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Cenozoic Calcareous Nannofossil Biostratigraphy of the Dover Je32-04 Drillhole, Kent County, Delaware

By Laurel M. Bybell, Jean M. Self-Trail, and Thomas G. Gibson

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CENOZOIC CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF THE DOVER Je32-04 DRILLHOLE, KENT COUNTY, DELAWARE

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INTRODUCTION

In March of 1957, the Dover Je32-04 test well was drilled in Kent County, Delaware at the Dover Air Force base, which is located two miles southeast of the city of Dover (fig. 1). The well was drilled to a depth of 1,422 ft, and one 18-inch split-spoon core was taken every 10 ft, for a total of 142 cores. These cores, which are currently stored in the Delaware Geological Survey Core and Sample Library, were given the numbers 20570 through 20711. The initial geologic interpretations and descriptive and geophysical logs for the drillhole can be found in Rasmussen, Groot and Depman (1958). The cuttings, which were described by Rasmussen, Groot, and Depman (1958), later were discarded. Although there is a thick cover of Tertiary sediments in this part of the Salisbury embayment, the Dover drillhole is one of the few wells in the state of Delaware that provides cores of Paleogene sediments. For this reason, the Dover well has been used as an important source of data for other geologic and hydrologic studies in Delaware. Jordan studied the planktonic foraminifers (1962a) and the stratigraphy (1962b) of the drillhole. Talley (1975) correlated the Dover well sediments with those of another well near Greenwood, Delaware. Pickett and Benson (1983) issued a geologic map of the Dover area. More detailed stratigraphic studies of the Dover drillhole can be found in Benson and others (1985), and Spoljaric (1988) presented a detailed study of clay minerals from the cores.

In the current study, calcareous nannofossils were examined from Cenozoic portions of the Dover Je32-04 drillhole in order to better understand how the Delaware sediments relate to similarly aged deposits that have been previously studied in New Jersey, Maryland, and Virginia.

METHODS

Thirty-four samples between the depths of 977 and 717 ft and between 377 and 297 ft in the Dover drillhole were examined for their calcareous nannofossil content (see Appendix 2 for a correlation of the sample depths in feet with the previously assigned sample numbers). Calcareous nannofossil slides were prepared using standard settling techniques and were examined with a Zeiss Photomicroscope III.

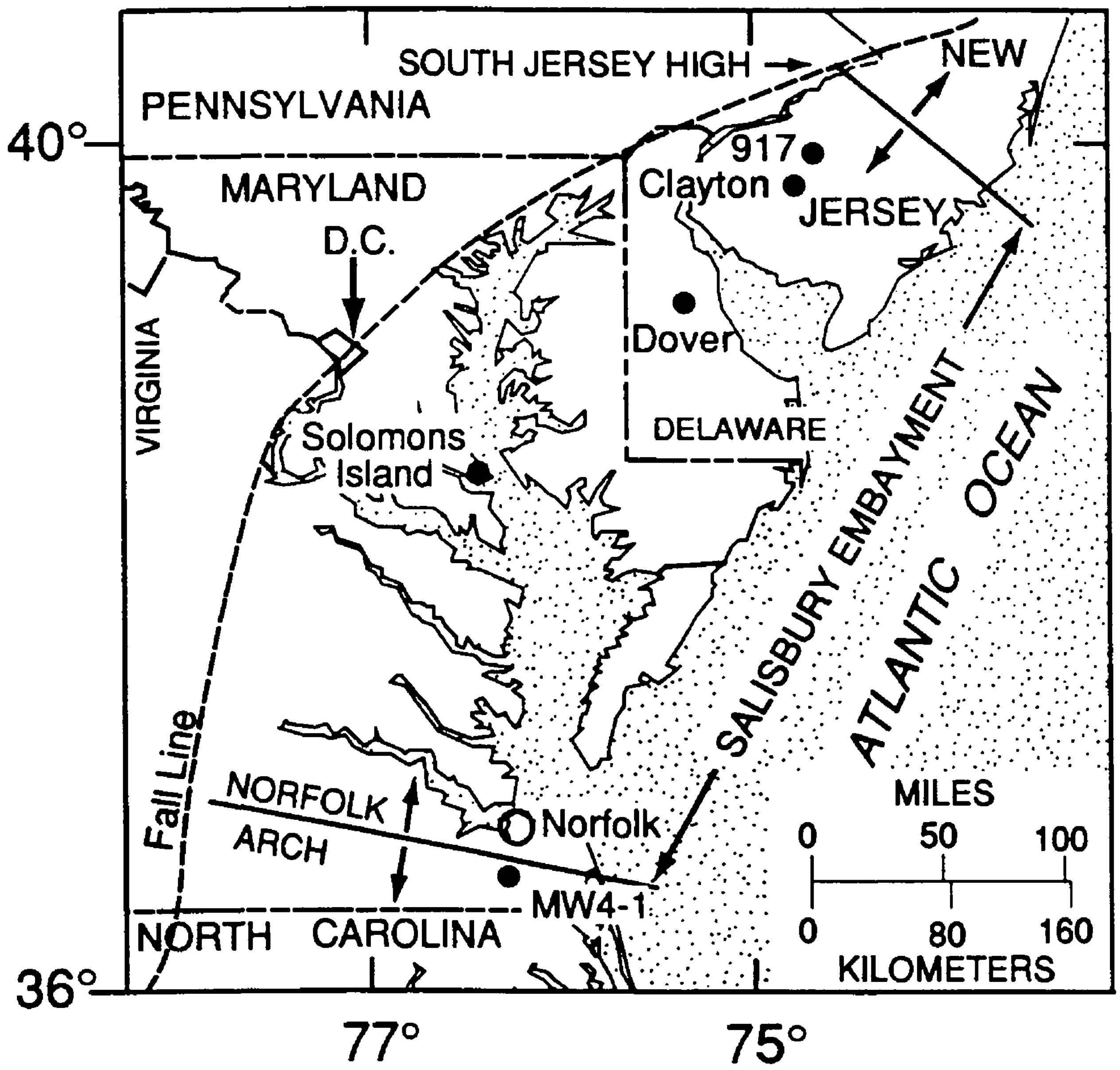

Figure 1. Location map for the Dover drillhole and other drillholes discussed in the text.

