State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 71

INTERNAL STRATIGRAPHIC CORRELATION OF THE SUBSURFACE POTOMAC FORMATION, NEW CASTLE COUNTY, DELAWARE, AND ADJACENT AREAS IN MARYLAND AND NEW JERSEY

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With a contribution on Palynology by

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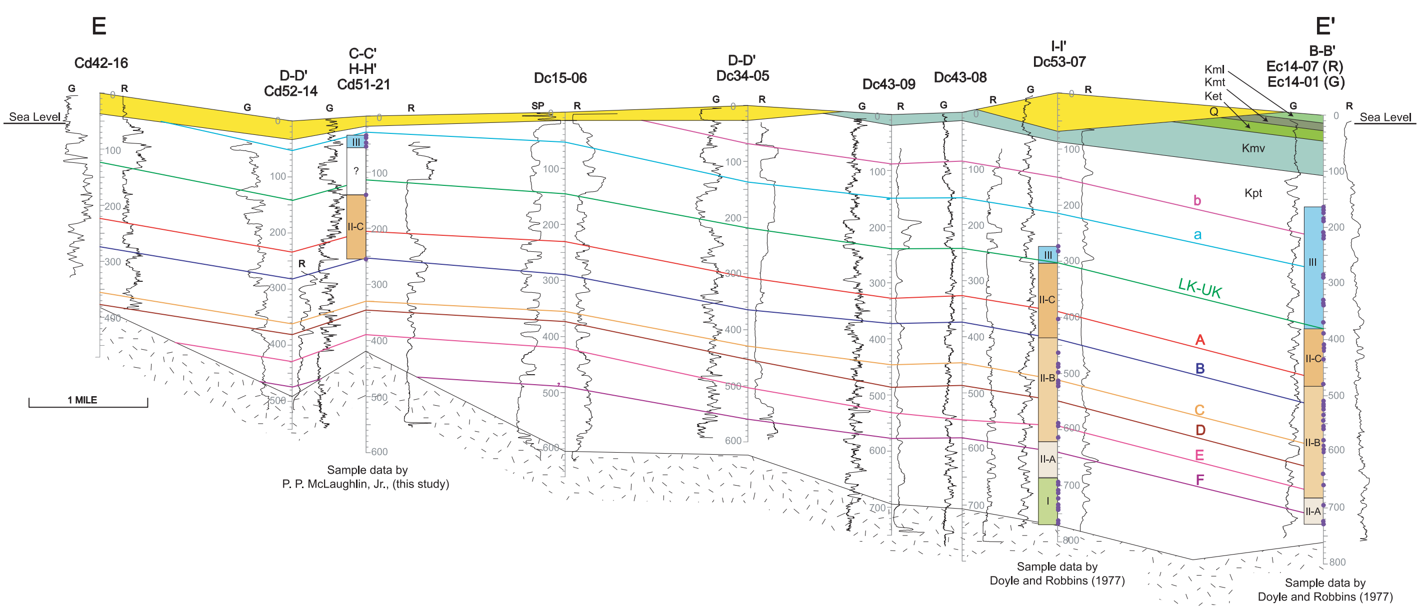

University of Delaware
Newark, Delaware
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INTERNAL STRATIGRAPHIC CORRELATION OF THE SUBSURFACE POTOMAC FORMATION, NEW CASTLE COUNTY, DELAWARE, AND ADJACENT AREAS IN MARYLAND AND NEW JERSEY

Richard N. Benson

ABSTRACT

This report presents a new time-stratigraphic framework for the subsurface Potomac Formation of New Castle County, Delaware, part of adjacent Cecil County, Maryland, and nearby tie-in boreholes in New Jersey. The framework is based on a geophysical well-log correlation datum that approximates the contact between Upper and Lower Cretaceous sediments. This datum is constrained by age determinations based on published and unpublished results of studies of fossil pollen and spores in samples of sediment cores from boreholes in the study area. Geophysical log correlation lines established above and below the datum approximate additional chronostratigraphic surfaces. The time-stratigraphic units thus defined are not correlated parallel to the basement unconformity, as in previous practice, but instead onlap it in an updip direction. In future studies, the sedimentary facies of the Potomac Formation within each time-stratigraphic layer may be mapped and analyzed as genetically related contemporaneous units. This new stratigraphic framework will allow better delineation of the degree of lateral connection between potential aquifer sands, thus enhancing understanding of aquifer architecture.

INTRODUCTION

The Potomac aquifer is the largest source of ground water in New Castle County, Delaware, supplying approximately 22 million gallons of water per day for public, domestic, industrial, and agricultural use (Wheeler, 2003). Thick fluvial sand layers within the Potomac Formation yield significant volumes of water. However, the subsurface geology of this interval is complex; individual aquifer sands are known in some cases to be laterally discontinuous between wells over distances of a few miles (McKenna et al., 2004). Given increasing development in rural areas, and the resulting increased demand for water, a sound understanding of the distribution and physical characteristics of Potomac aquifer sands is of growing importance to managing ground-water resources. An accurate stratigraphic framework is an essential starting point.

Geologic Background

The nonmarine Potomac Formation (or Group) constitutes a thick, predominantly subsurface, Lower to Upper Cretaceous wedge of sediments that underlies much of the Middle Atlantic Coastal Plain. The name Potomac was first applied to these sediments by McGee (1886a, b) in the District of Columbia and adjacent Maryland and Virginia. He later traced the unit from North Carolina to New Jersey (McGee, 1888). In Maryland, Clark and Bibbins (1897) elevated the Potomac Formation to Group rank with their subdivision of the unit into the Patuxent, Arundel, Patapsco, and Raritan Formations (oldest to youngest) in Maryland. On the basis of Berry's (1910) and Clark's (1910) determinations that the Raritan Formation is an Upper Cretaceous unit, Clark et al. (1911) removed the Raritan Formation from the Lower Cretaceous Potomac Group. Glaser (1969) noted that current practice in Maryland had reinstated the Raritan as the uppermost formation of the Group, although it is lithologically indistinguishable from the underlying Patapsco Formation. On the basis of palynological studies, Doyle and Robbins (1977) demonstrated that sediments equivalent in age to the Raritan Formation of New Jersey are absent in Maryland and Delaware. Edwards and Hansen (1979) accepted this and recognized the Patuxent-Arundel (undivided) and Patapsco Formations in their descriptions and cross sections of borehole geophysical logs in Cecil, Harford, Kent, and Queen Annes counties, Maryland. They noted that the subdivision of the Potomac Group in the Baltimore area is facilitated by the occurrence of the Arundel Clay, but the mappable Arundel Clay is absent northeast of Baltimore County.

In Delaware, Jordan (1962) applied McGee's original name, the Potomac Formation, to what Groot (1955) referred to as the "nonmarine Cretaceous sediments." Attempts to identify in Delaware the three formations recognized in Maryland were unsuccessful; therefore, the Delaware Geological Survey recognized the Potomac in Delaware as a formation, not a group, and it still does today. In this report, the Potomac is considered a formation, not a group, in the area of study.

In general, the sediments of the Potomac Formation (or Group) comprise the deposits of a vast aggrading alluvial plain bordering the Appalachian Piedmont (Jordan, 1983). In southern Maryland, Hansen (1969) characterized the sediments as comprising a fluvio-deltaic complex but representing only the flood-plain environments of a subaerial delta; in northern Delaware and nearby areas, the sediments are entirely of fluvial origin (McKenna et al., 2004). Potomac sediments were deposited during intervals of the Aptian, Albian, and Cenomanian Stages of the middle part of the Cretaceous Period, about 125 to 95 million years ago (Doyle and Robbins, 1977; Hochuli et al., 2006). They are the deposits of an anastomosing river system and consist of subordinate channel sands enclosed by overbank sands and flood-plain silts and clays, forming a three-dimensional labyrinthine network of channel sands in a matrix of flood-plain muds (McKenna et al., 2004). The thickness of the Potomac Formation ranges from zero at the Fall Line boundary between the Piedmont and Atlantic Coastal Plain Provinces to more than 4,600 ft at Ocean City, Maryland, at the Atlantic coast just south of the Delaware-Maryland border (Hansen, 1982). Its greatest thickness in the study area is more than 1,600 feet in southernmost New Castle County. The formation onlaps the eroded surface of the crystalline basement, which is composed of Paleozoic and older metamorphic and igneous rocks similar to the rocks now exposed in the Piedmont of northern Delaware. Its upper surface is truncated by an unconformity; the formation subcrops under Quaternary surficial sediments in the north and underlies the Upper Cretaceous Magothy and Merchantville Formations in the southern part of the study area. Scattered outcrops of the formation occur in the north of the study area, just south of the Fall Line.

Purpose and Scope

The purpose of this report is to establish a new stratigraphic framework for the internal correlation of the Potomac Formation in northern Delaware and nearby areas that will lead to a better understanding of the interconnectedness of important water-bearing sands. To do this, borehole data from New Castle County, Delaware, Cecil County, Maryland, and adjacent areas of New Jersey (Fig. 1) were examined. The principal basis for this new framework is correlation of geophysical logs. Detailed correlation of stratigraphic markers identified on the geophysical logs has defined approximately synchronous stratigraphic surfaces. Where available, age-significant fossil spore and pollen assemblages were additionally used to constrain these correlations. The time-stratigraphic framework thus established is presented in this report in a series of intersecting cross sections covering the study area (Pls. 1-3). This geological framework has been used by the U.S. Army Corps of Engineers (USACE) (2004) as the basis for a three-dimensional finite element ground-water model for the Potomac Formation requested by the Delaware Department of Natural Resources and Environmental Control (DNREC).

