State of Delaware
DELAWARE GEOLOGICAL SURVEY
Robert R. Jordan, State Geologist

REPORT OF INVESTIGATIONS NO. 47

AGES OF THE BETHANY, BEAVERDAM, AND OMAR FORMATIONS OF SOUTHERN DELAWARE

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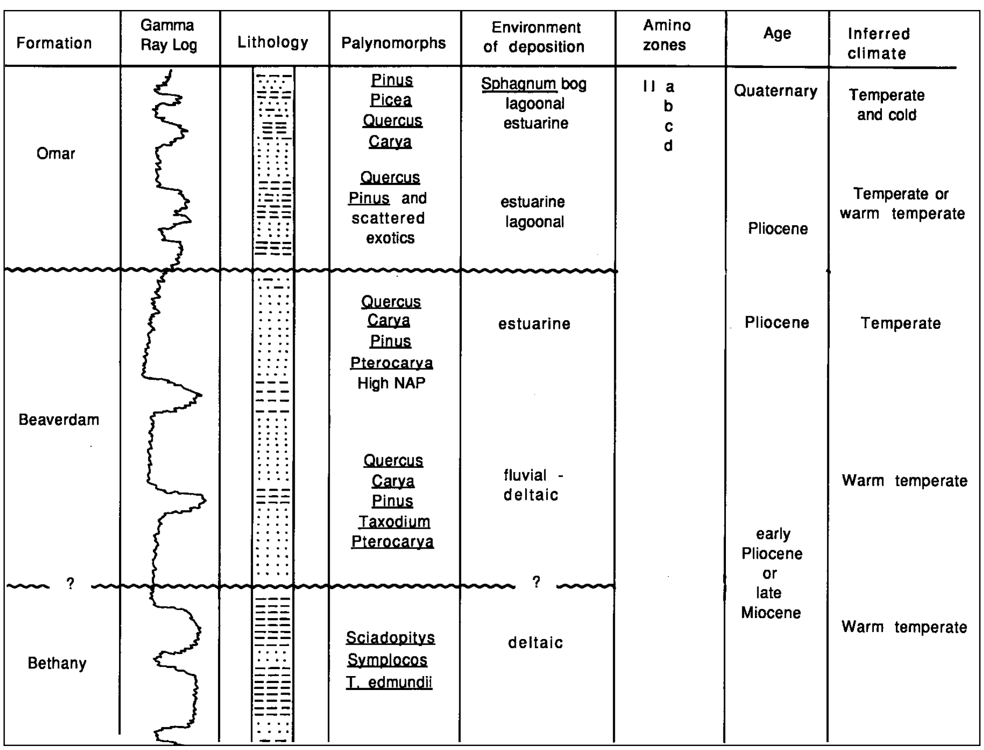

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THE AGES OF THE BETHANY, BEAVERDAM, AND OMAR FORMATIONS OF SOUTHERN DELAWARE

Johan J. Groot, Kelvin W. Ramsey, and John F. Wehmiller

ABSTRACT

The microflora of the Bethany formation and the lower part of the Beaverdam Formation is characterized by a *Quercus-Carya* assemblage, very few non-arboreal pollen, and *Pterocarya* and *Sciadopitys* as exotic constituents. This assemblage has much in common with that of the Brandywine Formation of Maryland and the Eastover Formation of Virginia which are of late Miocene or early Pliocene age. The environment of deposition of the Bethany was probably deltaic, and that of the lower Beaverdam fluviatile.

The upper part of the Beaverdam has a very high percentage of non-arboreal pollen, and the only exotic element is *Pterocarya.* This assemblage is similar to that of the Pliocene Bacons Castle Formation of Virginia. The non-arboreal pollen assemblage indicates a lagoonal or estuarine environment of deposition.

The lower part of the Omar Formation, which unconformably overlies the Beaverdam, is distinguished by scattered and rare occurrences of *Pterocarya, Tricolporopollenites edmundii, Cupuliferoidaepollenites fallax,* and other exotics and is interpreted to be of Pliocene age. The environment of deposition was lagoonal or estuarine.

The upper part of the Omar is characterized by assemblages indicating both cold and temperate climates and environments of deposition ranging from *Sphagnum* bog to lagoon or estuary. No exotic pollen have been found in that part of the formation. It is of Quaternary age and its deposition spanned both interglacial and glacial intervals. Amino acid racemization analyses indicate approximate ages of 100,000, 200,000, and 500,000 years before present (BP) for geographically separated outcrops of the upper part of the Omar.

INTRODUCTION

The Beaverdam and Omar formations of the Columbia Group and the Bethany formation of the Chesapeake Group occur in southern Delaware (Fig. 1). Jordan (1962, 1974) reviewed the reasons for considering a Quaternary age for the Beaverdam and Omar. Owens and Denny (1979) considered the Beaverdam to be of Pliocene age on the basis of palynological evidence.

Andres (1986) informally named the Bethany formation to include the Ocean City and Pocomoke aquifers and their confining beds. He considered the age of the Bethany to be late Miocene. New evidence questions this age assignment in Delaware.

The uncertainties regarding the ages of the various surficial sediments and those immediately underlying them prompted the Delaware Geological Survey to undertake an investigation of their palyno-, litho-, and aminostratigraphy, a matter of practical significance as these deposits are prolific sources of ground water and of sands suitable for beach nourishment.The main purpose of the investigation was to determine the ages of these sedimentary units - the Omar, Beaverdam, and Bethany formations. An attempt was also made to interpret their environments of deposition, particularly those of the Omar Formation.

This report does not deal with the ages of other surficial deposits that may be present in southern Delaware, nor is it concerned with the interesting question whether the Columbia Formation of northern and central Delaware is of Quaternary or Tertiary age (Owens and Denny, 1979). Work regarding these matters is now in progress and will be reported when completed.

The sections on lithostratigraphy and aminostratigraphy were written, respectively, by Kelvin W. Ramsey and John F. Wehmiller. The remainder of the report was the responsibility of the senior author.

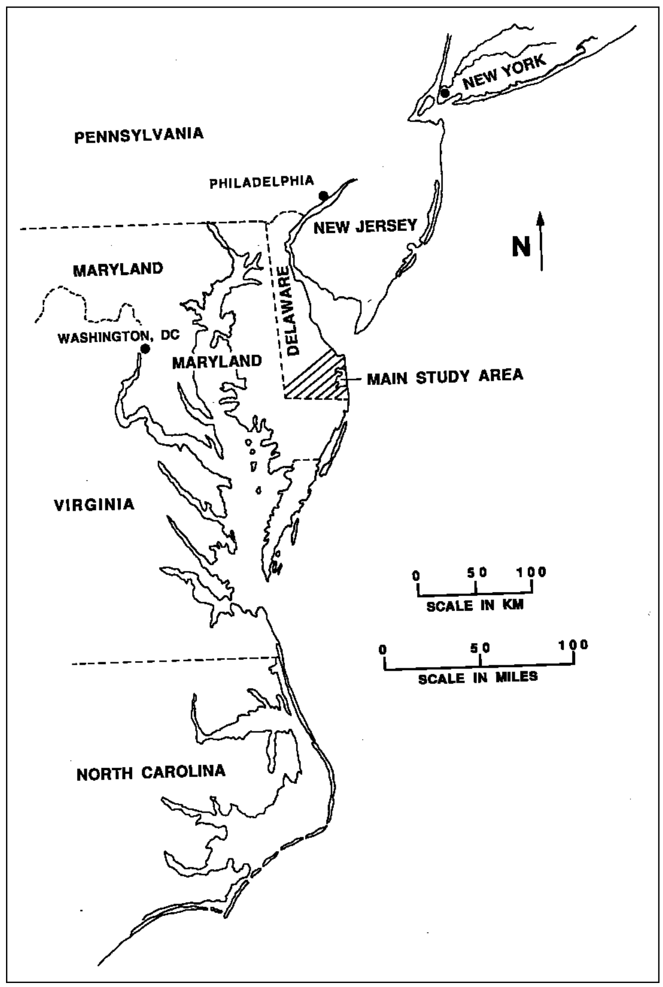

Figure 1. Location of the study area.

Acknowledgments

Thanks are due to Richard N. Benson and Nenad Spoljaric of the Delaware Geological Survey, Alfred Traverse of the Pennsylvania State University, and Harry J. Hansen of the Maryland Geological Survey for critically reviewing the manuscript. Traverse was especially helpful in checking the identification of some pollen grains of stratigraphic significance. The encouragement received from Robert R. Jordan, State Geologist and Director, Delaware Geological Survey, is gratefully acknowledged.

This research was supported in part by the Minerals Management Service, U.S. Department of the Interior, under MMS Agreement No. 14-12-0001-30432-DE.

METHODS OF INVESTIGATION

Lithostratigraphy

Lithostratigraphic units are bodies of sedimentary strata defined and delimited on the basis of lithic characteristics and stratigraphic position (NACSN, 1983). The lithostratigraphic units recognized in this study are defined by similarities in geophysical log characteristics and lithic character based on sample examination and drillers' and geologists' descriptive logs. Natural gamma radiation logs were the main source of well log data used. Gamma-ray logs are not affected by changes in aquifer water quality as are electric logs, and their characteristics can be directly related to lithologic properties. Hansen (1981) and Andres (1986) successfully used gamma-ray logs for lithostratigraphic correlation in the subsurface of the Delmarva Peninsula.

On a regional basis, gamma-ray log signatures characteristic for each of the units are recognizable and traceable. However, any individual log may not display all the signatures for a particular formation because facies changes occur within the units both along strike and downdip.

Palynology

Palynological analyses were done using outcrop, core, and auger samples, the last consisting only of stiff clays sticking to the drill bit or the lower part of the deepest auger. The type of sample used in these analyses is indicated by the sample number: 20,000 series, cores; 40,000 series, outcrop samples; 50,000 series, samples obtained outside Delaware; 80,000 series, auger or drill bit samples.

Palynomorphs were liberated from sediment samples using standard techniques, including removal of calcareous matter with HCl, HF treatment, and flotation in $ZnCl_2$. Many core samples were processed in the laboratory of the Delaware Geological Survey in the 1960s, and nearly all of the resulting slides are still in excellent condition. Samples collected in 1988 were processed by Travspore, Inc., of Huntingdon, Pennsylvania.

Identification of palynomorphs was aided by utilizing a reference collection of those pollen and spores which may be encountered in Quaternary and late Tertiary sediments, including pollen of *Sciadopitys*, various species of Taxodiaceae, Cupressaceae and Taxaceae, *Gordonia, Manilkara, Melia,* three species of *Engelhardia, Platycarya, Pterocarya, Planera,* and *Celtis.*

Aminostratigraphy

Amino acid D/L values were measured by both gas chromatographic and liquid chromatographic methods in mollusc samples from 34 Delmarva-Chesapeake sites. These samples have been analyzed by several investigators since 1975 as part of continuing research at the University of Delaware Department of Geology, and results were summarized by Wehmiller et al. (1988). Independent age information (in the form of radiometric dates) exists for a few sites in the region of study. In some cases biostratigraphic information can be used for relative age assignment (Cronin et al., 1984).

LITHOSTRATIGRAPHY

General Statement

Although this study is primarily concerned with the ages of the Bethany, Beaverdam, and Omar formations, it is necessary to briefly discuss some older formations of the Chesapeake Group, particularly the St. Marys Formation because it is the most easily recognizable subsurface unit on a regional scale. It is a persistent base marker for overlying units.

The sequence of strata overlying the St. Marys Formation in the central Delmarva Peninsula, in the most general terms, can be described as primarily sand with some clay. Within the sequence are some characteristically fine-grained strata, but even these have sandy intervals. Differentiating sandy intervals is not always possible, although some textural and compositional differences occur. The stratigraphic nomenclature for this sequence evolved from a series of hydrogeologic studies defining aquifers and confining strata (Rasmussen and Slaughter, 1955; Weigle and Achmad, 1982) and from studies of near-surface borings and surficial exposures (Jordan, 1962, 1964, 1974; Owens and Denny, 1978, 1979). The utility of the nomenclature has been restricted to areas where aquifers and confining beds are well developed or where there is enough exposure to recognize surficial units. The nomenclatural system is difficult to apply in areas where clayey strata are missing, leaving a thick sequence of sand from the land surface to depths of greater than 150 feet. In Delaware, this sequence has been called the Columbia aquifer or Columbia Group. Similar sequences have been recognized in Maryland and have been interpreted as fill of deeply incised paleochannels (Hansen, 1966).

Recently, Hansen (1981) and Andres (1986) have made progress in rectifying the nomenclatural difficulties. Both authors recognized the problems with the nomenclature, developed a lithostratigraphic system for strata above the St. Marys, and retained the existing terminology. The present study uses Andres's (1986) nomenclature (Fig. 2) and further defines and describes his lithostratigraphic units.