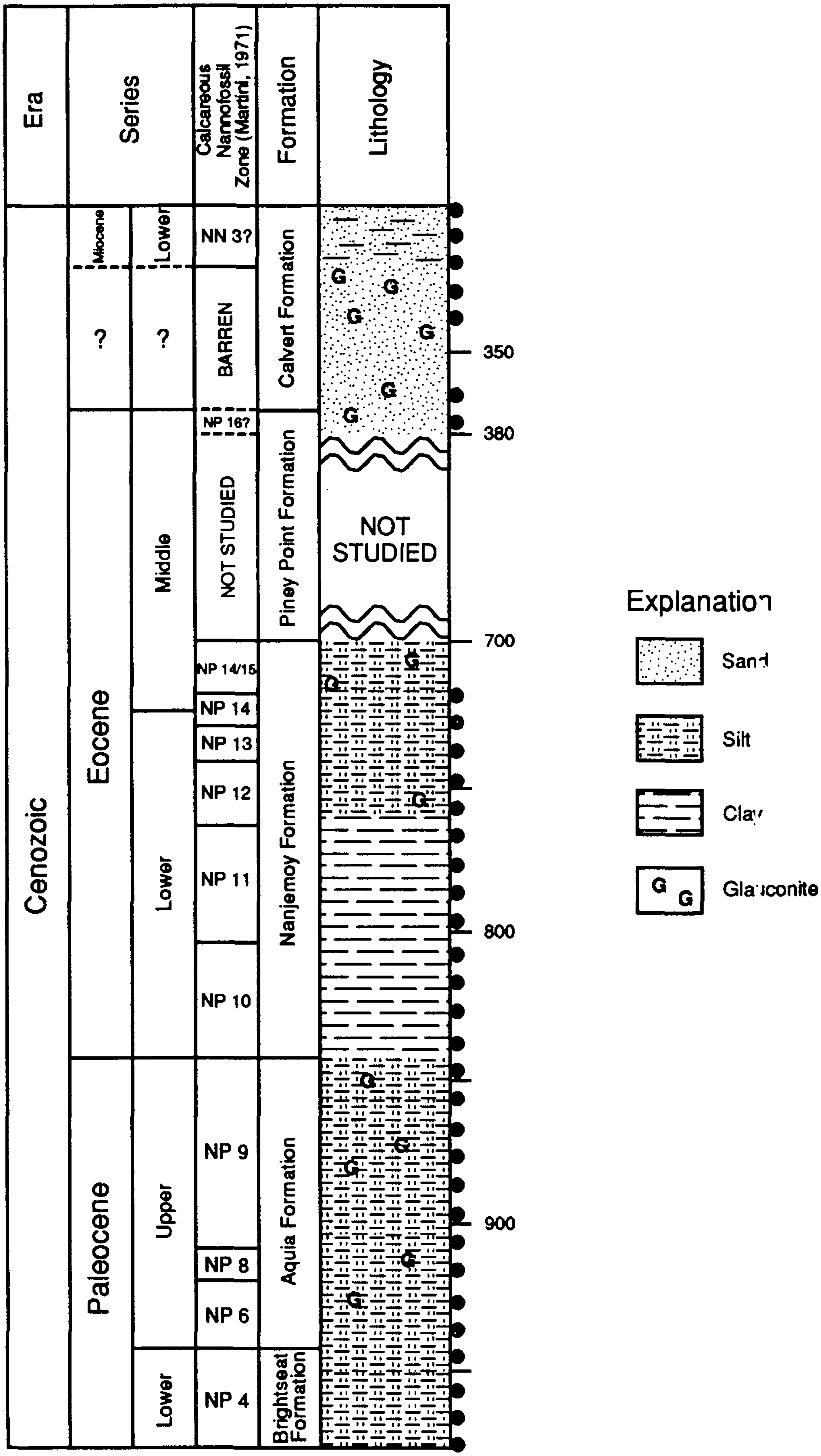

Figure 2. Calcareous nannofossil biostratigraphic zonation of intervals in the Dover drillhole. Lithology from Benson and others (1985) and Benson (pers. commun., 1995).

CENOZOIC LITHOLOGIC UNITS

Benson and others (1985) examined Cretaceous and Paleogene sediments in the Dover drillhole. They placed fine, glauconitic clays and silts that occur from 1,055 to 585 ft into the Pamunkey (?) Formation. Above the Pamunkey (?) Formation, Benson and others (1985) placed the fine to generally medium, glauconitic sands from 585 to 336 ft into the Piney Point Formation. This unit is overlain by the silt-sand sequences of the Calvert Formation from 336 to 44 ft and by the medium-grained subarkosic sand of the Columbia Formation from 40 ft to ground level. Benson (pers. commun., 1995) no longer uses the Pamunkey Formation for these sediments. He currently uses some formational names from the Maryland/Virginia area and some formational names from New Jersey: Hornerstown Formation (lower Paleocene) and Vincentown Formation (upper Paleocene) from New Jersey, Deal Member of the Manasquan Formation (lower to middle Eocene - this New Jersey unit is not used by members of the U.S. Geological Survey), and the Piney Point (middle Eocene) and Calvert Formations (lower Miocene) from the Maryland/Virginia area.

There has been some controversy concerning the lithologic units into which Delaware sediments are placed. The Paleogene and Neogene lithologic unit names commonly used in New Jersey are different from those used in Maryland and Virginia. In the past, the Delaware units have been given names from either New Jersey or the Maryland/Virginia region. In some cases, the sedimentary units in New Jersey and Maryland/Virginia are similar, both in lithology and age, and there are few problems in understanding their relationships. For example, the upper Paleocene Vincentown and Aquia Formations both are shelly glauconitic sands that have calcareous nannofossil biostratigraphic ranges from Zone NP 5 through Zone NP 9.

In other cases, there are significant differences between the two regions. For example, more complete Paleogene stratigraphic sections have been found in New Jersey than in Maryland and Virginia (Poore and Bybell, 1988), and there are biostratigraphic zones present in New Jersey that are absent in Maryland and Virginia. In addition, some of the New Jersey units were deposited in deeper water environments than comparable units in Maryland and Virginia with resulting lithologic differences (Thomas G. Gibson, unpubl. data). These differences result in some stratigraphic nomenclature complexities between the two areas.

The Dover drillhole, which is located between New Jersey and Maryland, contains units with lithologic characteristics that can be related to both areas. For example, the Marlboro Clay in Maryland is placed in the uppermost part of calcareous nannofossil Zone NP 9 and the lowest part of Zone NP 10 (Gibson and others, 1994). It is overlain by the Nanjemoy Formation, which contains very clayey glauconitic sand in Zones NP 10 and NP 11 and less clayey glauconitic sand in Zones NP 12 and 13 (Gibson and Bybell, 1994). In New Jersey, the lower part of the very clayey beds of the Manasquan Formation is coeval with the base of the Marlboro Clay (Gibson and others, 1993). However, deposition of these very clayey sediments continues for a longer period of time in New Jersey, and clayey sediments here extend up into Zone NP 14 (Poore and Bybell, 1988). In Delaware, the period of conspicuous clay deposition extends only into the lower part of Zone NP 12. This is a longer period of time than in Maryland, but less time than that in New Jersey.