Acknowledgments

I am grateful to Peter P. McLaughlin, Jr. of the Delaware Geological Survey (DGS) who provided valuable biostratigraphic palynological data for this report (see Appendix).

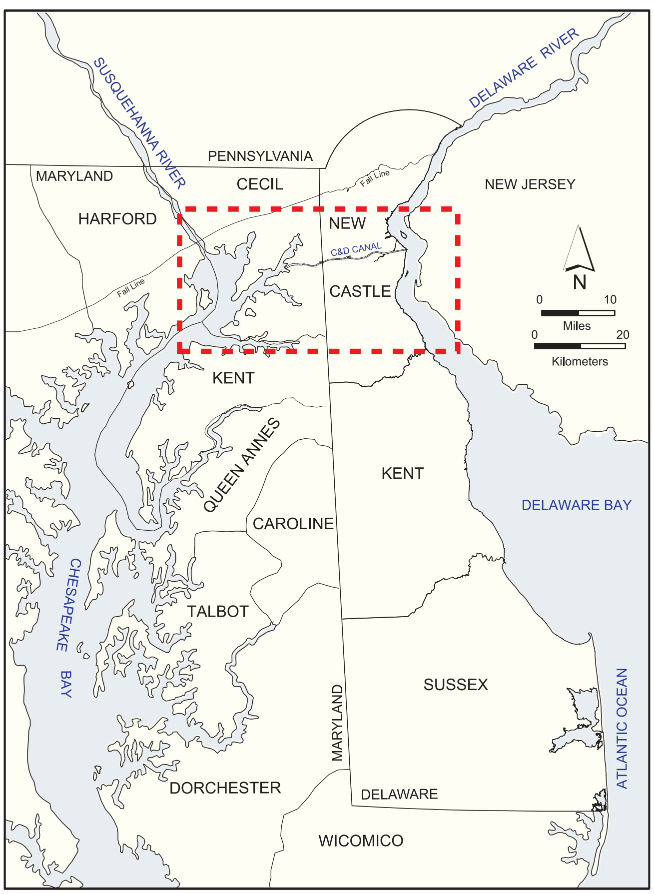

Figure 1. Location map of the study area. County boundaries in Maryland are generalized.

Fruitful discussions with DGS Potomac Project colleagues Peter P. McLaughlin, Jr. and Thomas E. McKenna enhanced the quality of this report. I thank DGS publications coordinator Stefanie J. Baxter and DGS cartographer Lillian T. Wang for diligent efforts in readying the manuscript for publication.

The manuscript was critically reviewed by Peter P. McLaughlin, Jr., and by Pierre Lacombe of the U.S. Geological Survey, who offered helpful suggestions for its improvement.

Previous Investigations

Past studies of the Potomac Formation in Delaware have long recognized lithologic variability of the unit, which creates difficulty in tracing individual sand or clay beds with certainty, even for distances of as little as a half mile (Jordan, 1962, 1968). Because of this, Sundstrom et al. (1967) lumped groups of beds together on the basis of their dominant aggregate characteristics, i.e., into dominantly sandy and dominantly clayey zones. For hydrologic purposes in the Chesapeake and Delaware (C&D) Canal area, they delineated two relatively sandy zones, referred to as the lower and upper hydrologic zones, with a persistent clayey zone between. The lower hydrologic zone tends to be sandier than the upper. The three zones were shown parallel to the basement surface, and they thicken downdip (Sundstrom et al., 1967, Sundstrom and Pickett, 1971). Woodruff (1977, 1981, 1986) also illustrated basement-parallel correlation of sands or sandy hydrologic zones for the Potomac Formation.

In contrast, in a study of a small area of 26 square miles west of Delaware City, Spoljaric (1967) considered the internal stratigraphy of the Potomac Formation to approximately parallel the top of the formation. On the basis of a quantitative lithofacies analysis of electric log data from 25 boreholes that reached basement, Spoljaric arbitrarily subdivided the entire Potomac section into seven 130-ft-thick layers parallel to the average dip of the unconformity at the top of the formation (about 20 ft/mi) and mapped the sand percentage within each of the layers

Palynological studies have provided a reasonable age framework for the Potomac Formation. As part of a study of the palynology of the Potomac Group of Maryland, Brenner (1963) examined samples from the study area (Cecil County, Maryland). He established two spore-pollen zones as well as subzones that could be recognized in some localities. On the basis of comparison of the assemblages to European localities, Brenner considered the Potomac Group to be upper Barremian to Albian. This zonation was advanced by Doyle and Robbins (1977), who established a more refined zonation utilizing angiosperm pollen from cores of two Delaware City boreholes, Dc53-07 and Ec14-01 (Pls. 1-3; Table 1). They recognized the Potomac Formation in these holes to range from Barremian-Aptian (upper part of the Lower Cretaceous) to lower Cenomanian (basal Upper Cretaceous). More recently, the age of some of the zones was slightly revised by Hochuli et al. (2006) on the basis of studies of angiosperm pollen records from two well-dated sections in Portugal (Table 1).

Previous studies in Maryland and New Jersey have demonstrated the importance of spore-pollen zones for correlation within Potomac strata. Edwards and Hansen (1979) used the pollen zones established by Doyle and Robbins (1977) for the Delaware City boreholes and the geophysical logs of those boreholes as tie-points for correlation to the

Table 1. Spore-pollen zones identified in the Potomac Formation and their ages.

Zone/Subzone	Age *(Doyle and Robbins, 1977)*	Age *(Hochuli et al., 2006)*
Zone III	early Cenomanian	not studied
Subzone II-C	latest Albian	early Cenomanian
Subzone II-B	middle and early late Albian	middle to late Albian
Subzone II-A	early to middle Albian	middle to late Albian
Upper Zone I	Aptian to early Albian	early Albian
Lower Zone I	Barremian to Aptian	Aptian

Maryland boreholes on their cross sections in Cecil, Harford, Kent, and Queen Annes counties, Maryland. On the basis of scattered samples from Maryland boreholes yielding fossil pollen that provided identifications of palynological zones, they made geophysical log correlations of broad, approximately time-stratigraphic lithologic units (Table 2). Similarly, Owens et al. (1998) used Doyle and Robbins's (1977) pollen zonation to subdivide the Potomac Formation into three informal units. The highest, unit 3, is the only outcropping unit; units 1 and 2 are entirely subsurface units (Table 2).

Table 2. Spore-pollen zones and correlation to Potomac strata in previous studies in Maryland and New Jersey portions of the study area.

<table>
<tr><th>Zone/Subzone</th><th>Eastern Maryland
(Edwards and Hansen, 1977)</th><th>New Jersey
(Owens et al., 1998)</th></tr>
<tr><td>Zone III</td><td rowspan="2">Patapsco Formation (Elk Neck Beds)</td><td>unit 3</td></tr>
<tr><td>Subzone II-C</td><td rowspan="3">unit 2</td></tr>
<tr><td>Subzone II-B</td><td>Patapsco Formation</td></tr>
<tr><td>Subzone II-A</td><td rowspan="2">Patuxent/Arundal Formation</td></tr>
<tr><td>Zone I</td><td>unit 1</td></tr>
</table>

The sedimentary facies of Potomac strata have been examined in detail in only a few previous studies. Hansen (1969) presented one of the earliest treatments of the sedimentary facies and depositional environments in subsurface Potomac sediments, focusing on southern Maryland. Using electric log profiles, Hansen identified intervals that he considered to be meandering-stream and braided-stream deposits and related these observations to aquifer characteristics.

More recently, McKenna et al. (2004) conducted a detailed sedimentological analysis of three continuously cored boreholes through the Potomac Formation—two near New Castle, Delaware (Cd51-21 and Cd51-23) and one at Fort Mott, New Jersey (Dd42-04). Five sedimentary facies were recognized on the basis of grain sizes, sedimentary structures, bedding, and geophysical log pattern.

(1) Amalgamated sand intervals 30 to 70 ft thick, mostly fine to medium in 10- to 30-ft-thick fining upward packages, representing a vertical succession of fluvial channels.
(2) Thick individual sands, 5 to 20 ft thick, representing isolated fluvial channels.
(3) Thin sands, less than 10 ft thick, usually 1 to 3 ft, representing crevasse splay/proximal levee deposits.
(4) Interlaminated sands and silts, representing distal levee/flood-plain deposits.
(5) Mottled silts and clays, red or variegated red and gray, representing weathered flood-plain deposits with paleosols.

The lateral distribution of these facies can be evaluated within each of the time-stratigraphic units defined in this report, which should lead to a better understanding of the interconnectedness of the important water-bearing sands.