St. Marys and Manokin Formations

The St. Marys Formation consists of fossiliferous, glauconitic, lignitic, gray to bluish-gray clay to fine sandy clay (Andres, 1986) that conformably to unconformably overlies the Choptank Formation (Hansen, 1981; Andres, 1986). The clayey nature of the unit produces a distinctive gamma-ray

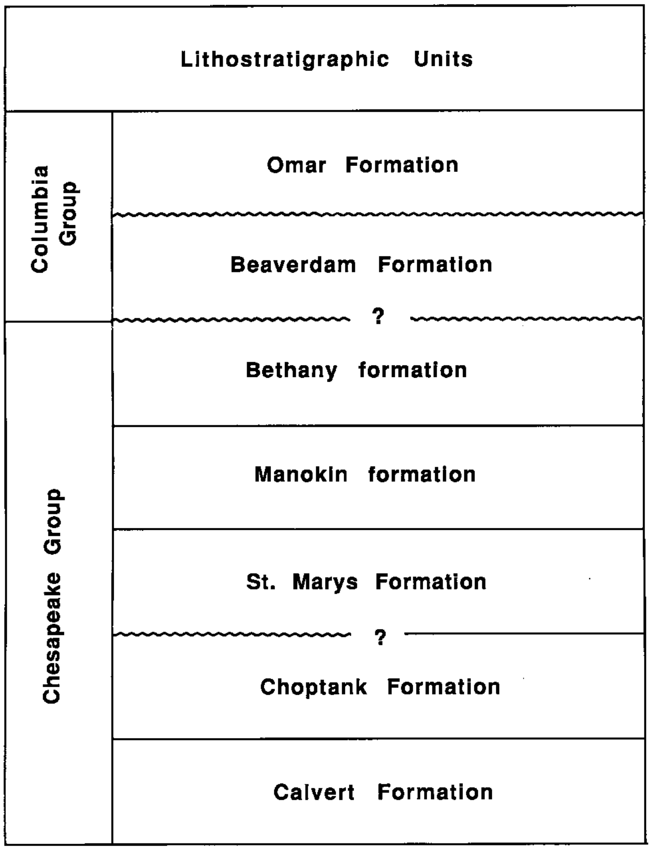

Figure 2. Lithostratigraphy of the Chesapeake and Columbia groups of southeastern Sussex County, Delaware (modified from Andres, 1986).

log signature recognizable throughout the central Delmarva Peninsula (Fig. 3). The contact of the St. Marys with the underlying Choptank Formation is marked by a sharp clay on sand "kick." Hansen (1981) inferred a thin phosphatic horizon above the contact in Maryland because of its association with a high gamma-ray kick; this phosphatic horizon has not been recognized in Delaware (Andres, 1986). Evidence for the nature of the contact is difficult to assess, but the presence of the phosphatic zone in Maryland and the regional extent and mappability of the surface (Andres, 1986, p. 16) seem to indicate an unconformity (see also Kidwell, 1989).

The St. Marys is relatively uniform lithologically. Gamma-ray signatures are box-shaped, indicating a clayey unit with no significant sand bodies. No detailed studies of the composition and texture of the unit in Delaware have been conducted; lithologic descriptions are of a few cores and well cuttings. Updip, the St. Marys contains a few sandy intervals. Lithologic and paleontologic evidence indicate deposition on a muddy, shallow marine shelf (R. N. Benson, personal communication) that throughout most of its history received little sand supply.

Overlying the St. Marys is a characteristically sandy unit, the Manokin formation (Andres, 1986). The Manokin in Delaware is a gray to olive gray, fine to coarse sand and silty and clayey sand. Beds of clay/silt are common. Woody material and lignite are also present in places. The contact of the Manokin with the St. Marys ranges from abrupt to gradational. Andres (1986) arbitrarily defined the base of the Manokin formation at the 50 percent clay/silt-50 percent sand boundary. This work follows that boundary definition with one revision. The boundary is placed at the 50 percent clay/50 percent sand where first encountered above the typical St. Marys (at the inflection point on the gamma-ray trace). Note placement of the boundary in Oh25-02 and Ri15-01 in Figure 3. Silty or clayey beds above this contact are included in the Manokin formation.

Gamma-ray log signatures indicate that the Manokin consists of a lower silty sand, herein designated the Manokin A, locally gradational with the clays of the underlying St. Marys, and an upper fine to coarse sand with scattered clay beds, the Manokin B (Oh25-02 and Ri15-01, Fig. 3). The lower silty sand is not present everywhere; where it is absent, the upper sands rest directly on the St. Marys, as indicated by a sharp break in the gamma-ray log signature (Pg53-14, Fig. 3). The Manokin A has a characteristic gamma-ray signature that shows coarsening upward from the clays of the St. Marys to the sands of the Manokin B. The Manokin B has a characteristic box-shaped gamma-ray signature with scattered clay-bed spikes in the middle of the section. The boundary between the Manokin A and Manokin B is at the base of the first major sand bed above the St. Marys, in most cases where sand percentage is 75 percent or greater. The sand bed is commonly found just above a distinctive clay "kick" at the top of the Manokin A sequence (Oh25-02, Fig. 3).

A decrease or absence of shelly material and an increase in wood and lignitic material indicate that the Manokin A

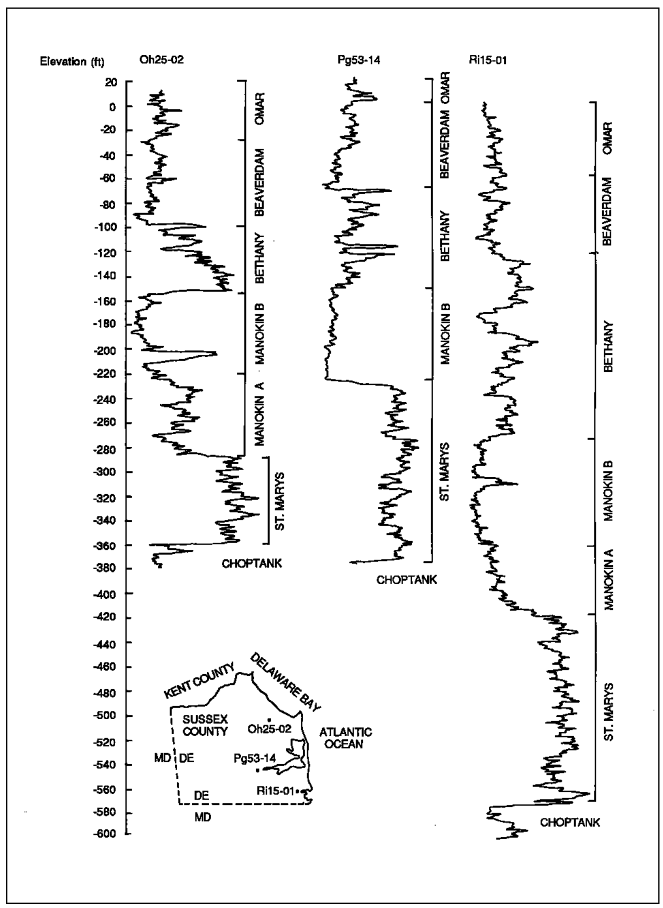

Figure 3. Characteristic gamma-ray log signatures for three wells that penetrate the St. Marys Formation.

represents a transition from the muddy shelf of the St. Marys to a sandy deltaic system of the Manokin B. It is not clear whether the deltaic system was marine- or fluvial-dominated. Andres (1986) indicated a wave-dominated deltaic system.

Bethany Formation

Hansen (1981) and Andres (1986) noted that the Ocean City and Pocomoke aquifers are not discrete sand bodies that can be regionally correlated, but rather are multiple lenses of sand in an overall characteristically clayey unit. Hansen (1981) used Weigle's (1974) term "Upper Miocene Aquifer Complex" for the two aquifers and their confining beds grouped with the underlying Manokin. Andres (1986) grouped the Ocean City and Pocomoke aquifers and their associated confining beds in southeastern Delaware into a recognizable lithostratigraphic unit and informally named it the Bethany formation.

The Bethany formation is a lithologically heterogeneous unit of gray, olive gray, and bluish-gray clay or silt interbedded with bluish-gray or olive gray, fine to very coarse sand (Andres, 1986). Lignitic and gravelly beds are common. Thicknesses of discrete sand or clay beds are on the order of 5 to 10 feet. The Bethany is recognized by its clayey nature (differentiating it from the underlying Manokin and overlying Beaverdam formations) and on gamma-ray logs by a sawtooth pattern (indicating interbedded sand and clay) and generally sharp breaks between the underlying and overlying formations (Fig. 3).

Andres (1986) picked the base of the Bethany at the base of a 5- to 30-foot thick clay or silt unit. The contact is herein further defined as the base of the first clay or silt greater than 5 feet in thickness above the well-developed sand of the Manokin B. On gamma-ray logs, the contact is gradational to sharp. It is probably an unconformity, but a gradational relationship with the Manokin cannot be ruled out (Andres, 1986).

Updip, the Bethany loses its characteristic clayey nature and cannot be differentiated from the overlying Beaverdam Formation. It is not known at this time whether this loss of clay represents a facies change, a pinch-out of the clayey Bethany, or truncation by the overlying Beaverdam Formation. The complex of interbedded sands and muds that becomes dominantly mud downdip indicates that the Bethany was deposited in a deltaic system comprising lobes, channels, and sheets of sand that grade laterally and downdip into inter-channel and prodelta clays.

Beaverdam Formation

The Beaverdam Formation is a pale white to buff to greenish-gray medium sand with scattered beds of coarse sand, gravelly sand, and light gray to greenish-gray silty clay. An admixture of white silt matrix is common (Hansen, 1981), especially in the upper half of the unit. Gamma-ray logs through the Beaverdam have a characteristic fining-upward (right-shift) signature (Fig. 3) best developed where the overlying Omar is thin or absent. Two facies are recognized within the Beaverdam, a lower coarse sand with scattered gravel and an upper silty, medium to coarse sand that fines upwards. Two- to ten-foot thick clay beds are common in the lower facies or just above it and occur sporadically in the upper facies.

There may be an unconformity between the Beaverdam and Bethany formations. The irregular contact between the two units may have resulted from erosion of the Bethany by streams prior to channel filling with Beaverdam sands. Where the Bethany is sandy, the contact between the two formations may be unrecognizable on gamma-ray logs.

The base of the Beaverdam is at the base of the lowermost medium to coarse sand or gravel above the silts and clays or fine to medium sands of the underlying Bethany formation. The contact is recognizable on gamma-ray logs as a left-shift signature above the siltier Bethany formation. The Beaverdam is recognized as far west as Delmar and to the northeast to between Milford and Georgetown (Fig. 4). Beyond this area, it cannot be delimited at this time because the underlying Bethany either pinches out, is truncated (Andres, 1986), or becomes sandy; the result is a thick sequence of sand lacking recognizable lithologic or gamma-ray signatures. This sequence may represent a stacked section of Beaverdam on Manokin, thus making the two formations indistinguishable on gamma-ray logs. This thick sand section was noted by Sundstrom and Pickett (1969) and Hansen (1981).

The Beaverdam is unconformably overlain by the Walston silt along the Maryland-Delaware state line near Delmar (Owens and Denny, 1979) and by the Omar Formation in southeastern Sussex County (Jordan, 1974). The Walston was not investigated during the course of this study. Its lithostratigraphic relationship to the Beaverdam or Omar formations is unknown in Delaware.

On the bases of outcrop observations, rare trace fossils, textures, sedimentary structures, the configuration of the topography upon which it was deposited, and its lack of a shelly fossil fauna, the Beaverdam is considered to have been deposited in a sand-dominated, fluvial to estuarine system. The lower sand of the Beaverdam represents the fluvial portion of the system. It grades upward into the silty sands deposited in estuarine environments.

Omar Formation

The Omar Formation is a heterogeneous unit consisting of fine to coarse sand, silty sand, clayey silt, and silty clay. Fine to very fine sand and silty clay to clayey silt are the dominant lithologies. Colors range from white to tan to bluish-gray for the sands and brown to bluish-gray for those portions of the unit found below the water table. Lithologic changes occur over short distances both laterally and vertically. Unlike the Beaverdam, shell beds occur within the Omar, most commonly bioherms of *Crassostrea virginica.*

The Omar is characterized by its heterogeneous lithology, with four lithofacies. The most distinct lithofacies is bluish-gray, very fine sand interbedded with clayey silt and silty clay. It forms the thickest portion of the Omar that fills paleovalleys cut into the underlying Beaverdam Formation. Bed thicknesses range from a few inches to several feet. Scattered shell beds occur within this unit. This lithofacies ranges from 10 to 80 feet thick and is rarely found at the land surface. The deposits below sea level in Qh44-01 (Fig. 4) are typical of this sequence.