For the purposes of this paper, we have chosen to use only stratigraphic units from the Maryland and Virginia region: the Brightseat Formation (lower Paleocene), the Aquia Formation (upper Paleocene), the Nanjemoy Formation (the lower Eocene but possibly also lower middle Eocene), the Piney Point Formation (middle Eocene), and the Calvert Formation (lower Miocene) (fig. 2). We believe that using terminology from one region is less confusing when presenting our data. However, other formational names may be more appropriate in the future. It may even be appropriate to establish new names for at least some of the lithologic units in Delaware.

BIOSTRATIGRAPHIC ZONATION

Calcareous Nannofossil Zonal Indicators

In this study, the biostratigraphic zonation of the Cenozoic strata is based primarily upon the calcareous nannofossil zonation of Martini (1971) and secondarily upon the zonation of Bukry (1973, 1978). The calcareous nannofossil assemblages typically are sufficient in numbers of specimens, diversity of taxa, and preservational state in the Dover drillhole strata to allow dating of almost all samples (fig. 3). There is evidence of contamination in several of the samples that were examined. The contaminated specimens can be distinguished fairly easily by their low numbers (one specimen per slide), inaccurate stratigraphic position, and somewhat poorer preservation.

The following calcareous nannofossil species can be used to date sediments of Paleocene, Eocene, and Miocene age. Many, but not all, of these species are present in the Delaware drillhole. FAD indicates a first appearance datum, and LAD indicates a last appearance datum. Zonal markers for the Martini zonation are indicated with an *, and a # indicates a zonal marker for the Bukry zonation. The remaining species are biostratigraphically useful in the Gulf and Atlantic Coastal Plains.

FAD *Discoaster variabilis* - near base of Zone NN 4; may occur sporadically within Zone NN 3, early Miocene
LAD *#*Sphenolithus belemnos* - top of Zone NN 3, early Miocene
LAD *Discoaster adamanteus* - within Zone NN 3, early Miocene
FAD **Sphenolithus belemnos* - base of Zone NN 3, early Miocene
LAD **Triquetrorhabdulus carinatus* - top of Zone NN 2, early Miocene
FAD *#*Discoaster druggi* - base of Zone NN 2, early Miocene
LAD *#*Chiasmolithus bidens/solitus* - top of Zone NP 16, middle Eocene
FAD *Cribrocentrum reticulatum* - within Zone NP 16, middle Eocene
LAD **Rhabdosphaera gladius* - top of Zone NP 15, middle Eocene
FAD *#*Nannotetrina fulgens* - base of Zone NP 15, base CP 13a, middle Eocene
FAD *#*Discoaster sublodoensis* - base of Zone NP 14, base CP 12a, early Eocene
FAD *Reticulofenestra* spp. - within Zone NP 13, early Eocene
LAD **Rhomboaster orthostylus* - top of Zone NP 12, early Eocene
FAD *Helicosphaera lophota* - near top of Zone NP 12; has been used to approximate the NP 12/NP 13 boundary, early Eocene
FAD *Helicosphaera seminulum* - mid Zone NP 12, early Eocene
FAD *#*Discoaster lodoensis* - base of Zone NP 12, base CP 10, early Eocene
FAD *Discoaster binodosus* - within Zone NP 11, early Eocene
LAD *#*Rhomboaster contortus* - top of Zone NP 10, top CP 9a, early Eocene
FAD *Rhomboaster orthostylus* - upper Zone NP 10, early Eocene
FAD #*Rhomboaster contortus* - mid Zone NP 10, base CP9A, early Eocene; Bukry places the base of the CP 9a Zone at the base of Martini's Zone NP 10, but this is much too low according to Perch-Nielsen (1985) and Bybell and Self-Trail (1995)
FAD #*Discoaster diastypus* - mid-Zone NP 10, base CP 9a, early Eocene
LAD *Placozygus sigmoides* - lower Zone NP 10, early Eocene
LAD *Fasciculithus* spp. - lower Zone NP 10, early Eocene
LAD *Hornibrookina* spp. - lower Zone NP 10, early Eocene
FAD **Rhomboaster bramlettei* - base of Zone NP 10, early Eocene
FAD *Transversopontis pulcher* sensu ampl. - upper Zone NP 9, late Paleocene
LAD *Scapholithus apertus* - upper Zone NP 9, late Paleocene
FAD *Discoaster mediosus* - within upper Zone NP 9, late Paleocene
FAD *Toweius occultatus* - within upper Zone NP 9, late Paleocene
FAD *Toweius callosus* - within Zone NP 9, late Paleocene
FAD *Lophodolithus nascens* - within Zone NP 9, late Paleocene
FAD #*Campylosphaera dela* - within Zone NP 9, base CP 8b, late Paleocene (includes *C. eodela*)
FAD *Discoaster lenticularis* - near base of Zone NP 9, late Paleocene
FAD *#*Discoaster multiradiatus* - base of Zone NP 9, base CP 8a, late Paleocene
FAD **Heliolithus riedelii* - base of Zone NP 8, late Paleocene
FAD #*Discoaster mohleri* - base CP 6, probably equivalent to base of Martini's Zone NP 7, late Paleocene
FAD **Heliolithus kleinpellii* - base of Zone NP 6, late Paleocene

FAD *Heliolithus cantabriae* - within upper part of Zone NP 5, late Paleocene
FAD *Scapholithus apertus* - within Zone NP 5, late Paleocene
FAD *Chiasmolithus bidens* - within Zone NP 5, late Paleocene
FAD *Toweius eminens* var. *tovae* - within Zone NP 5, late Paleocene
FAD **#Fasciculithus tympaniformis* - base of Zone NP 5, base CP 4, late Paleocene
FAD *Toweius pertusus* - within Zone NP 4
FAD *Ellipsolithus distichus* - near base of Zone NP 4, early Paleocene
FAD **Ellipsolithus macellus* - base of Zone NP 4, early Paleocene
FAD *Chiasmolithus consuetus* - within Zone NP 3, early Paleocene
FAD **Chiasmolithus danicus* - base of Zone NP 3, early Paleocene

