixon (1985) has described and illustrated additional good exposures of the Hudson Canyon Alloformation in the southern Delmarva Peninsula of Virginia and Maryland.



EXPLANATION

Alloformation missing or too thin to identify on seismic-reflection profiles

—0.2— Isochron—In seconds (two-way traveltime); contour interval of 0.1 sec represents approximately 100 m of thickness. Dashed where approximately located

——— Trackline—For multichannel seismic-reflection profiles. See figure 3 for designations

·····200m····· Bathymetry—In meters

Figure 50. Isochron map of Hudson Canyon Alloformation showing principal sediment dispersal routes (heavy arrows) and depocenters. Ancient rivers: C, ancient Connecticut River; D, ancient Delaware River; EM, unspecified ancient rivers in eastern Massachusetts; H, ancient Hudson River; P, ancient Potomac River; S, ancient Susquehanna River. Labeled boreholes identified in text. HF, Hudson Fan; HR, Hatteras Ridge. Onshore reference section: 1, Rappahannock River, Lancaster County, Va. See figure 3 for location of DSDP Site 603 and Cape Hatteras.

THICKNESS, LITHOLOGIES, AND PALEOENVIRONMENTS

The Hudson Canyon Alloformation, like the Mey and Toms Canyon Alloformations, is relatively thin (<100 m) over the continental shelf, except for a 200- to 300-m-thick wedge of sediments on the outer shelf south of New England (figs. 2 and 50).

Downslope erosional and depositional processes intensified during the sea-level fluctuations of the Pleistocene, and the locus of extensive cutting and filling shifted upslope by 20–40 km from its preceding Pliocene position on the upper rise. This intensification is manifest by deep incisions of the shelf edge and upper continental slope by submarine canyons, which channeled large volumes of terrigenous detritus to continental rise depocenters. Some of these canyons have been subsequently filled with as much as 700–800 m of terrigenous sediment.

The Hudson Canyon Alloformation is unusually thin (10–25 m) or absent along the base of the continental slope seaward of New Jersey and Long Island, where the chalky limestones of the middle Eocene Lindenkohl Alloformation are extensively exposed. To the southwest (off Virginia, Maryland, Delaware) and northeast (off Massachusetts), however, elongate slope aprons are 400–700 m thick.

Two principal submarine fan systems extend across the northern Hatteras basin. The largest and thickest fan system (600–700 m thick) is the Hudson Fan, which was fed mainly by sediments traversing Hudson Canyon. On the lower continental rise at the southeast corner of the study area, a 300-m-thick mound of sediment parallels the shelf edge and forms part of the current-built Hatteras Ridge (Mountain and Tucholke, 1985; McMaster and others, 1989; Locker and Laine, 1992).

Quaternary gravels and paralic terrigenous strata of the Hudson Canyon Alloformation are known in the New Jersey Coastal Plain (Minard and Rhodehamel, 1969; Owens and Minard, 1979). Downdip on the upper continental rise, sediments are characteristically dark-greenish-gray, homogeneous, gassy, organic-matter-rich, commonly diatomaceous muds, interbeds of quartzose, glauconitic sand, and occasional conglomeratic zones, as seen at Site 613 (figs. 28 and 47). The lithic and microfossil evidence (coarse sands, conglomerates, chunks of white Eocene chalk, displaced shelf-dwelling species) confirms the importance of downslope depositional processes (turbidity currents, debris flows) inferred from the sediment-distribution pattern of the isochron maps.

At DSDP Site 603 (fig. 15), approximately 31 m of Hudson Canyon strata are draped over the Hatteras Ridge. There the sediments are mainly greenish-gray, nannofossil-rich clay and claystone, which emit hydrogen sulfide gas. At DSDP Site 106, drilled on the lower continental rise terrace (figs. 2 and 50), the ponded, turbiditic Hudson Canyon section is 360 m thick and consists of gray to brown terrigenous mud and glauconitic, quartzose sand interbeds. Mica, wood, and plant fragments are common in some sandy layers, and siliceous microfossils are especially notable in the lower part.

Seismic-reflection profiles crossing the continental rise (fig. 16) show that the Hudson Canyon Alloformation can be divided into two distinct allomembers. Drilling at DSDP Site 105 proved that the lower allomember represents early Pleistocene deposition and the upper allomember represents late Pleistocene and Holocene deposition. On the upper rise prism, sediments of the lower allomember fill downslope-trending channels cut into the upper surface of the underlying Toms Canyon Alloformation. The contact between the two Quaternary allomembers is, in contrast, a relatively smooth surface (Poag, 1987). The upper surface of the upper allomember (the present sea floor), generally displays a marked relief, created by differential downslope and alongslope erosion and deposition. Far downdip, however, ponding behind the Hatteras Ridge has smoothed the sea-floor topography.

