STATE OF DELAWARE

UNIVERSITY OF DELAWARE

DELAWARE GEOLOGICAL SURVEY

ROBERT R. JORDAN, STATE GEOLOGIST

BULLETIN NO. 17

GEOLOGICAL STUDIES OF CRETACEOUS AND TERTIARY SECTION, TEST WELL Je32-04, CENTRAL DELAWARE

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ABSTRACT

A cored well 1,422 feet (433 meters) deep drilled two miles southeast of Dover is the basis for this integrated study of the lithology and paleontology of the Cretaceous-Tertiary section in central Delaware. The section is subdivided into lithostratigraphic, biostratigraphic, chronostratigraphic, and heavy mineral units. Data and results are presented on a common base in three plates.

Allowing for uncertainties due to the lack of areal investigation, the formations identified are: Potomac, Magothy, Merchantville, "Englishtown," "Marshalltown," Pamunkey(?), Piney Point, Calvert, and Columbia. These span from the Late Cretaceous to the Pleistocene.

Transgression in Santonian time resulted in deposition of the Magothy Formation on older, continental rocks. Marine conditions persisted into the Bartonian. The greatest water depths were present in the Paleocene and Eocene. Subaerial erosion occurred in late Eocene-early Oligocene, followed by marine deposition from late Oligocene to mid-Miocene. The Tertiary closed with another interval of subaerial erosion.

Three disconformities record the intervals of subaerial exposure. Three additional disconformities are recognized by missing biozones within the marine section: middle Maastrichtian-Danian, Danian-Thanetian, and Ypresian-Lutetian.

The study provides a basis for correlation in the middle Atlantic Coastal Plain and between that area and the offshore section. The geologic history should be applicable to the entire basin.

INTRODUCTION

Purpose and Scope

A cored test well drilled to 1,422 feet (433 meters) at the Dover Air Force Base near Dover, Delaware in 1957 yielded information for a variety of investigations of the lithology, paleontology, and stratigraphy of Cretaceous and Tertiary rocks in the central part of the State. The results of additional systematic studies, and restudies of older data, have been assembled for this Bulletin.

Deep, cored wells are rare in Delaware; therefore, comprehensive analyses of data and rock samples from this well provide a reference section important in understanding the geology of Delaware. Moreover, presentation of these results should encourage and facilitate correlation with the geology of adjacent States and the area being explored for oil and gas in the mid-Atlantic offshore region.

Emphasis has been placed here on the section penetrated by the test well, designated Je32-04 in the numbering system of the Delaware Geological Survey (DGS), rather than on regional geology. Because the designations of some units, especially lithostratigraphic units, depend on correlation and mapping beyond the scope of this study of a single well, uncertainty is indicated for some stratigraphic names.

Previous Investigations

Well Je32-04 was drilled to explore for additional ground-water supplies at the Dover Air Force Base (Figure 1). Rasmussen, Groot, and Depman (1958) described the drilling operations and pump test and presented descriptive and geophysical logs. They also presented the initial, "interim" geologic interpretations of the section penetrated, many of which have been refined by later work.

The DGS and others have drawn heavily on information from Je32-04 in subsequent years. Examples of such studies include Jordan (1962a; planktonic foraminifera), Jordan and Adams (1962; bentonite), Jordan (1962b; Delaware stratigraphy), Talley (1975; correlation), Spoljaric *et al.* (1976; remote sensing), and Woodruff (1976; geophysical logs). A cross section on the geologic map of the Dover area (Pickett and Benson, 1983) is in part characterized by information from the well.

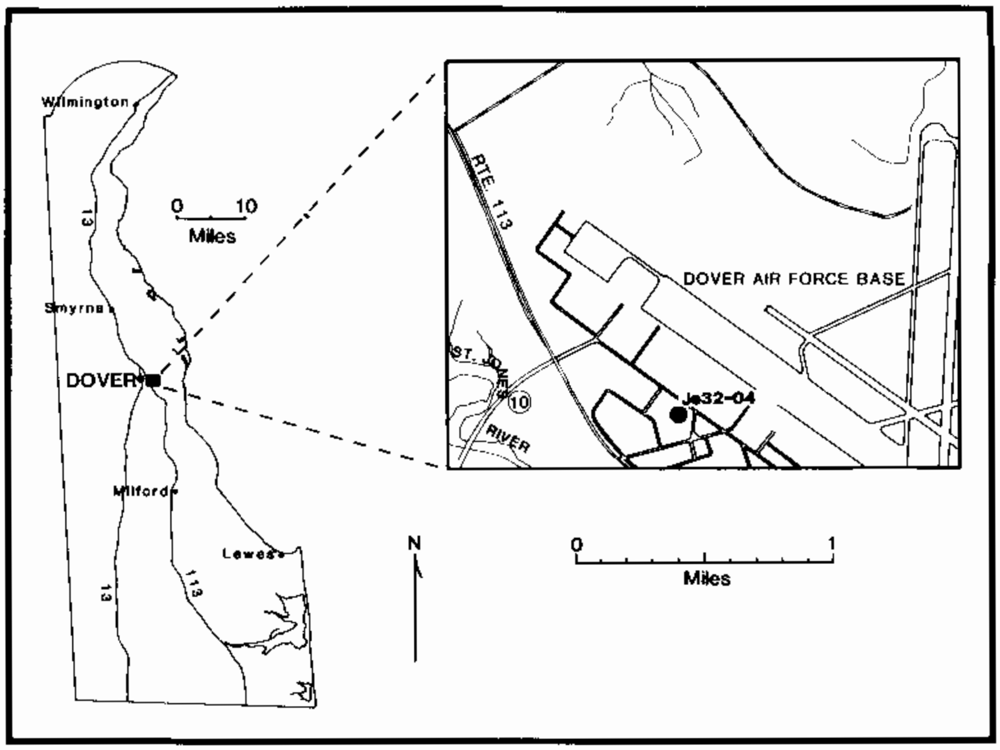

Figure 1. Location of well Je32-04.

Hydrologic information from Je32-04 has been applied in such studies as those of Sundstrom and Pickett (1968), Woodruff (1972), and Leahy (1982).

Stratigraphic investigations of the Delmarva region that have used Je32-04 as a reference point include Jordan (1963), Spoljaric (1975), and Benson (1976).

The regional geology of the Atlantic Coastal Plain that is the context for the section treated herein is discussed by Murray (1961), Owens *et al.* (1970), and Brown, Miller and Swain (1972). The regional stratigraphy, together with its nomenclature and problems have been recently discussed by Jordan (1983) and Jordan and Smith (1983; 1984). Additional references to pertinent older works may be found in the summaries provided by such papers and correlation charts.

Acknowledgments

John A. Conrad, David Giacomini, and June Mirecki, of the Department of Geology, University of Delaware drafted the plates that accompany this report. Ms. Mirecki also assembled Figures 2 and 3.

Johan J. Groot, former State Geologist of Delaware and the late Lincoln Dryden and his wife, Clarissa, were most helpful to Jordan in the earliest phases of these studies.

The manuscript was reviewed by Thomas E. Pickett and Kenneth D. Woodruff of the Delaware Geological Survey. C. Wylie Poag, U. S. Geological Survey, reviewed the chapters on biostratigraphy and chronostratigraphy, paleoenvironmental interpretations, and geohistory diagram in part.

The authors shared complexly in the development of this report and are listed alphabetically. However, principal responsibilities for specific aspects of the investigations lie with: Benson for paleontology, paleoenvironments, biostratigraphy, chronostratigraphy, sediment accumulation rates, and geohistory diagram; Jordan for texture, composition, heavy minerals, and lithostratigraphy; Spoljaric for gross lithology, special textural and compositional studies, and chemical composition. Other aspects of the report resulted from mutual efforts, including the assembly and editing of the manuscript.

METHODS OF INVESTIGATION

Drilling, Sampling, and Logging

Test well Je32-04 was drilled to a total depth of 1,422 feet (433 m) beginning in March 1957. All depths are referenced to land surface datum, 23.7 feet (7 m) unless otherwise specified.

The well was drilled by the hydraulic rotary method with split-spoon, wire-line cores taken approximately every 10 feet (3 m). One hundred and forty-one cores 18 inches (46.2 cm) long and 1-3/8 inches (3.5 cm) in diameter were obtained along with cuttings from the mud returns. Basic geophysical logs - single-point resistance, self-potential, and gamma - were run in the open hole with DGS equipment. The original resistance log had a 60-cycle "beat" from a nearby power plant; the reproductions herein have been redrawn through the middle of the band.

The hole was completed as an observation well in the Piney Point Formation and was still in service for that purpose in 1985.

Samples and Records

All cores from Je32-04 are entered in the DGS Core and Sample Library under numbers 20570 through 20711. Cuttings were described by Rasmussen, Groot, and Depman (1958), but were not preserved. DGS sample numbers are retained permanently for all splits, slides, and separations made from the original samples. All processed materials are retained in the collections of the DGS.

Mechanical Analyses

The primary mechanical analyses used in this study were made by sieve and hydrometry techniques for the entire range of grain sizes present. Samples were selected from every second core, except at significant changes of texture, where denser sampling was used, or where cores contained insufficient material for full mechanical analysis (20594, 20603, and 20604).

The hydrometry technique used for mechanical analysis of clay- and silt-sized particles is essentially the standard method of the American Association of State Highway Officials (AASHO, 1950). Results from the analyses of fine-grained fractions were combined graphically with those from U. S. Standard sieves for sand and gravel as cumulative frequency curves on linear probability paper (Doeglas, 1946). Calculations were done in Ø units (Krumbein, 1934) using formulas proposed by Inman (1952) for the textural parameters. The data points Ø16 and Ø84 did not fall within the range of sizes measured for all samples; therefore, in some cases those points were estimated by extending the curves, or could not be reasonably calculated. The textural data, including notes on these qualifications, are held in open file by the DGS. In all, 75 samples were analyzed by these methods.

Additional studies of textures in the sand-size range were performed on samples 20692, 20684, 20680, 20676, 20668, 20652, 20636, 20629, 20622, 20613, and 20604. Sand-size material was separated from silt and clay by sieving. Clay was separated from silt-size material by ultrasonic cleaning followed by centrifuging. Sand-size glauconite pellets were segregated by a

Franz Magnetic Separator. The weights of sand fractions (including glauconite pellets) were recomputed to 100%, and textural parameters (mean grain-size, sorting, skewness, and kurtosis) were calculated using the statistical method of moments.

Mineralogy

Major Constituents. Thin sections and point counts were used to quantify the major mineral constituents. Thin sections were prepared by a commercial laboratory by impregnating the generally unconsolidated sediments with epoxy resin. The sections were cut parallel to the axes of the cores. After general petrographic description, counts were made of at least 500 points per slide. In total 68 samples were studied, that is every other core, except where closer control was needed.

Additional information about mineral and fossil components contributing to the lithologies of the samples was derived from examination of the washed residues for microfossil studies.

Heavy Minerals. The samples used for heavy mineral separations and analyses were those used for mechanical analyses except here more detail was found desirable and additional samples studied. In all 73 determinations of heavy mineral content were made. The heavy components were separated from the medium to very fine sand fractions (500-62 microns) by means of flotation in tetrabromoethane (sp gr 2.94). Subsamples were split to less than 15 grams and boiled in dilute hydrochloric acid and in dilute nitric acid to remove iron oxide and other grain coatings. The "heavy" and "light" components were separated by centrifuging the washed samples in tetrabromoethane and freezing the bottoms of the centrifuge tubes to allow the light fractions to be decanted, a technique similar to that suggested by Fessenden (1959). About 100 non-opaque grains per sample were counted in linear traverses of petrographic slides such as described by Doeglas (1940). Samples 20636, 20643, and 20663 did not yield the desired 100 non-opaque grains. Abundances of opaque grains were noted, but these were not counted in detail as interpretation would be confounded by authigenic minerals dominant in some samples.

Count sheets and notes for all petrographic investigations are available for inspection at the DGS.

Paleontology

Two or three samples of each core from the well were studied for fossil content. The washed residues retained on a sieve with mesh openings of 63 microns were examined under a stereoscopic binocular microscope. Visual estimates of the relative abundances of biogenic components were made according to a scale ranging from very rare (V) (approximately five or fewer) counted per residue to a flood (F) representing a significant component of the residue (5 percent or greater). Results are plotted in Plate 1.

Because the emphasis of the paleontologic study was on biostratigraphy, species identification was limited to planktic foraminifera, certain age-diagnostic benthic foraminifera, and Radiolaria. For determination of paleoenvironments, benthic foraminiferal genera, generic groups, and selected species were noted and their abundances estimated, but the results were not plotted.

Colors

Descriptions of colors used in Plate 1 were derived from comparisons of dry samples with the Geological Society of America Color Chart.

Chemical Analyses

Chemical analyses were done by atomic absorption spectrophotometry and wet chemical techniques on samples: 20684, 20680, 20676, 20668, 20652, 20636, 20629, 20622, 20613, and 20604.

Sample solutions were prepared by means of lithium tetraborate fusion. U. S. Geological Survey (USGS) rock standards were used in determination of each oxide. The totals of oxide percentages for individual samples add up to less than 100%, probably indicating incomplete solution of SiO_2 and Al_2O_3. The spectrophotometric analyses were performed on a Varian M1000 Spectrophotometer and Varian CRA-90 Carbon Rod Atomizer.

Data Presentation

All data have been summarized on the plates found in the pocket attached to the back cover of this bulletin. Plate 1 summarizes the physical attributes of the section. Plate 2 presents paleontologic information. Plate 3 contains interpretations derived from the data appearing on the other two charts.

Geophysical logs and other basic information are repeated on each plate so that the various kinds of information may be related to stratigraphic position.

LITHOSTRATIGRAPHIC UNITS

General Statement

Rasmussen, Groot, and Depman (1958), in their preliminary report on well Je32-04, recognized the Raritan Formation, Magothy Formation, Matawan Group, Monmouth Group, Brightseat(?) Formation, Piney Point Formation, Kirkwood or Calvert formations, and the Talbot Formation. Importantly, this was the "discovery" well for the Piney Point Formation in Delaware that has since served as a major aquifer in central Kent County. Jordan (1962b) summarized revisions to the section penetrated, identifying the Potomac, Magothy, Matawan, and Monmouth formations, unit A, Piney Point Formation, Chesapeake Group, and Columbia Formation. Pickett and Benson (1983) interpreted unit A as being the Pamunkey Formation and found the Chesapeake Group to be represented by the Calvert Formation.

Thus, these and other less direct references to Je32-04 have refined the lithostratigraphy and nomenclature of the section beneath central Delaware. The more detailed analyses are presented in this report. Some conclusions appear in this section so as to better organize the information presented. Because this study focuses on a single well, uncertainties about stratigraphic nomenclature are indicated pending resolution by correlations to be established in areal studies. Names placed in quotation marks (" ") are for units uncertainly correlated with type localities; a query (?) following a name acknowledges that the name itself may be incorrectly applied.

Potomac Formation

Nomenclature. McGee (1886a;b) described the Potomac Formation from exposures in the District of Columbia and adjacent Maryland and Virginia. The use of the term in the area near the Fall Zone of the Mid-Atlantic States has been reviewed by Jordan (1983). The bottom (TD=total depth) of Je32-04 is in the Potomac Formation. The interval from 1,369 feet (417 m) to TD at 1,422 feet (433 m) is assigned to the Potomac Formation.

This is only the very top of the formation at this point; it is thought to continue to basement at a depth of 3,600 feet below sea level (Benson, 1984).

