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Palynostratigraphy of Cretaceous and Quaternary strata in the Robins Point corehole, Aberdeen Proving Ground, Harford County, Maryland

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ABSTRACT

The U.S. Geological Survey (USGS) Robins Point corehole was drilled on the U.S. Army's Aberdeen Proving Ground to study the stratigraphy and hydrology of the area and thus to better understand ground-water movement, which potentially carries contaminants, under the Proving Ground. Spore/pollen analysis was made of 22 Cretaceous and 18 Quaternary samples from the Robins Point core. Cretaceous samples were from the interval between 867.1 and 283.3 ft depth; pollen-bearing Quaternary samples were from the interval between 171.75 and 25.2 ft. Based on palynology and lithology, the Cretaceous-Quaternary boundary in the core is most likely at 177.2 ft.

Palynologically, the boundary between the Cretaceous Patuxent/Arundel and Patapsco Formations is between 758.7 and 638.75 ft; the boundary is picked lithologically at 647.3 ft. The Patapsco Formation can be divided into several parts, including Subzones IIA and IIB, and Zone III. Zone III is in the upper part of the Elk Neck Beds and at the top of the Patapsco Formation; therefore, the presence of probably 190-230 ft of Zone III in the core suggests that in the area of the core site (southeastern corner of Gunpowder Neck) most of the Potomac Group is preserved.

The Quaternary section consists of sediments that fill three ancient channels of the Susquehanna River; in the upper Chesapeake Bay, these paleochannels are stacked one atop the other. The channel deposits are rich in sands that are important aquifers under the Aberdeen Proving Ground and also on the Delmarva Peninsula. Pollen data are important for helping to date the channel deposits. Within the Quaternary sequence, six climatic phases can be distinguished that occur in the set of paleochannel deposits: Phase 1, climatically transitional between glacial and interglacial, in the Exmore paleochannel deposit, may be pre-Illinoian, early Illinoian(?) (Stage 11), or late but not latest Illinoian; Phase 2, representing a glacial climate, in the lowermost part of the Eastville paleochannel deposit, is apparently latest Illinoian; Phase 3, representing a warm-temperate interglacial climate, in the Eastville

paleochannel deposit, is Sangamonian; Phase 4, representing a cold-temperate to glacial climate, at the top of or overlying the Eastville paleochannel fill, apparently is very latest Sangamonian or earliest Wisconsinan; Phase 5, representing a late-glacial climate, in the Cape Charles paleochannel fill, is latest Wisconsinan; Phase 6 represents a Holocene temperate climate.

INTRODUCTION

The Robins Point corehole was drilled during several intervals of time between November 29, 1995, and April 17, 1996, by the U.S. Geological Survey in cooperation with the U.S. Army and the Army Corps of Engineers. The location was lat. 39°18'06" N., long. 76°16'53" W., at the southeastern tip of the Gunpowder Neck Peninsula on the Aberdeen Proving Ground, immediately northwest of the tower at Robins Point, Gunpowder Neck 7.5 min quadrangle, Harford County, Maryland (fig. 1). Surface elevation was about 4 ft above sea level, and the corehole reached a total depth of 961 ft. Most of the core was 2.25 inches in diameter. A generalized lithology of the core is shown in figure 2; the lithology of the core was described in detail by Powars (1997). The purpose of drilling the corehole was to gain stratigraphic and hydrogeological information about the coastal plain sediments underlying the Proving Ground and thus to improve knowledge about the movement of potentially contaminant-bearing ground-water under the Proving Ground.

We wish to thank Thomas A. Ager (U.S. Geological Survey, Denver) and Gilbert J. Brenner (State University of New York at New Paltz) for their helpful reviews of the first draft of this report.

SAMPLE PROCESSING METHODS

Most Cretaceous samples from the Robins Point core were processed by Advanced Power Technologies, Inc., Geosciences Division, Houston, Texas, using HCl, HF, HNO_3, and NH_4OH. At this point, most of the samples were treated with sodium polytungstate heavy liquids using first a solution of 1.5 s.g. and then, on the sink fraction, a solution of 1.85 s.g. However, samples from depths of 414.5-414.8, 409.4-409.9, and 283.9-284.1 ft were treated first with the heavy liquid of 1.85 s.g. and then the sink fraction was treated with the liquid of 1.5 s.g. A relatively light heavy liquid of 1.5 s.g. was used in order to remove as much of the abundant black woody material in the samples as possible, and it was observed that these residues were much richer in spores and pollen grains than the residues treated with a heavy liquid of 1.85 s.g. The residues were stained with Bismark brown and were not screened because many of the angiosperm pollen grains are very small. The residues were mounted on slides using a plastic mounting medium.

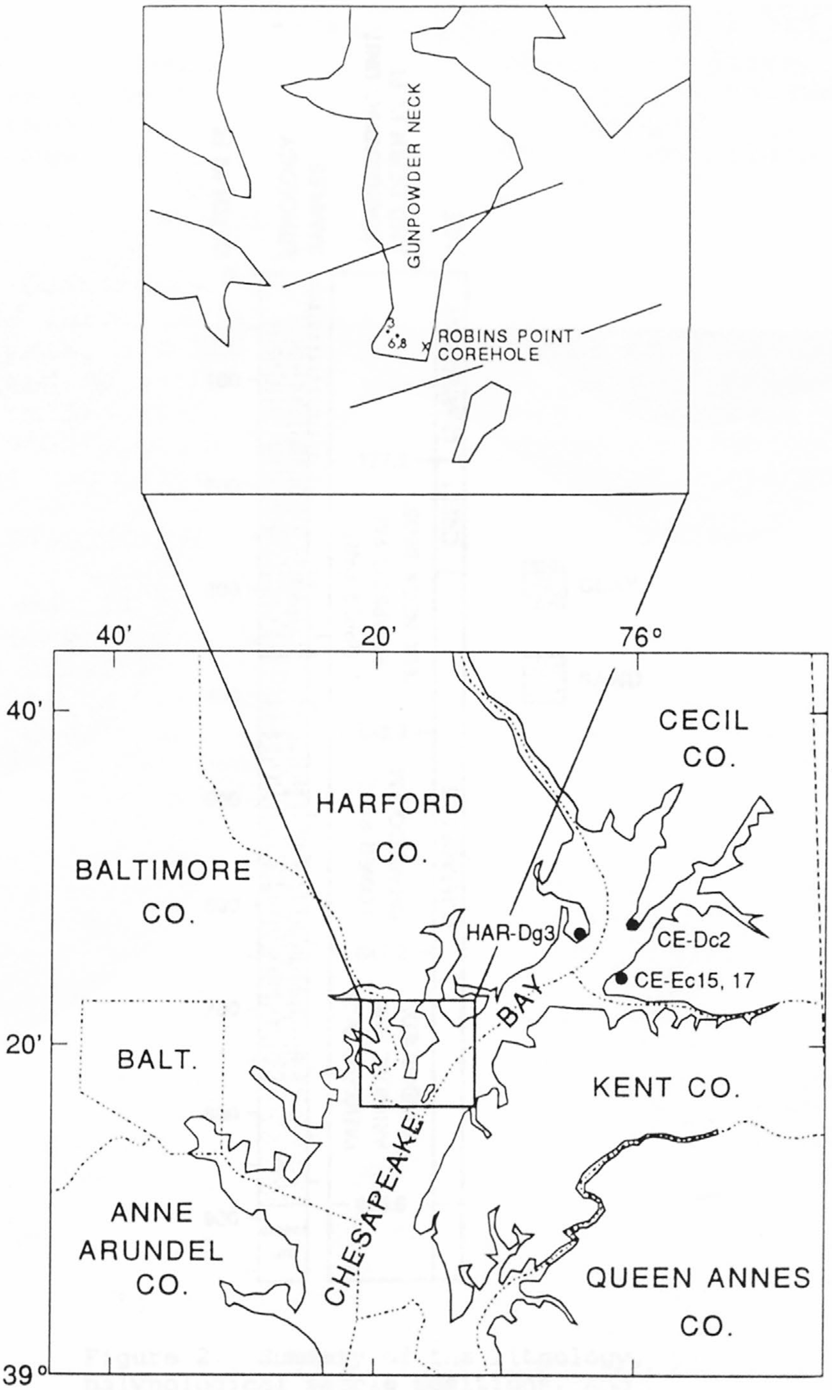

Figure 1. Location of the Robins Point corehole. HAR-Dg3 (Spesutie Island), CE-Dc2 (Turkey Point), and CE-Ec15, 17 (Grove Neck) are testholes from which 22 core, bit, and outcrop samples of Cretaceous rocks were studied palynologically by Doyle (1979). In the upper map, 3 and 6,8 are borehole 3 and well clusters 6 and 8 from which Pleistocene pollen samples were examined by G. S. Brush (in Hughes, 1993); diagonal lines mark "estimated extent of paleochannel deposits" (Hughes, 1993, fig. 11).