PRINCIPAL CONCLUSIONS

ALLOSTRATIGRAPHIC RELATIONS BETWEEN SEISMOSTRATIGRAPHIC SEQUENCES AND BOREHOLE STRATA

Direct correlations between unconformities seen on seismic-reflection profiles and unconformities identified in continuously cored and logged offshore sections are rare. DSDP Site 612 on the continental slope of New Jersey (figs. 6 and 7) is one of the best examples currently available. There stratigraphic changes on sonic logs and gamma-ray logs correspond closely to lithic and biostratigraphic discontinuities and to unconformable seismic-sequence boundaries. These relations firmly support the validity of seismostratigraphic interpretation methods proposed (but weakly documented) by Vail and others (1977a,b) and many subsequent authors, though Thorne and Watts (1984) would disagree. Similar data from DSDP Site 613 (fig. 28) corroborate conclusions drawn from Site 612 (Poag, Watts, and others, 1987; Van Hinte, Wise, and others, 1987). In fact, the geologic record at all the other New Jersey Transect boreholes studied (DSDP Sites 105, 106, 603, 604, 605; figs. 15–17 and 42) also supports the sequence-stratigraphy model, although no geophysical logging was carried out at these sites. These results, along with new continuously cored and logged boreholes on the coastal plain (for example, Exmore and Kiptopeke coreholes, fig. 33), strengthen prior stratigraphic interpretations (for example, Schlee, 1981; Poag and Schlee, 1984; Poag, 1985a; Poag and Ward, 1987; Mixon, 1989) derived from borehole data collected on the coastal plain and continental shelf and from offshore seismic profiles.

The location of the New Jersey Transect drill sites within a grid of single-channel and multichannel seismic-reflection profiles allows their bounding unconformities to be traced beneath most of the continental slope and rise and confirms their correlation with those of the adjacent shelf and other nearby shelf basins (Poag, 1982, 1985a, 1987, in press; Poag and Schlee, 1984; Popenoe, 1985; Poag and Sevon, 1989), of the coastal plain (Hazel and others, 1984; Kidwell, 1984; Owens and Gohn, 1985; Ward and Strickland, 1985; Poag and Ward, 1987; Poag, 1989, 1992), and of the margins of several other continents (Steele, 1976; McGowran, 1979; Barr and Berggren, 1980; Quilty, 1980; Loutit and Kennett, 1981; von Rad and Exon, 1982; Ziegler, 1982; Riggs, 1984; Schlee, 1984; Seiglie and Baker, 1984; Seiglie and Moussa, 1984; Aubry, 1985; Poag and others, 1985). On the basis of these relations, we have proposed a formal allostratigraphic framework of 12 alloformations for the U.S. Middle Atlantic margin.

PROXIMATE CAUSES OF UNCONFORMITIES

On the coastal plain and continental shelf, distinct, burrowed scour surfaces overlain by basal marine conglomerates, plus the absence of paralic lithofacies above the contacts (Darby, 1984; Ward and Krafft, 1984; Poag, in press), are evidence that allostratigraphic boundaries (unconformities) in the shallow marine environments were created largely in two steps; regressive subaerial erosion followed by transgressive submarine erosion and ravinement. On the continental slope and upper continental rise, the presence of sand layers, exotic clasts, and conglomeratic zones immediately above scour surfaces, and of faults or contorted bedding within alloformations, indicates that erosion by downslope mass sediment displacement (turbidity currents, debris flows, slumps) was the chief agent in forming many of the allostratigraphic boundaries in deep marine environments. Outcrops, cores, and seismic profiles clearly indicate that the accumulation rates and dispersal patterns of successive downslope sediment gravity flows were highly variable. Equivalent variability in the depth of submarine erosion created longer hiatuses in some sections than in others.