Texture. Throughout the Atlantic Coastal Plain the Potomac consists of alternating beds of sand, silt, and clay. Of the three cores analyzed from Je32-04, one is a fine sand, the second a silt, and the third a clay (MdØ). The sand (core 20709) is moderately well sorted and positively skewed. Typically, sorting is poorer in the silt and clay. Je32-04 penetrated 26 feet (8 m) of clay (above) and 27 feet (8 m) of sand and silt in the Potomac. The sand and silt are unconsolidated. The clay is stiff, dense, and dry with a soapy feel.

Composition. The Potomac sand is quartzose and, in the case of the sand fraction of sample 20711, highly micaceous (muscovite). A photomicrograph of the thin section of sample 20711 is shown in Figure 2. No feldspar, glauconite, or other rock-forming minerals were identified except clays. Clay minerals were not determined, but on the basis of other studies (e.g. Pickett, 1970; Obermeier, 1984) are expected to be dominated by kaolinite and illite.

Trace Minerals. Small pyrite nodules and flakes of lignite are present in small amounts. Heavy minerals in the two cores of the Potomac studied (20709 and 20711) are, in order of decreasing abundance: staurolite, tourmaline, zircon, rutile, chloritoid, and very rare anatase, epidote, and sillimanite.

Color. The clay is variegated (pale red, orange, and dark green). The sands are light gray and brown.

Log Signature. The contrasting lithologies of the Potomac Formation are strongly displayed on the spontaneous potential (SP) and gamma-ray logs. The SP is probably accentuated by mineralization of the formation water. The resistance log is suppressed, confirming the high dissolved solids content of the water. Water in the Potomac at this location and depth is expected to be brackish (Cushing *et al.*, 1973). Although only one sand-clay cycle was penetrated, the logs are typical of the repetitive sequences of the Potomac (Woodruff, 1976).

Magothy Formation

Nomenclature. The lithology described originally by Darton (1893) is persistent and characteristic (Jordan, 1983). The authors agree with the interval assigned to the Magothy

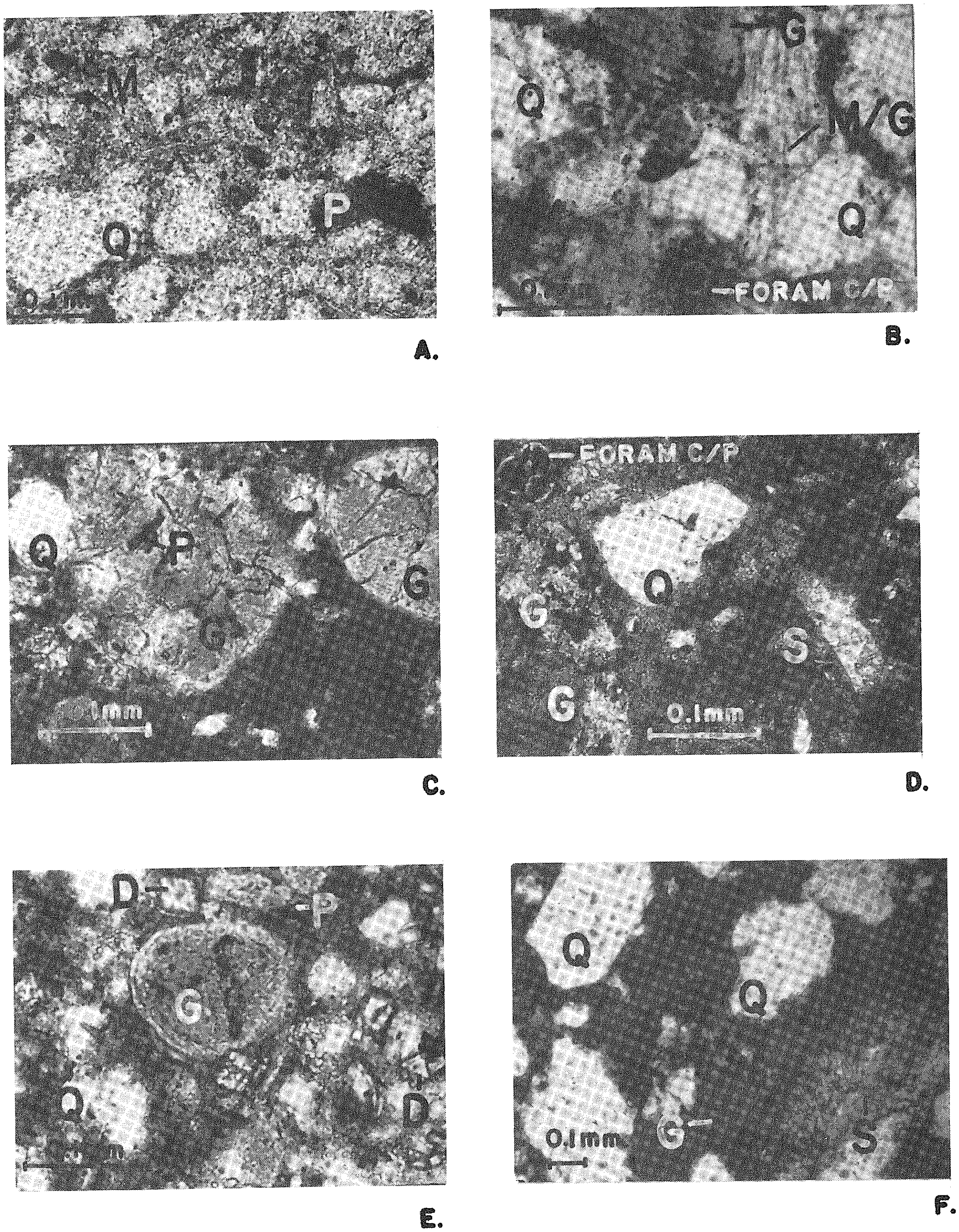

Figure 2. Photomicrographs of thin sections illustrative of lithologies of units found in Je32-04.

A. Potomac Fm. (sample no. 20711; depth 1,420ft, 432.9m)
B. Merchantville Fm. (20711; 1,167ft, 355.8m)
C. "Marshalltown" Fm. (20667; 1,087ft, 331.4m)
D. Pamunkey(?) Fm. (20673; 1,047ft, 319.2m)
E. Pamunkey(?) Fm. (20666B; 977ft, 297.9m)
F. Piney Point Fm. (20623; 557ft, 169.8m)

Key:
C/P-calcite filled with pyrite;
D-dolomite;
M-muscovite;
M/G-muscovite altering to glauconite;
P-pyrite;
Q-quartz;
S-shell calcite;

Formation by Rasmussen, Groot, and Depman (1958) with slight refinements. The Magothy is here found to lie between 1,369 and 1,265 feet (417 to 386 m). Cores 20705 through 20695 are available from this 103-foot (31 m) thickness. Core 20695 has some characteristics of both the Magothy and Merchantville formations; it is placed in the Magothy so that the contact is located at the top of a sand-silt shown most clearly on the SP log. The top few feet of the Magothy may be reworked.

Texture. The Magothy typically consists of alternating beds of light-colored sand and dark silt. Aside from pyrite nodules, the sediments are unconsolidated. Median grain sizes for two cores (20701 and 20699) fall in the fine sand range; three (20703, 20697, and 20695) are coarse silts; one (20705) is unusually fine, a clay. Sorting of the sand is fair; that of the silt and clay is poor. All samples are positively skewed.

Composition. Four thin sections were point-counted, 20705, 20703, 20698, and 20695. Core 20702 was examined, but too many sand grains were pulled from the slide in grinding the thin section to permit systematic counting. The sands consist of quartz with some admixture of "clay." Core 20695 contains 21.2 percent glauconite. About two to eight percent muscovite is present. Opaque masses identified in reflected light as pyrite comprise 0.4 to 5.6 percent of the samples. Lignite is present throughout, especially in the silts.

Trace Minerals. In six cores studied (20705, 20703, 20701, 20699, 20697, 20695) the heavy mineral suite is dominated by staurolite and tourmaline with significant amounts of zircon and kyanite. Rutile and chloritoid are persistent in small amounts. Trace amounts of sillimanite, garnet, epidote, anatase, and brookite were found. Epidote and garnet are more prominent in core 20695. Heavy mineral separates contain large quantities (55-80 percent) of opaque grains, mostly pyrite.

Color. The silts are gray and dark gray, almost black. The sands are light and very light gray.

Log Signature. The alternating silts and sands of the Magothy produce strong spontaneous potential and gamma-ray log signatures. In Je32-04 the resistance curve is suppressed due to brackish interstitial waters.

Matawan Group

Nomenclature

In their "interim report," Rasmussen, Groot, and Depman (1958) assigned the interval from 1,275 feet (389 m) to 952 feet (290 m) to the Matawan Group, undifferentiated. Jordan (1962b), restricted the Matawan to 1,275 feet (389 m) to 1,170 feet (357 m). He thought the subdivisions of the Matawan Group at the Chesapeake and Delaware Canal did not retain their lithologic identities as far downdip as Je32-04. The distinctive attributes of the Matawan Group, relatively fine texture and significant muscovite, present in the type areas of New Jersey (Clark, 1894), were, however, identified in the well. Jordan reasoned, then, that the name Matawan should be retained, but at formational rank. In this bulletin, however, we recognize three subdivisions of the Matawan: the Merchantville Formation and the provisionally assigned "Englishtown" and "Marshalltown." It is possible to describe in Je32-04 units from within the Matawan section that resemble formations of the Matawan Group present at the outcrop. Whether the subsurface divisions are the same ones as those found in outcrop must be demonstrated, at least for the "Englishtown" and Marshalltown," by correlation. That correlation is beyond the scope of this report, but the probabilities of the relationships are indicated here to suggest the direction of future research.

Table 1. *Subdivision of the Matawan Group in Je32-04.*

Group	Formation	Depths Feet	Depths Meters	Core Numbers
	"Marshalltown"	1108-1055	338-322	20679-20674
Matawan	"Englishtown"	1167-1108	356-338	20684-20680
	Merchantville	1265-1167	386-356	20694-20685

Merchantville Formation

Texture. Mechanical analyses were run on the complete ranges of sizes in five cores, 20693, 20691, 20689, 20687 and 20685. Core 20693 is coarse silt and 20687 a fine silt. Cores 20691 and 20685 are very fine sand; 20689 is a fine sand. All are poorly sorted and all but 20687 are positively skewed. The dominant texture of the Merchantville is coarse silt to very fine sand.

Composition. In the sand-size range glauconite and quartz are the dominant components (Figure 2). Considerable matrix is present throughout. Glauconite averages about 35 percent of the five samples analyzed (the same samples as used for mechanical analyses), but varies greatly. Muscovite averages about three percent. Opaque grains, mostly pyrite, are also conspicuous, averaging more than two percent. A few percent of shell calcite is present in cores 20689, 20687 and 20685. Trace amounts of authigenic calcite occur in 20691.

Trace Minerals. Heavy minerals were separated from the four cores used for mechanical analyses. Major components, in order of decreasing abundance are: tourmaline, garnet, staurolite, chloritoid, zircon, epidote, and rutile. Anatase, andalusite, brookite, kyanite, and zoisite occur irregularly in very small amounts. Sixty-eight to 98 percent of the heavy grains are opaque, largely pyrite.

Color. Samples from the Matawan are primarily dark greenish-gray.

Log Signature. Aside from kicks on the spontaneous potential log at 1,252 to 1,256 feet (382 m to 383 m) due to thin, fine sand, logs within the Merchantville are flat and indicative of a fine-grained section. A slight coarsening toward the top is shown on all three curves.

"Englishtown" Formation

Texture. The "Englishtown" is identified from 1,167 to 1,108 feet (356-338 m). It is unconsolidated except that hard streaks were reported while drilling from 1,124 to 1,129 feet (343 to 344 m). Cores 20684 through 20680 were obtained from the interval. Cores 20683 and 20681 were used to determine texture and mineralogy. The "Englishtown" is a fine to very fine sand. Sorting of the very fine sand (20683) is moderate; that of the fine sand (20681) is good. Both samples are positively skewed.

Composition. Quartz and glauconite average 62 and 3 percent of the two samples, respectively. The glauconite content is variable, however, as discussed in the chapter on glauconite. About 20 to 32 percent of the samples is matrix. A few percent of shell calcite is present in 20683. Feldspar and muscovite are present in both samples, averaging 2.6 and 2.1 percent, respectively. Pyrite is noticeable in 20683.

Trace Minerals. The dominant heavy minerals in samples from cores 20683 and 20681, in order of decreasing abundance, are: garnet, tourmaline, and staurolite, followed by epidote, zircon, chloritoid, rutile, kyanite, and andalusite. Trace amounts of sillimanite and zoisite were found. Opaque grains account for 76-80 percent of the heavy mineral suite.

Color. Samples from the "Englishtown" are gray near the bottom of the section and gray-brown above.

Log Signature. All three curves reflect a section that gradually coarsens upward. The response of the resistance curve is stronger than in the units below, indicating fresher interstitial waters. The bottom contact appears to be gradational, whereas there is a rather abrupt contact with a finer grained unit above.

Chemistry. The small amount of Fe_2O_3 in sample 20684 reflects scarcity of glauconite in the sediment (Table 2). Most of the FeO is contained in pyrite. Calcium and magnesium are probably primarily due to fossil shells.

The analyses of this and all other samples studied appear in Table 2.

The presence of glauconite in sample 20680 is reflected in its Fe_2O_3 content (9.3 percent), which is higher than expected for the low K_2O content (1.4 percent). It appears that a considerable portion of the Fe_2O_3 is contained in other than clay minerals. The high FeO is primarily due to pyrite developed as coating on foraminiferal shells. Most of the Ca, however, has been leached and only a small amount is retained in the sediment (1.5 percent).

"Marshalltown" Formation

Texture. The interval in well Je32-04 from 1,108 to 1,055 feet (338-322 m) is designated "Marshalltown" Formation on the basis of stratigraphic position and similarity to known Marshalltown strata updip. The name indicates the probability that correlation will eventually establish the physical continuity necessary to remove doubt about the terminology. The "Marshalltown" here is finer grained than at the outcrop, and it is likely that Dover is about as far downdip as the term can reasonably be applied. Cores 20779 to 20674 were taken in the "Marshalltown"; of these, 20675, 20677, and 20679 were used for determinations of texture and composition.

Table 2. *Chemical analyses of selected samples.*

Depth (in feet, SLD)	Sample Number	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	(Fe)*	MnO	MgO	CaO	Na_2O	K_2O	Cr_2O_3	H_2O**
							Percentages							
367-369	20604	50.9	0.35	6.4	0.74	4.19	(5.4)	0.22	0.82	16.98	0.18	1.40	nil	4.96
457-459	20613	69.1	0.13	4.8	9.36	1.52	(11.05)	0.04	1.66	4.93	0.20	3.60	0.035	3.70
547-549	20622	63.0	0.16	4.1	7.64	1.58	(9.4)	0.04	1.07	8.80	0.16	2.86	0.025	3.90
617-619	20629	55.9	0.36	6.7	4.43	3.12	(7.9)	0.04	1.48	9.30	0.46	2.60	0.02	7.25
687-689	20636	31.3	0.22	4.7	trace	4.21	(4.40	0.05	0.68	32.11	0.55	1.32	0.015	6.77
847-849	20652	70.3	0.74	8.3	0.84	4.28	(5.6)	0.04	1.05	1.87	0.57	2.46	0.02	6.34
997-998	20668	40.6	0.46	10.1	7.58	1.64	(9.4)	0.05	2.05	16.17	0.61	3.17	0.008	8.36
1077-1078	20676	46.6	0.50	8.4	4.02	3.76	(8.2)	0.06	1.48	28.45	0.41	3.58	nil	5.08
1117-1119	20680	69.5	0.62	6.8	9.27	2.32	(11.85)	0.07	2.72	1.49	0.275	1.35	nil	4.32
1157-1159	20684	72.8	0.83	7.4	1.42	3.13	–	0.06	0.27	4.18	0.50	1.9	0.015	3.62

* Total Fe

** Total H_2

Cores 20677 (Figure 2) and 20679 are poorly sorted, positively skewed, very fine sands. Core 20675 is fine silt, poorly sorted, and negatively skewed. These samples are probably representative of the range of textures present. The geophysical logs suggest variations in texture in the very fine sand- and silt-size ranges.