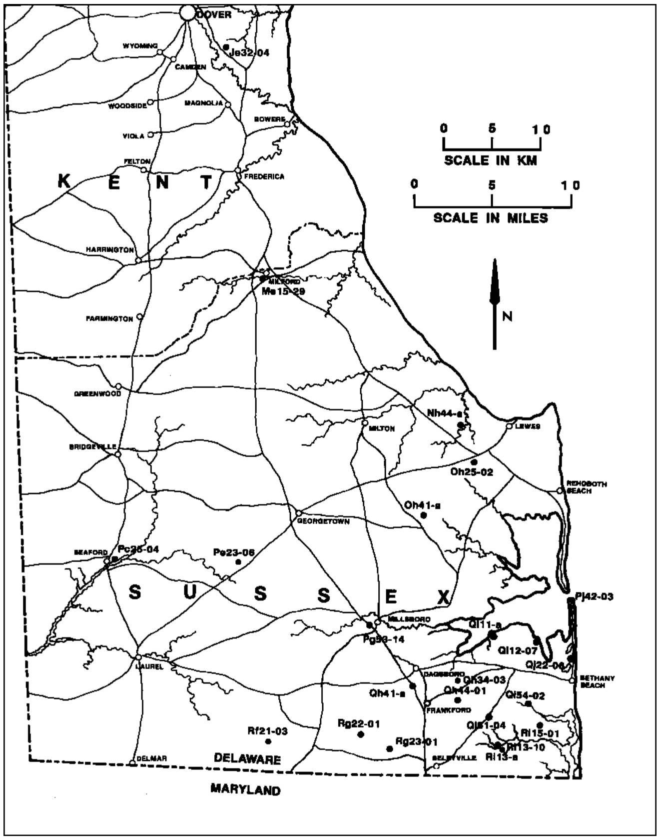

Figure 4. Delaware borehole and outcrop locations cited in this report.

Other recognizable lithofacies include a medium to coarse sand fining upward to interbedded clayey sand and sandy to silty clay; a coarsening-upward, gray, organic-carbon-rich, silty clay to gray to white, fine to medium sand; and a complexly interbedded, gray to white, fine to medium sand, gray silty clay, and gray clayey silt.

The Omar Formation unconformably overlies the Beaverdam Formation. As indicated by Owens and Denny (1979), the Omar fills a northwest-trending paleovalley that cuts into the Beaverdam south of Indian River Bay. That feature was not recognized in this study, but detailed investigation in the area may prove otherwise. The interbedded fine sand, silt, and clay that fills the paleovalley is the oldest part of the Omar. It is either gradational with or unconformably overlain by the other lithofacies. It is likely that the Omar was deposited during several transgressive-regressive cycles as indicated by the distribution of lithofacies within the unit and palynological and aminostratigraphic data.

The Omar Formation does not have as distinctive a gamma-ray log signature as the underlying units. Where the Omar is thickest in the central portion of the paleovalley, the signature is characteristic of a fining-upward, silty to clayey unit. Signatures on some logs indicate that the clays are sharply overlain by a sand near the land surface. Where the Omar is thick, its signature at the base is a sharp clay "kick" over the sands of the Beaverdam (Oh25-02, Fig. 3). The base of the Omar is defined as the base of the fine sands, fine clayey and silty sands, or sandy silty clays which overlie the medium to coarse sands of the Beaverdam Formation. This contact is also marked at many localities by a thin coarse sand or gravel bed that probably represents reworking of the underlying Beaverdam prior to deposition of the fine-grained sediments of the Omar.

On the bases of its distribution, macrofossils, sedimentary structures and textures, the interbedded fine sand, clayey silt, and silty clay lithofacies is interpreted to have been deposited in lagoonal to estuarine environments primarily restricted to a paleovalley system cut into the underlying Beaverdam Formation. The other lithofacies are interpreted to have been deposited in a wide variety of environments including barrier, marsh, tidal flat, lagoon, swamp, and fresh-water bog.

PALYNOSTRATIGRAPHY

Neogene Palynomorph Assemblages of the Mid-Atlantic Region

General Remarks

As pointed out by Traverse (1988, p. 324), Neogene pollen grains can usually be referred to extant genera or families, rarely to species. Few, if any, Neogene plant genera have become extinct, except locally. It is convenient, therefore, to forego the use of artificial (form) generic names and refer to pollen having the morphological characteristics of *Pterocarya* as *Pterocarya* rather than *Polyporopollenites stellatus,* for example. In some instances, the morphologic characteristics of pollen grains may suggest botanical affinity to more than one genus of a family. For instance, some triporate grains may be referred to *Engelhardia* or to *Alfaroa,* and inaperturate grains having the characteristics of *Taxodium* may actually represent another taxon in the TCT (Taxodiaceae, Cupressaceae, Taxaceae) group. In such cases reference has been made to *Engelhardia*-type and *Taxodium*-type pollen. Where botanical affinity is unknown, an artificial name is appropriate. For instance, a small, tricolpate, prolate, psilate pollen grain of unknown affinity is referred to *Cupuliferoidaepollenites fallax.* In general, however, the names of plant genera have been used in this paper.

In order to determine the ages of the Columbia Group formations and the Bethany sediments, a review of pollen assemblages found in Neogene deposits of the mid-Atlantic area is needed, particularly with regard to the distribution of foreign or exotic taxa that may have stratigraphic significance. This review is based on both published and unpublished data (Table 1). The term exotic taxa refers to those taxa that are absent in southern Delaware at present but are extant elsewhere. It also includes taxa whose pollen have not yet been found in sediments of undoubted Quaternary age, e.g., *Taxodium*-type and *Symplocos,* although both genera do live in a few places in southernmost Delaware and are common in Virginia.

The Calvert Formation (Miocene)

Leopold (1969) identified about thirty taxa from the Calvert Formation, the great majority of which are still present in the mid-Atlantic region. However, some are taxa now absent from the area: *Gordonia, Engelhardia-Alfaroa, Melia, Pterocarya,* and *Ephedra.*

TABLE 1

Occurrence of taxa of probable stratigraphic significance, Miocene to Pleistocene, mid-Atlantic Region

Stratigraphic Unit	Age	*Podocarpus*	*Taxodium*-type	*Tsuga diversifolia*-type	*Sciadopitys*	*Sequoia*-type	*Manikara*	*Melia*	*Gordonia*	*Cyrilla*	*Ulmus* sp. 2	*Symplocos*	Onagraceae	*Engelhardia*-type	*Platycarya*	*Pterocarya*	*Cupuliferoidae-pollenites fallax*	*Tricolporopollenites edmundii*	Source of date
Omar; upper part	Pleistocene																		Delaware Geological Survey
Omar; lower part	Pliocene	x	x	x	x	x				?	x	x		x		x	x	x	Delaware Geological Survey
Beaverdam; upper part	Pliocene															x			Delaware Geological Survey
Beaverdam; lower part, and Bethany	Late Miocene or early Pliocene		x	x	x					x	?	x	x	x		x	x	x	Delaware Geological Survey
Shirley	Pleistocene		x																Delaware Geological Survey
Windsor	Early Pleistocene?									?						?			Delaware Geological Survey
Bacons Castle	Pliocene		x		x											x			Delaware Geological Survey
Chowan River	Pliocene		x	x	?					x						x			Delaware Geological Survey
Yorktown	Pliocene		x		x						x					x			Delaware Geological Survey
Brandywine	Early Pliocene or late Miocene		x			x				?						x		x	Delaware Geological Survey
Eastover	Late Miocene?		x											x		x			Delaware Geological Survey
Miocene aquifer complex	Late Miocene	x												x	x	x			Brush in Hansen (1981)
Cohansey	Late Miocene	x	x						x	x				x		x			Rachele (1976)
St. Marys	Late Miocene	x						x								x			Leopold (1969); Brush in Hansen (1981)
Kirkwood V	Late Miocene		x					x		x						x			Goldstein (1974)
Choptank	Late Miocene													x		x			Leopold (1969)
Kirkwood IV	Late Miocene		x					x		x				x	x	x			Goldstein (1974)
Kirkwood III	Early to middle Miocene		x					x		x				x	x	x			Goldstein (1974)
Calvert	Early to middle Miocene	x	x	x		x	x	x	x	x		x		x		x	?		Leopold (1969); Delaware Geological Survey

Outcrop samples from the Calvert Cliffs, Maryland, and central Delaware (core samples from Je32-04 at the Dover Air Force Base and Me15-29 at Milford, Fig. 4) have yielded microfloras generally dominated by *Quercus* (several species) and *Carya,* although in some samples *Pinus* is more frequent than *Carya.* Other taxa identified are *Engelhardia, Castanea, Liquidambar,* Taxodiaceae-Cupressaceae-Taxaceae (TCT) (common to rare), *Pterocarya* (rare but present in most but not all samples), *Ulmus, Cyrilla, Gordonia, Manilkara, Sequoia*-type, *Podocarpus,* and *Picea* (all rare or very rare). So far no *Sciadopitys* has been found in the Calvert Formation.

The Kirkwood Formation (Miocene)

The Kirkwood Formation of New Jersey was studied by Goldstein (1974). He divided the formation into five units; he correlated his Unit III with the Calvert Formation on the basis of foraminiferal assemblages. The pollen assemblage of this unit is dominated by *Pinus, Quercus,* and *Carya.* Minor constituents mentioned include *Castanea, Melia, Nyssa, Platanus, Platycarya, Taxodium, Taxus,* and *Tilia. Engelhardia* and *Pterocarya* are apparently absent in this unit.

Goldstein correlated his Unit IV with the Choptank Formation. This unit is dominated by *Quercus, Pinus,* and *Carya.* The list of minor constituents is very similar to that of Unit III, except that *Engelhardia* and *Juglans* are mentioned. Unit V is correlated with the St. Marys Formation and is characterized by a *Pinus, Quercus, Carya* assemblage, with the minor constituents similar to those of the older units, except that *Platycarya* and *Engelhardia* are not mentioned, but *Pterocarya* is identified. The Appendix of Goldstein's thesis shows that the Tertiary exotics are rare; most taxa occur in a few samples only.

The Legner Lignite in the Cohansey Formation (Late(?) Miocene)

Rachele (1976) investigated the pollen assemblage of the lignite and reported that *Carya* and *Quercus* are common; other constituents are *Pinus, Ulmus, Tilia, Gordonia, Engelhardia-Alfaroa* (in nearly all samples), *Pterocarya, Podocarpus, Cyrilla,* and *Taxodium.*

The Pocomoke-Ocean City-Manokin Aquifer Complex (Late Miocene)

Pollen assemblages from five cores were studied by Brush (reported in Hansen, 1981). Among the arboreal pollen, *Carya, Quercus,* and *Pinus* occur in all samples, although in very different percentages. Exotics found include *Engelhardia* in three samples (highest frequency 2.3 percent), *Platycarya* in two samples (1.4 and 4.1 percent), and *Pterocarya* in three of the five samples (1.4 to 6.8 percent). *Podocarpus* was reported in one sample (1 percent). It is remarkable that no pollen of the TCT group are mentioned, as these appear to be rather common in Miocene deposits elsewhere.

The Brandywine Formation of Maryland (Late Miocene or Early Pliocene)

The Maryland Geological Survey provided a sample of gray clay from this formation for palynological analysis. Taxa identified include *Carya, Quercus, Pinus, Alnus, Liquidambar, Ulmus, Juglans, Cyrilla*(?), *Pterocarya, Taxodium*-type and Compositae. Also present is *Tricolporopollenites edmundii* originally described by Potonié and Venitz (1934, p. 29 and fig. 75) from the Eocene and Miocene lignites of Germany. The taxa listed above were also found by T. Ager (written commun.) except *Pterocarya* and *T. edmundii.* The pollen assemblage indicates an early Pliocene age, although it could be late Miocene.

The Eastover Formation of Virginia (Late Miocene or Early Pliocene)

Two samples were obtained from an outcrop of this formation near Richmond, Virginia. Both contained a rich microflora, generally similar to that of the Brandywine Formation. *Quercus* is dominant, *Carya* is common, and *Pinus* occurs at rather low frequencies. Minor constituents are *Liquidambar, Nyssa, Ostrya-Carpinus, Ulmus,* TCT, *Pterocarya, Engelhardia,* and among the non-arboreal pollen (NAP) Compositae and Gramineae are most common.

Pliocene and Early Pleistocene(?) Formations of Virginia

Three samples of the Yorktown Formation of Virginia have generally poorly preserved pollen assemblages with relatively high percentages of non-arboreal pollen (NAP) and marine palynomorphs ("microforams," dinoflagellates). Among the NAP, Compositae, including *Artemisia,* and Chenopodiaceae are the most frequently occurring pollen; *Pinus* is the dominant arboreal pollen, followed by *Quercus* and *Carya*. Minor constituents include *Alnus, Betula, Castanea, Tilia,* and TCT including rare *Taxodium*-type. The only exotic elements identified are *Pterocarya* in all three samples and *Sciadopitys* in two samples. Their occurrence is so rare, less than 1 percent of the pollen sum, that a brief reconnaissance of the pollen slides could easily miss these exotic elements and lead one to believe that the pollen assemblage is of Quaternary age, particularly in view of the rather high NAP percentage which is common in Pleistocene deposits.