METHODS

The first step in generating the cross sections presented here was to select a time-line datum recognizable on geophysical logs of boreholes. The datum chosen approximates the Lower Cretaceous-Upper Cretaceous (Albian-Cenomanian) contact as verified by palynological data. Next, silt-clay ("shale") markers were identified on the geophysical logs above and below the datum that were considered correlatable on the basis of the consistency of their stratigraphic positions from log to log. Because sand beds vary in thickness and character from borehole to borehole, detailed geophysical log correlations were focused on shale sections. Recall that in the study area, sediments of the Potomac Formation were interpreted as comprising a three-dimensional labyrinthine network of fluvial channel sands in a matrix of flood-plain muds (McKenna et al., 2004). The channel sands in such a system are irregularly distributed. The silts and clays are flood-plain deposits, many with paleosols, and in many cases are likely to be more areally extensive than the sands. Where these mud units can be correlated from log to log, they likely represent approximately synchronous time lines that bound time-stratigraphic units of sediments. The resulting cross sections are shown on Plates 1-3.

RESULTS AND DISCUSSION

Maps showing the network of cross sections are shown on Plates 1-3. Cross sections A-A′ through D-D′ (Pls. 1 and 2) include most of the borehole logs on Martin's (1984) cross sections A-A′ through D-D′ with a few additions and substitutions. In order to characterize the entire Potomac section, boreholes that penetrated basement were the primary ones chosen for inclusion on all the cross sections. Cross sections in Cecil County, Maryland, are included because there are additional supporting palynological data from boreholes there (Edwards and Hansen, 1979). This area is also included because much of it falls within the boundaries of the ground-water model for the Potomac Formation in New Castle County, Delaware, being developed by the USACE (2004). Cross sections B-B′, C-C′, and I-I′ extend across the Delaware River into New Jersey to tie-in with boreholes there which also are within the USACE model boundaries.

Datums for Time-Stratigraphic Correlation

Figure 2 shows three different approaches to selecting a time-line datum in the Potomac Formation in Delaware. Figure 2A illustrates the basement-parallel style of correlation of some workers. Jordan (1968) considered the contact between the Potomac Formation and basement to be a subsurface continuation of the Fall Zone Peneplain. He assumed that the gross stratification of the Potomac Formation is more or less parallel to this basement contact and attributed the downdip increase in thickness of the formation to the addition of younger beds rather than the thickening of older strata. This same approach was followed by Sundstrom et al. (1967) in establishing hydrologic zones in the Potomac Formation.

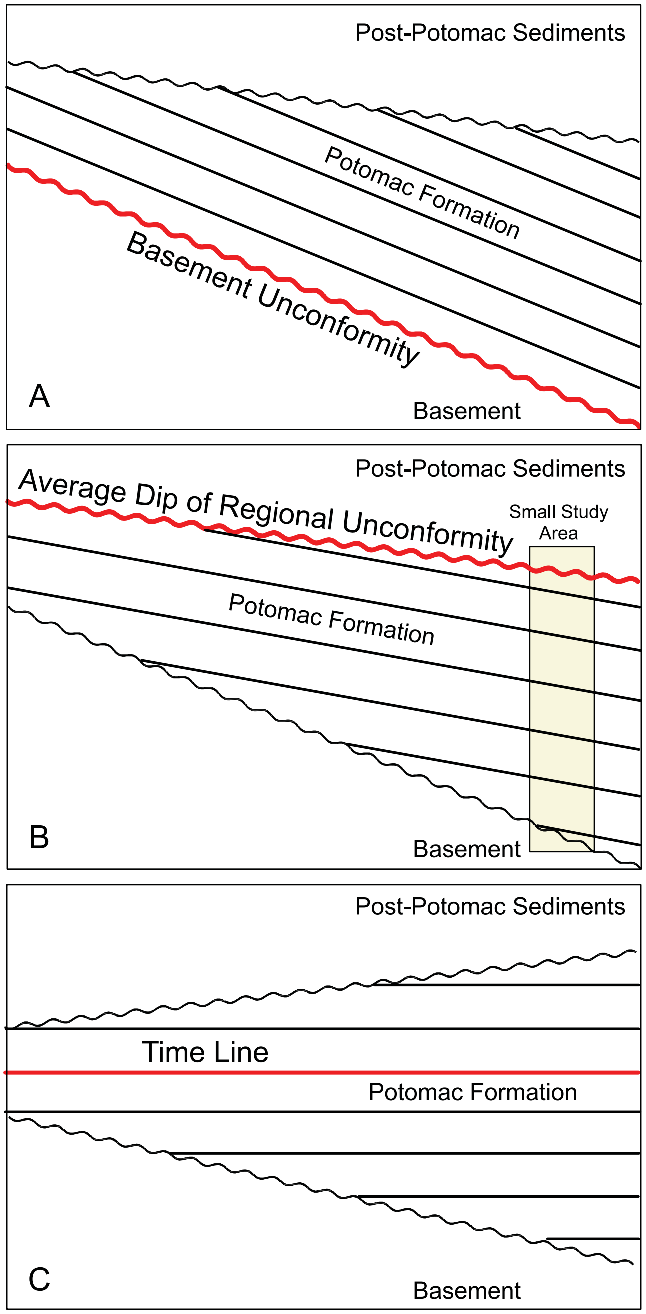

Figure 2. Diagram illustrating three different time-line correlation datums (red) and parallel time-lines (black) applied to the Potomac Formation. Note truncation of all layers by the top unconformity. A and B are structural sections (sea level datums).
A. Basement unconformity as a time line with time-line correlations parallel to it (Jordan, 1968).
B. Time-line correlations in a small study area parallel to the average dip of the regional unconformity at the top of the Potomac Formation (Spoljaric, 1967). Note the convergence of the apparent time lines with the unconformity where traced updip from the small study area.
C. Stratigraphic section with a paleontologically determined time-line datum (e.g., the Lower-Upper Cretaceous contact of this report) oriented horizontal. Correlatable time-line marker beds above and below the datum that are identified on geophysical logs become apparent during log-to-log correlation.

The second approach, shown in Figure 2B, correlates the internal stratigraphy of the Potomac Formation approximately parallel to the regional unconformity at the top of the formation. This approach was taken by Spoljaric (1967) to delineate time-stratigraphic units discussed previously.

The approach followed in this report (Fig. 2C) results in a very different pattern of correlation than those two past approaches. The cross sections (Pls. 1-3) are based on log-to-log correlations using a time-line datum, herein designated the LK-UK datum, that approximates the palynologically defined Albian-Cenomanian or Lower Cretaceous (LK)-Upper Cretaceous (UK) contact. The result is a pattern of stratigraphic correlation in which the Potomac Formation thins to the north through both onlap of the basement and truncation below the unconformity at the top of the formation.

The LK-UK datum is defined as the contact between a shale interval and overlying thick sand section that is conspicuous in the upper part of the Potomac Formation in two boreholes studied by Doyle and Robbins (1977) near Delaware City, Delaware, Dc53-07 and Ec14-01. On the downdip end of section E-E' shown on Plate 2, the samples they studied and their zones are plotted alongside the gamma and resistivity logs for the two boreholes. The boundary between Subzone II-C and Zone III was placed just below the position of this conspicuous sand-on-shale contact in both boreholes; as this feature appears on nearby geophysical logs, it represents a convenient time-line datum.

A similar correlation approach was taken by Edwards and Hansen (1979) for the Potomac strata in Cecil County, Maryland. In their geophysical log correlations in the area, which included Delaware wells Dc53-07 and Ec14-01, they noted that the thick clay-silt bed identified as Subzone II-C that underlies the sand section assigned to Zone III may become a shallow subsurface marker bed in the upper Chesapeake Bay area.

The LK-UK time-line datum is the horizontal datum for correlating all geophysical log correlations in this report. Additional time lines were identified by shale "kicks" above and below the datum; these are labeled A through F below and *a* and *b* above the datum. It is apparent that the time lines are mostly parallel to the LK-UK datum. This is not surprising as the Potomac Formation comprises the deposits of a vast alluvial plain of low relief in an anastomosing river environment consisting of subordinate channel sands enclosed by overbank sands, silts, and clays. Individual sand bodies are generally no thicker than 20 feet (McKenna et al., 2004); therefore, relief between channel and adjacent flood plain was low. The shale markers on the geophysical logs identifying the time lines are assumed to represent flood-plain surfaces, many of which are marked with paleosols. The overall effect on a regional basis is a distinct parallelism of time lines which is apparent on the cross sections.

Section E-E' (Pl. 2) provided a test of this method of correlation, extending from the area where this datum was established (Dc53-07 and Ec14-01, Delaware City) updip to a newer continuously cored borehole with palynological control (Cd51-21, New Castle, Delaware). The LK-UK datum identified on geophysical logs in Cd51-21 was determined to lie between samples placed in Subzones II-C and Zone III (palynological control provided by P. P. McLaughlin, Jr., DGS; see Appendix; McKenna et al., 2004). With the LK-UK datum identified in this updip borehole, the time lines shown in E-E' were successfully correlated from the Delaware City control boreholes to the New Castle control borehole and beyond.

The time-stratigraphic units shown on the dip-oriented cross sections on Plates 1, 2, and 3 onlap the basement in an updip direction. The top of the Potomac Formation on all cross sections is truncated by an erosional unconformity. In updip areas, Quaternary deposits (undifferentiated for this report) overlie the Potomac. Downdip, the Magothy Formation overlies the Potomac Formation in most places; locally, where the Magothy Formation is absent, the Potomac Formation is overlain by the Merchantville Formation. Correlation of post-Potomac stratigraphic units on the cross sections follows that of Benson and Spoljaric (1996).