Formation	Brightseat Formation			Aquia Formation											Nanjemoy Formation													Piney Point Formation	Calvert Formation					
Epoch	Paleocene														Eocene													Eocene	?			Miocene		
	Early			Late											Early												Middle	Middle	?			Early		
Calcareous Nannofossil Zone (Martini, 1971)	?	NP 4		NP 6			NP 8	NP 9							NP 10				NP 11				NP 12		NP 13	NP 14	NP 14/15	[illegible]	?			NN 3?		
Taxa / Depth (ft)	977	967	957	947	937	927	917	907	897	887	877	867	857	847	837	827	817	807	797	787	777	767	757	747	737	727	717	[illegible]	367	337	327	317	307	297
Barren	•									•																			•	•	•			
Biantholithus astralis							•					•																						
Biantholithus sparsus																			?															
Biscutum sp.		•		•				•					•	•			•																	
Blackites creber																									•									
Blackites scabrosus																												?						
Blackites spinosus																									?			•						
Blackites tenuis																									•	•	•							
Braarudosphaera bigelowii																																		•
Camplyosphaera dela																	•	•	•	•	•	•		•	•			•						
Cepekiella lumina																						?		•	•	•	•							
Chiasmolithus bidens				•	•	•	•	•	•			•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•						
Chiasmolithus bidens aff.		•	•																															
Chiasmolithus consuetus s.l.		•	•		•		•	•							•	•	•		•	•	•													
Chiasmolithus eograndis																						•	•	?										
Chiasmolithus grandis																										•	•							
Chiasmolithus large unsplit																									•									
Chiasmolithus small unsplit																							•				•							
Coccolithus cribellum			•																															
Coccolithus pelagicus				•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•				•	•	•
Cribrocentrum reticulatum																												?						
Cruciplacolithus primus			?																															
Cruciplacolithus tenuis		•	•									1																						
Cruciplacolithus sp.																		•				•				•	•	•						
Cyclagelosphaera prima		•	•		•		•								•		•	•																
Cyclagelosphaera reinhardtii			•																															
Cyclagelosphaera sp.						•						•		•																				
Cyclococcolithus formosus																								•	•	•	•	•						
Dictyococcites daviesi																																•		
Discoaster adamanteus																																	•	•
Discoaster barbadiensis																						?	?	?	•	•	•							
Discoaster binodosus																			•	•	•													
Discoaster deflandrei/distinctus																								•	•	•	•					•	•	•
Discoaster delicatus								•																										
Discoaster diastypus																	?		?															
Discoaster druggi																																		•
Discoaster falcatus															?																			
Discoaster kuepperi													?							•			•	•	•									
Discoaster lenticularis								•	•			•	•	•	•	•	•	•																
Discoaster limbatus												•				•	•	•	•	•		•		1										
Discoaster lodoensis																							•	•	•									
Discoaster mediosus															•		•	•																
Discoaster mirus																								•	•									
Discoaster mohleri aff.													•																					
Discoaster multiradiatus								•	•		•	•	•	•	•	•	•	•		•	•													
Discoaster nodifer																								?										
Discoaster saipanensis																											•							
Discoaster salisburgensis								•	•			•	•	•	•		•	•	•	•														

Figure 3. Distribution of calcareous nannofossil species in Dover drillhole. Abundance: A=abundant; C=common; F=few; R=rare. Preservation: G=good; F=fair; P=poor. Other symbols: 1, only one speciman observed in entire sample; C, specimens likely are contaminants; ?, possible occurrence.

Epoch	Brightseat Formation			Aquia Formation											Nanjemoy Formation													Piney Point Formation		Calvert Formation						
	Paleocene														Eocene														Eocene	?				Miocene		
Formation	Early			Late											Early												Middle	Not Sampled	Middle	?				Early		
Calcareous Nannofossil Zone (Martini, 1971)	?	NP 4		NP 6			NP 8	NP 9							NP 10				NP 11				NP 12		NP 13	NP 14	NP 14/1[illegible]		NP 16?	?				NN 3?		
Taxa / Depth (ft)	977	967	957	947	937	927	917	907	897	887	877	867	857	847	837	827	817	807	797	787	777	767	757	747	737	727	717		377	367	337	327	317	307	297
Discoaster splendidus							●					?		?																					
Discoaster sublodoensis																										●	●								
Discoaster tani																											?								
Discoaster variabilis																																	●		●
Discoaster sp.							●																												
Ellipsolithus bollii			?																																
Ellipsolithus distichus					●		●	●					●	●	●	●	●	●		●				●											
Ellipsolithus macellus			●				●								●		●	●	●	●	●	●													
Ericsonia subpertusa		●	●			●	●		●				●																						
Fasciculithus alanii												●	●																						
Fasciculithus cf. *aubertae*							●	●				●	●	●	●			●																	
Fasciculithus involutus				●	●		●	●	●			●	●	●	●		●	●																	
Fasciculithus schaubii													●	●																					
Fasciculithus sidereus													●	●																					
Fasciculithus thomasii													●	●																					
Fasciculithus tympaniformis					●	●																													
Fasciculithus sp.											●					●																			
Goniolithus fluckigeri							●																												
Helicosphaera carteri																																	●	●	●
Helicosphaera lophota																									●	●	●								
Helicosphaera seminulum																						C		●	●	●	●								
Heliolithus cantabriae		C		●	●	●																													
Heliolithus kleinpellii				●	●	●	?																												
Heliolithus riedelii							●																												
Holodiscolithus solidus																									●										
Hornibrookina arca															●	●		●																	
Lithostromation sp.																											●								
Lophodolithus nascens															●			●	●	●		●	●	●											
Lophodolithus reniformis																								●											
Markalius apertus		●	●				●	●	●			●	●							●															
Markalius inversus			●				●	●				●					●			●	●	●	●		●	●	●								
Markalius sp.																											●								
Micrantholithus sp.																											●								
Neochiastozygus concinnus		●	●	●	●	●	●	●					●		●	●	●	●	●	●	●														
Neochiastozygus denticulatus				?					●																										
Neochiastozygus digitosus					●																														
Neochiastozygus junctus					●	●	●																												
Neococcolithes cf. *dubius*																	●	●	●	●	●	●	●	●	●	●	●								
Neocrepidolithus sp.		●					●								●	●				●															
Pemma sp.																											●								
Placozygus sigmoides		●	●	●	●	●	●					●		●					1																
Pontosphaera aperta							●	●																											
Pontosphaera duocava																						●		●											
Pontosphaera multipora															●	●							●		●	●	●		●				●	●	●
Pontosphaera ocellata																									●										
Pontosphaera plana																				●		●			●										
Pontosphaera sp.																	●					●	●		●		●								