Composition. In the three cores analyzed, quartz and glauconite are the dominant components after the mud matrix. The matrix increases upward in the sequence (fining upward) and the sand-size mineral grains decrease. Calcite increases upward, both as shell fragments and as calcareous clay, from about two to more than ten percent. The thin section of core 20679 contained about 15 percent opaque material, mostly dark brown glauconite that is probably highly weathered. The opaque component of 20675 is mostly pyrite. Muscovite mica is present in trace amounts, decreasing upwards.

Trace Minerals. The heavy mineral suites of cores 20675, 20677, and 20679 are rather consistent. The minerals present are, in order of decreasing abundance: tourmaline, staurolite, garnet, chloritoid, zircon, kyanite, rutile, and andalusite with scattered traces of anatase, epidote, sillimanite, titanite, and zoisite.

Color. The rocks of the "Marshalltown" are predominantly gray, tinted with green where the glauconite content is high or, as is the case with core 20679, brown if the glauconite is weathered.

Log Signature. The gamma-ray log displays a distinct signature indicating a recognizable lithologic unit composed of alternating silty and sandy layers. Because of inadequate sensitivity the electric logs do not show the alternation well.

Chemistry. The analysis of core 20676 is characterized by low SiO_2 content, 46.6 percent, because of a large amount of glauconite and a correspondingly reduced amount of quartz (Table 2). The same condition is reflected in the relatively high total iron content of 4.0 percent. Most of the ferrous iron is probably contained in pyrite. The high CaO content (28.5 percent) is due to the presence of fossil shells, and perhaps to calcareous clay.

Pamunkey(?) Formation

Nomenclature. The fine-grained sediments in the middle of the section penetrated by well Je32-04 have presented authors with difficult choices in the selection of lithostratigraphic nomenclature. Rasmussen, Groot, and Depman (1958) considered the interval to include a part of the Matawan Group, the Monmouth Group, and the Brightseat Formation. Jordan (1962b) recommended that uncertainties about the assignment of names be acknowledged by the use of informal terminology and proposed "unit A" be used for the rocks between 1,090 and 615 feet (332 to 187 m). Pickett and Benson (1983) applied "Pamunkey Formation" to this interval, but placed its upper contact about 25 feet (8 m) higher in the cross section accompanying the geologic map of the Dover area. In the present study we make further adjustments to the boundaries and raise questions about the use of the name "Pamunkey."

Darton's original (1891) description of the Pamunkey may be applicable to rather homogeneous, fine-grained, glauconitic rocks in the general stratigraphic position represented by the middle of the section in Je32-04. However, comparison of the section at Dover, Delaware (this study) with that at the Pamunkey River, Virginia (Ward and Krafft, 1984) shows significant differences in lithologies. Control between the two localities is rather sparse. It seems prudent to acknowledge uncertainty about any detailed lithostratigraphic equivalency derived from a well representing a single point source of data. The additional information presented here may enhance the potential for correlation, but that correlation must yet be firmly established through three states.

The terms employed here do not include the Monmouth Formation or Group, which was recognized in earlier studies. The sandy Monmouth is replaced in the section in Je32-04 by the lower part of the thick sequence of glauconitic silt better, but not perfectly, described by the term "Pamunkey."

Pamunkey Formation(?) is used for the rocks between 1,055 and 585 feet (322 to 178 m) characterized by fine textures and the presence of glauconite. Darton (1891) and Clark (1896) early emphasized the homogeneous nature of the Pamunkey. At Dover lithologic homogeneity is a dominant aspect, but some subdivisions can be detected, primarily from their log signatures:

> 1,055-1,045 feet (322-319 m): The two-pronged signature on the electric logs is significant as it may represent a marker horizon here placed in the base of the Pamunkey(?). The textural and compositional differences between this horizon and the rocks above and below are not as great as the electric log suggests, however. Core 20673 was taken within the horizon and is a glauconitic silt similar to most of

the rest of the Pamunkey. The electric log signature appears to be related to improved sorting and to the presence of more calcareous clay in the matrix of the rock than found elsewhere in the well. Rasmussen, Groot, and Depman (1958) used the term "chalk" for essentially this interval. The sample is here considered too impure to be termed chalk, but the lithology is reasonably distinctive.

1,045-920 feet (319-280 m): The logs indicate that the rocks very gradually and irregularly become finer grained through this interval. The gamma log is especially sensitive. Aside from the presence of a bentonite in core 20666, the rocks vary in texture within the silt-size range and are glauconitic.

920-742 feet (280-226 m): The uniformity of this interval is evident on the electric and gamma logs. Measurements of textures of the cores yield median grain sizes principally in the silt range, but fine to clay around 800 feet (244 m). The logs suggest coarsening to silt above that point.

742-585 feet (226-176 m): The geophysical logs indicate less uniformity than immediately below and a tendency to coarsen upwards, especially in the transition to the overlying Piney Point above 600 feet (183 m). The gamma log is particularly sensitive to small changes in lithology through this interval.

No further distinction is made between the four divisions of the Pamunkey(?). They are reported here because they are features of the geophysical logs that may provide bases for more precise subdivision of the Pamunkey(?) and for correlation, perhaps with the formational components of the Pamunkey Group as recognized farther to the south in the Coastal Plain.

Texture. Forty-seven cores were taken in the 470-foot thick section (143 m) termed Pamunkey(?). Of these, 28 were used for determinations of mechanical composition: odd-numbered cores between 20673 and 20657, plus 20668 and 20666; even-numbered cores between 20654 and 20630, except 20646 and 20644, and with the addition of 20647, 20645, and 20643. The mechanical analyses confirm the fine textures of the rocks in this interval apparent from the geophysical logs and descriptions of the cores and cuttings. Because the rocks are so fine-grained, it was necessary to extend the cumulative curves into the clay-size range by estimation in most of the analyses. Where ϕ_{84} fell beyond 12ϕ, the projection was considered too speculative to use for the calculation of textural parameters; at such points gaps appear in the graphic displays of textural data on Plate 1. All of the cores analyzed have median grain sizes within the silt-size range, mainly between 6 and 8Ø, except that 20641 is a very fine sand and 20648, 20647, and 20645 are estimated to be clays with median diameters smaller than 10Ø. Texture is not completely uniform throughout the Pamunkey(?), but the variations determined are thought to be insignificant because textural terms change with very small fluctuations of absolute size at the fine end of the Wentworth scale.

Composition. Twenty-seven thin sections were point-counted to obtain estimates of the major mineral compositions of the Pamunkey(?). Samples were taken from the same cores used for mechanical analyses, except that cores 20671, 20669, 20668, 20648, and 20642 were not used for this purpose, and 20672, 20670, 20664, and 20649 were substituted. Photomicrographs of 20673 and 20666B appear in Figure 2. In these fine-grained rocks "matrix" is the principal component counted in thin section. Optically identifiable quartz is present in all samples, averaging about 8.7 percent. This figure is skewed upward by the unusually high quartz contents of cores 20654 and 20652, 35 and 49 percent, respectively. Those cores are also coarser than average for the section and, thus, reflect an increase in the influx of detrital sediment. Glauconite is also present in all of these samples. It averages almost 13 percent by point count and is variable, ranging from less than a percent in 20645 and 20664 to 30 percent in 20666 and 20667, and about half the sample in both 20641 and 20663. Shell calcite is present in all samples except 20657, averaging about eight percent of the points counted and ranging from trace amounts to 25-26 percent in samples 20661 and 20638. Calcite is also identifiable in small masses amounting to about one to three percent of the samples above 20634. The matrices of some samples were noted to be calcareous: 20673, 20663, and those of cores taken above 20640. Feldspar was noted in trace amount in about half the samples. Muscovite occurs in small amounts in most cores taken deeper than 20650. Opaque masses in the thin sections are mostly pyrite. Rhombs of dolomite occur in the sample from the lower part of core 20666. This same core contains the bentonite described in detail by Jordan and Adams (1962).

Trace Minerals. Twenty-six heavy mineral separations were made and analyzed from the interval designated Pamunkey(?). Subsamples were taken from the cores used for mechanical analyses, except that 20647 and 20643 were not run. The heavy mineral suites show gradual transitions through the interval from those of deeper units to those above. Other than in the transitions at the top and the bottom, suites from the Pamunkey (?) are distinctive in that tourmaline and andalusite dominate. Between these species, tourmaline is more prominent deeper in the unit and andalusite higher. The designation of heavy mineral suites is discussed in more detail in a later section. The principal and persistent minerals from the Pamunkey(?) are, in order of decreasing abundance: tourmaline, andalusite, staurolite, garnet, zircon, kyanite, and rutile. Also, scattered in the samples in trace amounts are: sillimanite, hornblende, epidote, titanite, chloritoid, brookite, anatase, actinolite, and zoisite. Opaque grains comprise 60 to 70 percent of the samples from the bottom of the unit, 20673 through 20668, but decrease to about 40 percent for the major part of the unit.

Color. The lowermost Pamunkey(?), from the base at 1,055 feet (322 m) to about 1,000 feet (305 m) is light gray, but gradually darkens; the samples are darker gray up to about 825 feet (251 m). Above that point the color gradually returns to light gray, but with a slight greenish tinge in many samples.

Chemistry. Core 20652 yielded a high (greater than 70 percent) SiO_2 concentration (Table 2). The amount of ferric iron in this sample is small because of the presence of reduced amounts of glauconite. Ferrous iron, however, is high and mostly contained in pyrite. The very low CaO content indicates the scarcity of shell material. The analysis is in agreement with the mineralogy determined by point count; this sample is anomalously high in quartz and low in calcite for the section.

Analyses from higher in the Pamunkey(?) reach up to 32 percent CaO, reflecting the calcareous nature of the sediment reported above. At the top of the interval as represented by sample 20629 the SiO_2 content is low (56 percent) and the Fe_2O_3 is high (4.4 percent) because of the high glauconite content. Ferrous iron is mainly a component of pyrite. Both CaO and MgO are relatively high because of the presence of calcareous shell material.

Piney Point Formation

Nomenclature. The Piney Point Formation was first clearly identified in Delaware in Je32-04 by Rasmussen, Groot, and Depman (1958). The Piney Point was extended from its type well in St. Marys County, Maryland (Otton, 1955) to the Eastern Shore of Maryland by Rasmussen and Slaughter (1957). Its occurrence in Je32-04 was confirmed by Jordan (1962b) and the name has continued in general use in central Delaware (e.g. Talley, 1975;

Pickett and Benson, 1983; Jordan and Smith, 1983). The Piney Point Formation is present from 585 to 336 feet (178 to 102 m) in the well and is represented by cores 20625 through 20601.

Texture. Mechanical compositions for samples from 14 cores were determined (odd numbers 20625 through 20605, plus 20624, 20602, and 20601). The predominant texture is medium sand with cores 20625, 20621, 20619, and 20617 being on the coarse side of fine sand. The lowermost cores reflect the gradational contact with the underlying Pamunkey(?) silts. This gradation occurs over approximately 50 stratigraphic feet (15 m). There is a general tendency for the unit to coarsen gradually upward. Only core 20605 is negatively skewed. The sorting of the sands is moderate except for 20624, which is well sorted. Within this section it is apparent that quartz is coarser than associated glauconite.

Composition. The cores studied were those selected for mechanical analyses, but 20625 and 20602 were not used. The principal minerals of the Piney Point, quartz and glauconite, are, on the average, almost equally abundant (37.8 and 36.5 percent, respectively). Quartz tends to become more abundant upward in the section. The lithology is illustrated by a photomicrograph of a thin section of 20623 shown in Figure 2.

Trace Minerals. Thirteen heavy mineral determinations were made from the same cores as those used for mechanical analyses except for 20625. In order of decreasing abundance the principal heavy minerals are: staurolite, tourmaline, garnet, sillimanite, kyanite, and epidote. Less persistent, and in smaller amounts, are: andalusite, zircon, chloritoid, and rutile. Very rare grains of hornblende, zoisite, titanite, spinel, and anatase were identified. Sillimanite occurs persistently and additionally as fibrolite. Opaque grains comprise 33 to 90 percent of the heavy separates, with the higher amounts influenced by altered glauconite. Andalusite abundances decrease gradually upward.

Color. Piney Point sediments are consistently green due to their high glauconite contents.

Log Signature. The electric log signature of the Piney Point Formation has been described by Woodruff (1976, p. 12) as "...perhaps one of the most distinctive and persistent in the central Delaware area." The SP and resistance curves from Je32-04 form the characteristic vase-shape, expanding gradually from the finer units below to a broad, rounded shoulder at the top. Gamma logs follow this form as well, but are suppressed due to the glauconite content of the unit. The small inflections in the curves around 385 feet (117 m) may relate to reworking of the top of the Piney Point as discussed in a later section.

Chemistry. The CaO content of the samples taken from the Piney Point Formation (20622 and 20613; the analysis of 20604 was unreliable because of incomplete solution) ranges between nine percent and five percent indicating the calcareous nature of the sediments (Table 2). Relatively low SiO_2 contents (70 and 63 percent) and high Fe_2O_3 contents (9.4 and 7.6 percent) result from the presence of significant amounts of glauconite. The FeO concentrations are low (1.6 percent and 1.5 percent); pyrite is rare.

Calvert Formation

Nomenclature. Rasmussen, Groot, and Depman (1958) suggested that the interval from 340 to 44 feet (104 to 13 m) in the well at Dover Air Force Base could be assigned to either the Calvert Formation of Maryland or the Kirkwood Formation of New Jersey. The bottom contact of the Calvert is adjusted here to 336 feet (102 m). Cores 20600 through 20572 were recovered from the Calvert Formation in Je32-04.

In Delaware strata of this general interval have been called Chesapeake Group (undifferentiated) as, for example, by Jordan (1962b) and Talley (1975) and, also, the Calvert Formation of the Chesapeake Group, e.g. Sundstrom and Pickett (1968) and Pickett and Benson (1983). Within the silts Marine and Rasmussen (1955) had recognized two sands informally named the Cheswold and Frederica aquifers.

Texture. Textures within the Calvert are those of the silt-sand-silt-sand-silt sequence identified in central Delaware by Marine and Rasmussen (1955). The predominantly sandy intervals in Je32-04 from 238 to 177 feet (73 to 54 m) and from 90 to 68 feet (27 to 21 m) are the Cheswold and Frederica aquifers, respectively. These medium sands are only moderately sorted and are positively skewed. Most of the remainder of the unit is silt or very fine sand with a large admixture of silt and clay. The fine admixture is particularly notable in the strongly positively skewed grain-size distributions of samples from cores 20600, 20596, 20592, 20582, and 20578. However, the silt in 20686 and fine sand in 20680 are well sorted. In total, 14 cores were analyzed (even numbers 20600 through 20572 except 20594).

Composition. The quartzose, unconsolidated, medium and fine sands of the Calvert were difficult to prepare as thin sections; therefore, point counts were made of only 10 of the samples, all silts or very fine sands. Clay and silt counted as matrix comprise almost two-thirds of the materials in these samples. Quartz is the dominant sand-size component. About one percent feldspar and two percent calcite shell fragments are present in almost every sample. Traces of glauconite were found in five samples and about six percent in another (20596). The glauconite is thought to be reworked from older units. A very small amount of muscovite is present in the upper half of the section. Opaque material ranges up to 7.5 percent (20592) and is primarily limonite, toward the top, or pyrite, toward the bottom.