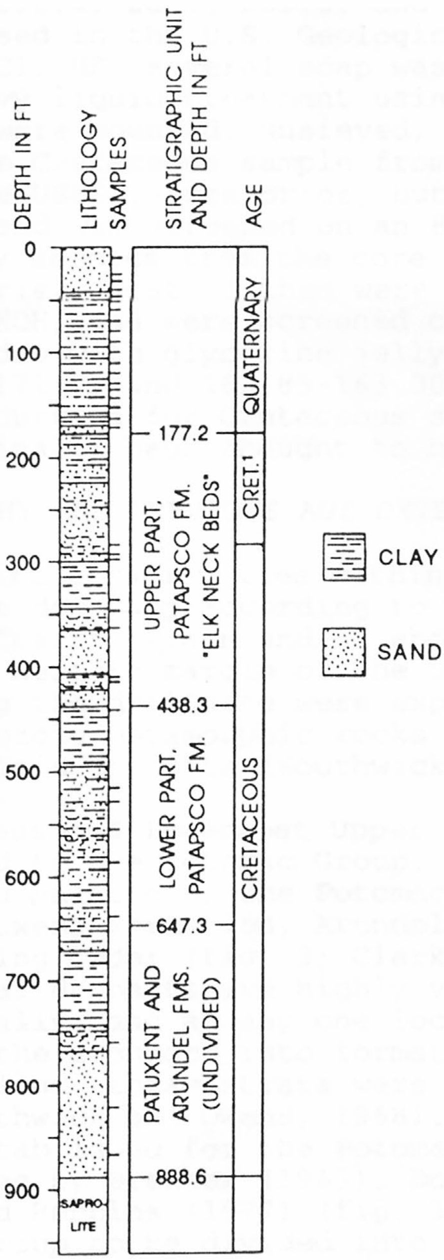

Figure 2. Summary of the lithology, palynological sample positions, and stratigraphic and age units in the Robins Point core. Data are from palynological studies in this report and from lithological studies by Powars (1997). Footnote 1 refers to the fact that strata between 283.3 and 177.2 ft are believed to be Cretaceous paleosols (Powars, 1997) although they lack fossils for age control.

The Cretaceous samples from 294.0-294.25, 293.3-293.6, 292.8-293.0, 292.15-292.4, 283.6-283.8, and 283.3-283.5 ft in the core were processed in the U.S. Geological Survey (USGS) laboratories using HCl, HF, several soap washes to remove fine material, then a heavy liquid treatment using a $ZnCl_2$ solution of 1.45 s.g. Residues were mounted, unsieved, on slides with glycerine jelly. The Cretaceous sample from 283.9-284.1 ft was also processed in the USGS laboratories, but using a heavy liquid of 2.1 s.g., and was screened on an 8-µm sieve.

The Quaternary samples from the core were also processed in the USGS laboratories; most of them were treated with HCl, HF, acetolysis, and KOH, and were screened on 8-µm sieves before being mounted on slides with glycerine jelly. The Quaternary samples from 171.60-171.75 and 162.85-163.00 ft were processed using the USGS procedure as for Cretaceous samples because these two samples had originally been thought to be Cretaceous in age.

STRATIGRAPHY AND PREVIOUS AGE DETERMINATIONS

The Robins Point locality lies within the Salisbury Embayment (a basement downwarp according to Richards, 1948) of the Middle Atlantic Coastal Plain and is about 10 miles east of the Fall Line on the western margin of the upper Chesapeake Bay (fig. 1). Underlying the drillsite were expected to be Precambrian and Paleozoic metamorphic rocks and Cretaceous and Quaternary coastal plain deposits (Southwick and Owens, 1968, line B-B').

Lower Cretaceous and lowermost Upper Cretaceous strata in Maryland are assigned to the Potomac Group. In the area between Washington, D.C., and Baltimore, the Potomac Group has been divided into the Patuxent Formation, Arundel Clay, and Patapsco Formation, in ascending order (fig. 3; Clark and Bibbins, 1897). However, these fluvial deposits are highly variable both laterally and vertically, and at any one locality it may be difficult to divide the sequence into formations. Therefore, in Harford County, Maryland, these strata were mapped as Potomac Group undivided (Southwick and Owens, 1968). A palynological zonation has been established for the Potomac Group of the Middle Atlantic States by Brenner (1963), Doyle and Hickey (1976), and Doyle and Robbins (1977) (fig. 3). This zonation allows the Potomac Group to be divided into (1) the Patuxent/Arundel Formations (undivided), (2) the lower part of the Patapsco Formation, and (3) the Elk Neck Beds (of Wolfe and Pakiser, 1971) in the upper part of the Patapsco Formation.

Owens (1969, p. 80) thought that "in the southern part of [Harford] County ... a large part of the [Potomac Group] section was removed by latest Tertiary and Quaternary erosion." Hughes (1993, p. 14) stated that, at the southern end of Gunpowder Neck, the top of the Cretaceous section was significantly (about

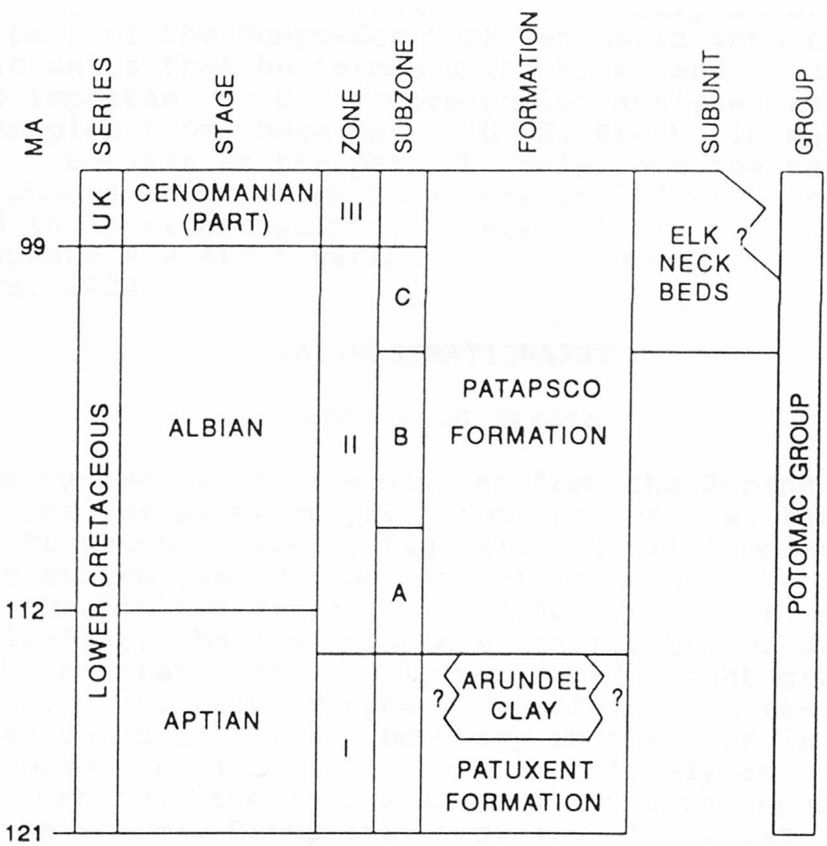

Figure 3. Stratigraphic units and palynological zones of the Potomac Group in the Middle Atlantic States. Zonation and age assignments are from Brenner (1963), Doyle and Hickey (1976), Doyle and Robbins (1977), and Doyle (1992). Ages of stage boundaries are from Gradstein and others (1995).

50 ft) deeper to the east than to the west, due to "erosion during a lower stand of sea level in the Pleistocene epoch."

Pleistocene strata in Harford County have been assigned by some authors (e.g., Owens, 1969; Hughes, 1993) to the Talbot Formation, which consists of paleochannel deposits of the ancient Susquehanna River that, in ascending order, are fills of the Exmore, Eastville, and Cape Charles paleochannels (e.g., Colman and Mixon, 1988). These paleochannel deposits are very sandy and therefore are important aquifers under the Aberdeen Proving Ground and also on the Delmarva Peninsula. "The paleochannels of the Susquehanna River system were carved during major relative sea-level minima ... the related channel-fill sediments were deposited during subsequent transgressions.... The seismic-reflection data, surface exposures, and borehole data indicate no major unconformities within each combined channel-fill and barrier-spit sequence" (Colman and Mixon, 1988, p. 109). Hughes (1993) divided the Quaternary strata in the southern part of the Gunpowder Neck Peninsula into three lithologic units that he termed units A, B, and C, and Hughes' units are important because spore-pollen analyses were made of several samples from these units (G. S. Brush, in Hughes, 1993, p. 21-22). Details on the paleochannels, and the terrestrial climatic phases under which they were filled with sediment, are discussed in later paragraphs. Overlying Pleistocene strata in the Chesapeake Bay are a variety of Holocene sediments (Mixon and others, 1989).

PALYNOSTRATIGRAPHY

Cretaceous Strata

Twenty-two Cretaceous samples from the Robins Point core were examined for palynomorphs, from the interval between 867.1 and 283.3 ft depth (table 1; fig. 2). All 22 samples contained spores and pollen grains. No samples were taken between 283.3-283.5 ft, the highest sample containing Cretaceous pollen, and 171.60-171.75 ft, the lowest sample bearing Quaternary pollen, because these strata were deeply weathered, light gray to white, no doubt barren of palynomorphs. Therefore, the exact position of the Cretaceous-Quaternary boundary in the core is not known, although, based on lithology, it is most likely at 177.2 ft.