Palynological Control for Correlation

In applying palynological zones as control for geophysical log correlations, it is important to note that resolution is limited because of scattered occurrences of samples which yield sufficient pollen and spores to identify zones. Although individual samples may provide enough data to identify a zone or subzone, precise zonal boundaries cannot be identified under many circumstances. Palynological data should be used only as a guide to the geophysical log correlation as geophysical logs are commonly the only available continuous record of a borehole.

Palynological control is available for Potomac strata in nearby areas of Maryland and New Jersey and is utilized to constrain correlations on the cross sections. Data from continuously cored borehole Dd42-04 at Fort Mott, New Jersey (Section I-I', Pl. 3), by G. Brenner and P. P. McLaughlin, Jr. are available in Sugarman et al. (2004). Data for three Maryland boreholes by J. A. Doyle are available in Edwards and Hansen (1979): Ce-Dc 2 near Turkey Point (DGS identifier Zz63-21; Section I-I', Pl. 3); Har-Dg 3 on Spesutie Island (Zz63-45; Section I-I', Pl. 3); and Ce-Ec 17 at Grove Point (Zz63-22; section K-K', Pl. 3).

Additional palynological control (Appendix) from seven sites in Delaware helps further constrain correlations. One feature of the stratigraphy supported by palynological constraints is increasing truncation of the top of the Potomac Formation in an updip (northwestward) direction. Near-surface construction-boring samples from two sites near the Fall Line, Cc52-a and Cc41-b (section H''-H', Pl. 3), are assigned to Zone II-B, indicating a considerable amount of Potomac strata was eroded from the top of the formation at those sites. This observation supports correlations from holes downdip in New Castle (Cd51-23, Cd51-21; section H''-H', Pl. 3) that indicate the erosional contact at the top of the Potomac Formation updip from those boreholes cuts down into strata below the LK-UK contact.

Another feature of the local stratigraphy made evident by palynological analysis is an apparent offset or elevation change within Potomac strata approximately along the Fall Line. On section H-H', there appears to be an abrupt change in the elevation of Potomac strata between boreholes Cb54-49 and Cb55-60. This location is near a high point of the basement near Christiana that was uncovered beneath a thin Quaternary layer during construction of a shopping center. The boreholes west of that area are interpreted to include the highest levels of the Potomac Formation based on cross correlation with sections A-A' and B-B' and the identification of Subzone II-C or lower Zone III in borehole Db12-49 (see Appendix). On the east side of that area, split-spoon core samples from a depth of 50 ft in borehole Cb55-60 yielded pollen that identified Subzone II-B; therefore, the overlying section equivalent to Subzone II-C and Zone III is considered to be missing, consistent with correlations east of that location (section H-H', Pl. 3). Faulting may account for this elevation difference, with the eastern part, including the Christiana basement high, as an upthrown block, and the western part a downthrown block in which the younger Potomac section is preserved (section H-H', Pl. 3).

Hydrogeologic Models of the Potomac Formation

Because stratigraphy exercises an important control on hydrology in sedimentary aquifers, hydrogeologic modeling projects should be built on a high-quality stratigraphic interpretation. The choice of a stratigraphic datum is an important element of hydrogeologic modeling in the Potomac aquifers. Figure 3 illustrates two different approaches to hydrogeologic modeling of the Potomac Formation in New Castle County, Delaware. Figure 3A shows an example of the configuration of model layers used by Martin (1984) in her digital ground-water model, which were derived from aquifer/hydrologic layer definitions of Rasmussen et al. (1957), Sundstrom et al. (1967), and Sundstrom and Pickett (1971). The stratigraphic framework is more or less parallel to the basement surface and is divided into three aquifers with intervening confining beds.

In contrast, the U.S. Army Corps of Engineers (2004) is using the stratigraphic approach presented in this report—correlation of time stratigraphic units that onlap basement—as the basis for their three-dimensional finite element ground-water model for the Potomac Formation. Utilizing the stratigraphic framework presented in this report, they divided the Potomac Formation into three layers, from youngest to oldest, A, B, and C, respectively (Fig. 3B). Unlike previous studies, these layers are not designated as an aquifer or confining unit. Model layer A comprises the section above the LK-UK datum, Cenomanian-age sediments that are placed in palynological Zone III. Model layer B extends from the LK-UK datum to the stratigraphic horizon labeled B; this comprises most of palynological Subzone II-C. Model layer C is the section between stratigraphic horizon B and basement. The three layers are shown for section B-B' from this report (Fig. 3B), revealing a significantly different model configuration between the U.S. Army Corps of Engineers (2004) and Martin (1984) studies (as a note, section B-B' in this report and section B-B' of Martin (1984) are essentially the same section, with some minor changes: the substitution of a basement hole, Db25-07, for Martin's Db25-06; and the addition of the gamma log of Dc31-12 to accompany the resistivity log of Martin's nearby Dc31-10).

The USACE model benefits from the time-stratigraphic framework presented in this report because it allows for potential correlation of aquifer-quality sands that may be genetically related at the time of their deposition and thus may be better connected hydraulically. In contrast, the aquifer units of Martin's (1984) model are not parallel to sedimentary layering and do not accurately represent the degree of lateral transmissivity of ground water. Also, the Martin model assumed direct recharge to all aquifers from the surficial aquifer, whereas in the USACE model there is direct recharge only to the uppermost aquifer sands and limited or no recharge to lower aquifer sands from the surficial aquifer.

Sands of Potential Aquifer Quality

The percentages of potential aquifer-quality sands in New Castle County boreholes for each of layers A, B, and C of the USACE model were calculated to aid in evaluation of

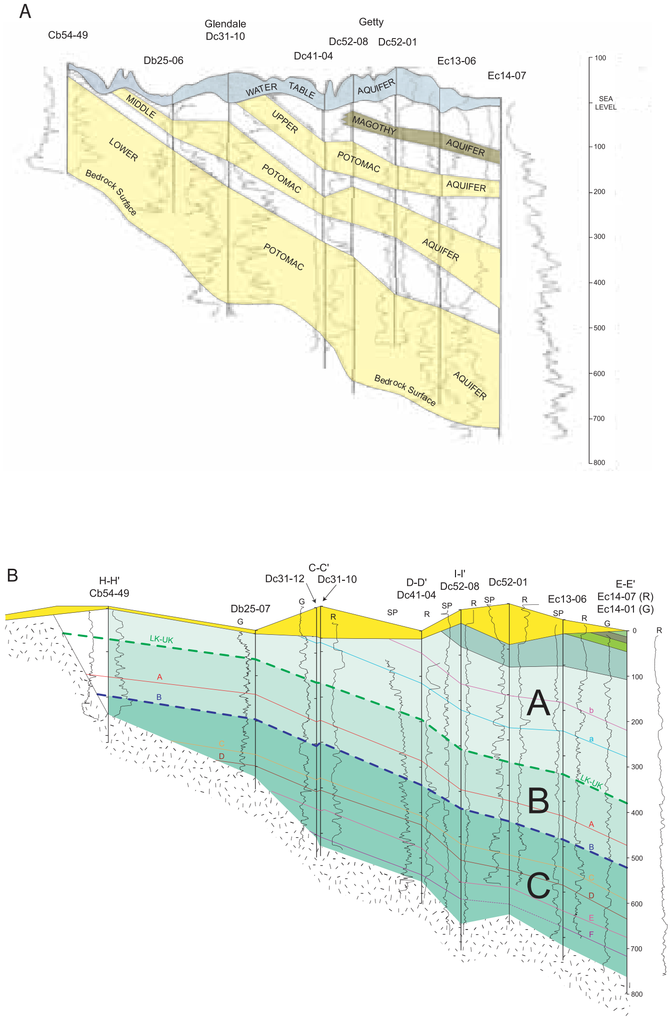

Figure 3. Contrasting hydrogeologic model layers.
A. Cross section B-B' of Martin (1984) showing three Potomac Formation aquifers and a supposed Magothy aquifer with intervening confining units more or less parallel to the basement surface. Note that all three Potomac aquifers are truncated by the top unconformity and show potential for direct recharge from the surficial Quaternary aquifer.
B. Part of B-B' of this report vertically exaggerated to match B-B' of Martin (1984 (but with the substitution of a basement hole, Db25-07, for Martin's Db25-06 and the addition of the gamma log of Dc31-12 to accompany the resistivity log of Martin's nearby Dc31-10) showing the U.S. Army Corps of Engineers (2004) geologic model of three basement-onlapping layers, from youngest to oldest, A, B, and C, none of which is defined as an aquifer or confining unit. The layers are the basis for their three-dimensional finite element ground-water model (in progress) for the Potomac Formation. Note that only the stratigraphically highest (youngest) sediments receive direct discharge from surficial Quaternary aquifer. See text for definition of the layers and formations depicted on the figure.

hydraulic properties. Boreholes Dc52-08 and Dc52-01 on section B-B' serve as examples; Figure 4 illustrates the correlation of the model layers between these boreholes with the LK-UK horizon as the horizontal datum. To identify sands of potential aquifer quality, intervals with geophysical log signatures indicative of relatively clean sands were identified. Log value cut-off levels termed 50 percent sand lines were identified on gamma, spontaneous potential, and resistivity logs. The methodology is outlined on Figure 4. Shale base lines (green) are shown for both spontaneous potential (SP, on left) and resistivity (R, on right); these lines are drawn at the maximum positive extent of the SP curve and the lowest values of the resistivity curve, which indicates shales or muds on these logs. The 100 percent sand lines (blue) are drawn at the maximum negative extent of the SP curve and the highest values on the resistivity curve; these log values indicate the cleanest, water-bearing sands. The 50 percent sand lines (red) are drawn halfway between the shale line and the 100 percent sand line. In this study, values between the 50 percent and 100 percent sand lines are considered likely sandy enough to be potential aquifers. The vertical thickness of the identified sand zones (yellow), divided by the total thickness of each layer A, B, and C, multiplied by 100, gives the percentage of sands of presumed aquifer quality for each layer.