Trace Minerals. Heavy minerals were separated from 15 samples (with the addition of 20594). The principal components of the suite occur in almost equal average amounts: staurolite, sillimanite, zircon, and tourmaline. Other persistent species in order of decreasing abundance are: garnet, epidote, rutile, chloritoid, and kyanite. Some sillimanite occurs as fibrolite. Minor, rare minerals noted include: actinolite, andalusite, titanite, spinel, brookite, anatase, and hypersthene.

Color. The Calvert sediments are gray, with the silts slightly blue-gray.

Log Signature. The sequence of alternating silt and sand in the Calvert is clearly reflected on all the geophysical logs.

Columbia Formation

Only one core was taken in the Columbia Formation. The materials from land surface to a depth of 40 feet (13 m) in Je32-04 conform in all characteristics to the Columbia Formation as described by Jordan (1964) and mapped in the Dover area by Pickett and Benson (1983). It is a slightly gravelly, medium-grained, subarkosic sand with a full heavy mineral suite, one containing all the common heavy minerals available in crystalline source rocks (Dryden and Dryden, 1956), including a large amount of hornblende.

HEAVY MINERALS

Minerals Represented

Similar heavy mineral species are present in most of the Cretaceous and Tertiary samples from the Dover well, but proportions of the minerals vary widely (Plate 1). Photomicrographs of selected minerals appear in Figure 3. The heavy mineral suite includes some species with noteworthy features:

Andalusite - The shapes of grains of andalusite are quite variable although there is a tendency toward tabular forms. In most grains the pleochroism is extremely weak, but in rare cases it is colorless to intense red. The quantity of black opaque inclusions, presumably carbonaceous, is also variable and in no case was a symmetrical distribution of inclusions noted. Andalusite is not commonly reported in heavy mineral suites from rocks of the Atlantic Coastal Plain. This may be due in part to difficulties with its identification.

Chloritoid - Chloritoid, found in two-thirds of the samples, retains its micaceous habit and distinctive (from chlorite) blue to green pleochroism throughout the section.

Epidote - Epidote occurs in irregular, roughly equidimensional grains displaying weak pleochroism in shades of green. Most grains are cloudy. Clear, bright green grains are very rare.

Garnet - Garnet was almost invariably found in angular grains commonly displaying some form of textured surface. Most of the grains are shades of pale pink; intense pinks and reds are very rare, except in core 20574. About one-sixth of the garnet grains are colorless.

Sillimanite - Sillimanite occurs typically in colorless, elongate grains controlled by cleavage and often striated parallel to the long (c-axis) dimension. The variety fibrolite is relatively rare, but persistent.

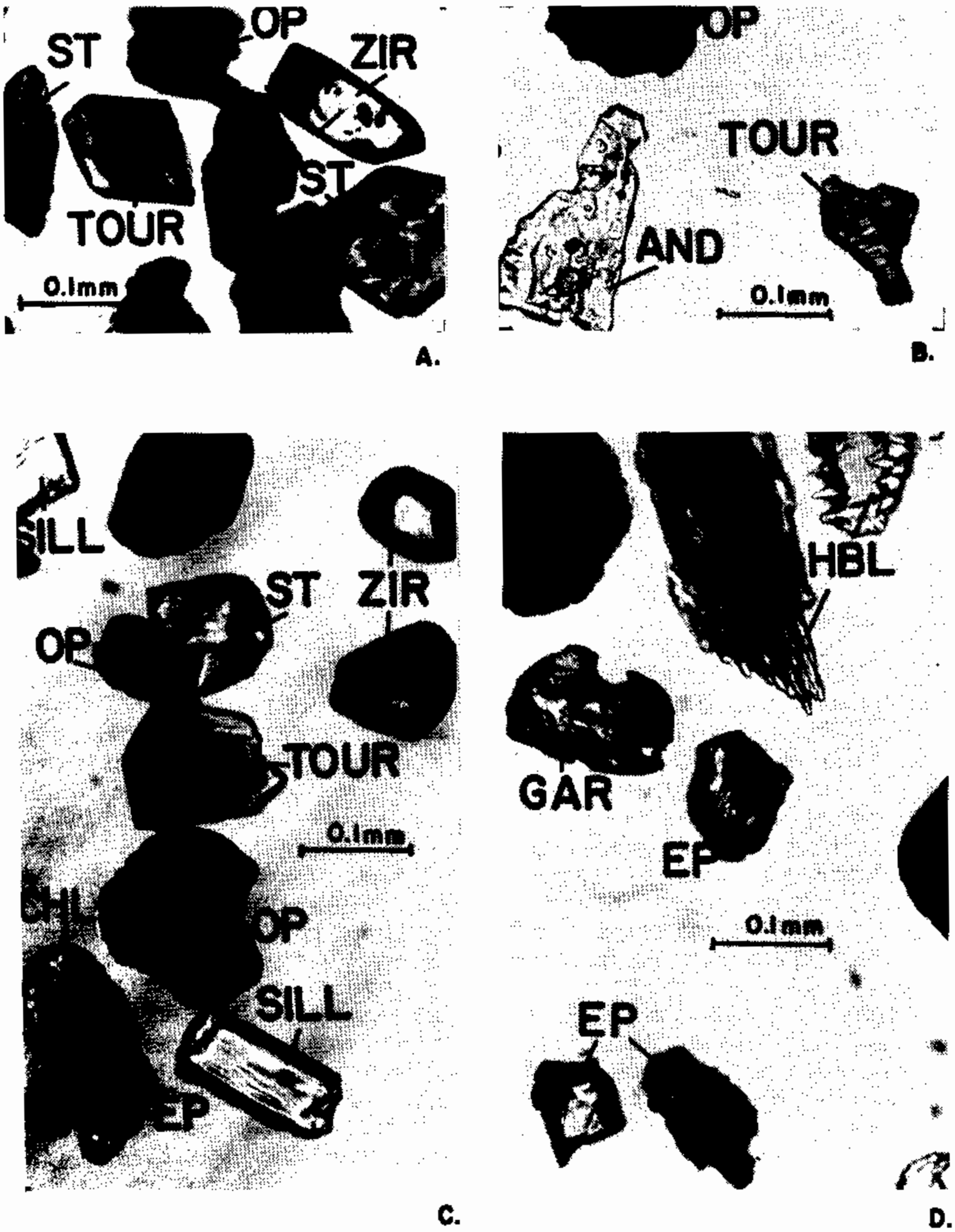

Figure 3. Photomicrographs of selected heavy minerals.

A. Staurolite-tourmaline zone, Potomac Fm. (sample no. 20711; depth 1,420ft, 432.9m)

B. Andalusite-tourmaline zone, Pamunkey(?) Fm. (20659; 970ft, 295.7m)

C. Staurolite-zircon-sillimanite zone, Calvert Fm. (20586; 187ft, 62.3m)

D. Full suite, Columbia Fm. (20570; 37ft, 11.3m)

Key:

And-andalusite; Chlor-chloritoid; Ep-epidote; Gar-garnet; Hbl-hornblende; Op-opaque; Sill- sillimanite; St-staurolite; Tour-tourmaline; Zir-zircon.

Staurolite - Staurolite is usually found in irregular, rather angular, roughly equidimensional grains that display some variation in the intensity of brown color and pleochroism. The staurolite is often cloudy with minute inclusions. Exceptionally bright, clean grains were noted in cores 20594 and 20654.

Tourmaline - There is a great deal of variation in the color and degree of roundness of the tourmaline. In samples 20574 to 20570 (72 to 37 feet; 22 to 11 m) and 20632 to 20598 (647 to 307 feet; 197 to 94 m) the number of rounded and angular tourmaline grains is approximately equal. In all other samples angular grains greatly exceed rounded grains. Throughout, the tourmaline tends to be prismatic and broken. Euhedra are very rare. Where angular grains are dominant, basal sections comprise about five percent of the tourmaline grains. The colors of tourmaline do not appear to change significantly with stratigraphic position. Grains showing pleochroism of brown to yellow and black to brown constitute about 96 percent of the tourmaline examined. These are followed, in order of decreasing abundance, by grains pleochroic yellow to colorless, green to pink, green to brown, blue to mauve, black to blue, blue to colorless, and blue to pink.

Zircon - The proportion of angular to rounded zircons is roughly equal through the section. The roundness of zircon, in this instance, is not necessarily an indication of its most recent transportational history because rounded zircon is known to occur in the rocks of the Piedmont Province (Dryden and Dryden, 1964). Pale pink zircons are occasionally encountered; zoned crystals are very rare.

Other minerals. Rutile and kyanite are present in almost every sample in relatively uniform and small amounts. Amphiboles are very rare in the Tertiary part of the section, but are common in the Pleistocene as typified by sample 20570. Also very rare are zoisite, anatase, brookite, titanite, hypersthene, and spinel.

Heavy Mineral Zones

A zonation based on heavy mineral content is shown in Plate 3. The boundaries of these heavy mineral zones were selected at major changes in the character of the heavy mineral suites. The designation of a particular heavy mineral zone is based on the appearance of minerals that are characteristic or distinctive of that zone but not necessarily dominant. Some gradation occurs between zones; the boundaries could reasonably be adjusted by the distance between cores in most cases.

Staurolite-Tourmaline zone - This is the deepest zone of Je32-04, from 1,422 (TD) to 1,250 feet (433 to 381 m). The characteristic mineral of the zone is staurolite (Figure 3). It is the most abundant non-opaque heavy mineral, in some cases exceeding 50 percent of the suite. Tourmaline is the second quantitatively important heavy material. It is relatively abundant in all samples of this zone. Kyanite is present in significant quantities in the upper part of the zone; however, it decreases in abundance downward and is absent from the lowermost part of the zone. Zircon is present in more or less uniform quantities throughout. Garnet, andalusite, and epidote occur in small quantities in the upper part of the zone and are rare or absent below. Sillimanite is found below 1,310 feet (400 m) in very small quantities. The suite is similar to the staurolite-tourmaline zone that Groot (1955) associated with the Magothy Formation, but here it extends downward into the top of the Potomac Formation.

Garnet-Tourmaline zone - The boundary between this zone and the staurolite-tourmaline zone below is transitional. It is placed arbitrarily at 1,250 feet (380 m) and is characterized by an increase in garnet and zircon and a decrease in staurolite. Tourmaline is present in relatively uniform quantities throughout the zone; in the zone below, tourmaline varies considerably from sample to sample. The upper boundary of the garnet-tourmaline zone is at 940 feet (387 m). Garnet, the mineral most diagnostic of this zone, averages about 20 percent of all non-opaque heavy minerals present. It is relatively uniformly distributed with only slight tendency to decrease in amount in the upper part of the zone. Tourmaline shows small variations in abundance; however, it does increase in the upper part of the zone. Zircon is present in smaller percentages than garnet, but is uniformly distributed. Staurolite is reduced compared to the deeper staurolite-tourmaline zone but is still an important component. Other non-opaque heavy minerals are: kyanite, andalusite, staurolite, and epidote. These vary in percentage from sample to sample and are always present in relatively small quantities.

Tourmaline-Andalusite zone - The lower limit of this zone lies at 940 feet (387 m); the upper boundary is placed at 760 feet (232 m). The characteristic heavy minerals of the zone are tourmaline and andalusite. The criterion for distinguishing this zone from the overlying andalusite-tourmaline zone is that here the amount of tourmaline greatly exceeds the amount of andalusite in each of the samples. In several cases tourmaline exceeds 50 percent of the entire non-opaque heavy mineral suite. Andalusite, nevertheless, occurs in important amounts. The third quantitatively important mineral is staurolite. Occurring in small amounts, in order of decreasing abundance are garnet, zircon, rutile, kyanite, chloritoid, epidote, sillimanite, hornblende, and very rarely, titanite, brookite, anatase, actinolite, and spinel.

Andalusite-Tourmaline zone - The interval between 760 feet (232 m) and 615 feet (187 m) is designated the andalusite-tourmaline zone. This zone is distinguished by the marked increase in the percentage of andalusite over that in the zones above and below. Together with tourmaline, andalusite dominates the heavy mineral suite (Figure 3). The percentage of andalusite is very nearly equal to, and sometimes exceeds, the percentage of tourmaline. The staurolite and rutile percentages are similar to those of the zone below. Relative percentages of the other minerals present decrease slightly, compared to the zones above and below, in response to the increase in andalusite. Additional members of the andalusite-tourmaline suite are zircon, kyanite, and garnet. Hornblende, chloritoid, sillimanite, and anatase are rare. The heavy mineral suite of sample 20630 (627 feet; 191 m) is intermediate between those characteristic of the andalusite-tourmaline zone and the overlying staurolite-sillimanite zone. It is considered to be part of the andalusite-tourmaline zone because the percentages of those minerals are almost equal although lower than average for that zone and also because of the low sillimanite content.

Staurolite-Sillimanite zone - The staurolite-sillimanite zone lies between 615 and 340 feet (187 to 104 m). These boundaries are arbitrarily chosen to coincide with those of the Piney Point Formation. Here sillimanite becomes a significant member of the heavy mineral suite, accompanied by a general increase in the percentages of staurolite, garnet, kyanite, and epidote. The andalusite content decreases greatly from that of the zone below. The percentage of tourmaline is also somewhat reduced. Zircon, rutile, chloritoid, hornblende, anatase, zoisite, hypersthene, and spinel are the minor and rare members of the suite.

Staurolite-Zircon-Sillimanite zone - The uppermost Tertiary heavy mineral zone extends from 340 feet to 40 feet (104 to 12 m). Here zircon becomes a major component of the suite (Figure 3). This zone also contrasts with the underlying staurolite-sillimanite zone in that the epidote content increases and the percentages of kyanite, tourmaline, and staurolite decrease; andalusite almost vanishes. Sillimanite and garnet remain as major members of the suite. Other minerals present, minor and rare, are rutile, chloritoid, hornblende, zoisite, actinolite, brookite, titanite, hypersthene, and spinel.

Hornblende zone - The staurolite-zircon-sillimanite zone is overlain by 40 feet (12 m) of Columbia sand. The Columbia is represented here only by sample 20570 (Figure 3), which yielded a heavy mineral suite very high in epidote and hornblende. Hornblende is one of the dominant minerals of the full suite of the Pleistocene sands of Delaware (Jordan, 1964). At Dover the full suite contrasts strongly with the heavy mineral suites of the underlying sediments.

GLAUCONITE

Types of Glauconite Present

The sediments of the Matawan Group, Pamunkey(?), and Piney Point formations in the Dover Air Force Base well are all glauconitic (Plate 1). Glauconite is present in these sediments mainly in the form of pellets or as matrix.

Sand-size pellets remaining after ultrasonic treatment were investigated and found to vary in amounts throughout the section. The pellets reach a maximum of 71 weight percent in the Merchantville Formation, a little less in the lower part of the Pamunkey(?) Formation, and are present only in trace amounts in the "Englishtown" Formation.

The most common type is spheroidal pellets characterized by equidimensional form and smooth, rounded surfaces. Mammillated pellets are also quite common. They are composed of rounded knobs and are characterized primarily by shallow sutures, although deep sutures are found in some grains.

Composite pellets are rare and composed of small glauconite grains embedded in glauconite or other clayey "cement." These pellets are usually the largest of all types present.

Vermicular pellets are also rare. They are worm-shaped and curved in complex forms. The surface is rough and they appear to be least resistant to physical breakage.

Capsule-shaped pellets are similar to mammillated pellets; however, they are elongated and sutures are very shallow. The break-up of these pellets produces glauconite grains smooth on the outside and very angular in the inner side.

These different types of pellets show significant variations in the shades of green color. The darkest green is displayed by spheroidal pellets. The other types show considerable variations within each group and the color may vary from dark green to yellowish-green.