Gravity-flow deposits sandwiched between allostratigraphic boundaries of the continental slope and rise of the Middle Atlantic States have equivalents elsewhere around the Atlantic basin, such as the opposing continental slope and rise off Ireland (Graciansky, Poag, and others, 1985a,b; Miller and others, 1987). Correlation of these deposits with paleobathymetric cycles derived from sites on the coastal plain and continental shelf (Poag and Schlee, 1984; Ward and Strickland, 1985; Olsson and Wise, 1987; Olsson and others, 1987; Poag and Ward, 1987; Miller and others, 1990) links these erosional episodes with relative sea-level falls and subsequent marine transgressions. The stratigraphic positions of five allostratigraphic boundaries of the U.S. Middle Atlantic continental margin (base of Lindenkohl, Baltimore Canyon, Babylon, Phoenix Canyon, and Mey Alloformations) correlate well with major Cenozoic supersequence boundaries ("global" unconformities) of the Haq and others (1987) version of the Exxon sequence-stratigraphy model (fig. 51); two boundaries (base of Toms Canyon and Hudson Canyon Alloformations) correlate better with the original version of the model (Vail and others, 1977b); four other boundaries (base of Accomac Canyon, Island Beach, Carteret, and Berkeley Alloformations) do not fit either version of the model. Furthermore, Poag and Sevon (1989) and Poag (1992) have shown that many bathymetric shifts in the location of major Late Cretaceous and Cenozoic depocenters of the U.S. Middle Atlantic margin correspond to eustatic changes postulated by the model. Thus, we conclude that second-order relative sea-level changes have been major forcing mechanisms for many, but not all, deposition and erosion cycles on the U.S. Atlantic margin and its conjugate margins of the eastern North Atlantic.

Relative sea-level change was a particularly effective control on depositional patterns during the Paleogene and early Neogene because siliciclastic accumulation rates were unusually low (Poag and Sevon, 1989; Poag, 1992). During the Late Cretaceous and middle Miocene, however, significant uplift of terrigenous source terrains accelerated the supply of siliciclastic sediments to the offshore basins (fig. 51). This rapid accumulation modified the second-order effects of relative sea-level change and may have been responsible for the poor correlation of some allostratigraphic boundaries with those of the Exxon sequence-stratigraphy model.

The ultimate cause of any given relative sea-level change is the subject of heated debate (eustasy vs. tectonism). Systematic changes in paleoclimate, seawater temperature, and global ice volumes, inferred from extensive analyses of oxygen and carbon isotopes, provide independent evidence that major eustatic changes have taken place during the Cenozoic. A clear link between widespread sublittoral and bathyal (and even abyssal) erosion, increased global ice volumes, cooler global climates, and lower sea levels has been established for the Cenozoic as far back as the late Eocene (Vail and others, 1977b; Frakes, 1979; Keller and Barron, 1983; Miller and Fairbanks, 1983; Keigwin and Keller, 1984; Poag and Schlee, 1984; Aubry, 1985; Miller and others, 1985, 1987, 1990; Poag, 1985a, 1987; Poag and others, 1987). The stratigraphic positions of major inflections in the oxygen-isotope curves (indicating increased ice volumes) correlate well with several of the principal allostratigraphic boundaries of the U.S. Middle Atlantic margin (fig. 51; Poag, 1987). Some authors have interpreted the oxygen-isotope record as an indication that significant global ice volumes were present even in the Late Cretaceous (Matthews and Poore, 1980; Matthews, 1984).