The sand percentage data thus determined, which were used by the USACE (2004), are summarized in Table 3 for each of the three modeling layers. Layer B has significantly less sand than layers A and C and, therefore, as a whole may have less transmissivity than A and C.

Table 3. Summary of sand percentage data for the three modeling layers used by the USACE (2004).

	No. of Boreholes	Range of % Sand	Mean % Sand	Standard Deviation
Layer A	62	0-82	32.3	19.4
Layer B	60	0-67	19.4	16.1
Layer C	61	0-72	32.8	17.1

CONCLUSIONS

The cross sections of this report establish a time-stratigraphic framework in which the spatial relationships between lithofacies of the Potomac Formation can be mapped and analyzed. This study meets the first of four objectives McKenna et al. (2004) listed for characterizing the aquifer sands of the Potomac Formation of the inner Atlantic Coastal Plain of Delaware.

(1) Establish an accurate stratigraphic framework as the basis for characterizing the depositional and aquifer architecture.
(2) Calibrate each of the five facies types (listed above under Previous Investigations) to geophysical log character using core data.
(3) Estimate the distribution of facies types within the updated stratigraphic framework.
(4) Assess aquifer characteristics (permeability, storage properties) and interconnectivity of facies types based on available aquifer test results.

The basis for the time-stratigraphic correlation presented in this report is a geophysical log datum approximating the contact between Lower Cretaceous sediments containing pollen identified with Palynozone II and overlying Upper Cretaceous sediments yielding pollen identified with Palynozone III. Additional time lines were identified on geophysical logs by correlatable log markers for mud beds above and below the datum. The log markers are assumed to represent flood-plain horizons, many of which are marked

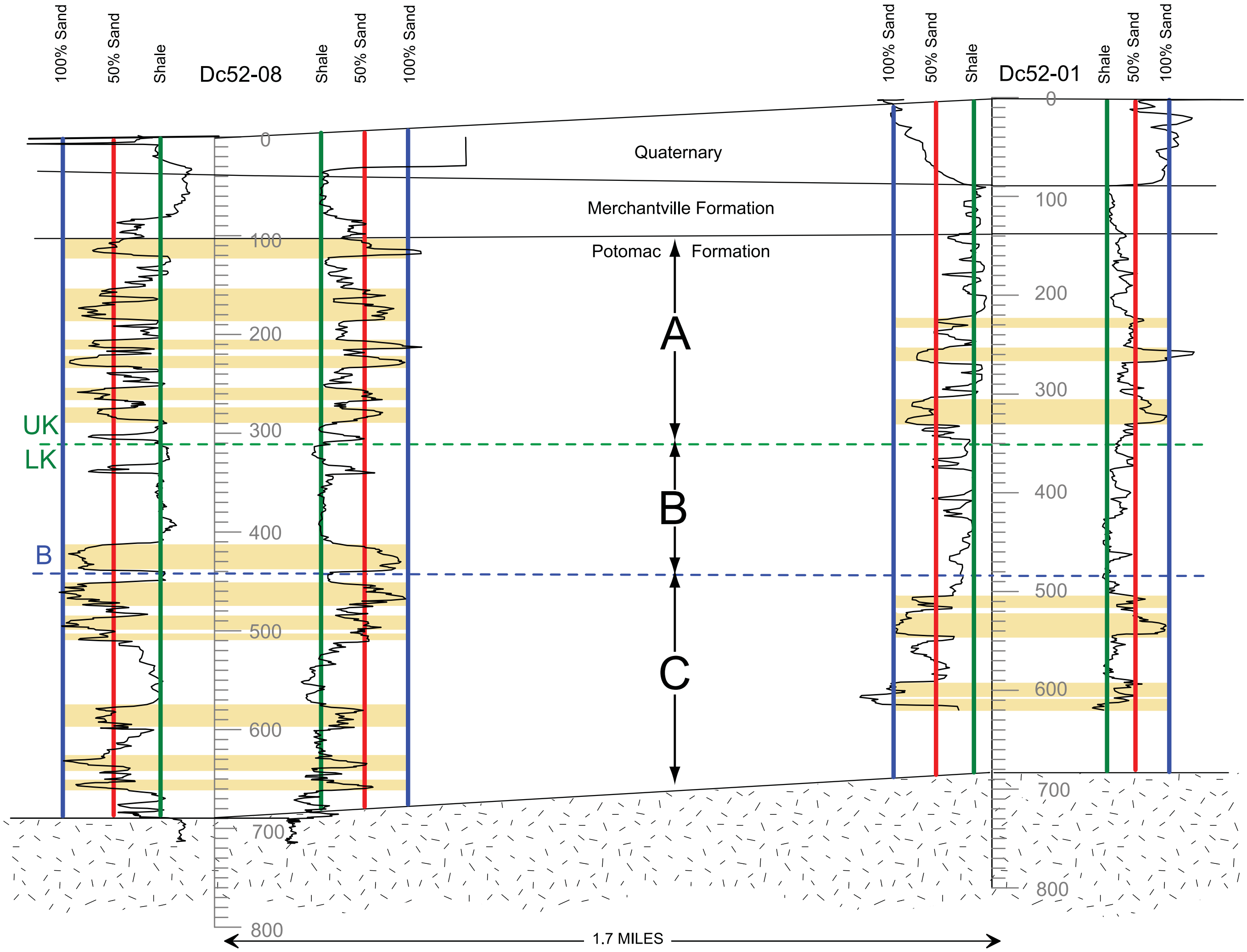

Figure 4. Stratigraphic section illustrating the procedure for analysis of borehole geophysical logs to define sands of potential aquifer quality and to determine their percentages. Boreholes Dc52-08 and Dc52-01 are on section B-B' (Pl. 1). For each borehole, spontaneous potential curves are on the left, and resistivity curves are on the right. The Lower-Upper Cretaceous datum is horizontal, and correlation line B is as depicted in Plate 1. Sands of potential aquifer quality are arbitrarily identified as those whose spontaneous potential and resistivity curves extend beyond the 50 percent sand line. See text for further explanation.

with paleosols. The overall effect on a regional basis is a distinct parallelism of time lines which is apparent on the cross sections.

This time-stratigraphic framework provides a genetic context for correlating and mapping the sedimentary facies of the Potomac Formation. It allows the degree of lateral connection, and therefore hydraulic conductivity, between potential aquifer sands to be better determined in order to define aquifer architecture. The network of cross sections created for this study provides a basis for correlation of data from additional boreholes in the study area. With the addition of these data, meaningful structure contour maps of stratigraphic horizons and thickness (isopach) maps of stratigraphic intervals can be constructed. Within stratigraphic intervals, net sand or sand percentage maps can be constructed to aid in the prediction of sand trends.

Finally, the new internal stratigraphy for the Potomac Formation established in this study provides an improved geological framework for aquifer modeling. The results of this study are being used in an aquifer modeling study by the U.S. Army Corps of Engineers (2004). The USACE model layers follow the time-stratigraphic framework of this report, with layers onlapping the basement as well as truncation from above. As a result, direct recharge from the surficial aquifer is only to the uppermost, youngest aquifer sands with limited or no recharge to lower aquifer sands. This is a significant advance over older hydrogeologic models based on basement-parallel correlations of broadly defined aquifer units of the Potomac Formation (e.g., Martin, 1984).

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APPENDIX

Preliminary Report on the Palynology of the Potomac Formation of Delaware

By Peter P. McLaughlin, Jr.

Summary of Findings

Palynological analyses have been conducted for samples from the Potomac Formation for seven sites in New Castle County, Delaware, to establish biostratigraphic constraints on stratigraphic correlation of aquifer sands. These palynological data support the internal correlations in the Potomac Formation presented in this report. In particular, the selection of a correlation datum approximating the Lower Cretaceous – Upper Cretaceous boundary (LK/UK) is supported by the occurrence of Zone II palynomorphs below this boundary and Zone III palynomorphs above. These palynological findings justify the significant revision to the stratigraphic framework presented in this study and provide a sound geologic basis for delineating aquifer geometry in these difficult-to-correlate non-marine facies

Palynology was first established as a useful stratigraphic tool in Potomac strata in the late 1950s and early 1960s. Groot and Penny (1960) published one of the first studies of the occurrence of fossil spores in the Cretaceous of Delaware and Maryland, including samples from Potomac strata. Brenner (1963) examined the palynomorphs of the Potomac Group in a detailed study of 21 surface and 22 subsurface samples from Maryland (one sample from Virginia). He established a predominantly spore-based zonation consisting of two zones, Zones I and II, with two subzones recognized for Zone II (Subzones A and B) and additional divisions of Subzone II-B (B-1 and B-2). On the basis of comparison to European faunas, Brenner considered the Potomac Group to range from upper Barremian (or slightly older) to upper Albian.