Poor preservation of the palynomorphs in a sample from the Chowan River Formation obtained in the Gomez pit, Virginia, makes it impossible to be certain about the occurrence of exotic elements. This sample differs from those of the Yorktown Formation in having a much lower percentage of NAP. Among the arboreal pollen, *Pinus* is dominant, followed by *Carya* and *Quercus.* Also present are *Tsuga* (both the *canadensis* and *diversifolia* types), *Alnus, Betula, Ostrya-Carpinus, Liquidambar, Taxodium*-type, *Castanea,* and *Cyrilla.* A marine environment of deposition is indicated by dinoflagellates and "microforams."

The pollen assemblage of a sample of the late Pliocene Bacons Castle Formation is dominated by *Quercus* and *Carya;* conifers are represented by *Pinus, Picea,* and TCT. Minor constituents are *Alnus, Betula, Nyssa,* and *Ulmus*. The NAP percentage is high: 20 percent. The only exotic element identified is rare *Pterocarya* (<1 percent of the pollen sum).

A sample from the Windsor Formation of early Pleistocene(?) age has a pollen assemblage with 40 percent NAP (mainly Compositae and Gramineae); the arboreal pollen are dominated by *Quercus,* followed by *Liquidambar;* minor percentages of TCT, *Pinus, Tsuga, Alnus,* and *Betula* were found. No exotic elements could be identified with certainty.

Stratigraphic Ranges of Exotic Taxa in the Neogene of the Mid-Atlantic Region and a Comparison with Those in Western Europe

The study of Neogene palynostratigraphy is hampered by the fact that the most common palynomorph taxa in Miocene and Pliocene deposits are *Quercus, Carya,* and *Pinus,* which are also the most frequently occurring taxa in many Pleistocene and Holocene sediments in the Delmarva area. It may be possible to distinguish some *Quercus* or *Carya* pollen species which are characteristic of the Miocene and/or Pliocene of the mid-Atlantic region, and which do not occur in Quaternary sediments, but so far, insufficient data have been obtained to use different species of these taxa for stratigraphic purposes. Therefore, Neogene palynostratigraphy in the study area depends primarily on the appearances and disappearances of taxa now absent from the region. As mentioned before, these exotic taxa are minor or rare constituents in Neogene sediments.

The stratigraphic ranges of exotics in the mid-Atlantic region are, as yet, not well known. Frederiksen (1984), in his study of Tertiary sporomorphs from Massachusetts, presented a diagram showing the ranges of, among others, *Pterocarya, Gordonia, Podocarpus, Cyrilla-Cliftonia, Sciadopitys,* Sapotaceae, and *Ephedra* in the middle Atlantic states and New England. However, the ranges of five of those seven taxa are questioned in his diagram and cannot be considered definitive. Some uncertainties pertaining to the geologic ranges of several taxa also persist in Western Europe. *Engelhardia*-type pollen are reported to disappear at the end of the Miocene (Traverse, 1988, table 15.1), but Thiele-Pfeiffer (1988) described *Momipites punctatus,* referred to *Engelhardia-Alfaroa,* as occurring from the Eocene to the late Tertiary, including the Pliocene. Some specimens of *Platycaryapollenites miocaenicus* are reported from the Pliocene of West Germany, although most species of this genus occur in Eocene to Miocene deposits.

Thiele-Pfeiffer (1988) agreed with Traverse (1988) that *Cupuliferoidaepollenites fallax,* common in the Eocene, still occurs, although rarely, up to the end of the Pliocene. It may therefore be useful in determining the Pliocene-Pleistocene boundary. It is found both in northwest Europe and the mid-Atlantic region of the United States.

Tricolporopollenites edmundii is found in late Oligocene to middle Miocene deposits in Germany, according to Thiele-Pfeiffer (1988). On the other hand, Traverse (1988, table 15.1) reported that it occurs up to the end of the Pliocene in Germany and up to the middle Pliocene in northwest Europe.

In trying to determine the ages of the Bethany, Beaverdam, and Omar formations of southern Delaware it is necessary to keep in mind that the stratigraphic ranges of various taxa are either not well known or differ somewhat from one area to another.

Palynomorph Assemblages of Southern Delaware

The Bethany and Beaverdam Formations

Pollen assemblages from these formations are presented in Table 2, and the borehole and outcrop locations from which samples were obtained are shown in Figure 4. Some pollen grains that are considered of stratigraphic significance are illustrated in Plates 1 and 2.

The assemblages from the Bethany and the lower part of the Beaverdam have much in common: high, although variable, percentages of *Quercus* and *Carya;* consistent presence of pollen of the Taxodiaceae-Cupressaceae-Taxaceae (TCT) including *Taxodium*-type; a low *Pinus* frequency; and the presence in all samples of one or more exotic taxa, particularly *Pterocarya* and *Sciadopitys.* Other taxa of stratigraphic significance present are *Cupuliferoidaepollenites fallax*, *Tricolporopollenites edmundii* and *Tsuga diversifolia*-type. There does not appear to be a discernable palynological difference between the Bethany and the lower (older) part of the Beaverdam; if there is a hiatus in deposition between the two formations, it is perhaps of relatively short duration.

Andres (1986) expressed the opinion that the Bethany formation in Delaware is the lithostratigraphic equivalent of the Pocomoke-Ocean City aquifer complex of the Eastern Shore of Maryland. That unit was considered to be of late Miocene age by Brush (reported in Hansen, 1981), presumably on the basis of the presence of *Engelhardia* and *Platycarya* in some samples. So far, *Platycarya* has not been found in the Bethany, and *Engelhardia* occurs in only one sample. More samples should be examined of both the aquifer complex and the Bethany formation before their biostratigraphic equivalence can be ascertained.

The upper part of the Beaverdam has a pollen assemblage similar to that of the Bacons Castle Formation of Virginia. It appears to be of late Pliocene age. Both the lithostratigraphic and palynological data suggest that the upper and lower parts of the Beaverdam represent somewhat different environments of deposition, changing from fluvial in the late Miocene or early Pliocene to lagoonal or estuarine in late Pliocene time.

Samples from the upper part of the Beaverdam

TABLE 2

Pollen assemblages of the Bethany and Beaverdam formations expressed as percentages of the pollen sum.

Sample No.	Well No. or Outcrop	Altitude (ft. m.s.l.)	*Pinus*	*Tsuga canadensis*	*T. diversifolia*-type	*Taxodium*-type	Other TCT	*Sciadopitys*	*Carya*	*Pterocarya*	*Castanea*	*Liquidambar*	*Quercus*	*Ulmus*	*Ulmus* sp. 2	*Tilia*	*Symplocos*	Onagraceae	*C. fallax*	*T. edmundii*	Other	Remarks
20959	Pe23-06	-17	3	1	P	1	15	P	36	P	–	5	20	1	?	P	P	P	P	P	16	Very rich microflora from lower part of Beaverdam Fm. NAP 8%.
83039	Qh34-03	-79	6	6	–	2	8	6	11	1	15	2	22	1	–	–	–	–	P	–	20	Preservation poor to good. NAP 4%. Top of Bethany fm. or lower part of Beaverdam Fm.
20859	Rf21-03	-141	1	–	–	1	7	–	13	1	1	–	54	1	–	–	–	P	–	–	20	Preservation poor to good. NAP 13%. Beaverdam Fm.
83042	Ri13-10	-150	1	–	–	5	24	3	13	2	7	1	23	–	–	–	–	P	1	–	21	Preservation poor to medium. NAP 7%. Bethany fm.
21333	Pj42-03	-120	6	3	P	4	8	P	10	2	P	2	47	2	–	P	P	P	–	–	15	Very rich microflora. Preservation poor to good. NAP 13%. *Cyrilla* and *Gleicheniidites* present. *Nyssa* common. Bethany fm.
41124	Oh41-a	+18	5	–	–	–	10	–	14	P	–	P	32	P	?	3	–	–	–	–	35	NAP 22%; upper part of Beaverdam Fm.
83094	Qi12-07	-160	6	4	P	–	4	P	31	P	–	P	41	–	–	P	–	–	–	–	13	*Engelhardia* present. NAP 3%. Bethany fm.
41109	Qi11-a	-1	6	–	–	–	2	–	34	P	–	–	28	P	–	2	–	–	–	–	32	*Engelhardia* present. NAP 15%. Upper part of Beaverdam Fm.
41110	Qi11-a	-3	5	–	–	P	5	–	8	P	–	–	25	5	–	1	–	–	–	?	50	NAP 40%. Upper part of Beaverdam Fm.
41111	Qi11-a	-5	14	–	–	–	4	–	5	P	–	–	24	P	–	4	–	–	–	–	48	NAP 40%. Upper part of Beaverdam Fm.

P = present, < 1%.

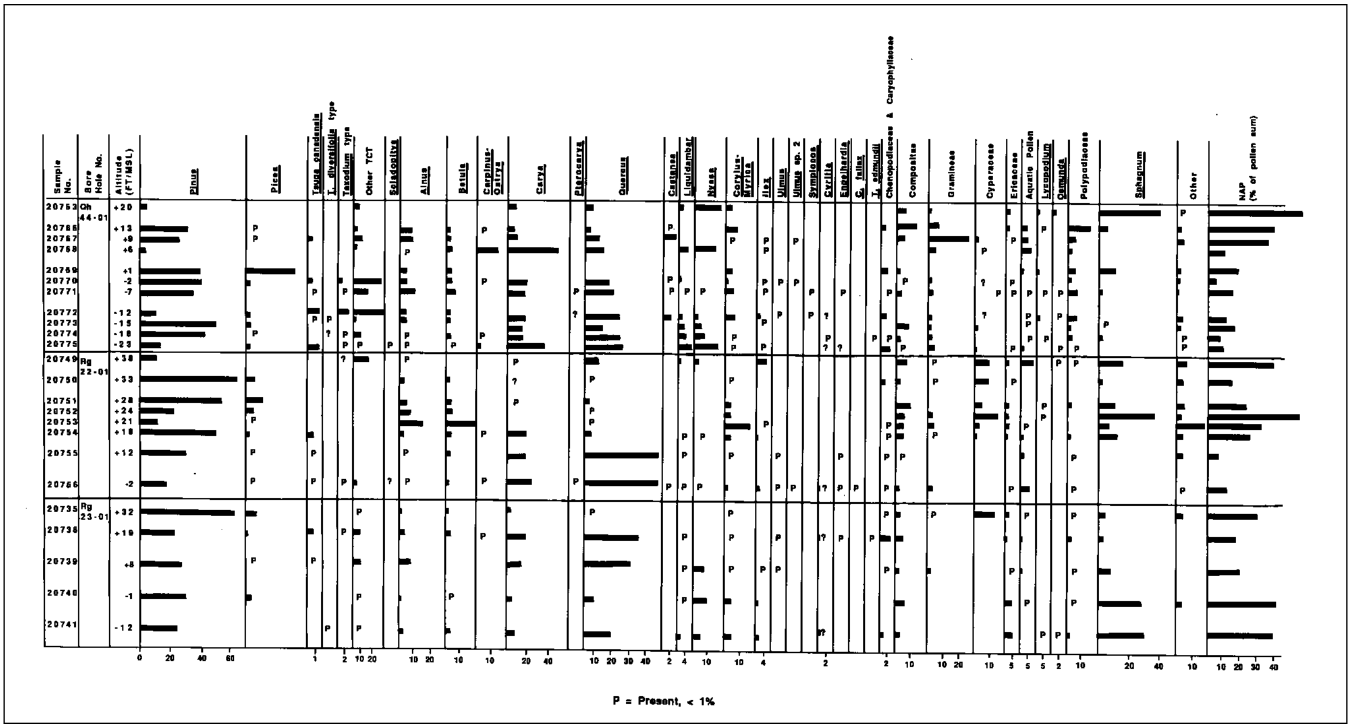

Figure 5. Pollen assemblages of the Omar Formation expressed as percentages of the pollen sum.

Formation (nos. 41009-11 and 41124) differ from those from its lower part (and the Bethany) in having very high percentages of non-arboreal pollen, mostly Compositae, a few dinoflagellate cysts, and no exotics except *Pterocarya* which has been found in all samples from the Beaverdam and the Bethany.

The pollen assemblages of the Bethany and the lower part of the Beaverdam are similar to those of the Brandywine and Eastover formations, except for the lack of *Sciadopitys* in the latter. It appears reasonable, therefore, to conclude that the ages of these formations are not very different, that is late Miocene or early Pliocene.