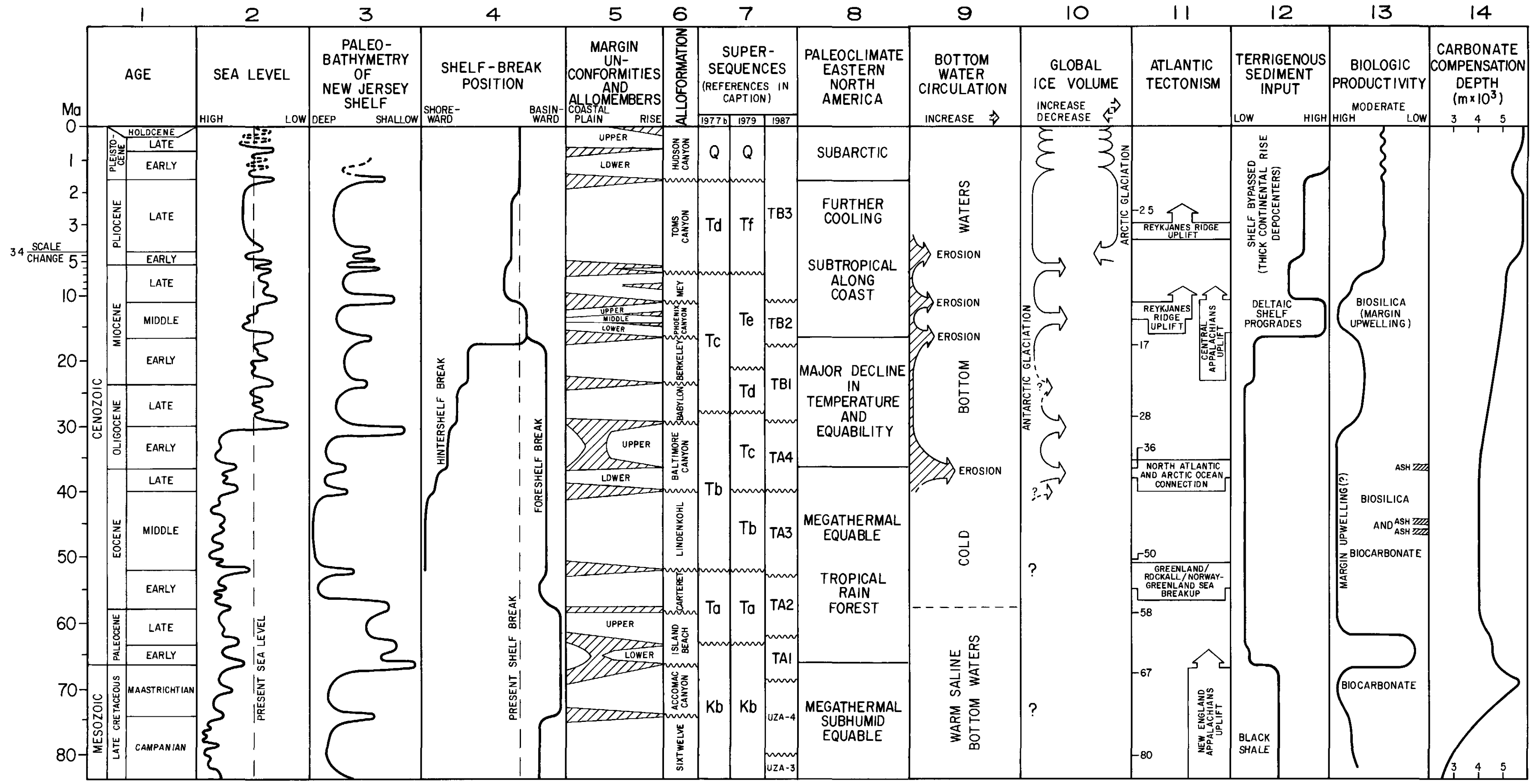


Figure 51. Schematic summary (modified from Poag, 1987) of important geologic, paleoclimatic, and paleoceanographic events affecting U.S. Middle Atlantic margin during last 84 m.y. (Campanian to Holocene) and their relations to alloformations proposed herein (column 6). Source of data and explanation for columns as follows: Column 1—Berggren and others (1985), Kent and Gradstein (1985). Column 2—Vail and Hardenbol (1979), Haq and others (1987); curve dashed where approximate. Column 3—Poag and Schlee (1984), Poag (1985a); curve dashed where approximate. Column 4—Poag (1987). Column 5—This report. Column 6—This report. Column 7—Vail and others (1977b), Vail and Mitchum (1979), Haq and others (1987). Column 8—Poag and Sevon (1989). Column 9—Tucholke and Mountain (1986), Berggren and Olsson (1986); boundary and curve dashed where approximate. Column 10—Kennett and von der Borch (1986), Tucholke and Mountain (1986); curve dashed where approximate; queried where uncertain. Column 11—Oceanic-tectonic events from Klitgord and Schouten (1986) and Appalachian uplifts from Poag and Sevon (1989); numbered ticks are ages (Ma) of major direction changes in plate motions identified by Klitgord and Schouten (1986). Column 12—Poag and Sevon (1989). Column 13—Tucholke and Mountain (1986), Poag (1987). Column 14—Tucholke (1979).

On the other hand, Cloetingh (1986, 1988, and several related papers) has established thermomechanical models to demonstrate that variations in external compression or tension (brought about by fluctuating intraplate stress) at the edge of passive-margin basins can produce the same types of onlap-offlap depositional patterns produced by eustasy.