Doyle and Robbins (1977) used angiosperm pollen from two cored wells near Delaware City (Dc53-07, Ec14-01) to improve and extend this zonation. The interval around the boundary between the Lower Cretaceous and Upper Cretaceous records the rapid evolution of angiosperms (flowering plants). This evolution is reflected in increasingly diverse and changing assemblages of pollen, which provide a number of useful taxa for biostratigraphy. The Doyle and Robbins zonation added several new biostratigraphic subdivisions above Brenner's zones: Subzone II-C, which was previously the upper part of Brenner's Subzone II-B, and three new zones in higher strata, Zones III, IV, and V. They updated the age interpretation of these zones, considering Zone I to likely be Barremian to lower Albian, Subzones II-A and II-B to be middle to upper Albian, Subzone II-C to be uppermost Albian, and Zone III to be lower Cenomanian.

We have used these previous palynostratigraphic studies as a starting point for the biostratigraphic subdivision here described. Palynological assemblages identified in this study provide independent criteria to constrain subsurface stratigraphic correlations within the Potomac Formation. Polynomorphs are abundant in many samples collected from darker gray mud lithologies. Spores and gymnosperm pollen are typically the most abundant palynomorphs. Angiosperm pollen, most of which are much smaller than the associated spores, are also present in the most fossiliferous samples. Charcoal fragments are commonly abundant, in some cases overwhelming the palynomorph abundance and making palynological analyses difficult.

The biostratigraphic assignments made in this study utilize Brenner (1963) and Doyle and Robbins (1977) zonations. For the age interpretations provided herein, we use an updated chronostratigraphy recently published by Hochuli et al. (2006) for Zones I and II on the basis of comparison of well-dated European sections to the Potomac zones.

The biostratigraphy findings can be summarized as follows:

Zone I (Aptian to lower Albian) is assignable to one sample, which includes abundant *Exesipollenites*, one of Brenner's (1963) criteria, and rare *Fraxinoipollenites constrictus*, which (as *Tricolpites crassimurus*) was considered indicative of upper Zone I by Doyle and Robbins (1977).

Subzone II-A (middle to upper Albian) is marked by the appearance of open reticulate tricolpates, according to Doyle and Robbins (1977), and the absence of Subzone II-B markers; this subzone was not identified in our samples.

Subzone II-B (middle to upper Albian) is characterized by the diversification of reticulate tricolpates (*Rousea geranioides* appears here) and the appearance of tricolporoidates (including *Tricolpites minutus* and tricolporoidate *Tricolpites micromunus*), as established by Doyle and Robbins (1977). Spores are most abundant, including common *Neoraistrickia robusta*, the key Subzone II-B marker of Brenner (1963).

Subzone II-C (lower Cenomanian) is, as characterized by Doyle and Robbins (1977), marked by the appearance of very small, psilate tricolporoidates (here, *Psilatricolporites subtilis*) and the predominance of small tricolp(oroid)ates, especially tricolporoidate specimens of *Tricolpites micromunus*.

Zone III (lower? Cenomanian) is consistent with the definition by Doyle and Robbins (1977) and contains larger, triangular tricolporates (*Tricolporopollenites* sp. B), which first appear in this zone, as well as very small, psilate tricolporoidates which can occur in lower intervals but are are more abundant in this zone (two of which, *Nyssapollenites triangulus* and *Psilatricolporites distinctus*, occur only in Zone III samples in this study).

Identifications and zonal interpretations are provided below for 17 samples examined from seven sites in New Castle County where fossiliferous Potomac strata have been collected. The lists of taxa are preliminary findings, with some taxa identified provisionally, and not necessarily a thorough inventory of all palynomorphs present. However, in most cases, the assemblages identified allow a reasonable estimate of biostratigraphic position.

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Detailed Findings

LOCATION: Cb55-60, borehole at intersection of Interstate 95 and Delaware 273
Depth: 49.4 ft

Sample number: 100590-0.4

Stratigraphic interpretation: Subzone II-B

Remarks: This sample contains *Striatopollis* sp. A, which is restricted to Subzone II-B. It also contains two taxa that range from mid Subzone II-B to basal Zone III - *Liliacidites* sp. F and *Striatopollis vermimura* - and two taxa that occur from basal Subzone II-B through Zone III - *Tricolpites* sp. B, and tricolporoidate specimens of *Tricolpites micromunus*. It lacks taxa that appear in Subzone II-C and III.

Spores:
Cicatricosisporites venustus
Cyathidites sp.
Inaperturopollenites dubius
Lycopodiacidites ambifoveolatus
Plicatella cf. *concentrica*
Plicatella tricornitata

Pollen:
bisaccate spp.
Pennipollis peroreticulatus
Classopollis parva
Clavatipollenites minutus
Liliacidites sp. F of Doyle and Robbins, 1977
Podocarpidites radiatus
Retimonocolpites dividuus
Rousea georgensis
Stephanocolpites fredericksburgensis
Striatopollis sp. A of Doyle and Robbins, 1977
Striatopollis vermimura
Tricolpites micromunus
Tricolpites minutus
Tricolpites sp. B of Doyle and Robbins, 1977

LOCATION: Cc41-b, hand sample, construction site at SW corner of Delaware 7 and Delaware 58
Sample number: 43845
Stratigraphic interpretation: Subzone II-B
Remarks: The presence of *Striatopollis* cf. *vermimura* suggests assignment to Subzone II-B or higher; the identification of *Tricolpites* cf. *albiensis* suggests a zone no higher than Subzone II-C. Taxa suggestive of Subzone II-C are absent.

Spores:
Aequitriradites spinulosus
Ceratosporites parvus
Cicatricosisporites dorogensis
Cicatricosisporites venustus
Cyathidites minor
Gleicheniidites senonicus
Plicatella tricornitata
Reticulatisporites arcuatus
Verrucosisporites oviformis?

Pollen:
Abietineaepollenites microreticulatus
Abietineaepollenites sp.
Alisporites thomasii
Clavatipollenites aff. *hughesii* of Doyle and Robbins, 1977
Cycadopites follicularis
Inaperturopollenites dubius
Retimonocolpites peroreticulatus
Striatopollis cf. *vermimura* of Doyle and Robbins, 1977
Taxodiaceaepollenites hiatus
Tricolpites cf. *albiensis* of Doyle and Robbins, 1977
Tricolpites minutus

LOCATION: Cc52-a, hand sample, SE side of Christiana Mall
Sample number: 43979
Stratigraphic interpretation: Subzone II-B
Remarks: The identification of *Rousea* aff. *geranioides* restricts this sample to Subzone II-B or higher. The presence of *Tricolpites albiensis*-related taxa suggests a zone no higher than Subzone II-C. Taxa that appear in Subzone II-C are absent, so the sample is assigned to Subzone II-B.

Spores:
Cicatricosisporites potomacensis
Cicatricosisporites venustus
Cyathidites minor
Gleicheniidites senonicus
Lycopodiacidites ambifoveolatus
Pilosisporites trichopapillosus
Plicatella tricornitata
Polycingulatisporites reduncus

Pollen:
Alisporites thomasii
Cupuliferoidaepollenites parvulus
Echimonocolpites spinosus
Fraxinoipollenites constrictus
Inaperturopollenites dubius
Platysaccus megasaccus
Rousea aff. *geranioides* sensu Brenner of Doyle and Robbins, 1977
Rousea georgensis
Taxodiaceaepollenites hiatus
Tricolpites aff. *albiensis* of Doyle and Robbins, 1977
Tricolpites cf. *albiensis* of Doyle and Robbins, 1977

LOCATION: Cd43-15, borehole east of intersection of Interstate 295 and Delaware 9
Depth: 135-136 ft
Sample number: 20868-bottom
Stratigraphic interpretation: Subzone II-B
Remarks: The presence of *Tricolpites minutus*, *Striatopollis* sp. A, and *Rugubivesiculites reductus* suggests a position of Subzone II-B or higher. The absence of indicators of Subzone II-C, such as common small psilate tricolpates and tricolporoidate forms of *Tricolpites micromunus*, suggests this sample should be assigned to Subzone II-B.