Figure 3. Continued

Formation	Brightseat Formation			Aquia Formation											Nanjemoy Formation													Piney Point Formation	Calvert Formation					
Epoch	Paleocene														Eocene													Eocene	?			Miocene		
	Early			Late											Early												Middle	Middle	?			Early		
Calcareous Nannofossil Zone (Martini, 1971)	?	NP 4		NP 6			NP 8	NP 9							NP 10				NP 11				NP 12		NP 13	NP 14	NP 14/15	[illegible]	?			NN 3?		
Taxa / Depth (ft)	977	967	957	947	937	927	917	907	897	887	877	867	857	847	837	827	817	807	797	787	777	767	757	747	737	727	717	[illegible]	367	337	327	317	307	297
Reticulofenestra floridana		C																																
Reticulofenestra sp.			C																	C		C		•	•	•	•	•				•	•	•
Rhabdosphaera truncata																						•	•											
Rhabdosphaera sp.																	•																	
Rhomboaster bramlettei															•	•	•	•																
Rhomboaster orthostylus																			•	•	•	•	•	•										
Scapholithus apertus						•	•	•										1																
Sphenolithus anarrhopus																			•	•	•	•	•											
Sphenolithus moriformis																				•	•	•		•			•							
Sphenolithus primus														•		•	•																	
Sphenolithus radians																								•	•	•	•							
Sphenolithus sp.							•						•		•			•																
Toweius callosus								•				•			•	•	•	•	•	•	•	•	•	•										
Toweius eminens eminens				•	•	•	•	•	•			•	•	•	•	•		•																
Toweius eminens tovae				•	•	•	•	•	•			•	•	•	•			1																
Toweius occultatus									1						•	•	•	•		•		•	•	•		1								
Toweius pertusus				•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•											
Toweius serotinus													•	•	•		•																	
Transversopontis pulcher															•	•	•	•		•	•	•	•	•	•	•	•	•						
Transversopontis pulcheroides																							•	•	•	•	•	•						
Transversopontis zigzag																												•						
Zygodiscus herlynii							•										•	•																
Zygrhablithus bijugatus						?														•		•	•	•	•	•	•	•						
Cretaceous forms			•																															
Placoliths											•																							
Abundance		C	C	A	A	A	C	A	F		R	F	F	C	C	C	A	A	C	C	A	A	A	C	A	C	C	C				C	C	C
Preservation		F	F	F	P	F	F	F	P		P	P	P	F	F	P	P	G	G	F	G	F	F	G	F	F	F	P				F	F	G

Figure 3. Continued

Brightseat Formation - early Paleocene, Zone NP 4

Three samples were examined from the unit the current authors call the Brightseat Formation. These samples are from 977, 967, and 957 ft. This interval is equivalent to the lower part of the Pamunkey (?) Formation of Benson and others (1985). Benson (pers. commun, 1995) currently uses Hornerstown Formation for these sediments. The lowest sample examined (977 ft) was barren of calcareous nannofossils. Calcareous nannofossils are common in the other two samples, and both are placed in calcareous nannofossil Zone NP 4 of Martini (1971). These samples contain *Chiasmolithus* aff. *C. bidens*, a form that resembles *Chiasmolithus bidens*, but differs in having an unsplit crossbar. Bybell (unpubl. data) has found that this form only occurs within Zone NP 4. In addition, the sample at 957 ft contains *Ellipsolithus macellus* (FAD defines the base of Zone NP 4). Neither sample contains *Fasciculithus tympaniformis* (FAD defines the base of Zone NP 5). The presence of one specimen each of *Heliolithus cantabriae* and *Reticulofenestra floridana* is attributed to contamination.

It is interesting to note that while sediments of an NP 4 age commonly occur within the Hornerstown Formation of New Jersey (Bybell, unpubl. data), no sediments of this age have been reported to date in Maryland or Virginia. In these two states, the Brightseat Formation contains strata belonging only to Zone NP 3.

Using planktonic foraminifers, Benson and others (1985) also placed these sediments within the early Paleocene.

Aquia Formation - late Paleocene, Zones NP 6, 8, 9

Eleven samples were examined from the unit the current authors call the Aquia Formation (947 to 847 ft). This unit is equivalent to the middle part of the Pamunkey (?) Formation of Benson and others (1985). Benson (pers. commun., 1995) currently uses Vincentown Formation for these sediments . The sample from 887 ft was barren of calcareous nannofossils, and they are rare in the sample from 877 ft.. The remaining nine samples contain frequent to abundant calcareous nannofossils.

Lower Aquia samples from 947, 937, and 927 ft are placed in Zone NP 6 by the presence of *Heliolithus kleinpellii* (FAD defines base of Zone NP 6) in all three samples. Several species that have their first appearance in Zone NP 5 are also present in this interval (*Chiasmolithus bidens, Fasciculithus involutus, F. tympaniformis, Heliolithus cantabriae, Toweius eminens* var. *eminens,* and *T. eminens*, var *tovae*). These taxa are not found in the underlying Brightseat sediments that are placed in Zone NP 4. *Discoaster gemmeus*, the FAD of which was used to define the base of Zone NP 7, is most probably equivalent to *Discoaster mohleri* as the latter is commonly used today. *Discoaster mohleri* is not present in this interval.

The sample from 917 ft is placed in Zone NP 8 by the presence of *Heliolithus riedelii* (FAD at base of Zone NP 8) and *Discoaster splendidus* (FAD within Zone NP 8) and by the absence of several species that first appear in Zone NP 9, particularly *Discoaster multiradiatus* (FAD defines the base of Zone NP 9).

Seven upper Aquia samples from 907 to 847 ft are placed in Zone NP 9 by the presence of *Discoaster multiradiatus* and the absence of *Rhomboaster bramlettei* (FAD defines the base of Zone NP 10). Several species that first appear in Zone NP 9 also first appear in this interval (*Discoaster lenticularis, D. limbatus, Fasciculithus schaubii,* and *F. sidereus*.

Benson and others (1985) also placed the sediments from 947 to 907 ft in the drillhole in the upper Paleocene. These sediments are in calcareous nannofossil Zones NP 6 and NP 8. However, they were unable to determine whether the sediments from 897 to 847 ft were late Paleocene or early Eocene in age. In the current study, calcareous nannofossils could accurately place these sediments in the late Paleocene Zone NP 9.

Nanjemoy Formation - early Eocene, Zones NP 10-14

Thirteen samples were examined from the unit the current authors call the Nanjemoy Formation from 837 to 717 ft. This unit is equivalent to the upper part of the Pamunkey (?) Formation of Benson and others (1985). Benson (pers. commun., 1995) currently uses the Deal Member of the Manasquan Formation for these sediments. The Paleocene-Eocene boundary is placed between the Aquia and Nanjemoy Formations, which is between Zones NP 9 and NP 10 or between 847 and 837 ft in the Dover drillhole. All of the Nanjemoy samples contain abundant or common calcareous nannofossils.

Four lower Nanjemoy samples from 837 to 807 ft are placed in Zone NP 10 by the presence of *Rhomboaster bramlettei* (FAD defines the base of Zone NP 10 and its LAD occurs near the top of Zone NP 10). The presence of *Fasciculithus involutus* in the uppermost Zone NP 10 sample (LAD in the lower part of Zone NP 10) and the absence of *Rhomboaster contortus* (FAD in the middle part of Zone NP 10) and *Rhomboaster orthostylus* (FAD near the top of Zone NP 10) indicates that much of the upper part of Zone NP 10 probably is missing in the Dover drillhole.