Stratigraphic Associations

Merchantville Formation. Sample 20692 is a highly glauconitic sand. The weight percent of glauconite pellets in the sand fraction after ultrasonic treatment was found to be 71 percent. The pellets are well-sorted, show typical microcrystalline texture, are mainly dark green in color, and appear to be fresh. They are quite uniform in size, reaching about 0.5 mm in long diameter.

"Englishtown" Formation. The ultrasonic treatment of glauconite from sample 20684 revealed that glauconite is developed either as a coating on other grains, or is easily disintegrated. The weight percent of pellets remaining after the treatment was less than two percent of the sand fraction. The pellets are primarily small, less than 0.5 mm in long diameter, although a few larger ones were observed. The glauconite is dark green and displays typical microcrystalline texture.

The characteristics of glauconite from sample 20680 are similar to those from 20684. True glauconite pellets are rare, making up less than one percent of the sand fraction. They are dark green and quite large, reaching up to about 1 mm in long diameter.

"Marshalltown" Formation. Core 20676 contained 69 percent glauconite by weight in the sand-size range after ultrasonic treatment. The glauconite pellets are rounded, mainly light to dark green, and vary in size from only a fraction of a millimeter to about one millimeter. Most display typical microcrystalline texture.

Pamunkey(?) Formation. Weight percentages of glauconite found in sand-size fractions after ultrasonic cleaning range from nine percent in sample 20636 to 69 percent in 20668. Higher concentrations of glauconite were found in separations from the upper and lower parts of the Pamunkey(?) than in the middle. The glauconite pellets are mainly light to dark green, and vary in size from only a fraction of a millimeter to about one millimeter. Most display typical microcrystalline texture. In thin section much of the glauconite in the Pamunkey(?) appears to be authigenic, a product of alteration of the clayey matrix of the mud.

Piney Point Formation. The glauconite tends to be better sorted and finer grained than the quartz in any given sample. Most glauconite occurs in roughly spherical, polylobate forms with only small amounts of elongate, platy grains. The sand-size glauconite in the Piney Point is thought to be allogenic.

The amount of glauconite pellets in samples 20622, 20613, and 20604 after ultrasonic treatment is quite consistent and ranges between 25 and 32 percent by weight of sand size fractions. The pellets are primarily dark green, display typical microcrystalline texture, and appear to be well-sorted.

Significance of Glauconite

There is still considerable controversy regarding the origin of glauconite. A team of scientists in the Federal Republic of Germany concluded that pelagic conditions involving upwelling of cold water from great depths into the marginal areas of cooler seas are the necessary conditions for the formation of glauconite (Kemper, 1982), rather than the conditions of slow rate of sedimentation and a transgressive sea, as commonly assumed. Similar conclusions were reached by L. Orkeny Bondor (personal communication, 1982) in Hungary and Berg-Madsen (1983) in Sweden. Our study also seems to support this conclusion as seen in Figure 4 (p. 51) where the glauconite-bearing sediments occupy the part of the diagram represented by the Campanian to Chattian stratigraphic sequence.

Bondor determined that slow rate of sedimentation is not a controlling factor in the process of glauconite formation. Berg-Madsen, in her study of some Middle Cambrian glauconites concurs with the German scientists that cool water is a necessary condition for the glauconitization process. These new findings, particularly elimination of slow sedimentation rate as a requirement for the formation of glauconite, contradict older assumptions.

The recent discovery of glauconite in the Pacific Ocean off the coast of Mexico at depths of 1,000 to 2,000 meters brings to light additional problems (Odin and Stephen, 1981). Although the known limitations for the formation of glauconite do not seem to require a shallow water depth, several hundred meters has been generally accepted as the depth-limit for glauconitization process. Thus these occurrences at great depths are yet to be satisfactorily explained. The problem of the origin of this mineral is unresolved. For this reason, interpretation of the significance of glauconite in the Dover Air Force Base well would be premature.

TEXTURES OF SAND FRACTIONS OF SELECTED SAMPLES

Sand fractions of 10 selected samples in the depth interval between 367 feet and 1,239 feet (112-378 m) were chosen for detailed textural analysis (Table 3). Both the percent of sand and the amount of glauconite pellets in the sand for each of the samples are shown in Plate 1.

The sand fraction, which is the coarsest fraction of the samples examined, is most likely to best reflect depositional processes and thus provide some information on the sedimentation of these deposits.

It is apparent that the significant amounts of glauconite pellets in sand fraction have a major influence on interpretation of textural parameters. For this reason, an attempt was made to determine whether glauconite is detrital or authigenic.

Visual inspection of both pellets and glauconitic matrix in the samples was inconclusive. Because of this, the samples containing the highest percentages of glauconite pellets (nos. 20668 and 20676; about 70% glauconite pellets) were chosen to determine the effect of the pellets on the textural parameters. Sands of both samples are well sorted in spite of relatively high matrix content (9% and 11%, respectively). They are negatively skewed and their kurtosis is close to normal.

These results are difficult to interpret meaningfully. The major problem is an apparent discrepancy between sorting and content of matrix. The problem is enhanced by the fact that most of the matrix is composed of glauconite as well. The presence of glauconite in the matrix could be suggestive of its authi-genic origin, or it may be the result of mechanical

Table 3. *Textural Parameters of Sand Fractions of Selected Samples.*

Depth (in feet, SLD)	Sample Number	Mean Grain Size (Phi units)	Sorting (Phi units)	Skewness (Phi units)	Kurtosis (Phi units)
367 - 369	20604	1.31	0.93	0.018	0.49
457 - 459	20613	1.65	0.85	0.064	1.01
547 - 549	20622	2.10	1.02	- 0.002	0.98
617 - 619	20629	2.70	0.61	- 0.406	1.01
687 - 689	20636	2.90	0.47	- 0.457	1.05
847 - 849	20652	3.39	0.17	- 0.052	1.06
997 - 998	20668	2.84	0.40	- 0.223	0.94
1077 - 1078	20676	2.48	0.59	- 0.103	0.89
1117 - 1119	20680	2.40	0.48	0.002	0.70
1157 - 1159	20684	2.71	0.37	0.009	1.13
1237 - 1239	20692	1.88	1.30	- 0.408	0.74

breakdown of glauconite pellets. On the other hand, a high degree of sorting (sorting coefficient of 0.4 and 0.6, respectively) indicates a rather mature sediment, assuming the pellets are detrital.

The presence of glauconite in the examined samples complicates interpretation of the textural parameters and depositional processes. The origin of the glauconite must be understood to overcome this problem.

BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

General Statement

Biostratigraphic and chronostratigraphic information is summarized in Plate 2. Age determinations are based on biostratigraphic information, most of which is sufficient for the recognition of standard radiolarian and foraminiferal biozones. Except for diatoms (Abbott, 1978) no other microfossil groups in the core samples have yet been studied.

Cretaceous planktic foraminiferal zones used are those of Petters (1977), whose zonation of the marine Cretaceous of New Jersey is based primarily on Pessagno's (1967) zonation of the western Gulf Coastal Plain. Petters' modifications elevated Pessagno's subzones and zonules to zones (concurrent-range or taxon-range zones). Although Petters' usage has been followed for the current study, where some key species he used in defining zones are missing in Je32-04, Pessagno's information on taxon ranges is used.

Tertiary planktic foraminiferal zones used are those of Stainforth *et al.* (1975). Their zonation scheme has practical utility in that it can be applied to areas other than tropical to subtropical ones, and it emphasizes those Cenozoic planktic foraminifera most useful in regional and interregional correlation and age determination. In their Figures 12 and 15 Stainforth *et al.* provide comparisons with other zonal schemes, including the numerical designations of Blow (1969, 1970) and Berggren (1971). Later revisions by Blow (1979) are not incorporated in the present study, but note is made of significant changes that may have a bearing on the zonal scheme given for Je32-04. Generic designations by Berggren (1977) are substituted for those used by Stainforth *et al.* (1975), otherwise the biozone names are the same as those of Stainforth *et al.* Numerical designations of the biozones are from Stainforth *et al.* (1975, Figures 12 and 15) and, if applicable, from Blow (1979).

Geochronometric ages in millions of years (Ma) are estimated from Harland *et al.* (1982) for the Cretaceous, Hardenbol and Berggren (1978) for the Paleogene, and Berggren and Van Couvering (1974) for the Neogene. Age estimates are given for rocks immediately above and below unconformities, at stage boundaries, and at some biozone boundaries.

Species lists with taxonomic notes are beyond the scope of this paper. Instead, the following authors' species concepts were used. For the Radiolaria they include Riedel and Sanfilippo (1978), Sanfilippo and Riedel (1980), and Sanfilippo *et al.* (1973). Identifications of Cretaceous foraminifera were based on Cushman (1946), Frizzell (1954), Hiltermann and Koch (1962), Olsson (1964), Pessagno (1967), Petters (1977), and Smith and Pessagno (1973). Works on Tertiary foraminifera include Berggren (1977), Blow (1979), Bolli (1957a, 1957b), Cushman (1935), Dorsey (1948), Jones (1983), Loeblich and Tappan (1957), Nogan (1964), Poag (1981), Stainforth and Lamb (1981), and Stainforth *et al.* (1975).

Cenomanian(?)

Cores 20706-20711 (1,377-1,422 feet; 420-433 m), from the Potomac Formation, are barren of calcareous and siliceous microfossils. Doyle and Robbins (1977) studied palynomorphs from the nonmarine Cretaceous rocks in two Delaware wells (Dc53-07 and Ec14-01) near Delaware City, about 30-35 miles updip from Je32-04. They also studied the same stratigraphic interval in three wells located downdip from the Dover well: the Hammond and Bethards wells in Maryland, about 55-60 miles to the south, and the Taylor well in Virginia, about 85 miles to the south. In the Delaware City wells and the Hammond well, they assigned the uppermost part of the Potomac Formation or Group to palynomorph Zone III. In the Bethards and Taylor wells they assigned the uppermost part to Zone IV. They provisionally dated Zone III as early Cenomanian and Zone IV as ranging from middle Cenomanian to perhaps early Turonian.

Inasmuch as the Dover well is in an approximate mid-dip position between the northern and southern groups of wells studied by Doyle and Robbins, it is likely that the Potomac Formation in Je23-04 would yield palynomorphs representative of Zone III. Zone IV cannot be ruled out, but it is recognized only in the two wells located farthest downdip. The unconformity recognized by Doyle and Robbins (1977) between the Potomac and either the overlying Magothy or the marine Upper Cretaceous truncates younger strata of the Potomac in a downdip direction.

Santonian(?), Campanian(?)

Another interval nearly barren of calcareous and siliceous microfossils extends from core 20695 to 20705 (1,267-1,369 feet; 386-417 m), representing the Magothy Formation. By palynologic analysis of outcrop samples of the Magothy from New Jersey, Wolfe and Pakiser (1971) dated the formation as late Santonian or early Campanian. They also suggested that the type Magothy section in Maryland is of the same age.

If the ages of the Potomac and Magothy sections of Je32-04 are the same as those determined for the formations elsewhere, there is a major unconformity between the two units. On the electrical and gamma logs of Je32-04 this was picked at a depth of about 1,368 feet (417 m).

Campanian

Benthic and planktic foraminiferal species of Campanian age occur sporadically in cores 20676 through 20694 (1,077-1,259 feet; 328-384 m). Because most of this interval was deposited in the inner to middle neritic environment, planktic foraminiferal assemblages were not well developed, and, consequently, marker species are rare if present.

The top of the Campanian is placed provisionally at core 20676 where *Gavelinella dumblei (= Planulina dumblei)* last occurs. This species is characteristic of Tayloran (= Campanian) strata of the Gulf Coast (Cushman, 1946; Frizzell, 1954) and Cretaceous Unit B (= Campanian) of the Atlantic Coastal Plain section (Brown, Miller, and Swain, 1972). From the same core one specimen questionably identified as *Globotruncana elevata* may be a transitional form between *G. stuartiformis* and *G. elevata* and, if so, indicates a late Campanian age (Pessagno, 1967).

The base of the Campanian interval is below core 20694 where *Globotruncana ventricosa* was found. Pessagno (1967) indicates that this species is confined to the Campanian and had its greatest abundance during the latest Campanian of the Gulf Coast region. Core 20695 is nearly barren and is probably from the older Magothy section.

Other diagnostic Campanian species present in the interval between 1,077-1,259 feet include *Archaeoglobigerina blowi*, *A. cretacea*, *Bolivinoides decoratus*, *Kyphopyxa christneri*, *Globorotalites michelinianus*, and *Gavelinella subcarinatus*.

Petters (1977) recognized four biozones in the Campanian of New Jersey: in ascending order the *Archaeoglobigerina blowi*, *Ventilabrella glabrata*, *Globotruncana elevata*, and *G. calcarata* zones. The uppermost zone can be detected only by the occurrence of *G. calcarata*. This species was not found in Je32-04, but it has been found updip at and near the Chesapeake and Delaware Canal

(Olsson, 1964; Houlick *et al.*, 1983) and downdip in the Hammond well of the Maryland Eastern Shore (Cushman, 1948). Its absence in the Dover well may reflect a shallower water environment than the updip and downdip sites; therefore, the time-equivalent section may be present in Je32-04 but only the *Globotruncana elevata* zone can be identified. The absence of *Planoglobulina (= Ventilabrella) glabrata* precludes detection of the *V. glabrata* zone in Je32-04, and the presence of *Globotruncana ventricosa* in core 20694 indicates that the base of the Campanian section is probably still within the *G. elevata* zone (Pessagno, 1967).

Maastrichtian

Of Petters' (1977) three New Jersey Maastrichtian biozones, only the two lower ones were identified in Je32-04. The lower Maastrichtian *Rugotruncana subcircumnodifer* zone includes cores 20673-20675 (1,047-1,069 feet; 319-326 m). The top is defined at core 20673 where *Globotruncana linneiana* and *G. fornicata* last occur (Pessagno, 1967). The base is placed between core 20675 and the top of the Campanian at core 20676.

The middle Maastrichtian *Globotruncana gansseri* Zone was identified in cores 20667-20672 (987-1,039 feet; 301-317 m). The base of the zone is defined by the first occurrence of *Guembelitria cretacea* and *Globotruncana aegyptica* in core 20672. Other species present in the interval with stratigraphic ranges beginning at the base of or within the *G. gansseri* Zone (Pessagno, 1967; Smith and Pessagno, 1973) include *Globotruncanella monmouthensis*, *Rugoglobigerina hexacamerata*, and *Planoglobulina carseyae*. The top of the zone lies between the uppermost Cretaceous core 20667 and the lowermost Tertiary core 20666. Core 20667 contains *Globigerinelloides prairiehillensis*, which ranges into (Petters, 1977) or to the top (Smith and Pessagno, 1973) of the zone, and *Guembelitria cretacea* whose stratigraphic range, according to Pessagno (1967) and Smith and Pessagno (1973), is confined to the zone. On the other hand, Petters (1977) indicates that *G. cretacea* ranges throughout all three Maastrichtian zones in New Jersey. However, he does not present clear proof that the uppermost Maastrichtian biozone, the *Abathomphalus mayaroensis* Zone, is present. The only species that Pessagno (1967) shows as confined to the zone, and thus capable of defining it, is *A. mayaroensis*, which Petters (1977) did not identify from New Jersey rocks. With the exception of *Guembelitria cretacea*, all species that Petters (1967, Fig. 2) shows ranging into the *A. mayaroensis* Zone in New Jersey also do so in the Gulf Coast region (Pessagno, 1967; Smith and Pessagno, 1973). It is possible that the *A. mayaroensis* biochronozone is represented by rocks in New Jersey that so far have not yielded any specimens of *A. mayaroensis*. Until *Guembelitria cretacea* can be demonstrated to co-occur with *A. mayaroensis*, the uppermost Cretaceous zone identified in Je32-04 is the *Globotruncana gansseri* Zone. There is, therefore, a hiatus at the Cretaceous-Tertiary contact wherein the latest Maastrichtian and earliest Danian are missing.