Two methods have been used to distinguish spore/pollen zones in the Potomac Group (see fig. 3). The first is to use relative frequencies of particular spore/pollen groups; the second method is to use stratigraphic distributions of certain spore/pollen taxa. Regarding relative frequencies, Brenner (1963, p. 37) reported that "*Classopollis torosus* and *Exesipollenites tumulus* (gymnosperms), *Cyathidites minor*, and schizaeaceous trilete spores form the dominant [spore/pollen] types of Zone I" and that angiosperm pollen is less than 2 percent of the spore/pollen assemblage in Subzone IIA but increases to 15 percent (commonly), and to as much as 40 percent of the assemblage, in Subzone IIB. Figure 4 presents results of counts of 100 spore/pollen specimens of *Exesipollenites tumulus*, *Classopollis torosus*, *Cyathidites minor*, Schizaeaceae, tricolpate + tricolporate angiosperms, and "other spore/pollen taxa" in seven samples from the core. These taxa are here termed the ECCSTO group for convenience. Inaperturate gymnosperm pollen(?) specimens were counted at the same time as the 100 specimens of the ECCSTO group and were abundant in all samples, but the relative frequencies of inaperturates seemed less meaningful; therefore, these percentages are presented separately in the column at the right, and were calculated by dividing the number of inaperturates by the total of all palynomorphs counted, that is, by the sum of inaperturates + 100 ECCSTO specimens.

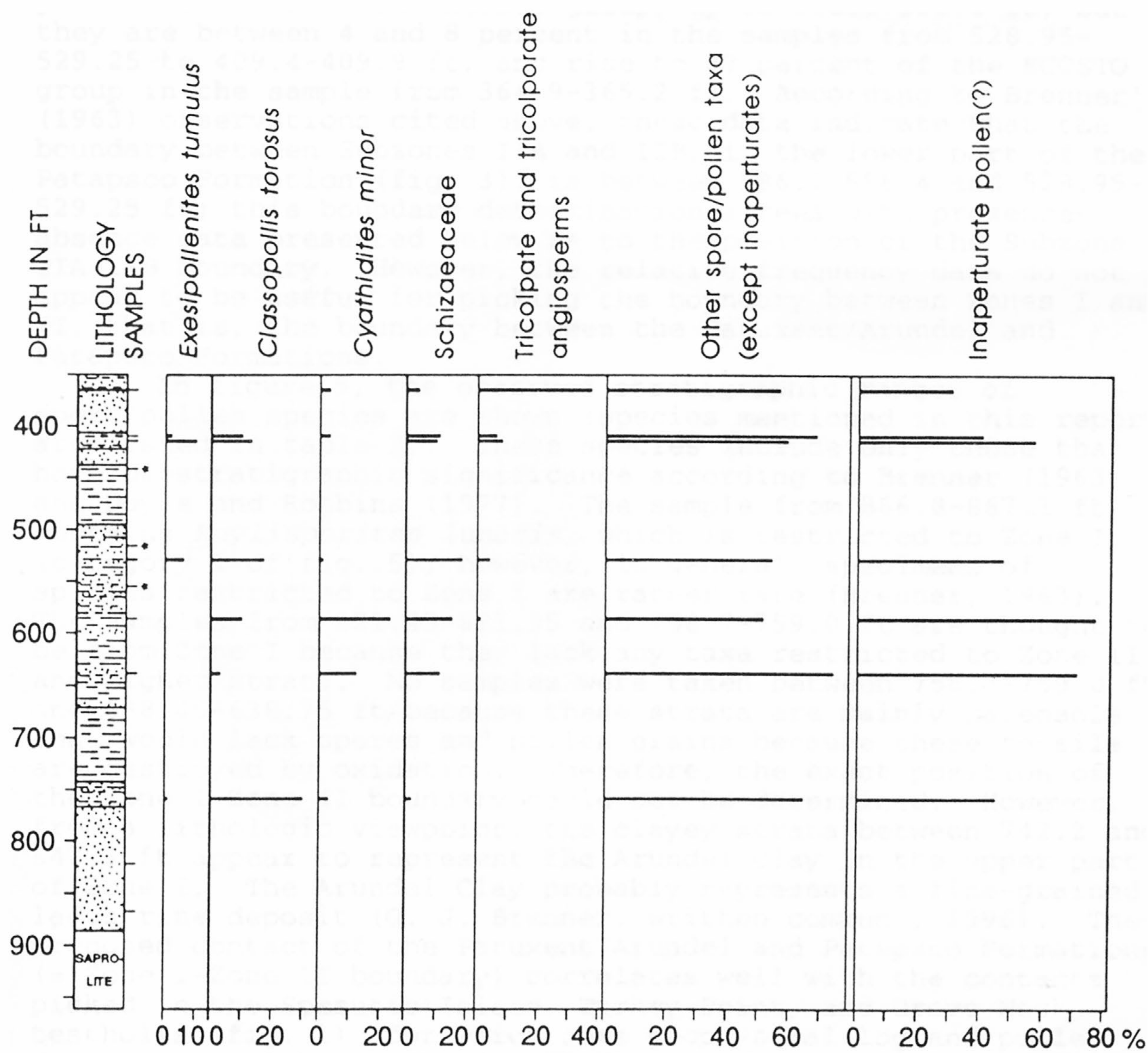

Figure 4. Relative frequencies of spore/pollen groups in seven Cretaceous samples between 758.7-759.0 and 364.9-365.2 ft depth in the Robins Point core. Samples marked with an asterisk contained such rare spores and pollen grains that no counts for these assemblages were possible, and no counts were made of samples below 758.7-759.0 ft because it seemed obvious that these were in Zone I.

One or more of the taxa *Exesipollenites tumulus*, *Classopollis torosus*, *Cyathidites minor*, and Schizaeaceae have moderate relative frequencies in all samples from 758.7-759.0 to 528.95-529.25 ft, slightly lower relative frequencies in samples from 414.5-414.8 and 409.4-409.9 ft, and distinctly low relative frequencies in the sample from 364.9-365.2 ft. Conversely, tricolpate/tricolporate grains have low relative frequencies (1 percent or less of the ECCSTO group) up to 586.1-586.4 ft, but they are between 4 and 8 percent in the samples from 528.95-529.25 to 409.4-409.9 ft, and rise to 37 percent of the ECCSTO group in the sample from 364.9-365.2 ft. According to Brenner's (1963) observations cited above, these data indicate that the boundary between Subzones IIA and IIB, in the lower part of the Patapsco Formation (fig. 3), is between 586.1-586.4 and 528.95-529.25 ft; this boundary determination agrees with presence-absence data presented below as to the position of the Subzone IIA-IIB boundary. However, the relative frequency data do not appear to be useful for picking the boundary between Zones I and II, that is, the boundary between the Patuxent/Arundel and Patapsco Formations.

In figure 5, the observed stratigraphic ranges of spore/pollen species are shown (species mentioned in this report are listed in table 2). These species include only those that have biostratigraphic significance according to Brenner (1963) and Doyle and Robbins (1977). The sample from 866.8-867.1 ft contains *Kuylisporites lunaris*, which is restricted to Zone I (category 1 of fig. 5); however, in general, specimens of species restricted to Zone I are rather rare (Brenner, 1963). The samples from 821.45-821.95 and 758.7-759.0 ft are thought to be from Zone I because they lack any taxa restricted to Zone II and higher strata. No samples were taken between 758.7-759.0 ft and 638.45-638.75 ft because these strata are mainly paleosols that would lack spores and pollen grains because these fossils are destroyed by oxidation. Therefore, the exact position of the Zone I-Zone II boundary could not be determined. However, from a lithologic viewpoint, the clayey strata between 742.2 and 647.3 ft appear to represent the Arundel Clay in the upper part of Zone I. The Arundel Clay probably represents a fine-grained lacustrine deposit (G. J. Brenner, written commun., 1996). The proposed contact of the Patuxent/Arundel and Patapsco Formations (= Zone I-Zone II boundary) correlates well with the contacts picked in the Spesutie Island, Turkey Point, and Grove Neck testholes (fig. 1), for which some geophysical log and pollen data are available (Edwards and Hansen, 1979).

The lowest, rare, occurrence of reticulate tricolpate pollen grains was considered by Doyle and Robbins (1977) to be in the upper part of Zone I, but G. J. Brenner (written commun., 1996) believes that the sampling locality from which these grains were obtained may actually have been in the Patapsco Formation (Zone II). In the present samples, the lowest occurrence of reticulate tricolpate pollen grains was observed in the sample from 638.45-638.75 ft, and this sample also contains *Reticulatisporites arcuatus*, a marker for Zone II and higher strata (category 2). *Cicatricosisporites dorogensis* is thought to be a marker for Zone I, but the specimen tentatively assigned to this species, in the sample from 586.1-586.4 ft, may have been misidentified.