The Omar Formation

Pollen assemblages from the Omar Formation are shown in Figure 5. The number of pollen grains counted in each sample ranged from 130 to 350, except in sample 20769 in which only 70 grains were available.

In borehole Qh44-01 (the type locality of the Omar Formation), sample 20769 is exceptional because the arboreal pollen content is nearly exclusively composed of *Pinus* and *Picea;* the non-arboreal component is 20 percent of the pollen sum and consists mainly of *Sphagnum* and Polypodiaceae. An open boreal forest or taiga, a cold climate, and a Quaternary age are indicated by this pollen assemblage. Above sample 20769 the pollen assemblages indicate a temperate and moist climate and environments of deposition ranging from a *Sphagnum* bog (sample 20763 has 40 percent *Sphagnum* spores) to bodies of fresh or brackish water. No exotic pollen grains were found except one of *Ulmus* sp. 2 (which probably is *Ulmus serotina* still growing in the southern United States).

Below sample 20769, the pollen assemblages are characterized by generally high percentages of *Pinus*, *Quercus,* and *Carya; Nyssa* and *Liquidambar* frequencies increase with depth, and *Taxodium* is generally also present. Of stratigraphic interest are the sporadic occurrences of *Sciadopitys, Pterocarya, Engelhardia, Symplocos, Cyrilla, Tsuga diversifolia*-type and *Tricolporopollenites edmundii.* This assemblage suggests a warm temperate, moist climate, and, if the exotic pollen are not reworked from older deposits, a late Tertiary age.

In borehole Rg22-01, cool or cold climatic conditions are indicated by relatively high *Picea* frequencies and low *Carya* and *Quercus* percentages in samples 20750 to 20752, which also contain *Thalictrum* pollen. Sample 20749, two feet below land surface, has a high *Quercus* frequency indicating a temperate climate. Below sample 20753, particularly 20755 and 20756, *Quercus, Carya,* and *Pinus* dominate the pollen assemblage; the non-arboreal pollen frequency is low; and some exotic taxa appear: *Engelhardia, Pterocarya,* and *Cupuliferoidaepollenites fallax.*

In borehole Rg23-01, only five fossiliferous samples are available, and only the uppermost one, 20735, indicates a cool or cold climate and a Quaternary age. Below this sample, *Quercus, Pinus,* and *Carya* dominate the arboreal pollen assemblage, and some exotics appear, e.g., *Tsuga diversifolia*-type, *Engelhardia,* and *Tricolporopollenites edmundii. Taxodium* is also present.

Nickmann and Demarest (1982) presented the results of pollen analysis of a 14.76-foot long core from the Omar Formation exposed in Agricultural Ditch (Ri13-a, Fig. 4). Their analysis and an amino acid racemization age estimate of 500,000 to 1,000,000 years indicate that the sediments of the Omar Formation at that locality and at the depth sampled were deposited during an interglacial stage in mid-Pleistocene time. No exotic pollen were reported. Additional amino acid data by Wehmiller (this report) imply different estimated ages of the Omar at different outcrops: at Pepper Creek Ditch (Qh41-a, Fig. 4) at least 100,000 years and more likely 200,000±30,000 years BP, and at Agricultural Ditch (Ri13-a, Fig. 4) 500,000±100,000 years BP. No exotics were found in samples from these outcrops. In well Qi51-04, an amino acid age estimate of 500,000±100,000 years was determined on shell material at a depth of 42 to 43.5 feet; no exotics were found in this borehole above a depth of 85-86.5 ft. (about -64 ft. msl). These data indicate that it is unlikely that exotic taxa were present in the area of deposition of the Omar Formation after at least half a million years ago. Meager palynological data available on the Pliocene and early Pleistocene of Virginia suggest that exotics are rare in most of the Pliocene formations and absent in the early Pleistocene(?) Windsor Formation.

Whether the lower part of the Omar Formation is of late Tertiary rather than early Pleistocene age depends on whether the exotics are reworked or not. The presence of exotics in the Omar Formation owing to redeposition is considered unlikely for three reasons.

(1) As pointed out previously, the underlying Beaverdam and Bethany formations have very low frequencies of exotics, and the same pertains to other Neogene formations. They are therefore poor sources of exotics for the Omar Formation.

(2) The formation that directly underlies the Omar is the Beaverdam, which is essentially a sand with a few silt beds. This sandy formation, which has a much larger geographic distribution than the Omar, can hardly be a significant source of pollen.

(3) No exotics have been found in samples having pollen assemblages indicating a cold climate and in samples younger than those suggesting a temperate climate. Therefore, sediments of undoubted Quaternary age do not have reworked exotics. Did reworking suddenly stop?

Thus it appears to be reasonable that the lower part of the Omar Formation is of Pliocene age, and the upper part of Quaternary age. The Quaternary section is composed mostly of sediments deposited during interglacial stages, but at least one cold stage is represented. The pollen assemblages also indicate that the Omar Formation contains several disconformities and was deposited in several different environments.

Discussion of Ages of the Upper Beaverdam and Lower Omar

As noted previously, the upper part of the Beaverdam differs from its lower part in having only one exotic taxon, *Pterocarya,* whereas the lower part contains, in some samples, *Symplocos,* Onagraceae, *C. fallax,* and *T. edmundii.* In addition, *Taxodium*-type pollen are much more common in the lower Beaverdam than in the upper part of this formation (Table 2). These differences indicate a definite cooling trend.

A well-documented Pliocene glacial period, determined by the oxygen isotope (^{18}O) record of foraminifera in deep sea sediments of the North Atlantic Ocean, occurred about 2.5 to 2.3 million years ago (Shackleton and Hall, 1984). Palynological evidence indicates a cool interval at approximately the same time in northwest Europe (see, for instance, Zagwijn, 1974). This interval is of Praetiglian age. Thus, the upper part of the Beaverdam, deposited during a cool Pliocene interval, may be of Praetiglian age, approximately 2.5 to 2.3 million years ago.

The lower part of the Omar Formation contains again some of the exotic elements that were absent in the upper part of the Beaverdam. Although these exotics are rare, they, and the presence of *Taxodium* in more than forty percent of the lower Omar samples, suggest a warming trend, which may be time equivalent to the relatively warm Tiglian age of northwest Europe, about 2.0 to 1.7 million years ago.

AMINOSTRATIGRAPHY OF SURFICIAL MARINE UNITS IN SOUTHERN DELAWARE AND ADJACENT AREAS

Aminostratigraphic Principles and Coastal Plain Applications

Aminostratigraphy relies upon the observation that amino acids contained in fossilized skeletal organic matter (in molluscs, for example) undergo racemization during diagenesis. Racemization produces D- (or right-handed) amino acids from the original L- (left-handed) amino acids that constitute the biomineralization protein. The degree of racemization is determined by measurement of D/L values for one or more amino acids in the total amino acid mixture of a fossil. The D/L value starts at 0.0 in modern samples and reaches an equilibrium value (1.0 for most amino acids) in about 1 to 2 million years at temperatures like those of the mid-Atlantic region. Because the reaction is temperature dependent, this time to equilibrium can be as little as 200,000 years in the tropics and as much as 10 million years at high latitudes. The simplest approach to the use of amino acid D/L data is as a stratigraphic tool, whereby relative ages are assigned to recognized clusters of D/L values (aminozones) from samples within a region of similar temperature histories.

Several previous publications have presented aminostratigraphic data for portions of the Atlantic Coastal Plain or for the entire region as a whole. They were recently reviewed and summarized by Wehmiller et al. (1988). Belknap (1979), Belknap and Wehmiller (1980), Demarest (1981), Nickman and Demarest (1982), and Demarest and Kraft (1987) have quoted amino acid “dates” for several sites in southern Delaware in discussing the Quaternary marginal marine units of the mid-Atlantic region. Because of the experimental nature of amino acid racemizaton dating methods, we prefer to interpret these data in terms of *age estimates* rather than dates (see nomenclature of Colman et al., 1987), pointing out that the most recent summary of Coastal Plain aminostratigraphic data (Wehmiller et al., 1988) presents age estimates for particular regional aminozones rather than for specific sites, a substantially different approach from that presented in most previous publications. We follow this regional aminozone approach in the summary of mid-Atlantic aminostratigraphic data presented here. Figures 6-8 and Table 3 contain relevant information on aminostratigraphic localities, analytical data, and pertinent references.

For the Delmarva-Chesapeake region, current mean annual temperatures (CMAT) are a smooth function of lati-

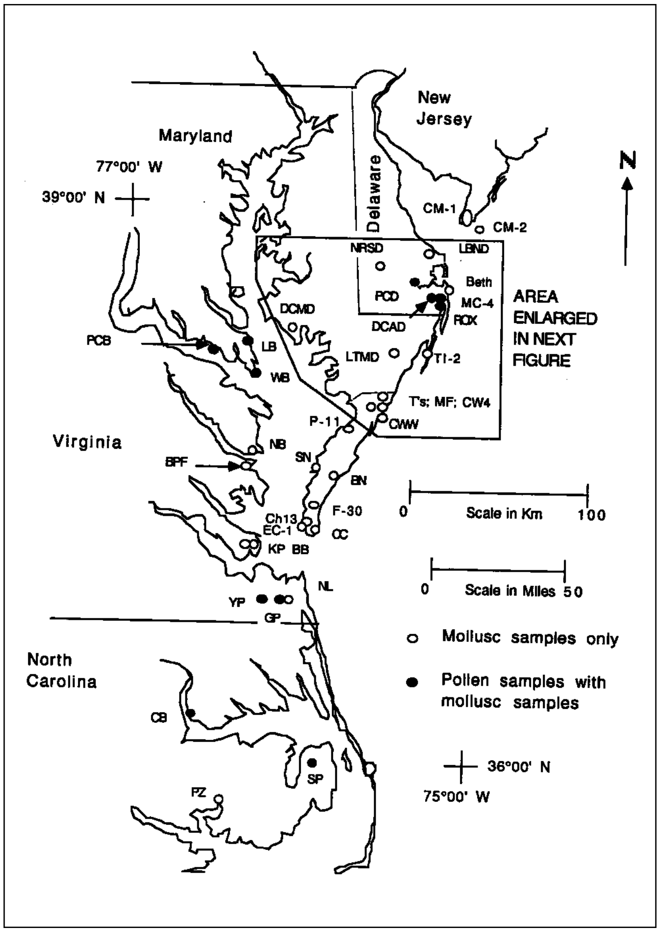

Figure 6. Mid-Atlantic Coastal Plain localities for aminostratigraphic study. Locality abbreviations identified in Table 3.

tude and range from 13˚C at the northern end of Chesapeake Bay to 16˚C around Norfolk. Samples from the northern portion of the area would be expected to have D/L values about 15-20 percent less than those of equal age from the southern portion of the area (Wehmiller et al., 1988). One of the fundamental assumptions of aminostratigraphic applications is that nearby sites with different CMAT values (such as the Delmarva-Chesapeake region) have been exposed to similar (and simultaneous) temperature reductions during Pleistocene climatic cycles. A corollary to this assumption is that present CMAT differences represent the *differences* in effective temperatures between sites, so that aminostratigraphic correlations between sites can be based on present CMAT differences. This method of aminostratigraphic correlation is particularly important in those cases where comparisons of amino acid data between calibrated (known-age) and uncalibrated samples at different sites (CMATs) must be made.

In spite of the temperature uncertainties inherent to aminostratigraphic correlations, there are several important reasons for conducting aminostratigraphic studies in conjunction with lithostratigraphic or biostratigraphic studies such as those reported here. Aminostratigraphic data, when abundant at closely spaced sites with the same CMAT, often permit stratigraphic resolution of units that cannot be distinguished by any other methods, the D/L values being quantitative stratigraphic characteristics of the unit in question. Given suitable calibration (radiometric) data, D/L values can be converted into numerical age estimates using appropriate models for racemization kinetics. The speed and economy of analysis permit multiple samples to be analyzed. These characteristics, coupled with the long time range (ca. 1 million years) over which D/L data can provide age resolution in the mid-Atlantic region, indicate that aminostratigraphic data are potentially quite useful both in mapping and age estimation of Pleistocene units of the Coastal Plain (Wehmiller et al., 1988).

Discussion of Aminostratigraphic Results

Mid-Atlantic Region

To facilitate comparison of results, the data for each site are grouped into aminozones based on D/L values and consideration of intergeneric differences in racemization rates. These aminozones are labeled in Table 3 as IIa, IIb, IIc, IId, and IIe. The system of aminozone definition is explained in Wehmiller et al. (1988). Aminostratigraphic Region II is identified as the area of southern New Jersey, Delaware, Maryland, and Virginia (CMAT 12-16˚C). The letter designations for the aminozones represent clusters of D/L values. In the case of Region II, aminozone IIa is represented by D/L values between 0.16 and 0.22, whereas the oldest aminozone (IIe) is represented by D/L values greater than 0.80. As additional data become available, it is likely that division of some of these aminozones will occur if stratigraphic and geochemical data justify such resolution.