Spores:
Aequitriradites spinulosus

Cicatricosporites patapscoensis
Cicatricosporites potomacensis
Cicatricosporites subrotundus
Cicatricosporites venustus
Cingulatisporites eukirchensoides
Converrucosisporites platyverrucosus?
Crybelosporites pannuceus
Cyathidites minor
Gleicheniidites senonicus
Pilosisporites trichopapillosus
Plicatella tricornitata
Polycingulatisporites reduncus
Schizosporis reticulatus
Trilobosporites apibaculatus
Trilobosporites marylandicus

Pollen:
Araucariacites australis
Classopollis classoides
Classopollis parva
Cupuliferoidaepollenites cf. *parvulus*
Equisetosporites virginiaensis
Eucommiidites troedssonii
Exesipollenites tumulus
Inaperturopollenites dubius
Pennipollis peroreticulatus
Phyllocladidites microreticulatus
Pinuspollenites sp.
Rugubivesiculites reductus
Singhia multicostata
Striatopollis sp.?
Striatopollis sp. A of Doyle and Robbins, 1977
Striatopollis vermimura?
Taxodiaceaepollenites hiatus
Tricolpites minutus

LOCATION: Cd43-15, borehole east of intersection of Interstate 295 and Delaware 9
Depth: 145-146 ft
Sample number: 20869
Stratigraphic interpretation: Subzone II-B?
Remarks: The presence of *Tricolpites minutus*, *Rugubivesiculites reductus*, and *Stellatopollis barghoorni* indicate a position of Subzone II-B or higher. Because this sample lacks characteristic criteria for Subzone II-C – conspicuous small psilate tricolpates and tricolporoidate specimens of *Tricolpites micromunus* – it is interpreted as Subzone II-B.

Spores:
Aequitriradites spinulosus
Cicatricosporites australiensis
Cicatricosporites subrotundus
Cicatricosporites venustus
Cyathidites minor
Gleicheniidites senonicus?
Impardecispora marylandensis
Laevigatosporites gracilis
Pilosisporites trichopapillosus
Plicatella tricornitata
Polycingulatisporites reduncus
Retitriletes austroclavatidites

Pollen:
Araucariacites australis
bisaccate spp.
Clavatipollenites tenellis
Classopollis classoides
Cycadopites follicularis
Exesipollenites tumulus
Inaperturopollenites dubius
Pennipollis peroreticulatus
Rugubivesiculites rugosus
Sabalpollenites asymmetricus
Stellatopollis barghoorni
Taxodiaceaepollenites hiatus
Tricolpites minutus
Tricolpites micromunus
Tricolpites sagax?

LOCATION: Cd43-15, borehole east of intersection of Interstate 295 and Delaware 9
Depth: 227 ft
Sample number: 20871
Stratigraphic interpretation: Subzone II-B?
Remarks: The presence of possible *Retitricolpites* cf. *magnificus* suggests placement in Subzone II-B or II-C; the lack of definitive Subzone II-C indicators in this sample, and in overlying samples, suggests placement in Subzone II-B.

Spores:
Cicatricosisporites australiensis
Cicatricosisporites subrotundus
Cicatricosisporites venustus
Foveotriletes subtriangularis
Polycingulatisporites reduncus
Retitriletes austroclavatidites

Pollen:
Abeitineaepollenites microreticulatus
Araucariacites australis
bisaccate spp.
Cupuliferoidaepollenites parvulus
Fraxinoipollenites constrictus
Inaperturopollenites dubius
Podocarpidites potomacensis
Retitricolpites cf. *magnificus?* of Doyle and Robbins, 1977
Sabalpollenites asymmetricus
Steevesipollenites patapscoensis
Taxodiaceaepollenites hiatus
Tricolpites micromunus
Tricolpites sagax?
Tricolporoidites minimus?

LOCATION: Cd51-21, borehole at New Castle
Depth: 36.4 ft
Sample number: 26388-1.4
Stratigraphic interpretation: Zone III
Remarks: This sample contains several taxa, or forms resembling taxa, that are diagnostic of Zone III: *Foveotricolporites rhombohedralis* (upper Zone III), *Tricolporopollenites* sp. A, and *Tricolpites nemejcii*.

Spores:
Cicatricosisporites aralica
Cicatricosisporites venustus
Cicatricosisporites subrotundus
Interulobites intraverrucatus
Plicatella tricornitata
Polycingulatisporites reduncus
Taurocusporites segmentatus

Pollen:
Abietineaepollenites microreticulatus
Clavatipollenites aff. *minutus?* of Doyle and Robbins, 1977
Cupuliferoidaepollenites parvulus
Cycadopites follicularis
Decussosporites microreticulatus
Echimonocolpites spinosus
Foveotricolporites rhombohedralis?
Inaperturopollenites dubius
Nyssapollenites cf. *triangulus* of Doyle and Robbins, 1977
Podocarpidites potomacensis
Psilatricolporites distinctus?
Retimonocolpites sp.?
Singhia multicostata
Taxodiaceaepollenites hiatus
Tricolpites micromunus
Tricolpites nemejcii?
Tricolporopollenites sp. A of Doyle and Robbins, 1977

LOCATION: Cd51-21, borehole at New Castle
Depth: 40.0 ft
Sample number: 26389-0
Stratigraphic interpretation: Zone III
Remarks: The presence of *Tricolporopollenites* sp. A, *Tricolporopollenites* cf. sp. B, and *Tricolpites* aff. *nemejcii,* all of which appear near the base of Zone III, suggests placement in Zone III. The presence of *Tricolpites sagax*, which disappears in the lower part of Zone III, suggests it should be placed in the lower part of the zone.

Spores:
Ceratosporites parvus
Cibotiumspora cf. *juriensis*
Cicatricosisporites dorogensis
Cicatricosisporites venustus
Cicatricosisporites subrotundus
Cingulatisporites distaverrucosus
Cyathidites minor
Lycopodiacidites ambifoveolatus
Lycopodiacidites cristatus
Interulobites intraverrucatus
Lycopodiacidites tortus
Lycopodiacidites triangularus
Microreticulatisporites crassiexinus
Plicatella tricornitata
Polycingulatisporites reduncus
Polycingulatisporites spackmani
Todisporites minor
Undulatisporites pannuceus

Pollen:
Abietineaepollenites microreticulatus
Ajatipollis cf. *tetraedralis?* of Doyle and Robbins, 1977
Cycadopites follicularis
Echimonocolpites spinosus
Inaperturopollenites atlanticus
Inaperturopollenites dubius
Liliacidites variegatus
Monosulcites chaloneri
Monosulcites epakros
Monosulcites sp.
Rousea georgensis?
Rousea prosimilis?
Sabalpollenites asymmetricus
Striatopollis sp. B of Doyle and Robbins, 1977
Taxodiaceaepollenites hiatus
Triatriopollenites sp.
Tricolpites aff. *nemejcii* of Doyle and Robbins, 1977
Tricolpites minutus
Tricolpites sagax
Tricolpites sp.
Tricolporopollenites planus
Tricolporopollenites sp. A of Doyle and Robbins, 1977
Tricolporopollenites cf. sp. B? of Doyle and Robbins, 1977

LOCATION: Cd51-21, borehole at New Castle
Depth: 48.2 ft
Sample number: 26390-3.2
Stratigraphic interpretation: Zone III
Remarks: This sample contains *Tricolporopollenites* sp. A and *Tricolpites nemejcii*, which indicate a placement in Zone III; the occurrence of a form similar to *Foveotricolporites rhombohedralis* suggests placement in the upper part of the zone.

Spores:
Cicatricosisporites dorogensis
Cicatricosisporites subrotundus
Cicatricosisporites venustus
Cingulatisporites distaverrucosus
Converrucosisporites platyverrucosus?
Foraminisporis dailyi
Interulobites intraverrucatus
Lycopodiacidites triangularis
Plicatella tricornitata
Taurocusporites segmentatus

Pollen:
Echimonocolpites spinosus
Foveotricolporites cf. *rhombohedralis?* of Doyle and Robbins, 1977
Inaperturopollenites dubius
Pinuspollenites spherisaccus
Psilatricolporites cf. *distinctus?* of Doyle and Robbins, 1977
Psilatricolporites cf. *subtilis?* of Doyle and Robbins, 1977
Steevesipollenites patapscoensis
Taxodiaceaepollenites hiatus
Tricolpites nemejcii?
Tricolporopollenites aff. sp. A? of Doyle and Robbins, 1977
Tricolporopollenites cf. *triangulus?* of Doyle and Robbins, 1977

LOCATION: Cd51-21, borehole at New Castle
Depth: 55.0 ft
Sample number: 26392-0
Stratigraphic interpretation: Zone III
Remarks: The presence of *Tricolporopollenites* sp. B and *Tricolpites nemejcii* suggest this sample should be assigned to Zone III. *Striatopollis vermimura* was also identified in this sample; Doyle and Robbins (1977) considered this form to disappear near the top of Zone II, but in several samples in this study this form co-occurs with likely Zone III forms.

Spores:
Cicatricosisporites subrotundus
Cyathidites minor
Gleicheniidites senonicus
Interulobites intraverrucatus
Polycingulatisporites reduncus
Stoverisporites lunaris

Pollen:
Alisporites cf. *thomasii?* of Doyle and Robbins, 1977
Clavatipollenites hughesii?
Ephedripites? sp.
Rugubivesiculites rugosus
Striatopollis vermimura
Tricolpites nemejcii?
Tricolporoidites sp. A? of Doyle and Robbins, 1977
Tricolporopollenites sp. B? of Doyle and Robbins, 1977
Tricolporopollenites triangulus?

LOCATION: Cd51-21, borehole at New Castle
Depth: 141.4 ft
Sample number: 26408-1.4
Stratigraphic interpretation: Subzone II-C
Remarks: *Psilatricolporites* cf. *subtilis* appears in Subzone II-C and no Zone III taxa are evident, suggesting placement in Subzone II-C.