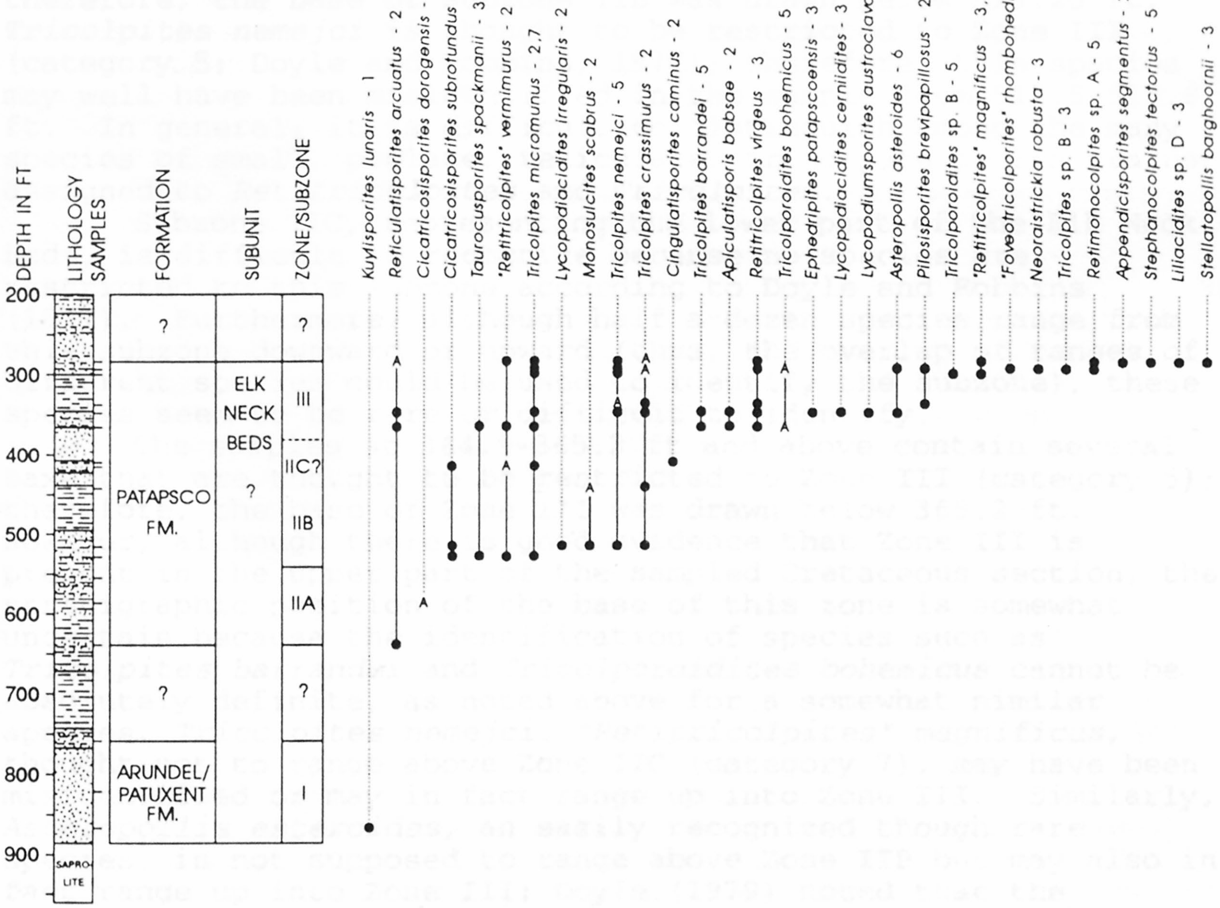

Figure 5. Distribution of biostratigraphically important Cretaceous spore/pollen taxa in samples from the Robins Point core. Occurrences represented by a filled circle are of specimens that seem to be identical to or are very similar to the species listed, or else the identification of the species was probable although not certain; A = aff., meaning that the specimen(s) observed were similar to but probably not the same species as the one listed.

Biostratigraphic categories (numbers following the species names) are:

1 - not known above Zone I
2 - not known below Zone II
3 - not known below Zone IIB
4 - not known below Zone IIC
5 - not known below Zone III
6 - only known from Zone IIB
7 - not known from higher than Zone IIC

The uppermost two sample levels include the following samples:

1. 283.3-283.5, 283.6-283.8, and 283.9-284.1 ft
2. 292.15-292.4, 292.8-293.0, 293.0-293.3, and 293.3-293.6 ft

Several species not known to range below Zone II (category 2 in fig. 5) are found in the samples from 528.95-529.25 and 515.5-515.8 ft, but these samples also contain two species not known to range below Subzone IIB (category 3); therefore, the base of Subzone IIB was drawn below 529.25 ft. *Tricolpites nemejci* is thought to be restricted to Zone III (category 5; Doyle and Robbins, 1977); therefore, this species may well have been misidentified in the sample from 515.5-515.8 ft. In general, it is difficult to distinguish among the many species of small, prolate, reticulate, tricolpate pollen grains assigned to *Retitricolpites* and *Tricolpites*.

Subzone IIC, representing the lower part of the Elk Neck Beds, is difficult to recognize because no species are restricted to this subzone according to Doyle and Robbins (1977). Furthermore, although half a dozen species range from this subzone downward or upward (thus, the overlap of ranges of different species could be used to identify the subzone), these species seem to be rare or difficult to identify.

The samples at 364.9-365.2 ft and above contain several taxa that are thought to be restricted to Zone III (category 5); therefore, the base of Zone III was drawn below 365.2 ft. However, although there is good evidence that Zone III is present in the upper part of the sampled Cretaceous section, the stratigraphic position of the base of this zone is somewhat uncertain because the identification of species such as *Tricolpites barrandei* and *Tricolporoidites bohemicus* cannot be absolutely definite, as noted above for a somewhat similar species, *Tricolpites nemejci*. *"Retitricolpites" magnificus*, thought not to range above Zone IIC (category 7), may have been misidentified or may in fact range up into Zone III. Similarly, *Asteropollis asteroides*, an easily recognized though rare species, is not supposed to range above Zone IIB but may also in fact range up into Zone III; Doyle (1979) noted that the documented range tops of rarely occurring species are not very reliable. The most easily recognized, definitive species of Zone III in the present material is *Stephanocolpites tectorius*, from 283.9-284.1 ft. Doyle and Robbins (1977) and Doyle (1979) stated that the presence of this species suggests a biostratigraphic position in the upper part of Zone III. Another definitive species of Zone III is *Retimonocolpites* sp. A of Doyle and Robbins (1977), observed in samples from 293.3-293.6 and 283.3-283.5 ft.

Edwards and Hansen (1979) and Doyle (1979) presented palynological data from core, bit, and outcrop samples from four localities along the upper Chesapeake Bay to the northeast of the Robins Point core (fig. 1, localities HAR-Dg3 = Spesutie Island, CE-Dc2 = Turkey Point, and CE-Ec15, 17 = Grove Neck). Zone III was identified at Turkey Point and Grove Neck, but in the Spesutie Island hole, Zone IIC was overlain by Plio-Pleistocene deposits. Based on the scanty palynological data from the four localities northeast of the Robins Point corehole, it could have been hypothesized that in the area of Harford, Cecil, and Kent Counties, Maryland, paleochannels of the Susquehanna River eroded more deeply into the top of the Cretaceous deposits on the west side of the upper Chesapeake Bay than on the east side, but now it is found that in southernmost Harford County, strata assigned to upper Zone III are still preserved in spite of the fact that at least one paleochannel passes directly under the area of the Robins Point corehole (fig. 1; Hughes, 1993, figs. 7, 11). Zone III is at least 250 ft thick in the Grove Neck hole and perhaps 150 ft thick at Turkey Point (Edwards and Hansen, 1979). If the Cretaceous-Quaternary boundary in the Robins Point core is at 177.2 ft, then Zone III is about 190-230 ft thick in this core.

In summary, palynological evidence does not support Owens' (1969) conclusion that, in southern Harford County, major amounts of the Potomac Group were removed by post-Cretaceous erosion. However, no Cretaceous samples have been examined palynologically from the southwestern corner of the Gunpowder Neck Peninsula. Therefore, no palynological data exist that could be used to evaluate Hughes' (1993) contention that, at the southern end of Gunpowder Neck, the top of the Cretaceous section is about 50 ft deeper to the east than to the west because of post-Cretaceous erosion.

Quaternary Strata

Nineteen Quaternary samples from the Robins Point core were examined for palynomorphs, from the interval between 171.75 and 9.7 ft depth (fig. 2; table 1). It was found that pollen data were important for dating the Susquehanna River paleochannel deposits which, as stated, form most of the Quaternary sequence under the Aberdeen Proving Ground. The topmost sample, from 9.7-10.0 ft, was barren of palynomorphs. The remaining 18 samples contained these fossils, and for each sample (with one exception), 200 spores and pollen grains were counted in order to obtain relative frequencies of the various taxa (table 3). In the sample from 25.2-25.3 ft, a thin light-gray silty clay layer in a fine- to medium-grained sand, only 100 specimens were present, and this assemblage is anomalous--large numbers of hickory grains but only a few of oak. Although the sample doubtless represents temperate forest vegetation, the counts shown in table 3 and the relative frequencies shown in figures 6 and 7 are probably not fully representative of the true spore/pollen spectrum that would have been obtained from a larger sample, or else sorting during transport and deposition has strongly influenced the composition of the assemblage.