Figure 8 presents the aminostratigraphy of the sites listed in Table 3. It shows the appropriate D/L value for each site plotted against CMAT. The slope of the identified aminozones relative to CMAT is consistent with data from

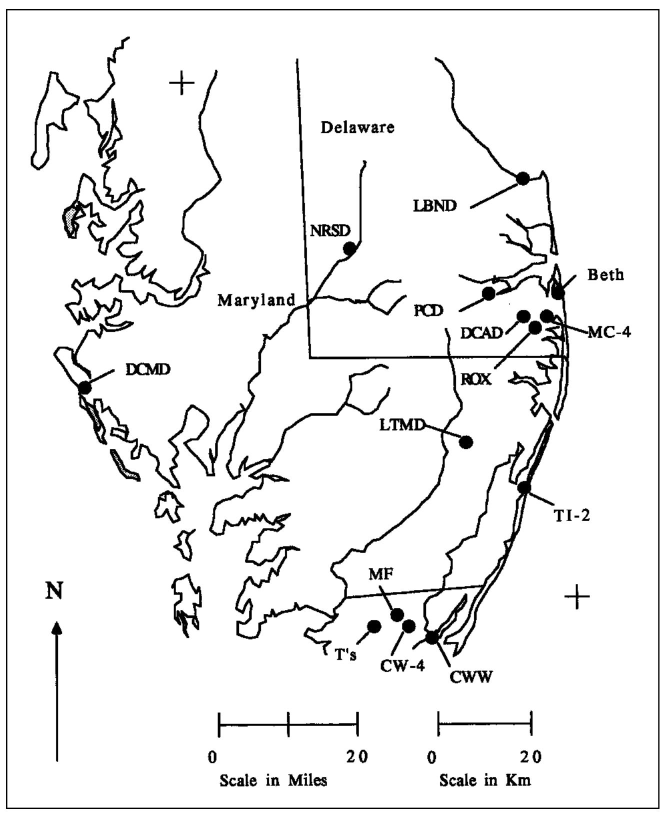

Figure 7. Aminostratigraphic collection sites, central Delmarva region. Locality abbreviations identified in Table 3.

TABLE 3

Mid-Atlantic Coastal Plain aminostratigraphic collection sites, data, and references.

UDAMS	Loc No.	LOCALITY	FULL NAME	UNIT	AMINOZONE	AAR DATA	D/L LEU	AILE/ILE
O5003		CM-1	Cape May 1, NJ	Cape May	IIa	*Mercenaria*	0.28	
O5042		CM-2	Cape May 2, NJ	Cape May	IIc	*Mercenaria*	0.46	
O5001		PCB	Poplar Creek Bluff, MD	Pamlico	IId	*Rangia*	0.6	
O5089		LBND	Lobiondo Property,DE	Probable Omar	IIc	*Mercenaria*		0.33
O5000		WB	Wailes Bluff, MD	Pamlico	IIa	*Mercenaria*	0.29	
O5002		LB	Langley Bluff, MD	Pamlico	IIa	*Mercenaria*	0.28	
O5007		DCMD	Dorchester Co., MD		IId	*Rangia*	0.65	
O6000		NB	Norris Bridge, VA	Omar-Accomack Member (or Shirley)	IId	*Mercenaria*	0.55	
O6001		BPF	Bush Park Farm, VA	Yorktown	IIe	*Mercenaria*	0.81	
O5011		NRSD	Nanticoke River, Seaford, DE	Omar	IIa or IIb	*Crassostrea*	0.23	
O5034	O5018-20	Beth	Bethany Barrier, DE	Omar	IIa	*Mulinia*	0.22	0.11
O5045		PCD	Pepper Creek Ditch, DE	Omar	IIb	*Mercenaria*	0.33	
O5048		DCAD	Dirickson Creek Ag. Ditch, DE	Omar	IId	*Mercenaria*	0.53	
O5033		MC-4	Miller Creek, DE	Omar	IId	*Crassostrea*	0.45	
O5080		ROX	Roxana, DE	Omar	IId	*Crassostrea*		0.43
O5004		TI-2	Tingles Island, MD	Sinepuxent?	IIa	*Mulinia*		0.105
O5005		LTMD	Libertytown, MD	Omar	IIc or IId	*Crassostrea*	0.37	
O5005		LTMD	Libertytown, MD	Omar	IIc or IId	*Mercenaria*	0.42	
O6002		T's	T's Corner, VA	Omar-Accomack Member	IId	*Mercenaria*	0.54	
O6004		MF	Mathew's Field, VA	Omar-Accomack Member	IId	*Mercenaria*	0.58	
O6009		CW-4	CW-4, VA	Omar-Accomack Member	IId	*Mercenaria*	0.59	
O6007		CWW	CWW, VA	Yorktown	IIe	*Mercenaria*	0.88	
O6008		P-11	Parksley, VA	Omar-Accomack Member	IId	*Mercenaria*	0.55	
O6012		SN	J24, - 4m, VA	Kent Island	IIa	*Mercenaria*	0.25	
O6013		BN	EX-24,VA	Wachapreague	IIa	*Mulinia*	0.24	0.1
O6013		BN	EX-24, VA	Wachapreague	IIa	*Mesodesma*	0.28	
O6010		F-30	F-30, - 7 m, VA	Nassawadox or Stumptown Unit C	(IIc or d ?)	*Mercenaria*	0.44	
O6011		Ch-13	Ch-13, - 5m, VA	Nassawadox-Butlers Bluff Member	IIa (IIc or d)	*Mulinia (Merc)*	0.23 (0.38)	
O6014		CC	Cape Center, - 3 m, VA	Nassawadox-Butlers Bluff Member	IIa	*Mercenaria*	0.25	
O6015		EC-1	Elliots Creek, - 4m, VA	Nassawadox-Butlers Bluff Member	IIa or IIb	*Mercenaria*	0.29	
O6021		KP	Krause Pit, VA	Tabb-Sedgefield	IIc	*Mercenaria*	0.41	
O6020		BB	Big Bethel, VA	Tabb-Sedgefield	IIc	*Mercenaria*	0.44	
O6029-32		GP	Gomez Pit, VA	Tabb-Sedgefield	IIa/IIc	*Mercenaria*	0.22/ -	0.16/0.33
O6023-5		NL	New Light Pit, VA	Tabb-Sedgefield	IIa/IIc	*Mercenaria*	0.25/0.42	
O6034-36		YP	Yadkin Pit, VA	Yorktown	IIc/IIe	*Mercenaria*	0.37/0.88	
O7023		CB	Chowan River Type Section, NC	Chowan River	IIe	*Mercenaria*	0.88	
O7002		SP	Stetson Pit, NC	multiple	IIIb/IIIc/IIId	*Mercenaria*		0.23/0.47/0.76
O7006		PZ	Ponzer, NC		IIIc	*Mercenaria*	0.4	

NOTES

UDAMS No. = UD AMino Stratigraphy Loc. No.
AAR DATA indicates the genera analyzed
D/L LEU = D/L leucine values
AILE/ILE = D-alloisoleucine/L-isoleucine

Parentheses ( ) around an aminozone implies probable reworking of sample
Slash between aminozones (/) implies stratigraphic superposition of samples

other regions and with theoretical considerations (Wehmiller et al., 1988; Wehmiller, 1989a, b).

The two aminozones that are most rigorously calibrated are aminozones IIa and IIc. Aminozone IIa is estimated to represent an age of 100,000±25,000 years based on U-Th dates on solitary corals from three sites in Virginia and North Carolina (GP, SP, and NL: Szabo, 1985; Wehmiller et al., 1988) and based on electron spin resonance dates at the Gomez Pit, Virginia (GP: Mirecki et al., 1989). Aminozone IIc is estimated to represent an age of 220,000±25,000 years based on a U-Th coral date at PZ, Ponzer, North Carolina (Szabo, 1985; Wehmiller et al., 1988) and electron spin resonance dates at GP (Mirecki et al., 1989). The two ages and two aminozones are encountered at GP in a well-exposed superposed section, so these data represent the central reference section for calibration of aminostratigraphy in the mid-Atlantic region.

Numerical Age Estimates for Observed Aminozones

Numerical age estimation is best accomplished by discussion of aminozone age estimates rather than specific site age estimates. This approach minimizes possible small age differences between sites, but given the typical ranges of D/L values seen at single sites and the possible thermal and chemical causes of small (ca. 10 percent) variations in D/L values, we prefer to emphasize mean D/L values for aminozones rather than mean D/L values for single sites. The specifics of the various approaches to kinetic model age estimation are discussed elsewhere (Wehmiller et al., 1988; Wehmiller, 1989a, b). The basic strategy is to extrapolate a kinetic model from a particular calibration point; uncertainties in age estimates result from the possible age range of the calibration site and possible differences in temperature histories between sites being compared. The general equation that describes the kinetic model extrapolation is:

$$D/L = k(t)^y$$

where t is time, and k and y are constants that describe the curve (parabolic or exponential) representing the D/L versus time function. Specific age estimates depend on the choice of particular calibration D/L values in a given region.

TABLE 3

Mid-Atlantic Coastal Plain aminostratigraphic collection sites, data, and references.

POLLEN	RADIOMETRIC DATES	OTHER COMMENTS	REFERENCES
		Cape May and Heislerville, NJ	H. Richards collection (ANSP)
		CM-119 offshore core	S. J. Williams collection (USGS)
yes			Belknap, 1979; Thompson, 1972
		DGS LOC. NO. Nh44-a; excavation April 1989	This report
yes			Belknap, 1979; Thompson, 1972
yes			Belknap, 1979; Thompson, 1972
			Jacobs, 1980; Colman and Mixon, 1988
	ca 200,000		Belknap, 1979; Mixon, 1985; Peebles et al., 1984
			Belknap, 1979; this report
		DGS LOC. NO. Pc25-04	Belknap, 1979; this report
yes		DGS LOC. NO. Qj22-06	McDonald, 1981; this report
yes		DGS LOC. NO. Qh41-a	Belknap, 1979; Wehmiller et al., 1988; this report
yes		DGS LOC. NO. Ri13-a	Belknap, 1979; Wehmiller et al., 1988; this report
		DGS LOC. NO. Qi54-02	Demarest, 1981; this report
yes		DGS LOC. NO. Qi51-04	This report
		Approx. 16 m below sea level; J. P. Owens collector	Belknap, 1979; York and Wehmiller, 1988; Owens and Denny, 1978
		Richard Hall to D. F. Belknap, 1977: Ninepins Quad	Owens and Denny, 1978; this report
		Acad. Nat. Sci. Phila. collection - no specific locality	This report
		H-8 and H-37 of Mixon, 1985	Belknap, 1979; Mixon, 1985
	ca. ≥350,000	H-27 of Mixon, 1985	Belknap, 1979; Mixon, 1985
		CW-4 of Mixon, 1985	Belknap, 1979; Mixon, 1985
			Belknap, 1979; Wehmiller et al., 1988
		P-11 of Mixon, 1985	Belknap, 1979; Mixon, 1985
		J24 of Mixon, 1985; 4 m below SL	Belknap, 1979; Mixon, 1985
		EX-24 of Mixon, 1985	Belknap, 1979; Mixon, 1985
		EX-24 of Mixon, 1985	Belknap, 1979; Mixon, 1985
			Belknap, 1979; Mixon, 1985
			Belknap, 1979; Mixon, 1985
		T-15 of Mixon, 1985	Belknap, 1979; Mixon, 1985
			Belknap, 1979; Mixon, 1985
			Belknap, 1979; Wehmiller et al., 1988
			Belknap, 1979; Wehmiller et al., 1988
yes	ca. 100,000/ca. 200,000		Belknap, 1979; Wehmiller et al., 1988
	ca. 100,000/ -		Belknap, 1979; Wehmiller et al., 1988
yes			Belknap, 1979; Wehmiller et al., 1988
yes			Belknap, 1979; Wehmiller et al., 1988
yes	ca. 100,000/ - / -		Wehmiller et al., 1988; York et al., 1989
	ca. 200,000		Wehmiller et al., 1988

Columns labeled POLLEN and RADIOMETRIC DATES indicate whether these data are available for the same sites from which samples for aminostratigraphic analysis have been obtained.

The numerical age estimates that we propose for the aminozones shown in Figure 8 are:

Aminozone	Numerical age estimate (yrs. BP)	Probable isotope stage equivalent*
IIa**	75,000 - 130,000	5a to 5e
IIc	200,000 to 250,000	7
IId	400,000 to 600,000	11, 13, or 15
IIb	see discussion below	

* see Shackleton (1987) for discussion of isotopic stage record of ice-volume and sea-level fluctuations.
** Aminozone IIa calibrated with radiometric dates.