It is easy to envision allostratigraphic processes at work on a shallow continental shelf. But it is more difficult to understand how erosion on the continental slope and rise, which were covered by thousands of meters of water, could be induced by a relative sea-level fall. Several possible mechanisms have been suggested. Sarnthein and others (1982) suggested that internal waves and turbulence, caused by density differences at water-mass boundaries, could cause significant erosion where a boundary intersects that sea floor. Where such a boundary intersects the continental slope, it would be depressed or elevated in unison with sea-level change or other major changes in circulation, creating a broad erosional swath. Poag and others (1985) suggested that evidence of such a process could be found in the sedimentary and microfossil record of the Goban Spur. Stanley and others (1983) discussed similar relations for water-mass boundaries on the New Jersey margin. They showed that the mudline on the modern New Jersey margin (above which intermittent deposition and erosion take place) can range from 200 m to 1,000 m, depending on several variables. Beneath the shelf water mass (shoreline to the shelf break; 0–200 m), erosion takes place continually from the interplay of storms, fronts, tides, and internal waves. The upper few hundred to 1,000 m below the intersection of the shelf and slope water masses is a transitional zone in which sediments are periodically resuspended by surface waves, tidal currents, wind-stress currents, internal waves, and shear forces between major water masses and oceanic fronts. This alternation of deposition and resuspension triggers sediment flow down the middle and lower slope. A falling sea level would depress this transitional zone of erosion even farther down the slope. The benthic microfossil record along the New Jersey Transect shows that one or more hydrographic boundaries have separated DSDP Site 612 (mid-slope) from DSDP Sites 604, 605, and 613 (upper rise) during much of the Late Cretaceous and Cenozoic.

Deep boundary currents (fig. 51), such as the Gulf Stream and the Western Boundary Undercurrent, also are effective agents for eroding the continental slope and rise (Tucholke and Mountain, 1979; Vail and others, 1980; Tucholke, 1981; Pinet and Popenoe, 1982; Ledbetter and Balsam, 1985; Mountain and Tucholke, 1985; Popenoe, 1985; McMaster and others, 1989). Geographic and bathymetric shifts of such currents, coincident with sea-level changes, have been demonstrated (for example, Tucholke and Laine, 1982; Ledbetter and Balsam, 1985; Popenoe, 1985). For example, the high-velocity core of the Western Boundary Undercurrent off New Jersey accelerated, moved shoreward by 150 km, and shoaled by 1,000 m (relative to its modern velocity and position) during the last Pleistocene glacial (Ledbetter and Balsam, 1985).

Seismicity also may have accelerated erosion on the slope and rise in unison with sea-level falls. The outer shelf growth faults of the Gemini fault system (Poag, 1987) were active along the outer shelf and upper to middle continental slope of New Jersey from at least the Late Jurassic until well into the middle Miocene. Shelf-edge and upper slope depocenters have been associated with this fault system since the Campanian, and broad erosional swaths have paralleled it at varying positions since the Paleocene. Presumably, sea-level falls, which reduce the hydrostatic pressure, could thereby create excessive sedimentary pore pressures and trigger periodic movements along these faults, displacing large volumes of sediment from the shelf edge and slope to cut erosional swaths across the continental rise (Booth, 1979).

Another mechanism that appears to have profoundly interrupted depositional processes in the study area, from coastal plain to continental rise, is the impact of an early late Eocene bolide that struck the outer continental shelf 40 km north of DSDP Site 612 (Poag and others, 1992). This event appears to have caused, directly or indirectly, much of the erosion that formed the lower bounding unconformity of the Baltimore Canyon Alloformation. Diverse parts of the unconformity could have been formed by at least four different processes related to the bolide. First, at the impact site, part of the unconformity was formed directly when the force of the collision deeply excavated the middle to early late Eocene sea floor and truncated beds of Late Cretaceous to late Eocene age. Second, at locations proximal to the excavation, such as DSDP Site 612, the impact triggered ejecta-bearing debris flows, which scoured the outer shelf and upper slope and truncated beds at least as old as middle Eocene. Third, seismic shock from the impact appears to have destabilized sediments over a large area of the continental slope. This presumably resulted in massive debris flows, which eroded deep downslope-trending channels (seen on seismic profiles) and truncated Upper Cretaceous to upper Eocene beds on the lower continental slope and upper continental rise. Fourth, a gigantic tsunamilike wave train, generated by the bolide impact, widely scoured the late Eocene inner continental shelf and coastal plain. This superwave truncated beds ranging in age from Early Cretaceous to late Eocene at the Exmore corehole and other sites in what now is southeastern Virginia.