It appears from the raw data in table 3 that the occurrences and frequencies of herbs and of spores (Pteridophytes = ferns and clubmosses; Bryophytes = mosses) do not have much stratigraphic or climatic significance. However, *Sphagnum*, sedge, cattail/bur-reed, and clubmoss may possibly be preferentially associated with cool intervals (as defined by occurrences and higher relative frequencies of fir and spruce), and ragweed type seems to be restricted to the interval at and above 90 ft depth.

Figure 6 shows relative frequencies of the most abundant taxa of trees and shrubs. In this diagram, the relative frequencies were calculated from the data of table 3, that is, on the basis of all spore and pollen taxa. Most of the taxa in this diagram seem to have at least some stratigraphic/climatic significance (to be discussed in the next paragraphs; "climatic" in the context of the Quaternary deposits of the Robins Point core refers primarily to temperature, not moisture). However, Taxodiaceae/Cupressaceae appears to have no obvious paleotemperature significance, although for some reason no specimens of this taxon were found in the upper three samples of figure 6 and table 3. In the coastal plain, the family Taxodiaceae is represented by bald cypress, and Cupressaceae is represented by white cedar, arbor vitae, and juniper. In the Quaternary of the Middle Atlantic States and North Carolina, higher relative frequencies of Taxodiaceae/Cupressaceae are generally interpreted to represent the presence of more swampy conditions that may result from increased precipitation, from minor rises in sea level, or from local to regional subsidence of the ground surface (Frey, 1951; Whitehead and Davis, 1969; Whitehead, 1981; Delcourt and Delcourt, 1986; York and others, 1989).

Figure 7 was drawn in order to emphasize climatic trends indicated by trees and shrubs, ranging from taxa generally having the coolest affinities on the left to those most or less restricted to the warmest intervals on the right. Alder, and to a lesser extent heath family, seem to be associated with occurrences of fir (table 3); therefore, these three taxa were combined in the first plant-group column of figure 7. "Other temperate hardwoods" include sweet-gum, black gum, sycamore, basswood, and elm. Some tree and shrub taxa do not have any obvious climatic affinity (table 3)--birch, chestnut, hazelnut, holly, wax myrtle?, hop hornbeam/ironwood, Rosaceae?, and Taxodiaceae/Cupressaceae--and these taxa were disregarded for purposes of calculating relative frequencies in figure 7. In other words, the pollen sum for calculating relative frequencies in figure 7 included only the taxa listed in that diagram; the pollen sum ranged from 94 to 190 specimens per sample but was mainly more than 150 specimens.

High relative frequencies of fir-alder-heath family and spruce indicate the coldest periods in the interval studied. Large percentages of pine generally follow the same trend, but pine consists of several species that each has a different climatic range (e.g., Whitehead, 1981); therefore, the pine data are difficult to interpret without differentiating among the species. Hemlock lives in temperate forests, but in the present data set it is mainly a taxon whose maximum relative frequencies indicate transitions between warm and cool climates. Like pine, there are many species of oak, each with a somewhat different climatic range, but as a genus, oak is most abundant in warmer

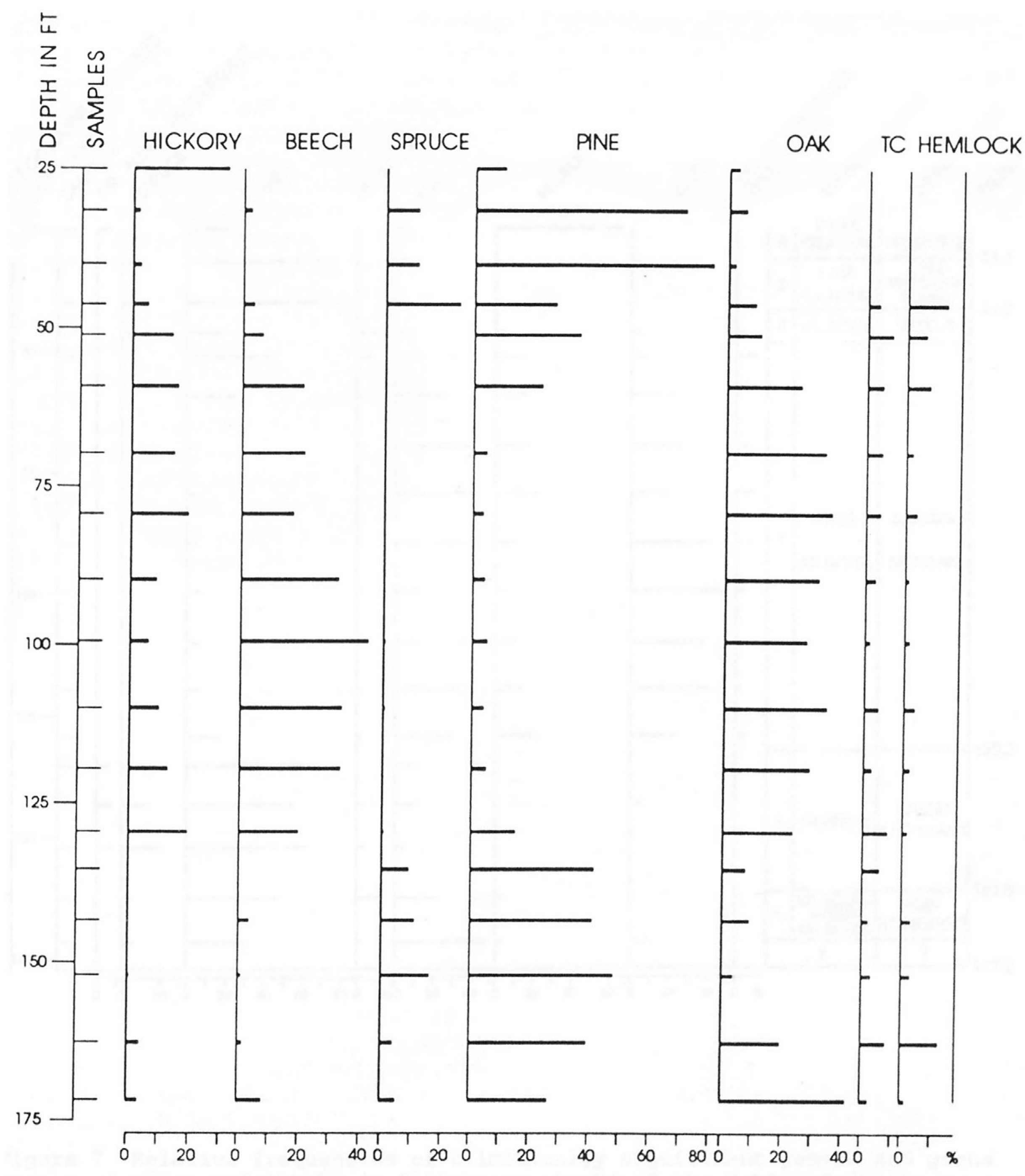

Figure 6. Relative frequencies of the most abundant pollen taxa of trees and shrubs in Quaternary strata of the Robins Point core, calculated from the count of all spore and pollen taxa. TC = Taxodiaceae-Cupressaceae, bald cypress and juniper families.

