Post-middle Miocene origin of modern landforms in the eastern Piedmont of Virginia

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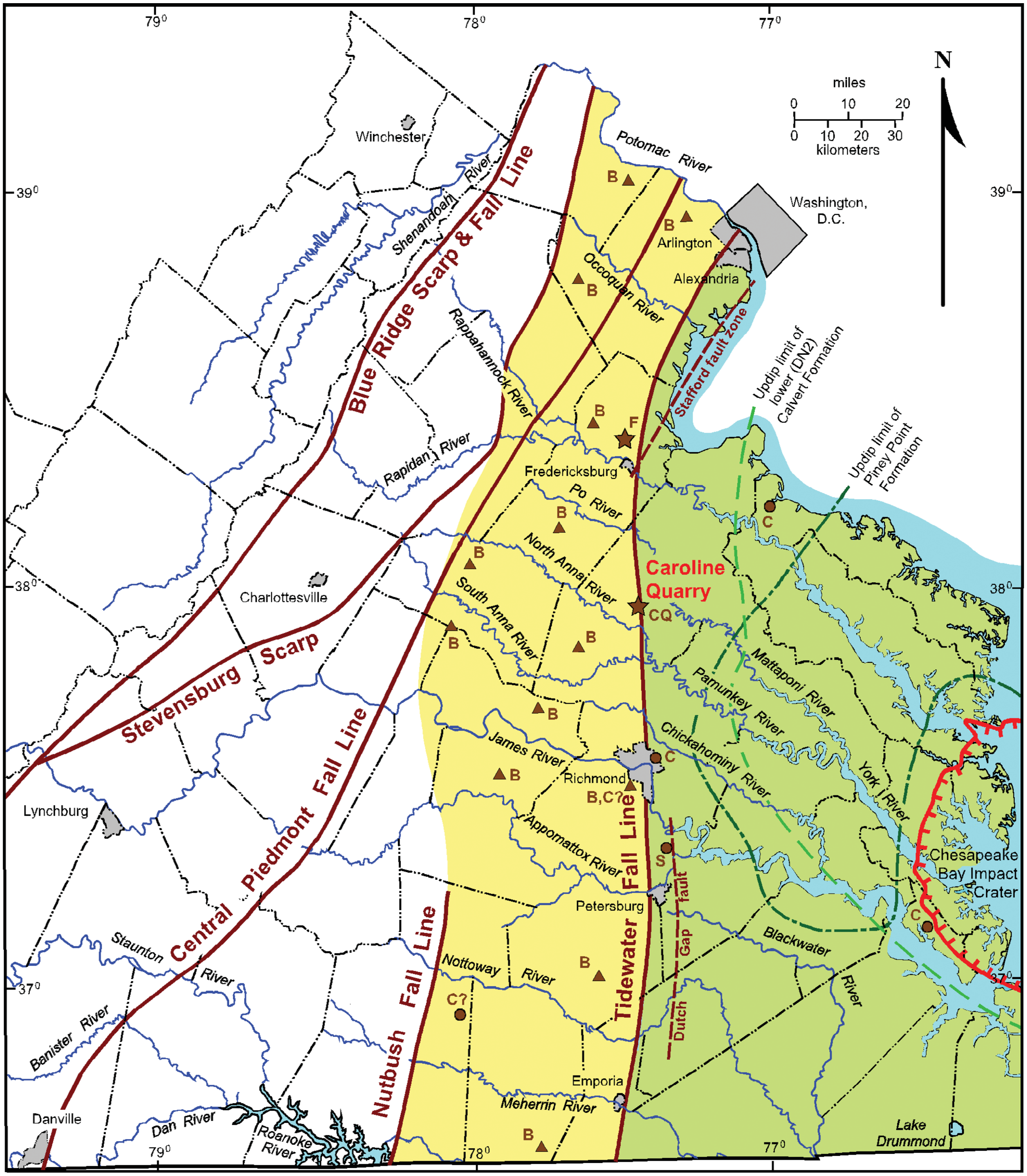
ABSTRACT: Diverse late middle Miocene dinoflagellate floras, obtained from two sites along the western edge of the Atlantic Coastal Plain in central Virginia, indicate that the eastern Virginia Piedmont was covered by marine waters about 12-13 Ma. This transgression extended farther westward across the Virginia Piedmont than any other transgression that has been documented. Extensive fluvial deposits that may be associated with this transgression covered earlier stream patterns in the eastern Piedmont and buried them beneath a thin (probably less than 100 foot-thick) veneer of sand and gravel. During the subsequent regression, a linear down-slope stream-drainage pattern developed. Although it has been somewhat modified by later stream captures, it still is easily recognizable. This interval of marine inundation and deposition explains why modern stream patterns in the eastern Piedmont of Virginia strongly resemble the stream patterns in the Coastal Plain and differ from the structurally adjusted trellis stream patterns typical of the western Piedmont, Blue Ridge, and Valley and Ridge regions. Uplift of the modern Southern Appalachian Mountains began at the time of this transgression and was largely completed by the late Pliocene.