The presence of a broad, elongate outcrop of middle Eocene chalk of the Lindenkohl Alloformation along the base of the New Jersey Continental Slope has raised the question of whether downslope or alongslope erosion has dominated its excavation (Poag, 1987). Some authors have suggested that a repetitious two-step combination of erosive processes has taken place: (1) the lower slope was undercut by alongslope boundary currents (perhaps aided by submarine ground-water discharge (Robb, 1984)); (2) pervasive downslope mass wasting took place as the margin sought a new equilibrium profile (Farre, 1985; Mountain and Tucholke, 1985). Data from the New Jersey Transect give evidence of both processes. For example, chunks of middle Eocene chalk were incorporated into debris-flow deposits of the upper rise during the late Miocene (Mey Alloformation) and Quaternary (Hudson Canyon Alloformation) (sampled at DSDP Sites 604, 605, and 613). Thus, it is certain that downslope erosion has helped excavate the Lindenkohl Alloformation at least since the late Miocene. Furthermore, extensive systems of downslope-trending erosional channels are present within each of the Upper Cretaceous and Cenozoic alloformations mapped on the upper continental rise. Thus, downslope erosion was significant in this region for at least the last 84 m.y. The presence of a marked shelf-edge declivity, coupled with the sedimentary record at DSDP Site 603 (Van Hinte, Wise, and others, 1987) and the regional depositional patterns mapped by Tucholke and Mountain (1979), Ewing and Rabinowitz (1984), Mountain and Tucholke (1985), Schlee and Hinz (1987), Poag and others (1990), McMaster and others (1989), Poag and Sevon (1989), and Poag (1992), attests to almost continuous passage of erosive turbidity currents and debris flows across the continental slope and rise since at least Bathonian time (Middle Jurassic; 165 Ma). Later, during the late Miocene and Quaternary, downslope deposition covered parts of the Lindenkohl outcrop belt, attesting to the preeminence of gravity-flow processes. As a final example, the Quaternary Hudson Canyon Alloformation has been truncated on both the updip and downdip edges of the Lindenkohl outcrop belt, forming a thin alongslope swath, several kilometers wide, which is interpreted to have resulted from late Quaternary, contour-following bottom currents. In combination, these relations are evidence that downslope sediment dispersal has nearly always been the principal agent of both deposition and erosion along the continental slope and upper rise off the Middle Atlantic States since sea-floor spreading began (~187 Ma).

There is little doubt, however, that alongslope boundary currents and other vigorous bottom currents have modified downslope depositional patterns on the middle to lower rise since the middle Miocene, when elongate, mounded, contourite drift deposits began to build up (Tucholke and Mountain, 1979, 1986; Tucholke and Laine, 1982; Miller and Tucholke, 1983; Emery and Uchupi, 1984; Mountain and Tucholke, 1985; McMaster and others, 1989; Poag and Sevon, 1989; Poag, 1992; Locker and Laine, 1992). Off the Middle Atlantic States, however, in the bathyal transitional zone from continental slope to continental rise (200–2,000 m water depth), mass gravity flows appear to have dominated both deposition and erosion.

A recent study of plate kinematics of the North Atlantic has provided an updated interpretation of plate motion changes (Klitgord and Schouten, 1986), which presumably would cause widespread, if not global, sea-level fluctuations (Hays and Pitman, 1973; Cloetingh, 1986). The timing of several of these plate motion shifts is nearly coincident with supersequence and alloformation boundaries of the study area (fig. 51) and thereby provides evidence that some preglacial sea-level cycles could have been caused by tectonism alone.

DEPOSITIONAL REGIMES AND SEDIMENT PROVENANCE AND DISPERSAL

Postrift sediment dispersal on the continental shelf, the continental slope, and the continental rise has involved a varied and complex series of processes (Poag, 1987, 1992; McMaster and others, 1989; Poag and Sevon, 1989; Locker and Laine, 1992). Processes such as delta progradation, downslope mass gravity flows, shallow surface currents (and associated gyres), deep boundary currents (and associated shear zones), shifting water-mass boundaries, storms, fronts, tides, and internal waves dominated different segments of the margin at different times in its depositional history. These processes often interacted to augment or diminish each other, so that their relative effectiveness was inconstant, varying temporally and spatially.

The continental slope, both now and in its earlier manifestations, has been a zone of transition between sublittoral (0–200 m) shelf processes and abyssal (>2,000 m) processes of the continental rise. Sediment dispersal routes and processes were complicated even more by the appearance of dual shelf breaks (resulting in hintershelves and foreshelves) during the early Eocene to middle Miocene, rapid progradation of massive, organic-matter-rich delta systems during the middle Miocene to Quaternary, and deep incision of shelf-edge submarine canyons, especially during the Pleistocene.