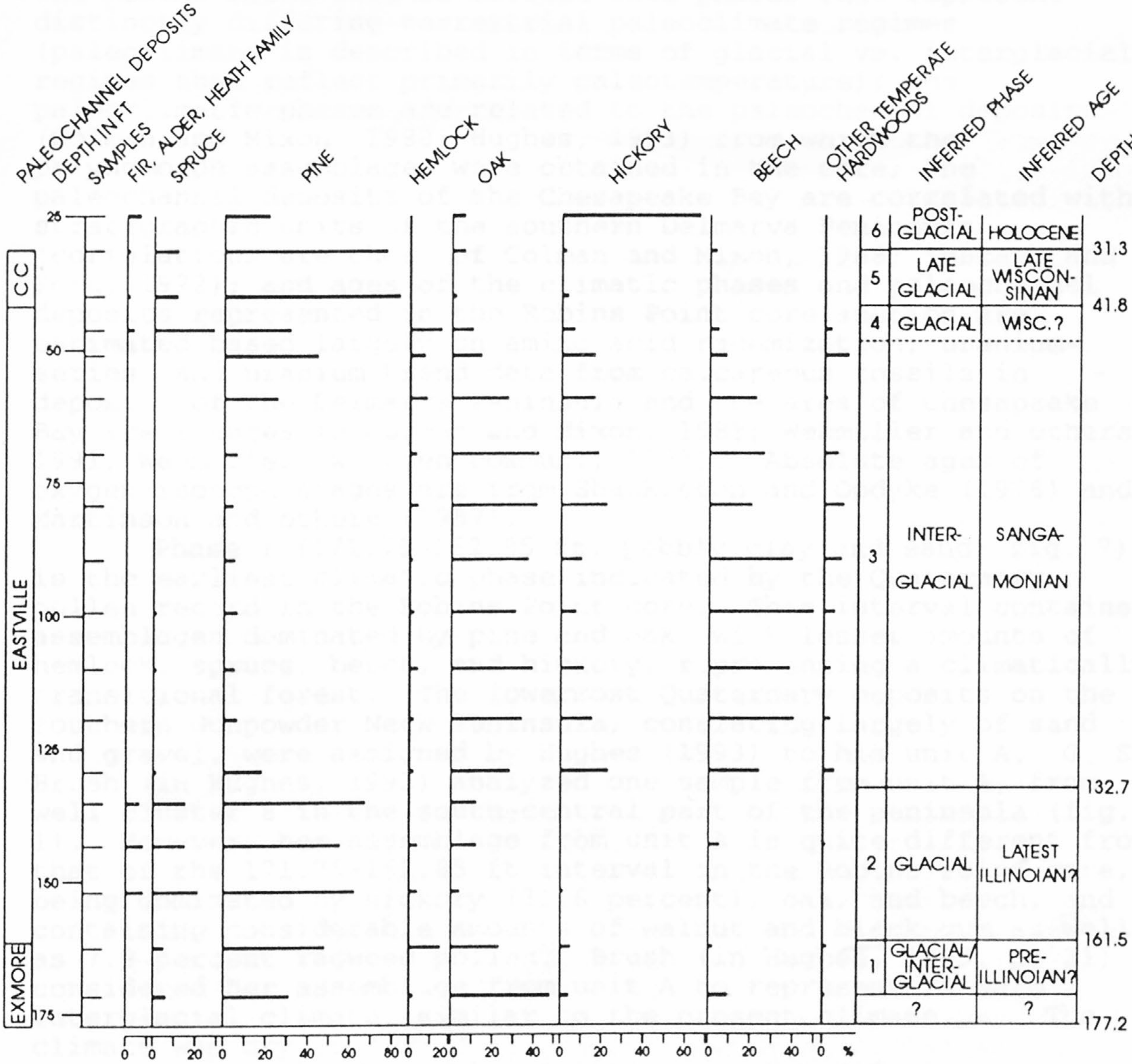

Figure 7. Relative frequencies of climatically significant genera and genus groups of trees and shrubs in Quaternary strata of the Robins Point core, calculated from the count of only the taxa included in this diagram; boundaries of paleochannel deposits; and inferred climatic phases and their ages. Taxa are listed in order of their climatic affinities, from coolest on the left to warmest on the right. In the Paleochannel Deposits column, CC = Cape Charles.

forests. Higher relative abundances of hickory, beech, and "other temperate hardwoods" seem to be the best indicators of warm intervals.

In the following paragraphs, the Quaternary sequence in the Robins Point core is divided into phases that represent distinctly differing terrestrial paleoclimate regimes (paleoclimate is described in terms of glacial vs. interglacial regimes that reflect primarily paleotemperature); the paleoclimatic phases are related to the paleochannel deposits (Colman and Mixon, 1988; Hughes, 1993) from which the palynomorph assemblages were obtained in the core; the paleochannel deposits of the Chesapeake Bay are correlated with stratigraphic units of the southern Delmarva Peninsula (correlations are those of Colman and Mixon, 1988; Toscano and York, 1992); and ages of the climatic phases and paleochannel deposits represented in the Robins Point core section are estimated based largely on amino acid racemization, uranium-series, and uranium-trend data from calcareous fossils in deposits of the Delmarva Peninsula and the area of Chesapeake Bay (references in Colman and Mixon, 1988; Wehmiller and others, 1991; Wehmiller, written commun., 1993). Absolute ages of oxygen-isotope stages are from Shackleton and Opdyke (1976) and Martinson and others (1987).

Phase 1 (171.75-162.85 ft, pebbly clay and sand; fig. 7) is the earliest climatic phase indicated by the Quaternary pollen record in the Robins Point core. This interval contains assemblages dominated by pine and oak, with lesser amounts of hemlock, spruce, beech, and hickory, representing a climatically transitional forest. The lowermost Quaternary deposits on the southern Gunpowder Neck Peninsula, consisting largely of sand and gravel, were assigned by Hughes (1993) to his unit A. G. S. Brush (in Hughes, 1993) analyzed one sample from unit A, from well cluster 8 in the south-central part of the peninsula (fig. 1). However, her assemblage from unit A is quite different from that of the 171.75-162.85 ft interval in the Robins Point core, being dominated by hickory (31.6 percent), oak, and beech, and containing considerable amounts of walnut and black gum as well as 7.9 percent ragweed pollen. Brush (in Hughes, 1993, p. 21) considered her assemblage from unit A to represent "a warm interglacial climate, similar to the present climate.... The climate was dry...."

Phase 1 in the Robins Point core existed during deposition of the Exmore paleochannel deposit, which has been correlated with the Accomack Member of the Omar Formation on the Delmarva Peninsula. The Accomack Member and the Exmore paleochannel deposit seem most likely to belong to Oxygen-Isotope Stage 7 (late but not latest Illinoian, approximate age 190-240 ka) or Stage 11 (pre-Illinoian?, approximate age 370-440 ka), but they may possibly be older than Stage 11 (Colman and Mixon, 1988). Two of the Pleistocene pollen assemblages described by Cronin and others (1981, localities 6 and 8A) from the Atlantic Coastal Plain contain mainly oak, pine and hickory, with small amounts (generally less than 2 percent) of spruce and hemlock, and these assemblages are somewhat similar to those of phase 1 in the Robins Point core. Localities 6 and 8A of Cronin and others (1981, table 1) are at Ponzer, North Carolina, and Canepatch, South Carolina, respectively, and both were considered to be "warm temperate with boreal influence (transitional: glacial-interglacial)." Localities 6 and 8A had uranium-series ages of about 189 ka (near the Oxygen-Isotope Stage 6/7 boundary within the Illinoian) and roughly 440-560 ka (Oxygen-Isotope Stages 12-15, pre-Illinoian), respectively, dates more or less comparable to those considered most likely for the Accomack Member of the Omar Formation on the Delmarva Peninsula.

In summary, the Exmore paleochannel deposit cored at Robins Point, which contains a pollen assemblage indicating a transitional phase between glacial and interglacial, may be late but not latest Illinoian, Stage 11 (pre-Illinoian?), or older pre-Illinoian.

Phase 2, from the interval 152.4-135.5 ft, clayey silt and sand, represents a glacial climate, and the pollen assemblages are dominated by pine, with significant amounts of spruce and fir-alder-heath family but sparse temperate hardwoods. Apparently there are no published pollen records of pre-Wisconsinan glacial phases from the Atlantic Coastal Plain (see especially Cronin and others, 1981; York and others, 1989), probably because glacials were times of lower sealevel and erosion rather than deposition.

Phases 2 (glacial), 3 (interglacial), and perhaps 4 (glacial) are present in the deposits filling the Eastville paleochannel, which have been termed the Stumptown Member of the Nassawadox Formation on the Delmarva Peninsula (Mixon, 1985). No pollen assemblages have been reported from the Stumptown Member in its type area, which is unfortunate because it would be interesting to know whether the lower part of the type Stumptown has a pollen flora representing near-glacial conditions as in phase 2. Colman and Mixon (1988) tentatively concluded that the Eastville paleochannel was filled during the earliest part of Oxygen-Isotope Stage 5 (earliest Sangamonian; ages within Stage 5 are discussed below); therefore, they tentatively inferred that the Eastville paleochannel was cut during the latter part of Oxygen-Isotope Stage 6 (latest Illinoian, about 130-140 ka). Toscano and York (1992) also concluded that no sediments representing Stage 6 were preserved along the coast of the Middle Atlantic States because of Eastville paleochannel cutting. However, because pollen-climatic phase 2 in the Robins Point core indicates glacial conditions at the beginning of deposition in the Eastville paleochannel, the paleochannel apparently began filling already at the end of Stage 6 (latest Illinoian) time as sea level began to rise.

Phase 3 is a warm-temperate interglacial phase (129.8-51.3 ft, clayey silt and silty clay) in which the pollen assemblages are dominated by oak, beech, and hickory, with lesser amounts of other temperate hardwoods and very little pine. This interval is bioturbated, and mollusk shells occur from 83.5 to 47.3 ft (upper half of phase 3), as expected considering the highstands of sea level during the Sangamonian interglacial (Oxygen-Isotope Stage 5). The maximum highstand occurred during deposition of Substage 5e (130-120 ka), immediately following the end of the Illinoian glacial stage, with progressively smaller sea level rises during deposition of Substages 5c (110-100 ka) and 5a (85-75 ka) (Toscano, 1991). Palynological analysis of continental slope sediments off New Jersey indicates that Substages 5e, 5c, and 5a represented very warm terrestrial paleoclimates (Groot and Ramsey, 1996), but details on these pollen assemblages from the continental slope have not been published. Amino acid racemization data do not indicate whether the youngest set of transgressive deposits present in Chesapeake Bay and the Delmarva Peninsula formed at various times throughout Stage 5 or whether they formed only during early Stage 5 (Substage 5e) (Wehmiller and others, 1994).