Cretaceous-Tertiary Contact

Jordan (1962a, 1963) previously placed the Cretaceous-Tertiary contact in Je32-04 between cores 20666 and 20667, at a depth of 983 feet (300 m). He studied the planktic foraminifera (Jordan, 1962a) before the publication of more detailed zonations and compilations of stratigraphic ranges of key species for the Cretaceous and Tertiary (e.g., Pessagno, 1967; Bolli, 1966; Stainforth *et al.*, 1975). He cited the presence of *Planomalina messinae subcarinata* (Bronnimann) in core 20669 and *Rugoglobigerina jerseyensis* Olsson in cores 20668 and 20669 as evidence for the presence of the *Abathomphalus mayaroensis* Zone. Pessagno (1967) subsequently placed the former species in synonymy with *Globigerinelloides subcarinatus* (Bronnimann), which he shows ranging from latest Campanian through the *A. mayaroensis* Zone. He placed *R. jerseyensis* in synonymy with *Globotruncanella petaloidea* (Gandolfi), which ranges from the *Globotruncana gansseri* (or earlier ?) through *A. mayaroensis* zones. Because these species' ranges are not confined to the *A. mayaroensis* Zone, they can no longer be offered as proof of the existence of the zone.

Neither in the present study nor in Jordan's (1962a) was the earliest Paleocene zone, the *Globigerina eugubina* Zone, identified. Stainforth *et al.* (1975, p. 63) note that this zone, first described from Italy in 1964 by Luterbacher and Primoli Silva, is known only "...patchily around the world," and that in its absence from a sedimentary section "Authors tend to postulate a hiatus or condensed section..."

In Je32-04 the Cretaceous-Tertiary contact must lie within the approximately eight feet of rock between cores 20666 and 20667 (979-987 feet, 298.4-300.8 m). It is possible that a condensed stratigraphic section containing the *A. mayaroensis* and *G. eugubina* zones might be found in this eight-foot interval. The drill cuttings from this interval have not been located, although they were described by Rasmussen *et al.* (1958, p. 19) as "Clay, sandy, fine, dark gray (contaminated with small bits of gravel and shell)." Jordan and Adams (1962) found no significant difference in texture or mineralogy between Cretaceous and Tertiary cores immediately below and above the contact.

Jordan and Adams (1962) reported a thin bentonite layer containing altered volcanic shards at the top of core 20666 (depth 977 feet; 297.8 m), the lowest Tertiary core in the hole (Danian). At the base of the same core (depth 979 feet, 298.4 m) they found authigenic dolomite in a matrix of montmorillonite clay (Figure 2). Core 20666 is below the lower of a two-pronged peak of the gamma-ray log (Plates 1-3). Woodruff (1976) reports the double peak is well-developed at about the Cretaceous-Tertiary contact in northern Delaware but becomes one distinct peak in central and southern Delaware. Core 20665 is from the interval giving the lower gamma peak, and Jordan and Adams (1962) described it as a silty clay, chiefly montmorillonite, with some quartz and glauconite. Talley (1975) ascribed the high gamma peak to unusally high concentrations of glauconite in well Nc13-03 near Greenwood. He picked the Cretaceous-Tertiary contact right at the maximum gamma peak.

If, as the data seem to suggest, the latest Maastrichtian and earliest Danian are missing in Je32-04, it may be very difficult to locate a stratigraphic section in the Coastal Plain that is complete across the Cretaceous-Tertiary boundary. A depositional hiatus or condensed section in the interval spanning the boundary, if of regional extent in the Atlantic continental margin, precludes finding the iridium abundance anomaly first reported by Alvarez *et al*. (1980) at the precise Cretaceous-Tertiary boundary in Italy, Denmark, and New Zealand.

Danian

The co-occurrence of *"Globigerina"* (= *Globastica* Blow, 1979) *daubjergensis*, *Planorotalites compressa*, *Subbotina inconstans*, *S. triloculinoides*, and *S. pseudobulloides*, and the absence of *S. trinidadensis*, *S. praecursoria*, and *Morozovella uncinata* in cores 20664-20666 (957-979 feet; 292-298 m) identify the upper part of the *Subbotina pseudobulloides* Zone as defined by Stainforth *et al*. (1975). This is equivalent to Blow's (1979) Zone P.1, and specifically his Zone P.1B, the base of which he defines as the first evolutionary appearance of *Globorotalia (Turborotalia) compressa compressa*. The rare specimens of *Planorotalites compressa* from Je32-04 are more like Blow's *G. (T.) compressa planocompressa* or *G. (T.) archeocompressa* which evolved earlier, however, there are a few that show the more acute peripheral margin and more ogyval later chambers typical of *G. (T.) compressa compressa*.

Thanetian

The Thanetian is represented by the *Planorotalites pseudomenardii* Zone (P.4) identified in cores 20659-20663 (907-949 feet; 276-289 m). Stainforth *et al.* (1975) defined this zone as the total range of *P. pseudomenardii*, which is present in cores 20659-20662. Blow (1979), on the other hand, extended the range of this species to within Zone P.7 (into earliest Eocene). The presence of *Acarinina pusilla*, which both Stainforth *et al.* (1975) and Blow (1979) show as not ranging higher than Zone P.4, confirms the presence of this zone in Je32-04. In addition, species present in the P.4 interval are shown by Stainforth *et al.* (1975) to have the overlapping of their ranges confined to the zone: *Morozovella aequa*, *M. angulata*, *M. conicotruncata*, and *Subbotina triloculinoides*.

A hiatus or condensed section representing missing Zones P.2 and P.3 is recognized between cores 20663 (base of Zone P.4) and 20664 (top of Zone P.1) at a depth of about 950 feet (290 m) where a strong gamma peak occurs.

Thanetian(?), Ypresian(?)

Cores 20652-20658 (847-899 feet; 258-274 m) are nearly barren of microfossils. Although the electrical and gamma logs do not reflect a significant change, the textures of the sediments coarsen from very fine silt below to coarse silt within the barren interval to medium clay above (Plate 1). This might indicate an influx of sediment in this interval that was rapidly deposited, perhaps from a nearby delta system, into the outer neritic/upper bathyal environment. This would have diluted or masked the biogenic contribution to the sediments, resulting in a nearly barren interval. The water depth may not have been appreciably changed; therefore, the paleoenvironment curve (Plates 2 and 3) is dashed where it shows an apparent shallowing in this interval.

An alternative explanation is no change in the sedimentary environment but an increased rate of carbonate dissolution. The basal core 20658 has rare planktic foraminifera that are poorly preserved, suggestive of an increased rate of dissolution. Radiolarians are common, which suggests outer neritic/upper bathyal conditions, and the increase in their numbers may simply reflect their concentration through dissolution of calcareous fossils.

The interval represented by cores 20652-20658 could not be zoned. Core 20651 immediately above the interval is placed in the basal zone of the Eocene, the *Morozovella subbotinae* Zone (Stainforth *et al.*, 1975) of Ypresian age. The *M. velascoensis* Zone (P.5 and lower part of P.6, late Thanetian) cannot be recognized although the time-equivalent stratigraphic section may be present in the unzoned interval. The first appearance of *Morozovella subbotinae* marks the base of Zone P.6 according to Blow (1979), but Stainforth *et al.* (1975) indicate its first appearance within the upper part of their *M. velascoensis* Zone (within but not at the base of Zone P.6). In Je32-04, *M. subbotinae* was noted in the uppermost core of Zone P.4., 20659, but its presence may be the result of downhole contamination. In the overlying unzoned interval it first appears in core 20653.

The unzoned interval may represent continuous deposition across the Paleocene-Eocene boundary (Thanetian-Ypresian). If there is a hiatus or condensed stratigraphic section within or bounding this interval, it cannot be recognized either by paleontological means or on the gamma and electrical logs.

Ypresian

Lower Eocene (Ypresian) rocks are represented by the *Morozovella subbotinae* Zone in cores 20641-20651 (737-839 feet; 225-256 m). As defined by Stainforth *et al.* (1975, p. 67, Fig. 12) this zone is equivalent to Zone P.6b, the interval from the "...extinction of *Globorotalia velascoensis* to first occurrence of *Globorotalia aragonensis*." Zone P.6a is equivalent to the upper part of their immediately underlying *Globorotalia velascoensis* Zone and represents the interval between the first occurrence of *Morozovella subbotinae* and the extinction of *Morozovella aragonensis*.

Species present in the core 20641-20651 interval that occur no higher in the well and do not range higher than the *M. subbotinae* Zone of Stainforth *et al.* (1975) include *Planorotalites chapmani*, *Subbotina velascoensis*, and *Morozovella aequa*. Species that occur no lower than core 20651 and that range no lower than Zone P.6b include *Acarinina broedermanni*, *Morozovella gracilis*, and *M. lensiformis*. Other species present in the interval that Stainforth *et al.* (1975) indicate as part of the normal assemblage of the zone or that evolved during the time represented by the zone include *Morozovella subbotinae*, *M. marginodentata*, *Acarinina soldadoensis soldadoensis*, *A. wilcoxensis*, and *Pseudohastigerina wilcoxensis*. Berggren *et al.* (1967) claim that *P. wilcoxensis* developed from *Planorotalites chapmani* at the base of the Ypresian (Paleocene-Eocene boundary).

Specimens of *Pseudohastigerina wilcoxensis*, *Morozovella subbotinae*, and *Acarinina wilcoxensis* found in the uppermost core (20659) of Zone P.4 are stratigraphically out of place, most likely the result of downhole contamination. Also, down-section stratigraphic mixing, perhaps through downhole contamination or by bioturbation(?), is indicated by the presence of specimens of middle Eocene species *Acarinina bullbrooki*, *A. spinuloinflata* group, *Globorotalia cerroazulensis frontosa*, *Subbotina eocaena*, and *Pseudohastigerina sharkriverensis* in the two uppermost cores (20641-20642) of the *Morozovella subbotinae* Zone. It is possible, however, that these specimens are stratigraphically in place within Zone P.11 (Lutetian) and that the species identifying Zone P.6 in cores 20641-20642 were reworked into the base of the overlying middle Eocene section. This would put the top of Zone P.6 (Ypresian) between cores 20642 and 20643 (749-757 feet; 228-231 m). The gamma log, however, shows a peak, suggestive of a depositional hiatus, higher than this at 734-741 feet (224-226 m); therefore, the down-section stratigraphic mixing explanation is favored.

Lutetian

Rocks of known Lutetian age in Je32-04 are represented by Zones P.11 and P.12 (Hardenbol and Berggren, 1978), the *Globigerinatheka subconglobata* and *Morozovella lehneri* zones, respectively, as defined by Stainforth *et al.* (1975). Typical middle Eocene species identified from these zones are listed in Plate 2.

Zone P.11 is identified on the basis of the co-occurrence of *Subbotina eocaena* and *Acarinina broedermanni* within the core 20631-20640 interval (637-729 feet; 194-222 m). Stainforth *et al.* (1975) indicate the first occurrence of *S. eocaena* at the base of the *Globigerinatheka subconglobata* Zone and the last occurrence of *A. broedermanni* at the top of the zone.

Zone P.12 represents the 617-629-foot (188-192-m) cored interval between the highest occurrence of *Acarinina broedermanni* and the highest occurrence of *Globorotalia cerroazulensis frontosa* in core 20629. Stainforth *et al.* (1975) indicate the highest occurrence of *G. cerroazulensis frontosa* at the top of the *Morozovella lehneri* Zone.

Lutetian-Bartonian(?)

Middle Eocene rocks of Lutetian-Bartonian(?) age comprise the unreworked portion of the Piney Point Formation from cores 20605-20628 (377-609 feet; 115-186 m). Because of shoaling to middle neritic (or shallower?) water depths, planktic foraminifera are rare to absent above core 20628, making it difficult to assign zones to this interval. *Acarinina pentacamerata* occurs as high as core 20625, and a specimen with conferred designation of this species was found in core 20619. According to Stainforth *et al.* (1975) this species ranges no higher than Zone P.12. Jones (1983), on the other hand, identified it in North Carolina rocks assigned to Zones P.12-13 but later decided that it was not this species and assigned it to *A.* sp. aff. *A. pentacamerata*. A specimen of *Pseudohastigerina wilcoxensis* was found in core 20615 and a questionable one in core 20613. According to Stainforth *et al.* (1975) this species last occurs in the middle of Zone P.12. The interval from cores 20613-20627 (457-599 feet; 139-183 m), therefore, could be assigned to Zone P.12 (Lutetian), but because this is based on a few single occurrences of key species in cores, such a designation is tenuous. Because a younger zone (or zones?) cannot be ruled out, the interval is at least as old as Zone P.12 (Lutetian) and may include the next younger zone P.13, *Orbulinoides beckmanni* Zone (Bartonian). Garry D. Jones (personal communication) examined the samples from the interval and concluded that the foraminiferal assemblages are definitely of middle Eocene age and similar to the ones from Zones P.12-13 he studied from North Carolina (Jones, 1983).

The upper part of the unreworked portion of the Piney Point Formation (cores 20605-20612) is nearly barren of planktic foraminifera and cannot be zoned. The rare benthic foraminifera present, such as *Alabamina mississippiensis* and "*Eponides cocoaensis*" (Cushman, 1935) indicated in Plate 2, are of Eocene age. The highest occurrence of *Acarinina* spp. in core 20604 just above the base of the reworked part of the Piney Point indicates that the unreworked part of the formation is no younger than middle Eocene (Berggren, 1977). This confirms the work of Brown, Miller, and Swain (1972, Pl. 39) who assigned a Claibornian age (middle Eocene) to the Piney Point in Je32-04 (including, as it turns out, the reworked portion of late Oligocene age). They also recognized the Claibornian age of the type section of this formation, rather than Jacksonian age (late Eocene) as indicated by Otton (1955), who first defined it.

There is some minor contamination of a few core samples from the unreworked portion of the Piney Point with foraminifera from the overlying Oligocene-Miocene section. As shown in Plate

2, the following species typical of the Chesapeake Group occur rarely and sporadically in the interval from cores 20610-20622: *Buliminella elegantissima*, *B. elongata*, *Florilus pizzarensis*, *Bolivina paula*, and *Uvigerina subperegrina*.

Eocene-Oligocene Contact

A major regional unconformity between rocks of Eocene age and Oligocene or Miocene age is present throughout the Atlantic Coastal Plain from South Carolina northward (Jordan and Smith, 1983) and in the offshore Baltimore Canyon trough as well (Poag, 1980; Valentine, 1980). The magnitude of the hiatus in Je32-04 is estimated at about 12 Ma (Plate 2), but biostratigraphic control is lacking immediately above and below the unconformity. From Poag's (1980, Figs. 23 and 24) data for the offshore COST B-3 and COST B-2 wells in the Baltimore Canyon trough, the magnitude of the hiatus, according to Hardenbol and Berggren's (1978) Paleogene time scale, is 6.5-10 Ma and 5.5-8.5 Ma, respectively. Late but not latest Eocene-age rocks are present in the wells. Olsson *et al.* (1980, Fig. 5) show the magnitude of the hiatus in New Jersey decreasing from 25 Ma at the outcrop to about 11 Ma in the Dickinson No. 1 well at Cape May.