As the Cretaceous drew to a close and the deposits of the Sixtwelve and Accomac Canyon Alloformations accumulated, the position of the shelf edge off the Middle Atlantic States was still controlled in large part by the position of a buried Jurassic reef structure (Poag, 1987, 1991; Meyer, 1989; Poag and others, 1990). Erosional channels at the base of the Late Cretaceous continental slope provided numerous conduits for shelf- and slope-derived siliciclastic debris of the Sixtwelve and Accomac Canyon Alloformations to reach the continental rise (Poag, 1992). Concomitantly, relatively high sea levels allowed principally clay-sized particles to reach the outer part of the northern Hatteras basin, where they formed multicolored pelagic shales. The supply of siliciclastic components to the study area dwindled in the Maastrichtian, and the dominant offshore lithofacies of the Accomac Canyon Alloformation became calcareous sands, clays, chalks, and limestones. Chaotic seismic facies in Accomac Canyon channel-fill deposits are evidence, however, that some parts of the upper continental rise continued to receive considerable amounts of terrigenous gravity-flow detritus.

A major shift in depositional regime took place in the Paleocene, as siliciclastic deposition rates diminished by two-thirds (fig. 51; Poag and Sevon, 1989; Poag, 1992) and carbonate accumulation dominated the continental shelf and deep-water sites above the carbonate compensation depth. Systems of downslope-trending channels continued to distribute these carbonate-rich sediments onto the upper continental rise into the early and middle Eocene, as indicated, for example, by an increase in the number of slumps and microfaults in the Carteret and Lindenkohl Alloformations at DSDP Site 613.

During the middle Eocene, another significant shift in depositional regime occurred as a second shelf break (hintershelf; figs. 2, 30, and 51) developed 120 km landward of the buried Late Jurassic reef system, which still controlled the position of the seaward shelf edge (foreshelf). Thus, middle Eocene deposition of the Lindenkohl Alloformation was greatest on the hintershelf and just seaward of the foreshelf edge. The foreshelf was a bypass area of relatively thin, mainly carbonate, accumulation. Gravity-flow mechanisms continued to be important in dispersing sediments on the middle Eocene upper continental rise.

The hintershelf edge prograded progressively seaward following the middle Eocene (figs. 2, 33, 35, 36, 39, 43, 48, 50, and 51), and terrigenous deposits dominated the margin depocenters again from the late Oligocene to the present (fig. 51). Siliciclastic progradation culminated in the middle Miocene with the development of a complex system of shelf-edge deltas that formed much of the Phoenix Canyon Alloformation. Terrigenous detritus was pumped across the foreshelf in huge volumes, until by the end of the middle Miocene, the major shelf depocenter was near the shelf break (figs. 2 and 39), giving the continental slope a modern aspect, with its relatively steep declivity. Having this major detrital source at the shelf edge significantly increased the volume of sediment reaching the continental rise, where these sediments were distributed by gravity-flow mechanisms through upper rise channels, onto the lower rise.

Similar sedimentary processes dominated late Miocene through Pliocene deposition and formed the Mey and Toms Canyon Alloformations. But depocenters on the continental rise received the largest volumes of sediment, fed from smaller depocenters perched at the shelf break. On the middle and lower rise, contour-following bottom currents redistributed fine-grained hemipelagic sediments into elongate, mounded, contourite drift deposits. Continental-rise depocenters dominated margin accumulation in the Quaternary as well, as the Hudson Canyon Alloformation was deposited (figs. 2 and 50). Sediment conduits across the continental slope became more localized, however, as large submarine canyons incised the shelf edge and created some channel systems that built large submarine fans on the lower rise.

Punctuating these Late Cretaceous and Cenozoic depositional episodes were periodic intervals of shelf and coastal-plain erosion (fig. 51), during which large volumes of sediment were redistributed to the continental slope and rise.