Four Nanjemoy samples from 797 to 767 ft are placed in Zone NP 11 by the absence of *Rhomboaster bramlettei* and the presence of *Discoaster binodosus* (FAD within Zone NP 11) and *Discoaster multiradiatus* (LAD within Zone NP 11). *Discoaster lodoensis* (FAD defines the base of zone NP 12) is also absent within this interval.

Two Nanjemoy samples from 757 and 747 ft are placed in Zone NP 12 by the presence of *Discoaster lodoensis* (FAD defines the base of Zone NP 12) and the continued presence of *Rhomboaster orthostylus* (LAD defines the top of Zone NP 12). A sample from 737 ft is placed in Zone NP 13 by the absence of *Rhomboaster orthostylus* and the presence of *Helicosphaera lophota* (FAD occurs within the uppermost part of Zone NP 12, but the first appearance of this species has been used to approximate the Zone NP 12/13 boundary).

The sample from 727 ft is place Zone NP 14 by the presence of *Discoaster sublodoensis* (FAD defines the base of Zone NP 14 and LAD is within Zone NP 15) and the absence of the genus *Nannotetrina* (FAD marks the base of Zone NP 15). The sample from 717 ft is placed in either the upper part of Zone NP 14 or in the lower part of Zone NP 15. The genus *Pemma*, which first appears in the upper part of Zone NP 14, is present in the sample at 717 ft, but is absent in the underlying sample from 727 ft. Another indication that this material is from the upper part of Zone NP 14 is the presence in the sample from 717 ft of late forms of *D. sublodoensis*.

Benson and others (1985) also placed the majority of these sediments within the lower Eocene. They placed the lower-middle Eocene break between 737 and 727 ft in the Dover drillhole. Using calcareous nannofossils, the lower-middle Eocene break is within Zone NP 14 (Berggren and others, 1985). If the sample at 727 ft is in lower Zone NP 14, then this would have a early Eocene age. If the sample is in the upper part of Zone NP 14, then it is in the middle Eocene. For the purposes of this paper, based upon the appearance of *Discoaster sublodoensis*, we placed this sample in the lower part of Zone NP 14, thus within the early Eocene. However, this isn't completely conclusive, and there is a possibility that this sample could be within the middle Eocene.

We agree with Benson and others (1985) that the samples between 717 (Zone NP 14/15) and 377 ft (probable Zone NP 16), which were not examined in the present study, are middle Eocene in age.

Piney Point Formation - middle Eocene, probably Zone NP 16

One sample was examined from the unit that the current authors and Benson and others (1985) call the Piney Point Formation. This sample at 377 ft. is most likely in Zone NP 16 on the presence of a probable occurrence of *Cribrocentrum reticulatum* (FAD within Zone NP 16) and definite occurrence of *Chiasmolithus bidens* (LAD at the top of Zone NP 16). We agree with Benson and others (1985) that the sample from 377 ft is in the middle Eocene.

Calvert Formation - early Miocene, probably Zone NN 3

Six samples were examined from the unit that the current authors and Benson (pers. commun., 1995) call the Calvert Formation. This is a change from Benson and others (1985), who originally placed the samples at 367 and 337 feet in the Piney Point Formation. The samples from 367, 337, and 327 ft are barren of calcareous nannofossils. Calcareous nannofossils are common in the samples from 317, 307, and 297 ft. These three samples are probably in Zone NN 3 on the presence of *Discoaster adamanteus* (LAD in upper part of Zone NN 3) and *Discoaster variabilis* (probably first occurs sporadically within the upper part of Zone NN 3). The FAD and LAD of *Sphenolithus belemnos* defines Zone NN 3, but this species was not observed.

Based on planktonic foraminifers, Benson and others (1985) originally placed the three samples from 317, 307, and 297 ft in the upper Oligocene. Benson (pers. commun, 1995) now places these samples in the lower Miocene (probably in foraminiferal Zone N5).

CLAY MINERALOGY

Additional information on the completeness of the upper Paleocene and lower Eocene record in the Dover drillhole can be gained from an examination of the clay mineral suites. Gibson and others (1993) found large-scale changes in the proportions of different clay minerals in upper Paleocene and lower Eocene strata in the Clayton and GL 917 drillholes of New Jersey (fig. 1). In the lower and middle parts of the upper Paleocene, the clay mineral suites are dominated by illite/smectite, with kaolinite usually composing less than five percent of the suite. In the uppermost Paleocene deposits of calcareous nannofossil Zone NP 9, however, the proportion of kaolinite rapidly increases and composes more than 50 percent of the suite, and there is a corresponding decrease in the proportion of illite/smectite. The kaolinite proportion begins to decrease through the uppermost part of Zone NP 9. After the peak values near the top of Zone NP 9, it rapidly decreases through the lowest part of Zone NP 10 until there are low values of five percent or less in the lower part of Zone NP 10.

Gibson and others (1994) found that this pattern of a great increase in the proportion of kaolinite in the uppermost Paleocene also is present in deposits in the central and southern parts of the Salisbury embayment in Maryland and Virginia. In more upbasin locations in these states, Eocene and younger erosional truncation of many outcrop and subsurface sections commonly removed the upper part of this kaolinite "curve" that shows the upward decrease from the peak proportion of kaolinite. The erosion leaves only the lower part of these strata, the part that records the increase from low to high kaolinite proportions. In drillholes located in more downbasin areas of these two states, however, such as Solomons Island and MW4-1 (fig. 1), only the portion of the kaolinite curve showing the decrease from high or peak values to lower values is present. Beds that contain the uppermost Paleocene increase in kaolinite either were deposited here and subsequently eroded, possibly by submarine currents, or they never were deposited. Gibson and others (1993) showed that the uppermost Paleocene kaolinite increase occurs during a time of rising sea level. With the relatively low sedimentation rates that characterize Paleocene and Eocene strata in the Salisbury embayment, a significant rise in sea level would cause much or all of the incoming sediment to be trapped in nearshore areas because of the increased accommodation space that would be available. Under these conditions, little or no sediment would reach the more downbasin areas. This condensation of section is our presently preferred explanation for the absence of the kaolinite increase because all downbasin drillholes, including DSDP Site 605, do not have this part of the section. Somewhat lower sea levels that are suggested by the New Jersey deposits at approximately the Zone NP 9/10 boundary (Gibson and others, 1993) presumably would have allowed the basinward progradation of slightly younger sediments that document the kaolinite decrease.