Chattian

The unconformity between middle Eocene and late Oligocene (Chattian)-age rocks in Je32-04 is placed at a depth of 370 feet (113 m), between cores 20604 and 20605, at slight deflections of the resistance curve to the low side and of the spontaneous potential curve to the positive side on the electrical log. This marks the base of the upper 34 feet of the Piney Point Formation that was reworked into sediments of Chattian age. Cores 20601-20604 (337-369 feet; 103-112 m) are from the reworked interval in which benthic species *Buliminella elongata*, *Florilus pizzarensis*, *Uvigerina subperegrina*, and *Hanzawaia concentrica* are rare to common (Plate 2) among other species present that are typical of the Chesapeake Group. One planktic species, *Globigerina praebulloides*, which ranges from late Eocene to late Miocene (Blow, 1979), was identified from core 20601 at the top of the reworked Piney Point.

Above the reworked Piney Point, planktic foraminifera present in cores 20597-20599 (297-319 feet; 91-97 m) identify the *Globigerina ciperoensis* Zone of late Oligocene (Chattian) age. Stainforth and Lamb (1981) indicate that this zone, whose nominate species disappears at or just above the top, is equivalent to most of Blow's (1969) Zone P.22, the uppermost part of which they correlate with the lower half of the *Globorotalia kugleri* Zone. The co-occurrence of *Globigerina ciperoensis* and *Globigerinoides quadrilobatus primordius* in core 20597 strongly suggests but does not prove beyond doubt the presence of the *Globigerina ciperoensis* Zone. Stainforth and Lamb (1981, Fig. 5A-B), working from coreholes and surface sections in the Gulf Coast-Atlantic region, extended the range of *Globigerinoides quadrilobatus primordius* downward from its first appearance at the base of the *Globorotalia kugleri* Zone to the base of the *Globigerina ciperoensis* Zone, which places core 20597 (and cores 20598-20599) in the *G. ciperoensis* Zone. By extension, on the basis of the benthic species present in the reworked part of the Piney Point Formation, the entire section represented by cores 20597-20604 is considered of Chattian age.

Although biostratigraphic evidence from the fossil groups studied for this report is lacking, an early Oligocene (Rupelian) age cannot be ruled out for the section between the unreworked Piney Point and Zone P.22.

Age of the Piney Point Formation

Considerable controversy exists with regard to the age of all or just the upper part of the Piney Point Formation (Brown, Miller, and Swain, 1972; Valia *et al.*, 1977, 1978; Benson and Jordan, 1978; Olsson *et al.*, 1980). Data from a single well are not sufficient to solve all of the problems, but conclusions based on study of the closely spaced cores of Je32-04 rather than on ditch samples (which are typical of most Coastal Plain drill holes) must be acknowledged.

Age determinations for the Piney Point in Je32-04 were based on judgments as to (1) which fossils are *in situ* in core samples, (2) which are present as the result of downhole contamination or other means of down-section stratigraphic mixing, and (3) of those that are *in situ* which are present as the result of having been reworked from older into younger sediments during deposition of the latter. Our conclusions support in part those of Valia *et al.* (1977, p. 727) who observed from study of ditch samples from a few Delaware drill holes that the upper part of the Piney Point, a "...pebbly..." glauconitic greensand, "...represents the transgressive basal unit of the undifferentiated Miocene Chesapeake Group in Delaware..." Their conclusion was based on the presence in the upper Piney Point of benthic and a few long-ranging planktic foraminiferal species typical of the Chesapeake Group. However, Benson and Jordan (1978) considered their evidence inconclusive because of the problems posed by ditch samples. Valia *et al.*

(1977) assumed the Chesapeake Group to be of middle Miocene age and the Piney Point of late Eocene age. From their study they concluded that the basal sandy facies of the Chesapeake Group derived from reworking of the underlying Piney Point Formation is of large areal extent, consisting of a relatively thin veneer at least 20-50 feet (6-15 m) thick. We disagree because it is premature to assume a thin veneer everywhere overlying the unreworked Piney Point until more drill holes are evaluated. We also have not observed pebbles in the uppermost Piney Point in Delaware.

It is more difficult to evaluate the late Oligocene age assigned to the entire Piney Point Formation in New Jersey and Maryland by Olsson *et al.* (1980). Inasmuch as the formation is confined to the subsurface, it has been recognized on the bases of its electric log characteristics and its glauconitic quartz sand lithology. Because most of the subsurface work on this formation was done by hydrogeologists, its age was seldom investigated. Both the original marine deposit of middle Eocene age and a basal sand of the Chesapeake Group (or Kirkwood Formation in New Jersey) of Oligocene-Miocene age that was derived from erosion of Eocene-age glauconitic sands, such as the Piney Point or units of the Rancocas Group, could and probably do give similar electric log responses and have similar lithologies. A completely reworked Piney Point Formation in the wells they studied would explain the age assignment of Olsson *et al.* (1980). In their paper they do not document their paleontologic work in Maryland; only in New Jersey do they present evidence for the Oligocene age of the glauconitic sand unit they refer to as Piney Point. They emphasize the weathered nature of the glauconite in the Maryland and New Jersey drill hole samples they studied. In Je32-04 and other wells in Delaware, the Piney Point glauconite is generally fresh appearing, and weathered glauconite is present only at a few stratigraphic horizons, particularly, in the uppermost part. We believe that the originally deposited Piney Point Formation is of middle Eocene age and that its upper beds in places but not everywhere (J. H. Talley and K. D. Woodruff, personal communication) have been reworked during the Oligocene-Miocene transgression following a long period of subaerial erosion. In New Jersey the so-called Piney Point may in some places be a completely reworked formation of Oligocene-Miocene age, but we do not recognize this situation in Delaware.

Aquitanian(?)-Burdigalian

Because of the absence of diagnostic microfossils, the precise contact between Oligocene- and Miocene-age rocks cannot be located. The uncertain contact is placed between core 20597, the highest core representing the late Oligocene *Globigerina ciperoensis* Zone (P.22), and core 20596, from the base of a shallow to marginal marine section lacking diagnostic fossils, at a depth between 289-297 feet (88-91 m).

Diagnostic planktic foraminifera are absent above Zone P.22, but diatoms and radiolarians provide biostratigraphic control for the middle part of the Calvert Formation present in Je32-04. Abbott (1978) studied the diatoms from the cores in the Tertiary section of the well and was able to identify three diatom biozones that he could correlate with Blow's (1969) planktic foraminiferal zones.

He identified his Zone I, *Actinoptychus heliopelta* Zone, between 52 and 60 m below sea level which corresponds to cores 20587-20589 (197-229 feet; 60-70 m). He writes that this zone is best preserved in the Fairhaven (diatomite) Member of the Calvert Formation near Dunkirk, Maryland, and that it is of early Miocene age and probably is equivalent to Blow's (1969) Zones N.6-N.7. Blow's Zone N.6 straddles the Aquitanian-Burdigalian boundary, as shown in his Figure 20, but Berggren and Van Couvering (1974) place zones N.6 and N.7 wholly within the Burdigalian. Aquitanian-age rocks might be present in the unzoned interval between the top of Zone P.22 and the base of Abbott's Zone I.

Langhian

Abbott (1978) correlates Zone II, *Delphineis ovata* Zone [25-52 m below sea level corresponding to cores 20579-20586 (117-189 feet; 36-58 m)], with Blow's (1969) Zones N.8-N.9, and Zone III, *Delphineis ovata/D. penelliptica* Zone [24-25 m below sea level corresponding to core 20578 (107-109 feet; 33 m)] with Blow's Zone N.9. Zones N.8-N.9 comprise the Langhian Stage (Berggren and Van Couvering, 1974). On the basis of Abbott's diatom zonation, the early/middle Miocene contact in Je32-04 is between cores 20586 and 20587 (189-197 feet; 58-60 m).

Radiolarian data support the age determinations of Abbott (1978). The undifferentiated *Calocycletta costata-Dorcadospyris alata* combined zones are recognized from core 20577 through core 20587 (97-199 feet; 30-61 m). The *C. costata* Zone is defined from the first appearance of the *C. costata* morphotype to the first appearance of the *D. alata* morphotype (Riedel and Sanfilippo, 1978). Because *C. costata* ranges into the lowermost part of the *D. alata* Zone and *D. alata* was not found in Je32-04, the two zones cannot be differentiated. Species listed in Plate 2 occur throughout or within part of the combined zones. The combined zones straddle the early/middle Miocene boundary which Riedel and Sanfilippo (1978) placed between the two zones but, later, Westberg and Riedel (1982) placed in the lower *D. alata* Zone.

The unzoned interval represented by cores 20571-20576 (47-89 feet; 14-27 m) is considered of middle Miocene age-Langhian and perhaps, in part, Serravallian.

Pleistocene

The base of the Columbia Formation is at 40 feet (12 m). The only core from the formation is 20570 (37-39 feet; 11-12 m) which is barren of all fossils. Although not proven, Jordan (1964, 1974) attributes the fluvial deposition of the Columbia sand sheet to conditions that prevailed during the transition from a glacial to interglacial stage of the Pleistocene that probably predates the Wisconsinan (> 0.08 Ma, Stuiver *et al.*, 1978). We assume this age for the formation because we believe that an earlier age (Owens and Denny, 1979) based on palynological analysis is inconclusive. We also agree with Hansen (1981) who presents evidence that the Columbia unconformably overlies rocks of Miocene age and does not interfinger with them as postulated by Owens and Denny (1979).

PALEOENVIRONMENTAL INTERPRETATIONS

A detailed analysis of the benthic foraminifera and other microfossil groups present in the core samples that are useful in interpretation of paleoenvironments is beyond the scope of this report. Bandy and Arnal (1957, 1960), Phleger (1960), and Poag (1981), among others, present general methods of foraminiferal biofacies analysis and review works of others. Gibson (1967), Gernant (1970), Poag (1980), Jones (1983), and Olsson and Nyong (1984) have applied these and other methods to the interpretation of Atlantic Coastal Plain and offshore stratigraphic sections.

The paleoenvironments indicated on the curve in Plates 2 and 3 were interpreted for each core primarily on the basis of the quantity, quality, and diversity of the benthic foraminifera and the quantity and diversity of the planktic foraminifera. The range chart of foraminifera in Plate 2 is primarily for the planktic species. Benthic genera, generic groups, and selected species were noted and their abundances estimated for each core sample examined, but their analysis was not sufficiently comprehensive to include them on the distribution chart. The quantity and diversity of other biogenic components (Plate 1) and the lithology determined from sample descriptions and geophysical log responses were also considered in the paleoenvironmental determinations, especially for cores lacking foraminifera.

The paleoenvironmental curve shown in Plates 2 and 3 was constructed by joining the points representing the environmental interpretation for each core. This results in a curve that is more detailed and apparently more precise than it really is. For example, the apparent shallowing of the marine environment interpreted for the unzoned Paleocene(?)-Eocene(?) section may not be real because of possible dilution of the foraminiferal assemblage by a high rate of clastic sedimentation. Or, diagenetic effects such as carbonate dissolution may have removed calcareous fossils from parts of the sedimentary section, for example, from the diatomaceous part of the Calvert Formation. Both Gibson (1967) and Poag (1980) noted the absence of foraminifera in diatomaceous beds of equivalent age elsewhere.

The water depths in feet are indicated for the marine paleoenvironments, but they should not be taken literally. They are on the chart to provide some magnitude of the range of water depth for each environment. Van Hinte (1978, Fig. 19) illustrates the magnitude of uncertainty of water depth interpretations made for individual samples but points out that a succession of such determinations shows a trend that can establish relative changes in water depth between parts of the section. Water depth determinations also put restraints on the interpretations of environments of deposition. For example, a sand represented on the geophysical logs is unlikely to be interpreted as a beach sand if the paleoenvironmental interpretation is outer neritic.

The paleoenvironmental curve of Je32-04, interpreted broadly, clearly shows the transition from continental deposits of the Potomac through transitional marine to marine deposition during the Upper Cretaceous. Deepest marine environments attained during Paleocene and Eocene times match the time of the deepest environments interpreted for the offshore COST B-2 and B-3 wells (Poag, 1980). Shoaling during deposition of the Piney Point Formation followed by a major period of erosion probably reflects eustatic lowering of sea level and consequent regression or, possibly, regional tectonic uplift. Oligocene-Miocene transgression followed by shoaling marks the final cycle of marine deposition that was characterized by progradation of a clastic wedge across the entire middle Atlantic continental margin, reflecting renewed uplift of the Appalachian area.

The history of deposition summarized in Plate 3 was interpreted by combining information from lithology and the paleoenvironmental curve with that supplied by the character of the electrical log of the corresponding units.

SEDIMENT ACCUMULATION RATES

Sediment accumulation rates for Je32-04 are illustrated in Figure 4, which is a plot of estimated time points vs. their depth in the drill hole. The rates are properly designated as sediment accumulation rates rather than rates of deposition because corrections for compaction were not made as described by van Hinte (1978). Because sediments are predominantly silts and sands compaction effects for the section drilled are less than for one with clay as the dominant lithology.

Biostratigraphic control points are mainly confined to the silty intervals. Sandy intervals probably represent higher rates of accumulation that could not be determined from the available data. Rates of accumulation noted on the diagram, therefore, are averaged over both sandy and silty intervals.

Of the six unconformities shown, the two youngest ones and the oldest one are interpreted as representing subaerial exposure and erosion. The others are submarine unconformities that represent significant submarine erosion and/or periods of nondeposition or very slow sedimention. A seventh unconformity or hiatus (submarine origin) might be present in the upper Oligocene-lower Miocene interval where the average sediment accumulation rate is quite low.

GEOHISTORY DIAGRAM

The geohistory diagram shown in Figure 5 was constructed according to the method of van Hinte (1978). Estimated time points with biostratigraphic control are represented by solid triangles and circles; those without such control are open triangles and circles. The paleobathymetry at each time point

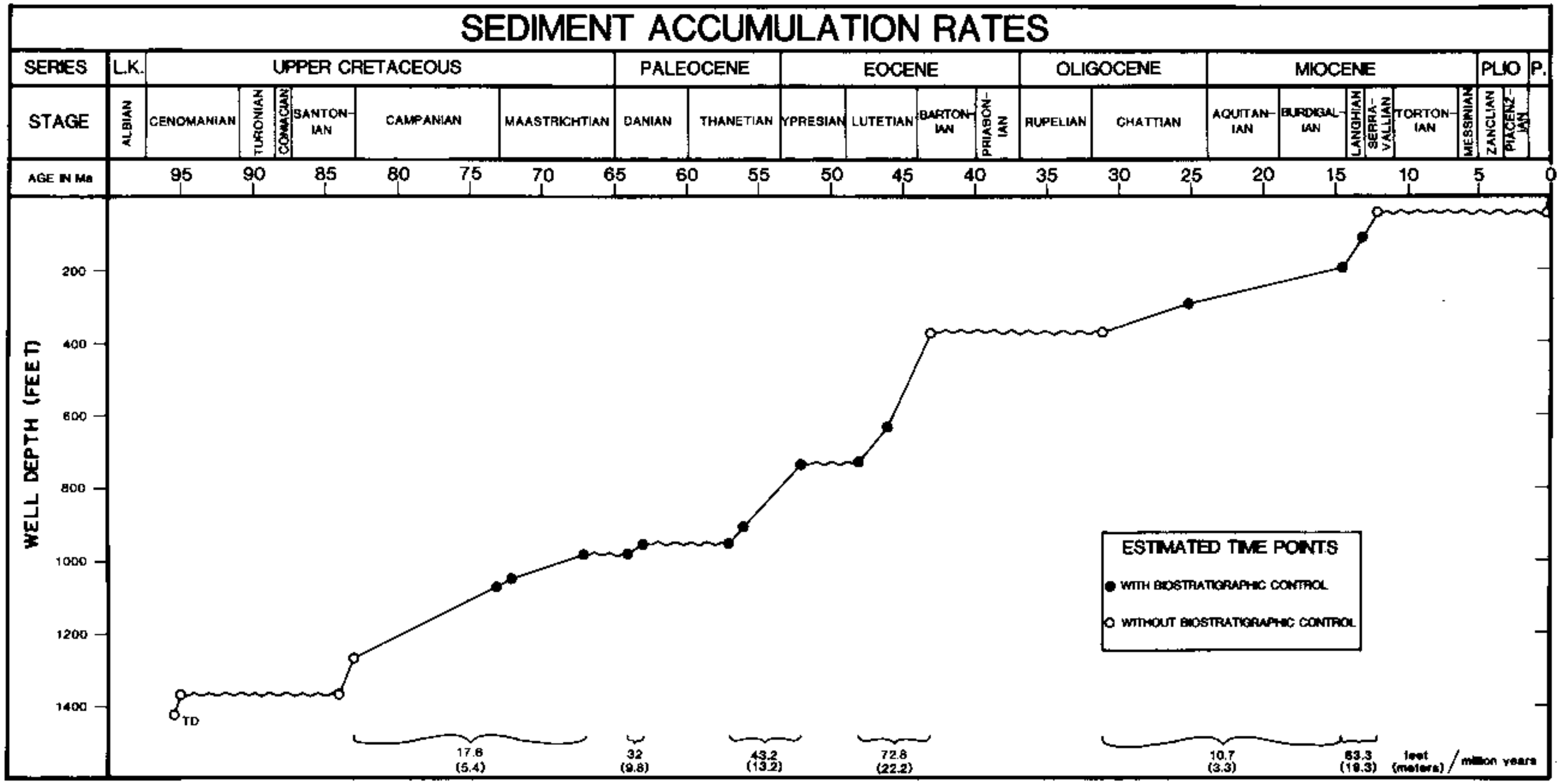

Figure 4. Sediment accumulation rates.