Spores:
Cicatricosisporites venustus
Cyathidites minor
Foraminisporis dailyi
Interulobites intraverrucatus
Laevigatosporites gracilis
Polycingulatisporites reduncus

Pollen:
Araucariacites australis
Classopollis parva
Clavatipollenites minutus
Cycadopites follicularis
Inaperturopollenites dubius
Podocarpidites potomacensis
Psilatricolporites cf. *subtilis* of Doyle and Robbins, 1977
Rousea aff. *geranioides* sensu Brenner, 1963
Striatopollis vermimura?
Taxodiaceaepollenites hiatus
Tricolpites micromunus
Tricolpites minutus
Vitreisporites pallidus

LOCATION: Cd51-21, borehole at New Castle
Depth: 256.5 ft
Sample number: 26420-6.5
Stratigraphic interpretation: Subzone II-C
Remarks: The presence of *Tricolporoidites* aff. sp. A, which appears in Subzone II-C, and forms similar to *Tricolpites* cf. *albiensis*, which disappears near the top of Subzone II-C, indicates placement of this sample in Subzone II-C.

Spores:
Cicatricosisporites venustus
Cyathidites minor
Plicatella tricornitata

Pollen:
bisaccate spp.
Striatopollis cf. *vermimura?* of Doyle and Robbins, 1977
Araucariacites australis
Clavatipollenites hughesii?
Echimonocolpites spinosus
Eucommiidites troedssonii
Inaperturopollenites dubius
Cycadopites follicularis
Taxodiaceaepollenites hiatus
Tricolpites cf. *albiensis?* of Doyle and Robbins, 1977
Tricolpites micromunus
Tricolpites minutus
Tricolporoidites aff. sp. A? of Doyle and Robbins, 1977

LOCATION: Cd51-23, borehole at New Castle
Depth: 130.2 ft
Sample number: 26731-0.2
Stratigraphic interpretation: Subzone II-C (upper)
Remarks: This sample is considered to lie in the upper part of Subzone II-C on the basis of the occurrence of *Tricolporoidites* aff. sp. A, which appears high in this subzone, and the general absence of Zone III taxa. However, forms similar to *Tricolpites nemejcii*, which appears in Zone III, are noted in this sample.

Spores:
Cicatricosisporites dorogensis
Cicatricosisporites subrotundus
Cicatricosisporites venustus
Cyathidites minor
Foraminisporis dailyi
Impardecispora marylandensis
Interulobites intraverrucatus
Laevigatosporites gracilis
Lycopodiacidites triangularus
Neoraistrickia robusta
Plicatella tricornitata
Retitriletes austroclavatidites
Taurocusporites segmentatus

Pollen:
Ajatipollis sp. A of Doyle and Robbins, 1977
Alisporites thomasii
Araucariacites australis
Eucommiidites troedssonii

Fraxinoipollenites constrictus
Rugubivesiculites rugosus
Sabalpollenites asymmetricus
Taxodiaceaepollenites hiatus
Tricolpites cf. *nemejcii?* of Doyle and Robbins, 1977
Tricolpites micromunus
Tricolpites minutus
Tricolporoidites aff. sp. A? of Doyle and Robbins, 1977

LOCATION: Cd51-23, borehole at New Castle
Depth: 156.0 ft
Sample number: 26735-1.0
Stratigraphic interpretation: Subzone II-C (upper)
Remarks: Like the sample above, this sample is placed in the upper part of Subzone II-C on the basis of the occurrence of *Tricolporoidites* aff. sp. A, which appears high in this subzone, and the general absence of Zone III taxa.

Spores:
Aequitriradites spinulosus?
Appendicisporites tricornitatus
Cicatricosisporites australiensis
Cicatricosisporites venustus
Cyathidites minor
Gleicheniidites apilobatus
Gleicheniidites senonicus
Laevigatosporites gracilis
Neoraistrickia robusta

Pollen:
Araucariacites australis
Clavatipollenites minutus
Cupuliferoidaepollenites parvulus
Cycadopites follicularis
Eucomiidites troedssonii
Inaperturopollenites dubius
Monosulcites glottus
Pennipollis peroreticulatus
Taxodiaceaepollenites hiatus
Tricolpites minutus
Tricolporoidites aff. sp. A? of Doyle and Robbins, 1977

LOCATION: Cd51-23, borehole at New Castle
Depth: 260.9 ft
Sample number: 26749-0.9
Stratigraphic interpretation: Subzone II-B
Remarks: *Rousea* aff. *geranioides*, which appears in Subzone II-B, is noted in this sample. The general lack of tricolporoidate forms of *Tricolpites micromunus*, which should appear in mid-Subzone II-B, and the absence of forms that characterize Subzone II-C, together suggest this sample should be placed in the lower part of Subzone II-B.

Spores:
Aequitriradites spinulosus
Alisporites sp.
Cibotiumspora juncta
Cicatricosisporites aralica
Cicatricosisporites subrotundus
Cingulatisporites cf. *eukirchensoides* sensu Brennner, 1963
Concavissimisporites punctatus
Cyathidites minor
Laevigatosporites gracilis
Neoraistrickia robusta
Pilosisporites trichopapillosus
Plicatella potomacensis
Plicatella tricornitata
Schizosporis reticulatus

Pollen:
Alisporites sp.
Araucariacites australis
Callialasporites dampieri
Clavatipollenites cf. *tenellis?* of Doyle and Robbins, 1977
Clavatipollenites hughesii
Cycadopites follicularis
Decussosporites microreticulatus
Inaperturopollenites dubius
Monosulcites sp.
Pennipollis peroreticulatus
Pristinuspollenites sp.
Retimonocolpites dividuus
Rousea aff. *geranioides* sensu Brenner, 1963
Taxodiaceaepollenites hiatus
Tricolpites micromunus

LOCATION: Cd51-23, borehole at New Castle
Depth: 411.3 ft
Sample number: 26767-1.3
Stratigraphic interpretation: Uppermost Zone I
Remarks: This sample is placed in the uppermost part of Zone I because it lacks forms that appear in Zone II, has *Fraxinoipollenites constrictus* (syn. *Tricolpites crassimurus)*, and has conspicuously higher abundances of *Exesipollenites* and *Classopollis* than noted in other samples.

Spores:
Cibotiumspora juncta
Cicatricosisporites dorogensis?
Cyathidites minor
Gleicheniidites senonicus
Laevigatosporites gracilis
Plicatella tricornitata
Stereisporites antiquasporites

Pollen:
Cerebropollenites mesozoicus
Classopollis parva
Cycadopites follicularis
Decussosporites microreticulatus
Eucommiidites troedssonii
Exesipollenites tumulus
Fraxinoipollenites constrictus
Inaperturopollenites dubius
Pristinuspollenites sp.
Sabalpollenites asymmetricus
Taxodiaceaepollenites hiatus

LOCATION: Db12-49, borehole just south of Newark
Depth: 43.7-44.5 ft
Sample number: 26624
Stratigraphic interpretation: Subzone II-C or lower Zone III
Remarks: The zonal assignment of this sample is a bit unclear, with some evidence suggesting Zone III and other suggesting Subzone II-C. The occurrence of *Psilatricolporites* cf. *subtilis* indicates it could be either in Subzone II-C or Zone III. The presence of forms similar to *Tricolpites nemejcii* and *Tricolporoidites bohemicus,* which appear in Zone III, suggests placement in Zone III. However, the presence of forms resembling *Striatopollis vermimura* and *Tricolpites albiensis,* taxa that are restricted to Zone II, together with the lack of triangular *Tricolporopollenites*-types indicative of Zone III, suggests placement in Zone II.

Spores:
Cicatricosisporites aralica
Cicatricosisporites venustus
Cyathidites minor
Gleicheniidites senonicus
Laevigatosporites gracilis
Plicatella potomacensis
Taurocusporites segmentatus

Pollen:
Alisporites thomasii
Araucariacites australis
Asteropollis? sp.
Classopollis classoides
Clavatipollenites hughesii?
Clavatipollenites minutus
Concentrocystes sp.
Cupuliferoidaepollenites aff. *parvulus* of Doyle and Robbins, 1977
Cycadopites follicularis
Eucommiidites troedssonii
Foveotricolpites cf. *concinnus* of Doyle and Robbins, 1977
Fraxinoipollenites constrictus
Inaperturopollenites dubius
Monosulcites glottus
Pennipollis peroreticulatus
Pristinuspollenites? sp.
Psilatricolporites cf. *distinctus?* of Doyle and Robbins, 1977
Psilatricolporites cf. *subtilis* of Doyle and Robbins, 1977
Retimonocolpites sp. A of Doyle and Robbins, 1977
Rousea georgensis?
Singhia multicostata
Striatopollis vermimura?
Taxodiaceaepollenites hiatus
Tricolpites cf. *albiensis* of Doyle and Robbins, 1977
Tricolpites cf. *micromunus* of Doyle and Robbins, 1977
Tricolpites minutus
Tricolpites aff. *nemejcii* of Doyle and Robbins, 1977
Tricolpites sp. B of Doyle and Robbins, 1977
Tricolpites vulgaris
Tricolporoidites cf. *bohemicus?* of Doyle and Robbins, 1977

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