These age estimates are generally consistent with independent geologic-age information. There is some uncertainty about whether aminozone IIa represents late Stage 5 (substage 5a) or early Stage 5 (substage 5e) deposits (e.g., Bloom, 1983; Wehmiller et al., 1988). Aminozone IIc has independent geologic-age control at two sites, supporting the Stage 7 age estimate. The age estimate for aminozone IId is controversial because the zone includes a site with a 200,000 year U-Th coral date (NB, Norris Bridge, Virginia - see Szabo, 1985) but also includes a site (MF, Mathew's Field, Virginia) with an older U-Th coral (≥ 340,000 yrs) date and another site (DCAD = Ri13-a, Dirickson Creek Agrigultural Ditch, Delaware) with a biostratigraphic age estimate of "middle Pleistocene" (Cronin et al., 1984).

Results for Southern Delaware

The preceeding discussion indicates that two major aminozones, representing times of deposition about 100,000 years and 500,000 years ago, are found in southern Delaware. The younger unit (IIa) is found at several sites in the Delmarva region and is interpreted as having been deposited during one or more of the high relative sea levels during marine isotope stage 5. The IIa unit includes sites that have been mapped as Omar as well as other units (Table 3). The older unit (IId) is represented by shells from Miller Creek, Delaware, core hole Qi54-02 (MC-4), Dirickson

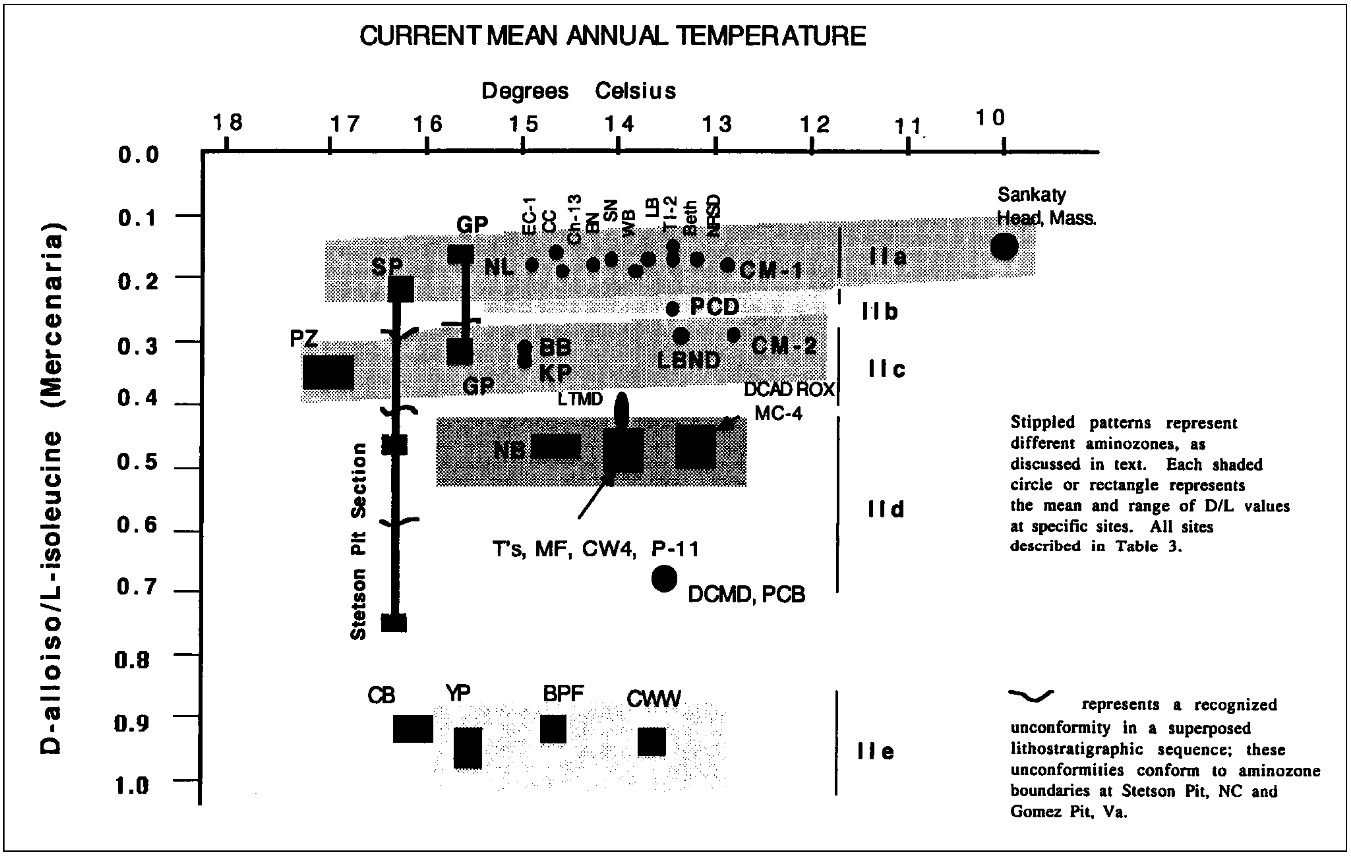

Figure 8. Aminostratigraphic data for sites from Massachusetts, New Jersey, Delaware, Maryland, Virginia, and North Carolina. Aminozones defined for Region II span the temperature range from 12.5˚ to 16˚ C (southeast New Jersey to southeast Virginia, respectively). Region I includes Massachusetts and New York (10-12˚ C), and Region III includes North Carolina (16˚-18˚ C). Locality abbreviations are identified in Table 3.

Creek Agricultural Ditch, Delaware, outcrop Ri13-a (DCAD), and from borehole Qi51-04 near Roxanna (ROX). Samples from these sites all apparently represent the upper (Quaternary) portion of the Omar Formation.

In April 1989 an excavation west of Lewes, Delaware (Nh44-a, Fig. 4; LBND, Figs. 6-8 and Table 3), exposed a bed of well-preserved molluscs, several of which have been analyzed for their amino acid enantiomeric ratios. These shells fall into aminozone IIc and represent the first example of this aminozone in Delaware (though it is also seen in southern New Jersey, J. Wehmiller, unpublished data).

Aminozone IIb is represented by samples from only one site, Pepper Creek Ditch, Qh41-a (PCD), so it is not clear if this particular aminozone is regionally significant. It is possible that the PCD samples belong to aminozone IIc and that the data from this site are misleading. The shells analyzed from PCD are not as well-preserved as at many other sites in the region, and poor preservation is often suspected as a cause of lowered D/L values. The effect of poor shell preservation on D/L values is under further investigation, but our current preferred interpretation of the Pepper Creek results is that samples from the site are probably pre-Stage 5 in age. A U-Th date of about 120,000 years was obtained on oyster shells from Pepper Creek (Mixon et al., 1982). This date is not unreasonable but its accuracy is doubtful because of the inherent problems of U-Th dating of molluscs (Kaufman et al., 1971; Mixon et al., 1982). The recognition of aminozone IIc at site Nh44-a (LBND) near Lewes (Figs. 6 and 7) provides some support for placing samples from site Qh41-a (PCD) in IIc, because shells from the former site were much better preserved than those from the latter.

SUMMARY AND CONCLUSIONS

A composite schematic summary of the geology of the Omar, Beaverdam, and Bethany formations is shown in Figure 9. The Bethany formation is composed of silts and clays with sand lenses. This lithology and lateral and vertical lithostratigraphic relationships indicate a deltaic environment with distributary channels. Palynologically, the formation is characterized by having low non-arboreal pollen and *Pinus* percentages, high frequencies of *Quercus* and *Carya,* and *Pterocarya, Sciadopitys,* and *Tsuga diversifolia*-type pollen as minor constituents; *Taxodium*-type pollen occur in most samples. This assemblage is similar to that of the Brandywine Formation in Maryland and the Eastover of Virginia; it suggests a warm temperate climate and a late Miocene or early Pliocene age.

The lower part of the Beaverdam Formation is a coarse sand with some gravel and scattered clay beds. It is overlain by a silty medium to coarse sand that fines upward. The boundary between these two lithofacies is gradational to sharp. The lower lithofacies is probably of fluvial origin and fills valleys eroded in the underlying Bethany formation; the upper one is of fluvial to estuarine origin.

Palynologically, the lower part of the Beaverdam cannot be distinguished from the Bethany; it suggests that the hia-

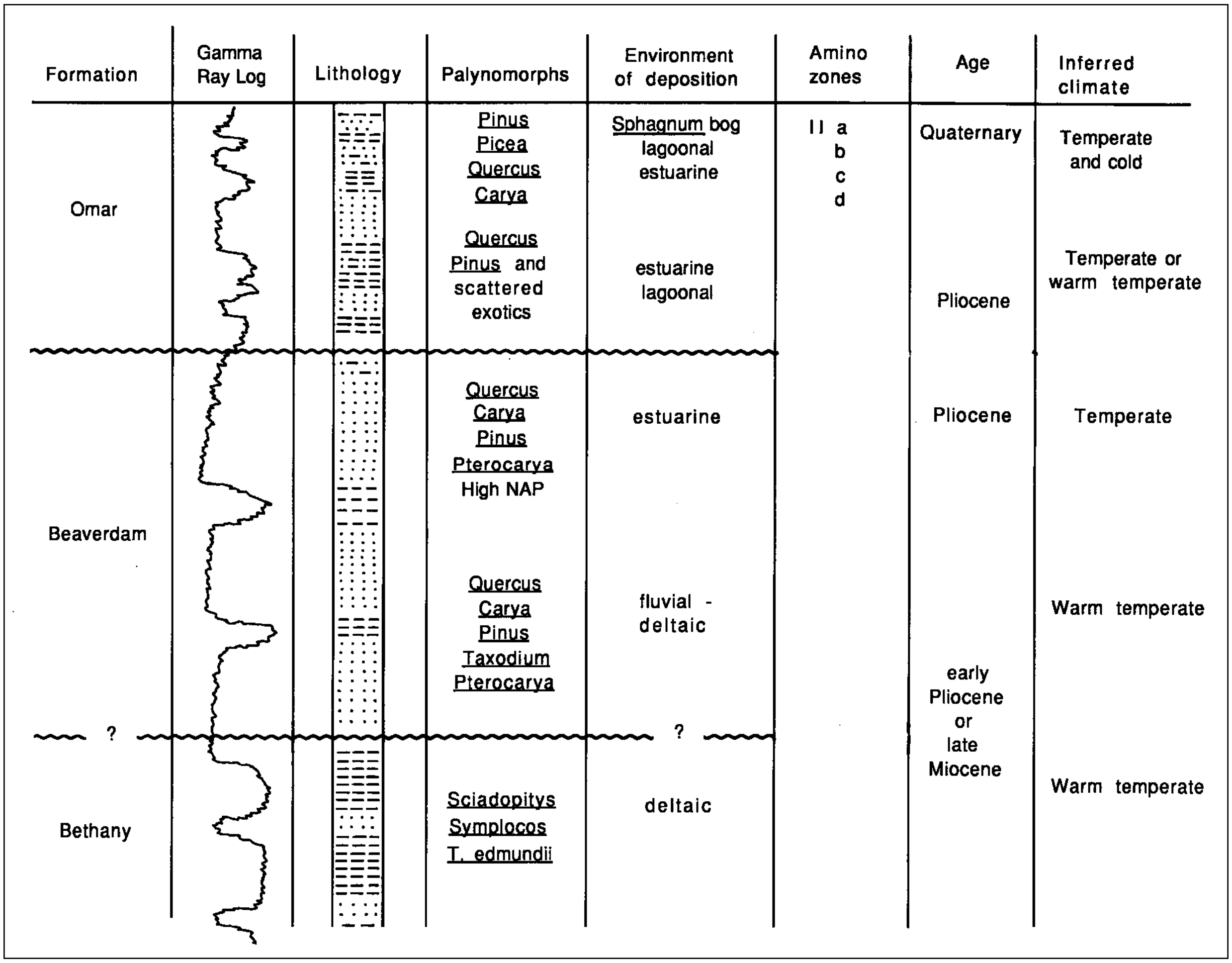

Figure 9. Composite schematic summary of the geology of the Omar, Beaverdam, and Bethany formations.

tus, if any, between the deposition of these two formations was relatively short, and that the lower part of the Beaverdam is of early Pliocene or late Miocene age and was deposited during a time of warm temperate climate. The upper Beaverdam facies has a rather different pollen assemblage, with high percentages of non-arboreal pollen (Compositae, Gramineae, Chenopodiaceae, fern, and *Sphagnum* spores), and exotic pollen limited to *Pterocarya.* This assemblage is similar to that of the Bacons Castle Formation of Virginia and indicates a late Pliocene age and a temperate climate. These different pollen assemblages and lithofacies may possibly indicate a disconformity between the two facies in the middle Pliocene. However, it is also quite possible that analysis of additional samples from different parts of the Beaverdam Formation would show a gradual change in the pollen assemblages of the two facies.