Unit B of Hughes (1993) on the Gunpowder Neck Peninsula is more or less equivalent to Eastville paleochannel deposits in the region. Amino acid racemization data from shells in unit B suggest a Sangamonian age (J. F. Wehmiller, written commun., 1993). G. S. Brush (in Hughes, 1993, p. 21) examined spores and pollen grains in three borehole samples from the southern part of Gunpowder Neck (localities 3, 6, and 8 of fig. 1) and interpreted them as representing "an interglacial period, probably mid-to-late interglacial." On the average, Brush's samples contained more ragweed, walnut, and black gum, and much less beech pollen, than the Robins Point samples.

Samples from the lower parts of the Kent Island and Wachapreague Formations on the Delmarva Peninsula have warm-temperate pollen assemblages consisting mainly of pine, oak, and hickory, with some chestnut, holly, cypress, wax myrtle, sweet-gum, black gum, and occasionally hemlock (Mixon, 1985). Toscano and York (1992) suggested that these samples are Sangamonian in age, which seems reasonable because the Sangamonian is the only interglacial stage in the latter half of the Pleistocene. Thus, it appears that the Stumptown Member of the Nassawadox Formation and the lower parts of the Kent Island and Wachapreague Formations on the Delmarva Peninsula are all Sangamonian, although the Stumptown Member may well be older than the other two units within the Sangamonian.

Several Sangamonian pollen assemblages similar to those of phase 3 in the Robins Point core were reported from Virginia, North Carolina, and South Carolina by Owens and Denny (1979), Cronin and others (1981), and York and others (1989); these were interpreted to represent warm temperate or even subtropical climates. However, all of the Sangamonian pollen assemblages reported from Virginia, North Carolina, and South Carolina have much less beech pollen than the Robins Point assemblages. Thus, abundant beech pollen appears to be a characteristic of relatively more northern localities, although a sample from the Omar Formation (lower Sangamonian) from Worcester County, southeastern Maryland, yielded a warm-temperate pollen assemblage dominated by pine, oak, and hickory in which beech pollen apparently was not abundant (Owens and Denny, 1978).

Phase 4 in the Robins Point core (one sample from 46.4-46.6 ft, silt and clay) is at the top of the Eastville paleochannel fill or occurs in sediments that spread over the paleochannel deposits. Phase 4 is represented by a cold-temperate to glacial pollen assemblage immediately overlying the shelly strata of interglacial phase 3. The assemblage is dominated by pine and spruce and is similar to some cold-climatic assemblages from the Kent Island Formation (from its upper part?) and from the upper part of the Wachapreague Formation on the Delmarva Peninsula (Owens and Denny, 1978, 1979; Mixon, 1985). The Kent Island and Wachapreague spruce-rich pollen assemblages were thought by Owens and Denny (1978, 1979) to be middle Wisconsinan in age based on a radiocarbon date of 37 ka for a wood sample associated with a cool- or cold-climatic pollen assemblage from the type locality of the Kent Island in southeastern Maryland (Owens and Denny, 1978). However, when this sample was later rerun, using better techniques, it was found to be too old for radiocarbon dating (R. B. Mixon, oral commun., 1997). Therefore, Mixon (1985) considered cool- and cold-climatic pollen assemblages from the Kent Island and Wachapreague Formations possibly to be earliest Wisconsinan, and Toscano and York (1992) suggested a Sangamonian age, although it seems unlikely that phase 4 could be Sangamonian unless the assemblage represented a transition to the Wisconsinan glacial stage, in other words very latest Sangamonian.

Phase 5 (40.2-31.7 ft, sand) consists of Late Wisconsinan (late glacial) pollen assemblages dominated by pine and spruce. Phase 5 occurs in the lowermost deposits of the Cape Charles paleochannel, which was cut during Oxygen-Isotope Stage 2 (Middle to Late Wisconsinan), and the lowermost deposits in the paleochannel have been dated at 15 ka (Colman and Mixon, 1988, and references therein). Thus, sediments containing phase 5 pollen assemblages were deposited as sea level was beginning to rise during the latest Wisconsinan. The Late Wisconsinan full glacial (23-16.5 ka) and late glacial (16.5-12.5 ka) intervals on the coastal plain of New Jersey, Maryland, and northeastern North Carolina had boreal woodland dominated by pine and spruce, somewhat similar to the samples from phase 5 in the Robins Point core; birch was also prominent in late glacial coastal plain deposits of New Jersey and Maryland, but not in deposits of this age to the south, at the mouth of Chesapeake Bay in Virginia (summarized by Delcourt and Delcourt, 1986) nor in samples from the Robins Point core. However, herb pollen was generally fairly abundant in the Late Wisconsinan full glacial and late glacial coastal plain sediments from New Jersey, Maryland, and North Carolina, indicating the presence of open forest or patches of closed forest interspersed with meadows (Delcourt and Delcourt, 1986). In contrast, the low relative frequencies of herb pollen in the Robins Point Late Wisconsinan assemblages indicate that this area was covered by a closed forest, perhaps furnishing additional evidence that phase 5 represents climates at the very end of the Wisconsinan when closed forest was already being reestablished in the region.

Phase 6 represents a Holocene temperate climate (one sample from 25.2-25.3 ft). As noted previously, this sample contained an anomalous spore/pollen assemblage (large numbers of hickory grains but only a few of oak) that is not fully representative of a typical Holocene spore/pollen spectrum from the region.

SUMMARY AND CONCLUSIONS

The Robins Point corehole was drilled on the Aberdeen Proving Ground to study the stratigraphy and hydrology and thus to better understand ground-water movement, which potentially carries contaminants, under the Proving Ground.

1. Twenty-two Cretaceous and 19 Quaternary samples from the Robins Point core were examined for the presence and, in many cases, relative frequencies, of spore/pollen taxa. One Holocene sample was barren of palynomorphs, and one Holocene sample had a sparse, anomalous assemblage; all remaining samples contained abundant spores and pollen grains. Cretaceous samples were from the interval between 867.1 and 283.3 ft depth; pollen-bearing Quaternary samples were from the interval between 171.75 and 25.2 ft. Strata between the highest Cretaceous sample and the lowest Quaternary sample were deeply weathered, barren of palynomorphs. However, based on lithology, the Cretaceous-Quaternary boundary in the core is most likely at 177.2 ft.
2. Within the Cretaceous Potomac Group, the Zone I-Zone II boundary, equated with the boundary between the Patuxent/Arundel and Patapsco Formations, occurs within the paleosol interval of 758.7 to 638.75 ft, which was barren of palynomorphs. From a lithologic viewpoint, the boundary between the Arundel Clay and the Patapsco Formation is at 647.3 ft. The boundary between Subzones IIA and IIB, in the lower part of the Patapsco Formation, is between 554.85 and 529.25 ft. Subzone IIC, which forms the base of the Elk Neck Beds in the upper part of the Patapsco Formation, could not be identified, but Zone III, also in the Elk Neck Beds and at the top of the Patapsco Formation, has its base between 409.4 and 365.2 ft. Probably about 190-230 ft of Zone III is present in the core; therefore, palynological data do not support Owens' (1969) contention that major amounts of the Potomac Group were removed in this area by post-Cretaceous erosion.

3. Relative frequencies of climatically significant Quaternary pollen taxa indicate the presence of strata representing six climatic phases in the Robins Point core. Most of these phases occur in sediments that fill a stack of three ancient channels of the Susquehanna River, and these paleochannel deposits are very sandy and therefore important aquifers under the Aberdeen Proving Ground and also on the Delmarva Peninsula. Knowledge of the climatic phases (based on pollen data) is shown to be critical, in addition to previously determined geochemical ages, for dating the economically important paleochannel deposits. The following Quaternary phases in the core are reconstructed, in ascending order:

Phase 1 (171.75-162.85 ft), climatically transitional between glacial and interglacial, in the Exmore paleochannel deposit, correlated with the Accomack Member of the Omar Formation on the Delmarva Peninsula, may be pre-Illinoian or late but not latest Illinoian.

Phase 2 (152.4-135.5 ft), representing a glacial climate, in the lowermost part of the Eastville paleochannel deposit, correlated with the lower part of the Stumptown Member of the Nassawadox Formation on the Delmarva Peninsula, is apparently latest Illinoian. This appears to be the first reported record of a Quaternary pre-Wisconsinan glacial phase from the Atlantic Coastal Plain.

Phase 3 (129.8-51.3 ft), representing a warm-temperate interglacial climate, found through most of the Eastville paleochannel deposit in the core, correlated in part with the Stumptown Member of the Nassawadox Formation and also apparently in part with the lower portions of the Kent Island and Wachapreague Formations on the Delmarva Peninsula, is Sangamonian.

Phase 4 (one sample from 46.4-46.6 ft), representing a cold-temperate to glacial climate, at the top of the Eastville paleochannel fill or in sediments that spread over the paleochannel deposits, correlated with (the upper part of?) the Kent Island Formation and with the upper part of the Wachapreague Formation on the Delmarva Peninsula, apparently is very latest Sangamonian or earliest Wisconsinan.