The Dover drillhole is located in a considerably downbasin position in relation to the Clayton corehole (Richard Benson, written commun., 1995). Spoljaric (1988) illustrated x-ray traces of the clays and clay-size minerals from each of the cores in the Dover drillhole. The x-ray traces for the samples that we place herein in Zone NP 9 and NP 10 show only relatively small amounts of kaolinite. Neither an appreciable increase or decrease of kaolinite during this time interval is readily visible on the x-ray traces. Thus, the Dover drillhole also appears to demonstrate the absence of sediments containing the kaolinite increase in more downbasin areas. In addition, beds containing the kaolinite decrease in the uppermost part of Zone NP 9 and lowermost part of Zone NP 10 appear to be absent as well. A likely possibility for the absence of these beds is that the Dover drillhole is located sufficiently downbasin so that sedimentation did not reach this offshore area until somewhat after the lowermost Zone NP 10 time of kaolinite decrease. Another possibility is that the kaolinite decrease is represented by a condensed interval that is present in the relatively thick intervals between cores.

The sample at 807 ft does show a modest increase in kaolinite. This is the lowest sample in what Spoljaric (1988) called Zone XIII. Gibson and others (1994) reported that thin intervals of high kaolinitic sediments commonly occur in lower and middle Eocene beds immediately above disconformities. We feel that erosion of the highly kaolinitic sediments, which occurs in more upbasin areas during the time of lowered sea level, is represented by a disconformity and that these kaolinitic sediments are recycled into the basal part of the succeeding sequence.

The absence of sediments in the Dover drillhole belonging to the uppermost part of Zone NP 9, which is suggested by the absence of the uppermost Paleocene increase in kaolinite proportion, is supported by the composition of the calcareous nannofossil assemblage. Gibson and others (1993) and Bybell and Self-Trail (1995) show that some species have either their last appearance datum (LAD) or first appearance datum (FAD) in the upper part of Zone NP 9 at approximately the same time as the beginning of the kaolinite increase. In the northeastern U.S. *Biantholithus astralis* and *Scapholithus apertus* occur through the lower part of Zone NP 9 but not in the uppermost part of this zone where the kaolinite increase occurs. The presence of these species in the Zone NP 9 strata in the Dover well suggests that only beds belonging to the lower part of Zone NP 9 occur here. The absence in the Dover Zone NP 9 samples of *Campylosphaera dela*, *Discoaster mediosus* s.l., *Toweius occultatus*, and *Transversopontis pulcher*, all species which have their FAD's in the upper part of Zone NP 9, suggests that the uppermost part of this zone is not present. It is possible, however, that the upper part of Zone NP 9 was present in the 8.5 ft uncored intervals between the 18 inch long cores and was simply not sampled.

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REFERENCES CITED

Benson, R.N., Jordan, R.R., and Spoljaric, Nenad, 1985, Geological studies of Cretaceous and Tertiary section, Test Well Je32-04, central Delaware: Delaware Geological Survey Bulletin No. 17, 69 p.

Berggren, W.A., Kent, D.V., Flynn, J.J., and Van Couvering, J.A., 1985, Cenozoic geochronology: Geological Society of America Bulletin, v. 96, p. 1407-1418.

Bukry, David, 1973, Low-latitude coccolith biostratigraphic zonation, *in* Edgar, N.T., and others, Initial reports of the Deep Sea Drilling Project, v. 15: Washington, D.C., U.S. Government Printing Office, p. 685-703.

Bukry, David, 1978, Biostratigraphy of Cenozoic marine sediments by calcareous nannofossils: Micropaleontology, v. 24, p. 44-60.

Bybell, L.M., and Self-Trail, J.M., 1995, Evolutionary, biostratigraphic, and taxonomic study of calcareous nannofossils from a continuous Paleocene-Eocene boundary section in New Jersey: U.S. Geological Survey Professional Paper 1554, 113 p.

Gibson, T.G., and Bybell, L.M., 1994, Paleogene stratigraphy of the Solomons Island, Maryland corehole: U.S. Geological Survey Open-file Report 94-708,p. 1-39.

Gibson, T.G., Bybell, L.M., and Owens, J.P., 1993, Latest Paleocene biologic and lithologic events in neritic deposits of southwestern New Jersey: Palaeoceanography, v. 8, p. 495-514.

Gibson, T.G., Bybell, L.M., Owens, J.P., Mason, D.B., McCartan, Lucy, and Snow, J.N., 1994, Climatic and stratigraphic implications of clay mineral changes in Paleocene/Eocene boundary deposits of the eastern U.S.: Geological Society of America Abstracts with Programs, v. 26, no. 4, p. 15.

Jordan, R.R., 1962a, Planktonic Foraminifera and the Cretaceous-Tertiary boundary in central Delaware: Delaware Geological Survey Report of Investigations No. 5, 13 p.

Jordan, R.R., 1962b, Stratigraphy of the sedimentary rocks of Delaware: Delaware Geological Survey Bulletin No. 9, 51 p.

Martini, Erlend, 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation: Planktonic Conference, 2d, Rome 1969, Proceedings, p. 739-785.
Pickett, T.E., and Benson, R.N., 1983, Geology of the Dover area, Delaware: Delaware Geological Survey Geologic Map Series No. 6, 1:24,000.
Poore, R.Z., and Bybell, L.M., 1988, Eocene to Miocene biostratigraphy of New Jersey core ACGS # 4: Implications for regional stratigraphy: U.S. Geological Survey Bulletin 1829, 22 p.
Rasmussen, W.C., Groot, J.J., and Depman, A.J., 1958, High-capacity test well developed at the Dover Air Force Base: Delaware Geological Survey Report of Investigations No. 2, 36 p.
Spoljaric, Nenad, 1988, Clay and clay-size mineral composition of the Cretaceous-Tertiary section, test-well Je32-04, central Delaware: Delaware Geological Survey Bulletin No. 18, 28 p.
Talley, J.H., 1975, Cretaceous and Tertiary section, deep test well, Greenwood, Delaware: Delaware Geological Survey Report of Investigations No. 23, 51 p.

APPENDIX 1. Complete Names for Calcareous Nannofossil Species Mentioned in Paper

Biantholithus astralis Steinmetz & Stradner, 1984
Blackites creber Deflandre *in* Deflandre and Fert, 1954) Stradner & Edwards
Blackites spinosus (Deflandre & Fert, 1954) Hay & Towe, 1962
Blackites tenuis (Bramlette & Sullivan, 1961) Sherwood, 1974
Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947
Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Cepekiella lumina (Sullivan, 1965) Bybell, 1975
Chiasmolithus bidens (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus consuetus (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus danicus (Brotzen, 1959) Hay & Mohler, 1967
Chiasmolithus eograndis Perch-Nielsen, 1971
Chiasmolithus grandis (Bramlette & Riedel, 1954) Hay, Mohler, & Wade, 1966
Chiasmolithus solitus (Bramlette & Sullivan, 1961) Hay, Mohler, & Wade, 1966
Coccolithus cribellum (Bramlette & Sullivan, 1961) Stradner, 1962
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930
Cribrocentrum reticulatum (Gartner & Smith, 1967) Perch-Nielsen, 1971
Cruciplacolithus primus Perch-Nielsen, 1977
Cruciplacolithus tenuis (Stradner, 1961) Hay & Mohler, *in* Hay and others, 1967
Cyclagelosphaera prima (Bukry, 1969) Bybell & Self-Trail, 1995
Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968) Romein, 1977
Cyclococcolithus formosus Kamptner, 1963
Discoaster adamanteus Bramlette & Wilcoxon, 1967
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster binodosus Martini, 1958