IMPLICATIONS REGARDING THE EXXON SEQUENCE-STRATIGRAPHY MODEL

Much of the observed allostratigraphic framework (stratigraphic position of unconformities) of the middle segment of the U.S. Atlantic margin fits the second-order (supersequence) cyclical framework of the Exxon sequence-stratigraphy model (Vail and others, 1977b; Vail and Mitchum, 1979; Vail and others, 1984; Haq and others, 1987, 1988; Van Wagoner and others, 1988). However, there are significant differences between the postulated distributions of seismic depositional sequences and the observed distribution of alloformations. The sequence-stratigraphy model postulates, for example, that during the Paleogene, four major lowstands occurred, during each of which a significant pulse of siliciclastic sediment should have reached the Hatteras basin. On the other hand, Poag and Sevon (1989) and Poag (1992) have shown that the Paleogene was characterized by the lowest sustained accumulation rates of the entire 187 m.y. of postrift deposition on this margin. The sparsity of Paleocene and Eocene deposition can be attributed to development of a tropical rainforest in eastern North America (Wolfe, 1978). The presence of such heavy vegetation, according to Cecil's (1990) model of depositional response to paleoclimate, would have minimized the availability and dispersal of siliciclastic sediment. Although the rainforest disappeared abruptly in the early Oligocene, approximately coincident with a postulated major lowstand (Wolfe, 1992), no thick Oligocene lowstand deposits have been identified anywhere in the study area.

During the middle Eocene, depositional patterns were additionally complicated by development of a dual shelf system, in which the hintershelf was characterized by a prograded series of deposits (Lindenkohl Alloformation), whereas the broad foreshelf was a starved bypass region. Deposition increased significantly again seaward of the foreshelf edge, where biosilica-rich carbonate ooze accumulated in thicknesses as great as 200–300 m.

INTRINSIC ADVANTAGES OF ALLOSTRATIGRAPHY

Sequence stratigraphy, in the sense of Vail and others (1977a,b), offers a powerful methodology for organizing complex three-dimensional sedimentary geometries, lithofacies, and paleoenvironmental regimes into a comprehensive basinwide (or marginwide) depositional framework. The method has been widely adopted as a basic tool in exploring marine basins for natural resources, especially oil and gas (Payton, 1977; Berg and Woolverton, 1985; Shell Oil Company, 1987; Wilgus and others, 1988). Even though an intense controversy is raging over the mechanisms that control the formation of depositional sequences (tectonism vs. eustasy; see Cloetingh, 1988; Hallam, 1988; Haq and others, 1988; Hubbard, 1988; Kendall and Lerche, 1988; Galloway, 1989), the sequence concept is immensely popular and has been applied even to Paleozoic successions (Ross and Ross, 1987).

Our experience in analyzing the stratigraphic record of the U.S. Middle Atlantic margin convinces us that the application of sequence stratigraphy, as modified by allostratigraphic principles, provides significant advantages over traditional biostratigraphic, lithostratigraphic, and chronostratigraphic approaches. This advantage is particularly evident in geological frontiers, where regional synthesis requires one to establish genetic relations between disparate subsets of sedimentary rocks, which accumulated in widely divergent paleobathymetric (fluvial to abyssal) and paleophysiographic (coastal plain to abyssal plain) regimes.

The allostratigraphic framework also is more applicable to the U.S. Middle Atlantic margin than the concept of "genetic stratigraphic sequences," which Galloway (1989) has eloquently espoused for dominantly siliciclastic Cenozoic deposits of the northern Gulf of Mexico region. Galloway pointed out that his genetic stratigraphic sequences are a half-cycle out of phase with the depositional sequences of the Exxon sequence-stratigraphy model (and thus with the alloformations we propose), because Galloway's sequence boundaries are marine flooding surfaces, not erosional unconformities. Marine flooding surfaces, where identifiable, should occur *within* (near the middle of) alloformations. The detailed geologic history of the U.S. Middle Atlantic margin (incorporating sediment supply, basin subsidence, source-terrain tectonism, paleoclimate, and paleoceanography) was sufficiently different from that of the Gulf of Mexico region that only a few basinwide flooding surfaces can be easily recognized in borehole and seismic data. We have been able to readily identify only two or three thin, widespread shale or carbonate units in the entire postrift succession of our study area that would qualify as Galloway's sequence boundaries.

The formal allostratigraphic nomenclature we have proposed is intended, first of all, to stabilize the stratigraphic terminology applied to deposits in the study area. Already as many as 10 different sets of descriptors have been applied to some of the seismic units recognizable there. Furthermore, we believe that the allostratigraphic nomenclature will clarify conceptual relations between genetically related deposits of the study area and will facilitate discussion and comparisons with sedimentary deposits of other basins. The allostratigraphic nomenclature is far more flexible in accommodating local and subregional perturbations (such as source-terrain tectonism, paleoclimate change, basin subsidence, depocenter migration) than the familiar "global" sequence models characterized by awkward alphanumeric nomenclature, which is changed frequently and is applied inconsistently by different workers. Furthermore, the use of allostratigraphy precludes the subjective forcing of "anomalous" features to fit simplistic, stylized preconceptions inherent to the models. The investigator is free to recognize the individuality of each basin.

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Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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