Phase 5 (40.2-31.7 ft), representing a late-glacial climate, in the Cape Charles paleochannel fill, is latest Wisconsinan.

Phase 6 represents a Holocene temperate climate (one sample from 25.2-25.3 ft).

The deposition of sediments in the upper Chesapeake Bay during cold phases is noteworthy because these should have been times of low sea level and erosion rather than deposition.

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Table 1. List of samples that were processed for spores and pollen grains. * indicates barren sample.

Quaternary samples		Cretaceous samples	
Palynology number	Depth in ft	Palynology number	Depth in ft
R5116A*	9.7-10.0	R5215B	283.3-283.5
R5116B	25.2-25.3	R5215A	283.6-283.8
R5116C	31.7-31.9	R5116T	283.9-284.1
R5116D	40.0-40.2	R5215C	292.15-292.4
R5116E	46.4-46.6	R5215D	292.8-293.0
R5116F	51.3-51.5	R5215G	293.0-293.3
R5116G	59.4-59.6	R5215E	293.3-293.6
R5116H	69.9-70.1	R5215F	294.0-294.25
R5116I	79.55-79.75	R5215H	336.7-337.0
R5116J	89.8-90.0	R5215I	347.05-347.35
R5116K	99.6-99.8	R5215J	364.9-365.2
R5116L	110.2-110.4	R5215K	409.4-409.9
R5116M	119.7-119.9	R5215L	414.5-414.8
R5116N	129.6-129.8	R5215M	441.7-442.0
R5116O	135.5-135.7	R5215N	515.5-515.8
R5116P	143.5-143.7	R5215O	528.95-529.25
R5116Q	152.25-152.4	R5215P	554.85-555.15
R5116R	162.85-163.00	R5215Q	586.1-586.4
R5116S	171.60-171.75	R5215R	638.45-638.75
		R5215S	758.7-759.0
		R5215T	821.45-821.95
		R5215U	866.8-867.1

Table 2. List of Cretaceous spore/pollen taxa mentioned in this report. *"Foveotricolporites"* and *"Retitricolpites"* are genus names placed by Doyle and Robbins (1977) in quotation marks to indicate that the species in question do not really belong to these genera.

Apiculatisporis babsae Brenner
Appendicisporites segmentus Brenner
Asteropollis asteroides Hedlund & Norris
Cicatricosisporites dorogensis Potonié & Gelletich
Cicatricosisporites subrotundus Brenner
Cingulatisporites caminus Balme
Classopollis torosus (Reissinger) Balme
Cyathidites minor Couper
Ephedripites patapscoensis Brenner
Exesipollenites tumulus Balme
"Foveotricolporites" rhombohedralis Pierce
Kuylisporites lunaris Cookson & Dettmann
Liliacidites sp. D of Doyle and Robbins (1977)
Lycopodiacidites austroclavatidites (Cookson) Potonié
Lycopodiacidites cerniidites (Ross) Brenner
Lycopodiacidites irregularis Brenner
Monosulcites scabrus Brenner
Neoraistrickia robusta Brenner
Pilosisporites brevipapillosus Brenner *auct. non* Couper
Reticulatisporites arcuatus Brenner
Retimonocolpites sp. A of Doyle and Robbins (1977)
"Retitricolpites" magnificus Habib
"Retitricolpites" vermimurus Brenner
Retitricolpites virgeus (Groot, Penny, & Groot) Brenner
Stellatopollis barghoornii Doyle
Stephanocolpites tectorius Hedlund
Taurocusporites spackmanii Brenner
Tricolpites barrandei Pacltová
Tricolpites crassimurus (Groot & Penny) Singh
Tricolpites micromunus (Groot & Penny) Burger
Tricolpites nemejci Pacltová
Tricolpites sp. B of Doyle and Robbins (1977)
Tricolporoidites bohemicus Pacltová
Tricolporoidites sp. B of Doyle and Robbins (1977)

Table 3. Counts of 200 spores and pollen grains in Quaternary samples from the Robins Point core. In the sample from 25.2-25.3 ft depth, only 100 specimens could be counted; this count was doubled so that the numbers would be equivalent to those in the 200-counts of the remaining samples. X indicates that the taxon was observed in the sample but not included in the 200-count. (Continued on next 4 pages)

Table 3. (continued)

	25.2-25.3'	31.7-31.9'	40.0-40.2'	46.4-46.6'	51.3-51.5'	59.4-59.6'	69.9-70.1'	79.55-79.75'
PTERIDOPHYTES AND BRYOPHYTES								
1. *Lycopodium* (clubmoss)			1	1	X			
2. Psilate monolete spores	16	2		5	6	1	10	7
3. Psilate trilete spores	6	3	1	X	1	1	7	2
4. *Sphagnum* (moss)		1	3		2			
5. Miscellaneous spores	12	1	1	3	3		X	3
TREES AND SHRUBS								
6. *Abies* (fir)		2		3				
7. *Alnus* (alder)	2		1	1				
8. *Betula* (birch)		1			1	1	1	
9. *Carya* (hickory)	62	4	5	10	26	30	28	37
10. *Castanea* (chestnut)								
11. *Corylus* (hazelnut)	4			1			1	
12. Ericaceae (heath family)	4	X	1	2				
13. *Fagus* (beech)		5		7	13	40	41	34
14. *Ilex* (holly)	2							
15. *Liquidambar* (sweet-gum)				2	10	2	5	5
16. *Myrica* (wax myrtle)	12			1				
17. *Myrica*?	12							
18. *Nyssa* (black gum)					4			
19. *Ostrya-Carpinus* (hop hornbeam-ironwood)								
20. *Picea* (spruce)		21	21	49				
21. *Pinus* (pine)	20	140	158	55	71	46	9	7
22. *Platanus* (sycamore)					1		1	
23. *Quercus* (oak)	6	11	4	18	22	49	66	70
24. Rosaceae? (rose family)					1			
25. Taxodiaceae-Cupressaceae (bald cypress and juniper families)				7	16	10	10	9
26. *Tilia* (basswood)							1	2
27. *Tsuga* (hemlock)				26	12	15	4	7
28. *Ulmus* (elm)	X			3	2	X	2	8
HERBS								
29. *Ambrosia* (ragweed) type	2	1			1		1	X
30. *Artemisia* (sage) type		1						

Table 3. (continued)

	25.2-25.3'	31.7-31.9'	40.0-40.2'	46.4-46.6'	51.3-51.5'	59.4-59.6'	69.9-70.1'	79.55-79.75'
31. Chenopodiaceae-Amaranthaceae (goosefoot and amaranth families)	12	1			1	1	2	
32. Compositae (sunflower family), high-*spined*		3			1		1	
33. Compositae, low-spined							X	1
34. Cyperaceae (sedge family)		1	3	3			2	1
35. Gramineae (grass family)	6				1	1	4	2
36. *Nuphar* (pond-lily)			1					
37. *Polygonum* (knotweed)	8							
38. *Stellaria* (chickweed)	4		X					
39. *Typha-Sparganium* (cattail, bur-reed)								
40. Umbelliferae (parsley family)				1			1	2
41. Miscellaneous angiosperms	10	2		2	5	3	3	3

Table 3. (continued)

	89.8'-90.0'	99.6-99.8'	110.2-110.4'	119.7-119.9'	129.6-129.8'	135.5-135.7'	143.5-143.7'	152.25-152.4'	162.85-163.00'	171.60-171.75'
1.				2		4	7	2	2	1
2.	7	6	6	12	10	18	8	7	4	8
3.	3	2	1	3	2	4	3	3	4	1
4.								1		
5.	3	3	1	4	1	8	7	6		2
6.						3	4	8		
7.						5	8	4		
8.	1	2	3			9	3	2	2	1
9.	17	12	19	25	38	X		1	8	7
10.								1		
11.		2	2	3	2	3	1	2	4	1
12.										
13.	64	84	67	66	39		7	2	3	16
14.										1
15.	1	1	3	3	3		2		4	
16.										1
17.										
18.		3								1
19.							5			4
20.		1	1		1	18	22	32	8	10
21.	8	10	8	10	30	83	82	96	79	53
22.	2									
23.	62	54	68	57	46	15	18	7	39	83
24.										
25.	6	3	9	5	16	11	4	6	16	5
26.	X	1	1		2	X				
27.	2	3	7	4	3		6	6	25	3
28.	10	3	2	2	3	X				
29.	2									
30.										

Table 3. (continued)

	89.8' 90.0'	99.6- 99.8'	110.2- 110.4'	119.7- 119.9'	129.6- 129.8'	135.5- 135.7'	143.5- 143.7'	152.25- 152.4'	162.85- 163.00'	171.60- 171.75'
31.		3			1			1	X	
32.				1		2				
33.		5	2		1	1		1		
34.	2					9	6	2		
35.	2			1		1	4	2	X	
36.		1								
37.										
38.										
39.						4				
40.								1		
41.	8	1		2	2	2	3	7	2	2