The lower part of the Omar Formation consists of interbedded fine sands, clayey silts, and silty clays that fill valleys cut into the underlying Beaverdam. This part of the Omar is palynologically characterized by the (scattered) presence of rare exotics, including *Pterocarya, Tricolporopollenites edmundii, Cupuliferoidaepollenites fallax, Engelhardia*-type (not the same species as found in the Calvert Formation), *Sciadopitys,* and *Taxodium*-type. This assemblage and the stratigraphic position of the formation indicate a Pliocene age. Above these sediments, complexly interbedded sands, silts, and clays have yielded microfloras indicating both cold and temperate climates and environments of deposition ranging from *Sphagnum* bog to brackish lagoon and estuary. These microfloras do not contain exotic pollen and indicate a Quaternary age.

Amino acid racemization analyses from shells in the upper (Quaternary) part of the Omar indicate the presence of three aminozones, representing discrete ages of roughly 100,000, 200,000, and 500,000 yrs for different outcrops included in the Omar Formation. No exotic pollen have been found in sediments of these ages, indicating that *Pterocarya, Sciadopitys,* and other exotic taxa were no longer present in southern Delaware at least half a million years ago.

The palynological data (Fig. 5) show abrupt changes in the pollen assemblages of the Omar that indicate changing environments of deposition related to sea level and climatic fluctuations and disconformities within the formation.

In summary, it has been shown that

(1) the Bethany formation is of late Miocene or early Pliocene age;

(2) the Columbia Group sediments (Beaverdam and Omar formations) range in age from late Miocene or early Pliocene to late Quaternary; and

(3) the thickness of Quaternary sediments in southeastern Sussex County is much less than was previously indicated, and Quaternary sediments are absent in some areas.

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APPENDIX

Borehole locations

Well Number	Latitude N	Longitude W
Je32-04	39˚ 07' 39"	75˚ 28' 58"
Me15-29	38˚ 54' 58"	75˚ 25' 16"
Oh25-02	38˚ 43' 50"	75˚ 10' 14"
Pc25-04	38˚ 38' 35"	75˚ 35' 49"
Pe23-06	38˚ 38' 13"	75˚ 26' 21"
Pg53-14	38˚ 35' 24"	75˚ 17' 42"
Pj42-03	38˚ 36' 26"	75˚ 04' 46"
Qh34-03	38˚ 32' 49"	75˚ 11' 31"
Qh44-01	38˚ 30' 54"	75˚ 11' 30"
Qi12-07	38˚ 34' 26"	75˚ 08' 58"
Qi51-04	38˚ 30' 20"	75˚ 09' 27"
Qi54-02	38˚ 30' 42"	75˚ 06' 31"
Qj22-06	38˚ 33' 32"	75˚ 03' 34"
Rf21-03	38˚ 28' 12"	75˚ 24' 54"
Rg22-01	38˚ 28' 45"	75˚ 18' 06"
Rg23-01	38˚ 28' 22"	75˚ 17' 14"
Ri13-10	38˚ 29' 05"	75˚ 07' 51"
Ri15-01	38˚ 29' 53"	75˚ 05' 47"

Outcrop locations

Outcrop Number	Latitude N	Longitude W
Nh44-a	38˚ 46' 15"	75˚ 11' 54"
Oh41-a	38˚ 41' 12"	75˚ 14' 33"
Qh41-a	38˚ 31' 37"	75˚ 14' 48"
Qi11-a	38˚ 34' 57"	75˚ 09' 18"
Ri13-a	38˚ 29' 45"	75˚ 07' 57"

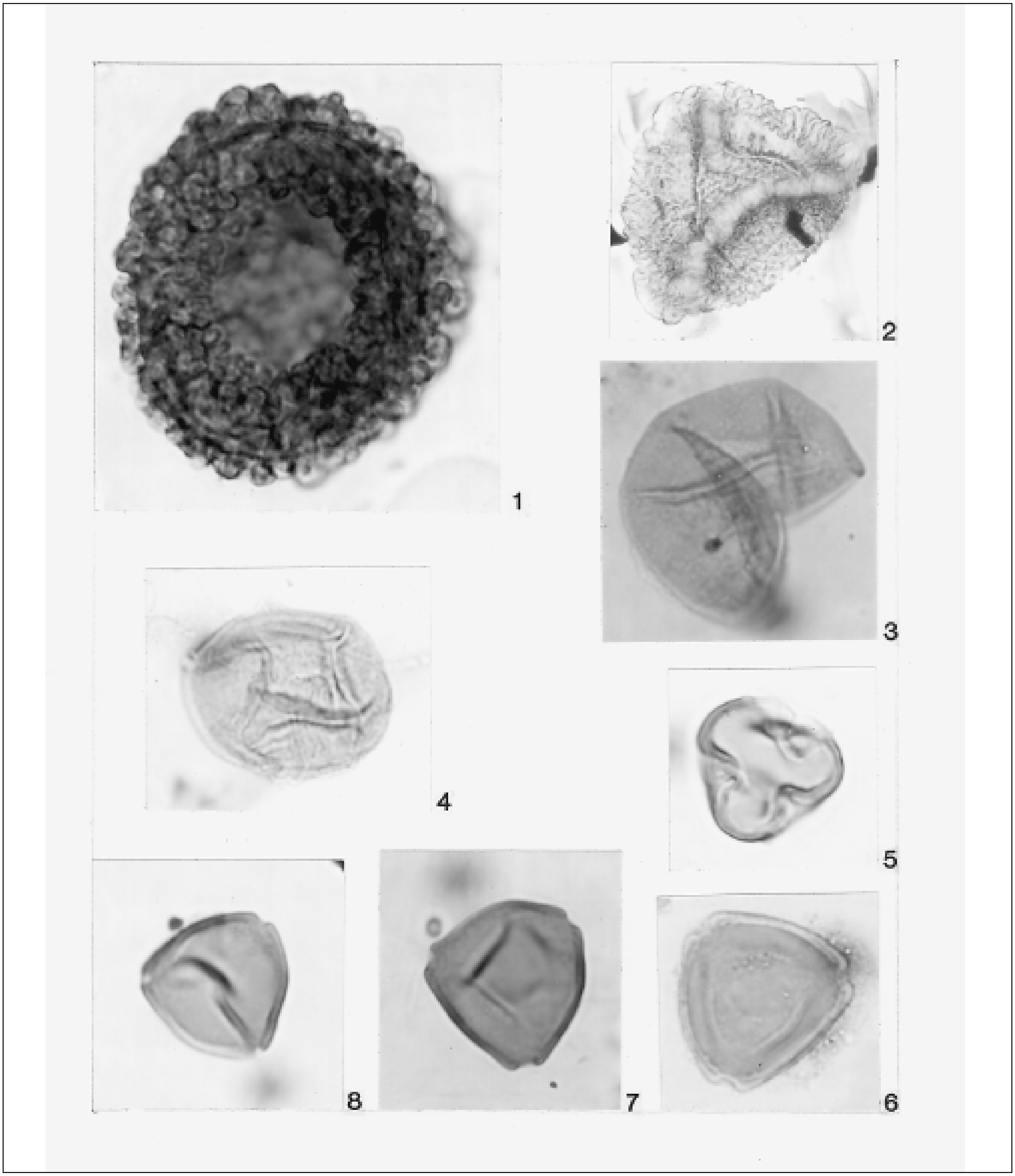

Figure 1. *Sciadopitys*, 44µ; sample 20775-2; Omar Formation; location V29 (England finder locations)

Figure 2. *Tsuga diversifolia*-type, 56µ; sample 20959; Bethany formation; location R48.

Figure 3. *Taxodium*-type, 25µ; sample 21333-A; Bethany formation; location V32.

Figure 4. *Sequoia*-type, 22µ; sample 20770-3; Omar Formation; location Y29/3.

Figure 5. *Cyrilla*, 15µ; sample 20741-1; Omar Formation; location S37.

Figure 6. *Engelhardia*-type, 18µ; sample 20756-1; Omar Formation, location U33/4.

Figure 7. *Engelhardia*-type, 18µ; sample 20754-1; Omar Formation, location T34.

Figure 8. *Engelhardia*-type, 16µ; sample 20771-1; Omar Formation, location Q36/4.

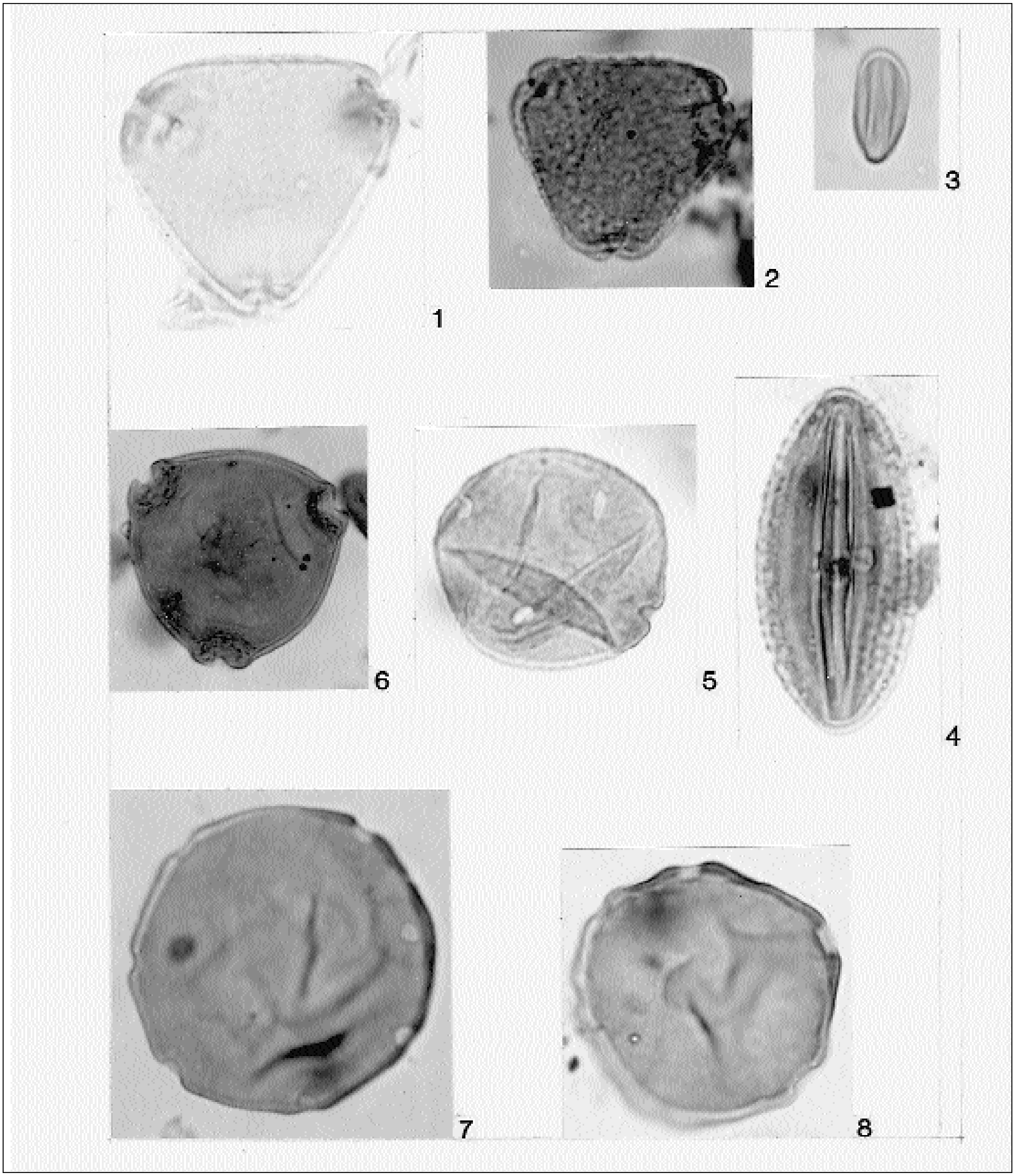

Figure 1. *Symplocos,* 28µ; sample 20772-2; Omar Formation; location Q36/3.

Figure 2. *Symplocos,* 22µ; sample 20959 IIA; Beaverdam Formation; location O35/3.

Figure 3. *Cupuliferoidaepollenites fallax,* 12 x 6µ; sample 20959 II A; Beaverdam Formation; location S42.

Figure 4. *Tricolporopollenites edmundii,* 36 x 17µ; sample 20738-1; Omar Formation; location X36/3.

Figure 5. *Ulmus serotina* type, 23µ; sample 20770-3; Omar Formation; location W35.

Figure 6. Onagraceae, 76µ; sample 20959 IIA; Beaverdam Formation; location Q38/3.

Figure 7. *Pterocarya,* 30µ; sample 20959 II A; Beaverdam Formation; location O36.

Figure 8. *Pterocarya,* 27µ; sample 21333-A; Bethany formation; location W32/2.