Discoaster deflandrei Bramlette & Riedel, 1954
Discoaster delicatus Bramlette & Sullivan, 1961
Discoaster diastypus Bramlette & Sullivan, 1961
Discoaster distinctus Martini, 1958
Discoaster druggi Bramlette & Wilcoxon, 1967
Discoaster falcatus Bramlette & Sullivan, 1961
Discoaster gemmeus Stradner, 1959
Discoaster kuepperi Stradner, 1959
Discoaster lenticularis Bramlette & Sullivan, 1961
Discoaster limbatus Bramlette & Sullivan, 1961
Discoaster lodoensis Bramlette & Riedel, 1954
Discoaster mediosus Bramlette & Sullivan, 1961
Discoaster mirus Deflandre *in* Deflandre and Fert, 1954
Discoaster mohleri Bukry & Percival, 1971
Discoaster multiradiatus Bramlette & Riedel, 1954
Discoaster nodifer (Bramlette & Riedel, 1954) Bukry, 1973
Discoaster salisburgensis Stradner, 1961
Discoaster splendidus Martini, 1960
Discoaster sublodoensis Bramlette & Sullivan, 1961
Discoaster variabilis Martini & Bramlette, 1963
Ellipsolithus bollii Perch-Nielsen, 1977
Ellipsolithus distichus (Bramlette & Sullivan, 1961) Sullivan, 1964
Ellipsolithus macellus (Bramlette & Sullivan, 1961) Sullivan, 1964
Ericsonia subpertusa Hay & Mohler, 1967
Fasciculithus alanii Perch-Nielsen, 1971
Fasciculithus aubertae Haq & Aubry, 1981
Fasciculithus involutus Bramlette & Sullivan, 1961
Fasciculithus schaubii Hay & Mohler, 1967
Fasciculithus sidereus Bybell & Self-Trail, 1995
Fasciculithus thomasii Perch-Nielsen, 1971
Fasciculithus tympaniformis Hay & Mohler *in* Hay and others, 1967
Goniolithus fluckigeri Deflandre, 1957
Helicosphaera carteri (Wallich, 1877) Kamptner, 1954
Helicosphaera lophota (Bramlette & Sullivan, 1961) Locker, 1973
Helicosphaera seminulum Bramlette & Sullivan, 1961
Heliolithus cantabriae Perch-Nielsen, 1971
Heliolithus kleinpellii Sullivan, 1964
Heliolithus riedelii Bramlette & Sullivan, 1961
Holodiscolithus solidus (Deflandre *in* Deflandre and Fert, 1954) Roth, 1970
Hornibrookina arca Bybell & Self-Trail, 1995
Lophodolithus nascens Bramlette & Sullivan, 1961
Lophodolithus reniformis Bramlette & Sullivan, 1961
Markalius apertus Perch-Nielsen, 1979
Markalius inversus (Deflandre *in* Deflandre and Fert, 1954) Bramlette & Martini,

1964

Nannotetrina fulgens (Stradner, 1960) Achuthan & Stradner, 1969
Neochiastozygus concinnus (Martini, 1961) Perch-Nielsen, 1971
Neochiastozygus denticulatus (Perch-Nielsen, 1969) Perch-Nielsen, 1971
Neochiastozygus digitosus Perch-Nielsen, 1971
Neochiastozygus junctus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre *in* Deflandre and Fert, 1954) Black, 1967
Placozygus sigmoides (Deflandre *in* Deflandre and Fert, 1954) Black 1967
Pontosphaera aperta (Perch-Nielsen, 1971) Aubry, 1986
Pontosphaera duocava (Bramlette & Sullivan, 1961) Romein, 1979
Pontosphaera multipora (Kamptner ex Deflandre, 1959) Roth, 1970
Pontosphaera plana (Bramlette & Sullivan, 1961) Haq, 1971
Reticulofenestra floridana (Roth & Hay *in* Hay and others 1967) Theodoridis, 1984
Rhabdosphaera gladius Locker, 1967
Rhabdosphaera truncata Bramlette & Sullivan, 1961
Rhomboaster bramlettei (Brönnimann & Stradner, 1960) Bybell & Self-Trail, 1995
Rhomboaster contortus (Stradner, 1958) Bybell & Self-Trail, 1995
Rhomboaster orthostylus (Shamrai, 1963) Bybell & Self-Trail, 1995
Scapholithus apertus Hay & Mohler, 1967
Sphenolithus anarrhopus Bukry & Bramlette, 1969
Sphenolithus belemnos Bramlette & Wilcoxon, 1967
Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967
Sphenolithus primus Perch-Nielsen, 1971
Sphenolithus radians Deflandre *in* Grasse, 1952
Toweius callosus Perch-Nielsen, 1971
Toweius eminens var. *eminens* (Bramlette & Sullivan, 1961) Bybell & Self-Trail, 1995
Toweius eminens var. *tovae* Bybell & Self-Trail, 1995
Toweius occultatus (Locker, 1967) Perch-Nielsen, 1971
Toweius pertusus (Sullivan, 1965) Romein, 1979
Toweius serotinus Bybell & Self-Trail, 1995
Transversopontis pulcher (Deflandre *in* Deflandre and Fert, 1954) Perch-Nielsen, 1967
Transversopontis pulcheroides (Sullivan, 1964) Baldi-Beke, 1971
Transversopontis zigzag Roth & Hay *in* Hay and others, 1967
Triquetrorhabdulus carinatus Martini, 1965
Zygodiscus herlyni Sullivan, 1964
Zygrhablithus bijugatus (Deflandre *in* Deflandre and Fert, 1954) Deflandre, 1959

APPENDIX 2. Depth in Feet of Dover Well Samples Examined for Calcareous Nannofossils Correlated to Sample Numbers from Benson and others (1985).

depth in feet	sample number
297	20597
307	20598
317	20599
327	20600
337	20601
367	20604
377	20605
Interval not sampled in present study	
717	20639
727	20640
737	20641
747	20642
757	20643
767	20644
777	20645
787	20646
797	20647
807	20648
817	20649
827	20650
837	20651
847	20652
857	20653
867	20654
877	20656
887	20657
897	20658
907	20659
917	20660
927	20661
937	20662
947	20663
957	20664
967	20665
977	20666