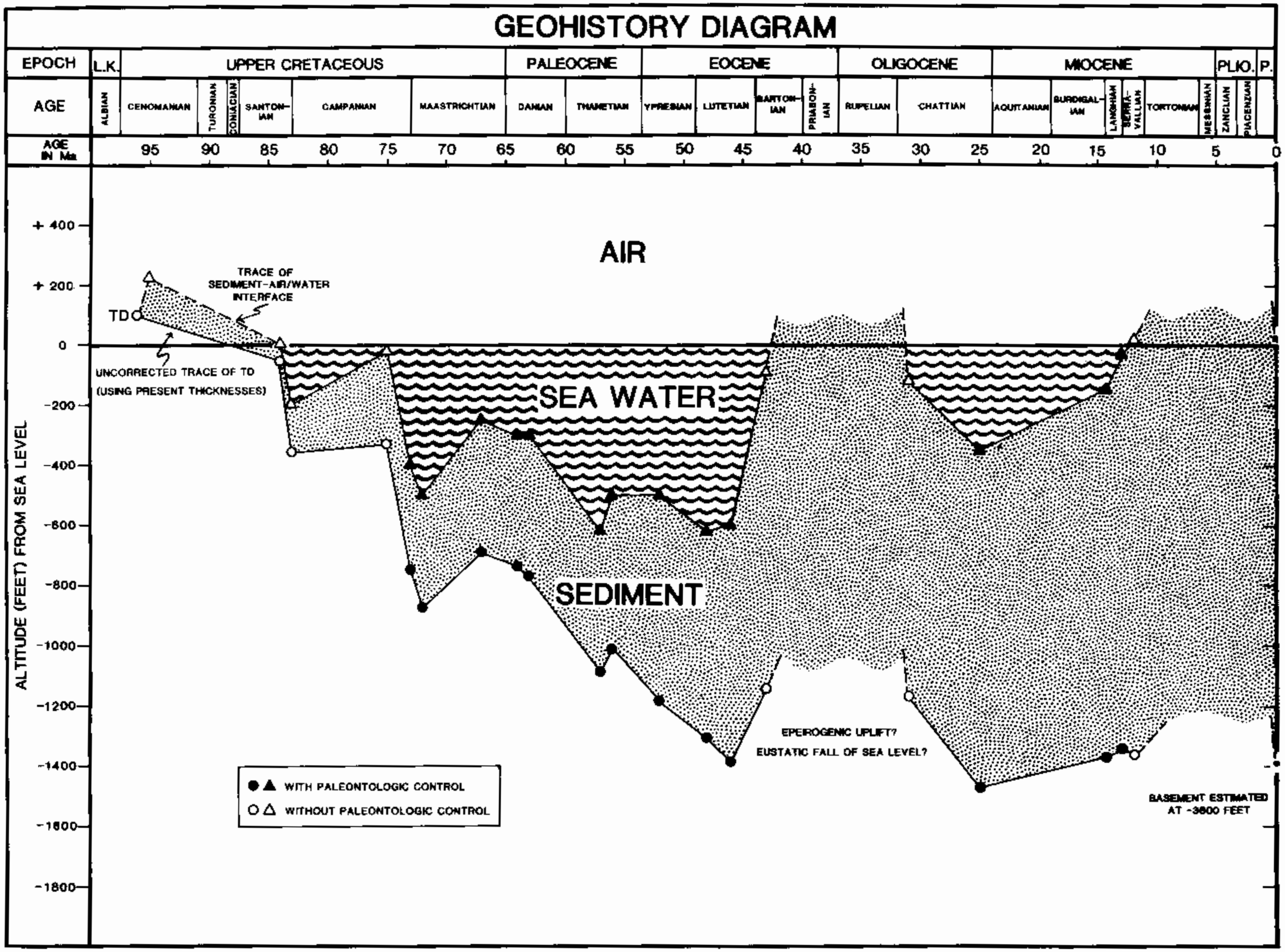

Figure 5. Geohistory diagram.

was determined from the paleoenvironment curve of Plate 2 and plotted as a triangle. The cumulative thickness of sediment at each time point is plotted as a circle. Because the circles represent current thicknesses, they are uncorrected for compaction and thus do not represent restored thicknesses. Lines connecting the circles therefore represent the uncorrected subsidence rate of the total depth (TD) of the well, not of the basement, which is estimated at -3,600 feet. Lines connecting the triangles trace the altitude, with respect to the sea level of the time, of the sediment-air or-water interface.

In reading the diagram note that the apparent uplifts of TD shown along the curve do not necessarily imply tectonic uplifts or temporary decreases in the rate of subsidence; they only indicate the position of TD with respect to the sea level at the time. The position of sea level with respect to land at any time is a combination of the effects of tectonic subsidence or uplift, rate of sediment deposition and compaction, and eustatic rise or fall of sea level.

The diagram indicates three intervals when the area of the well was above sea level. The first interval was during deposition of the nonmarine Potomac Formation followed by a period of subaerial erosion of the formation prior to the first major marine transgression heralded by the Magothy Formation. The last interval, during the late Cenozoic, probably was of shorter duration than that shown on the diagram. There may have been additional marine section deposited above the Calvert Formation at the well site that was removed by erosion at a much later time during lowered sea levels of Pliocene-Pleistocene glacial times. The middle interval of Eocene-Oligocene age represents a widespread unconformity and might have resulted, in part, from regional tectonic uplift instead of or in addition to a eustatic fall of sea level.

Olsson *et al.* (1980, p. 552) propose that the Eocene-Oligocene unconformity "...resulted from a eustatic lowering of sea level, which resulted in the largest regional hiatus of the Late Cretaceous to Tertiary in the northeast Atlantic continental margin." They point to the Gulf Coast and Europe where the same hiatus is observed and argue that a low stand of sea level during the late Eocene-early Oligocene is supported by Pitman's (1978) sea-level curve derived from volume changes of the mid-ocean ridge system.

Vail and Hardenbol (1979), however, indicate a major eustatic fall of sea level during the late Oligocene (29 Ma ago). From the record of Je32-04, this occurred just before the regional marine transgression that reworked the upper part of the Piney Point Formation prior to deposition of the Calvert Formation. The uppermost cores of the unreworked portion (middle Eocene age) of the Piney Point in Je32-04 show evidence, in the form of iron-oxide staining, that the formation was subaerially exposed prior to the late Oligocene marine transgression. If Vail and Hardenbol's sea level curve is valid, marine deposition should have occurred throughout late Eocene and early Oligocene time, the period of time represented instead by the major regional unconformity. Whether or not marine sediments of this age were ever deposited on the Coastal Plain or continental shelf of the northeastern United States is not certain. If they were, according to the Vail and Hardenbol curve they would have been removed by erosion following the late Oligocene fall of sea level 29 million years ago.

On the basis of studies of Oligocene foraminiferal ^{18}O records, Miller *et al.* (1985) suggest that ice caps developed at about 36, 31, and 25 million years ago. They speculate that erosion during an inferred glacio-eustatic fall of sea level near the early/late Oligocene boundary (32-31 Ma) developed a regional unconformity on the U. S. mid-Atlantic and Irish continental margins.

Regional uplift of the northeastern United States continental margin during late Eocene-early Oligocene time is an alternative to eustatic fall of sea level for explaining the regional Eocene/Oligocene-Miocene unconformity. Heating of the lithosphere beneath the continent in this region at about this time would have provided the mechanism for uplift. However, the only evidence for continental igneous activity is of an earlier but still Eocene age in the eastern United States. Towe and Gibson (1968) found altered volcanic ash in rocks of early Eocene age (50-52 Ma old) from widely separated localities in the western North Atlantic region. This suggested to them a significant volcanic event or series of events that produced large quantities of silicic volcanic ash. Fullagar and Bottino (1969) dated Eocene-age felsite intrusives from west-central Virginia at about 47 million years (middle Eocene) and concluded from isotopic studies that the magma was derived from the lower crust or upper mantle. Dennison and Johnson (1971) associate doming of the Schooley erosion surface in the Appalachian Plateau and adjacent Valley and Ridge region in Virginia and West Virginia with these Eocene intrusive rocks.

Later volcanic activity and regional uplift occurred in the North Atlantic ocean basin. Tucholke and Vogt (1979) estimated that uplift of the Bermuda Rise began about 42-43 million years ago (middle Eocene) and continued into late Eocene time. They were uncertain of the nature of the (thermal?) event that formed the Rise. There could have been a similar event at about the same time but beneath the northeastern U. S. continental margin that resulted in uplift of the margin and subsequent development of the regional Eocene-Oligocene unconformity.

CONCLUSIONS

This Bulletin has presented the results of an integrated study of the materials generated by drilling a deep test well in central Delaware. It is important that such wells be drilled for essential subsurface geologic information and that their usefulness be maximized by comprehensive investigation and documentation. Opportunities for this type of investigation have been rare in the Atlantic Coastal Plain, and exceedingly rare in Delaware. The information presented here establishes a reference section that will enhance investigation of the subsurface for a variety of purposes throughout much of the State.

The integration of a variety of studies in this investigation of a single well has been particularly beneficial because the interrelationships of physical, paleontologic, and temporal aspects of the section may reinforce or modify interpretations of geologic history. Further, because other wells generally are not cored or otherwise closely controlled, a comprehensive reference is required to use whatever fragmentary information they may produce.

Several "packages" of sediment have been defined by the various techniques employed here. Different techniques do not necessarily produce the same subdivisions of the section. In some cases there is a clear coincidence of change recorded in lithology, trace mineralogy, paleontology, and other characteristics; at other points these properties vary independently. It may be concluded that the geologic history of the mid-Atlantic Coastal Plain is more complex than has generally been recognized in the literature.

The stratigraphic division of the Cretaceous and Tertiary sections has been refined, especially with regard to biostratigraphy and chronostratigraphy. However, this study is primarily a presentation and interpretation of data from one point (well) and, therefore, cannot be a "stratigraphy." A study of the stratigraphy requires areally distributed, mappable information and correlation within the region. The study of a single well provides the bases for correlations and points the way to the development of an improved regional stratigraphy. Work is in progress toward an improved understanding of the stratigraphic framework based in large part on the information herein.

Unconformities represent one major basis for the subdivision of the stratigraphic section. Six, possibly seven, disconformities are recognized in this study. Three of these are interpreted as representing subaerial exposure: (1) between the Potomac and Magothy formations, (2) between middle-Eocene- and late-Oligocene-age rocks, and (3) between Pliocene-Pleistocene-age rocks. The other three are submarine unconformities within the Pamunkey(?) Formation at places that could only be recognized through close sampling and detailed study: (1) middle Maastrichtian-Danian, (2) Danian-Thanetian, and (3) Ypresian-Lutetian. Detection of these disconformities is significant in understanding basinal history and in regional correlation. Future work will undoubtedly attempt to relate them to regional or worldwide tectonic and eustatic events.

The unconformable contact between the Potomac Formation below and the Magothy Formation above is characterized by a significant change in lithology. The Potomac clays are in sharp contact with the overlying Magothy sands. The sediment accumulation rates in both formations were high (Fig. 4). The staurolite-tourmaline heavy mineral zone extends into both formations at this point. Spoljaric (1972) interpreted this similarity in heavy mineral composition to indicate that the lower (older) part of the Potomac was the source for the Magothy Formation in northern and central Delaware.

The first Late Cretaceous marine transgressive-regressive phase is represented by the Merchantville and "Englishtown" formations. The phase correlates with the tourmaline-garnet heavy mineral zone suggesting a sediment source area different from that of the underlying formation. Groot (1955) proposed a source south of the present area of distribution of these formations, with the sediments brought in by the action of the sea. The sediment accumulation rate during the deposition of the Merchantville and "Englishtown" formations appears to have been rather uniform.

The second Late Cretaceous transgressive phase resulted in the deposition of the "Marshalltown" and lower part of the Pamunkey(?) formations. It is also characterized by an increase in both benthic and planktic foraminifera. The content of these microfossils remains high through the remainder of the Pamunkey(?) Formation. The Danian-age segment of the Pamunkey(?), bounded by small unconformities, signifies the first major appearance of Radiolaria. The "Marshalltown" and the part of the Pamunkey(?) up to the base of the Lutetian correlate with the tourmaline-andalusite heavy mineral zone. The rest of the Pamunkey(?) coincides with the andalusite-tourmaline zone as well as with the last occurrences of Paleogene Radiolaria.

The segments of the "Marshalltown"-Pamunkey(?) sequence described above are also characterized by corresponding changes in sediment accumulation rates possibly reflecting subtle tectonic movements both in the source areas of the sediments and their depositional environments.

Most of the Piney Point Formation is in the staurolite-sillimanite heavy mineral zone, and the sediments characteristically do not contain siliceous biogenic material. The deposition of the Piney Point occurred during a regressive phase which began with the deposition of the uppermost part of the Pamunkey(?) Formation. The rate of sediment accumulation is the highest recorded in the whole stratigraphic section studied.

The Calvert Formation correlates well with the staurolite-zircon-sillimanite heavy mineral zone and is also characterized by the presence of siliceous microfossils, both radiolarians and diatoms. Uplift of western source areas is indicated by a significant increase in sediment accumulation rate during the middle Miocene.

Reliable biostratigraphic control has been developed from closely spaced core samples for the entire marine section for the first time in Delaware. Only a small portion of the section penetrated by Je32-04 could not be zoned. Future biostratigraphic studies should be conducted on other microfossil groups, particularly calcareous nannofossils, ostracodes, and palynomorphs, to fill in the gaps and calibrate the results obtained from planktic foraminifera, diatoms, and radiolarians.

Although reasonably comprehensive, this study has not been exhaustive. In addition to the remaining potential for paleontologic study, investigation of the clay mineralogy, and especially the glauconite, of the section remains. Study of the clay mineralogy is underway in mid-1985. The geologic history will not be fully understood until the origin(s) of the glauconitic components of the section is satisfactorily explained.

The test well at the Dover Air Force Base has been used for many purposes since it was drilled in 1958. It is for Delaware something of a geologic monument pointing downward. The data it has yielded are now made available as contributions to future studies of the subsurface of Delaware.

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