INTRODUCTION

The boundary between the Coastal Plain and Piedmont provinces of Virginia is the Tidewater Fall Line (Weems 1998), a hinge zone where Piedmont streams flow eastward across fall zones down to the flat or very low gradients that characterize the Coastal Plain (text-fig. 1). This hinge zone separates areas that have undergone long-term regional uplift to the west from areas that have undergone long-term regional subsidence to the east. The Tidewater Fall Line in Virginia was established at least as long ago as late in the Early Cretaceous (about 115 Ma), when the predominantly non-marine Patuxent Formation accumulated across the entirety of the present Virginia Coastal Plain (Spangler and Peterson 1950). Although Late Cretaceous sediments are absent across most of the western and central Virginia Coastal Plain, numerous marine transgressions during the Paleogene and Neogene left sedimentary deposits across this region (Reinhardt and others 1980; Newell and Rader 1982; Mixon and others 1989, among others).

At least once during the Neogene, the eastern Piedmont also was covered by Coastal Plain sediments. Burial can be demonstrated by the occurrence of widespread but now discontinuous patches of a deeply weathered sand and gravel unit, here termed the eastern Piedmont upland gravel unit, up to 70 feet thick (Goodwin 1970). This deposit previously has been called the Bryn Mawr Formation north of Virginia (Lewis 1881; Pazzaglia and Gardner 1993), the Tenley Formation in the District of Columbia and northern Virginia (Wentworth 1930) and the Bon Air gravel in central and southern Virginia (Mathews and others 1965; Johnson and others 1987). The unit occurs on high hilltops in the eastern Virginia Piedmont at elevations ranging from 300 to 530 feet. The exceptionally high elevations of occurrence and the presence of faults within the unit (Johnson and others 1987) suggest that the eastern Piedmont upland gravel unit was tectonically uplifted and warped after it was deposited. The unit is encountered along the highest interfluves between major river valleys, so it probably was once continuous over most or all of the eastern Piedmont (text-fig. 1, yellow area). The age of this unit has remained controversial. At various times, its age has been considered to be Oligocene and Miocene (Pazzaglia and Gardner 1993), Miocene (Owens and Minard 1979; Pazzaglia 1993), middle Miocene or older (Johnson and others 1987), late Miocene (Fleming and others 1994; Drake and Froelich 1997), late Miocene or early Pliocene (Weems 1986), or Pliocene(?) (Wentworth 1930). Until now, the only firm older age limit that could be placed on this unit in the vicinity of Virginia was early Miocene (mid-Burdigalian, ca. 17 Ma), based on the age of the Fairhaven Member of the Calvert Formation that lies unconformably beneath it in the District of Columbia (Fleming and others 1994). The younger age limit is the age of the Thornburg Scarp along the western edge of the Tidewater Fall Line (text-fig. 1) that bounds the unit on its east, which is mid-Pliocene (Piazencian, ca. 3.5 Ma) in age (Mixon and others 1989).

Beneath the western margin of the Coastal Plain, intermittent Cenozoic fault motion has been documented in two areas (text-fig. 1): the northeast-trending Stafford fault system near the city of Fredericksburg (Mixon and Newell 1977) and the north-south trending Dutch Gap fault east of the city of Petersburg (Dischinger 1987). Some of this or similar fault motion formed local sediment traps that preserve remnants of marine stratigraphic units once widespread across the western Virginia Coastal Plain but subsequently removed from most areas by erosion. One such locality is the Caroline Stone Quarry in Caroline County (text-fig. 1, locality CQ, approximately 170 feet original pre-excavation ground-surface elevation). There, six thin Coastal Plain marine units have been recognized in what is probably a fault-bounded trough (Marr and Ward 1987; Dooley 1993). This locality offers an exceptional opportunity to gauge the original extent of a number of major marine transgressions across the western Coastal Plain in Virginia. Additionally, northwest of Fredericksburg, Virginia (text-fig. 1, locality F, approximately 315 feet ground surface elevation), an auger hole



TEXT-FIGURE 1
Map of much of eastern Virginia, showing the major geomorphic boundaries in that region. Fall lines and scarps are from Weems (1998). Fall lines follow deeply eroded scarps, and are expressed as fall zones (typically several miles long) along major and many minor streams. The Tidewater Fall Line coincides with the Thornburg Scarp. The modern Coastal Plain (shaded green) lies mostly east of the Tidewater Fall Line and is characterized by roughly linear, down-slope stream-drainage patterns. Stream patterns across most of the eastern Piedmont region (shaded yellow) are similar to those found in the Coastal Plain, which suggests a former veneer of Coastal Plain sediments once blanketed that region as well. The star marked "CQ" is the Caroline Stone Quarry. The star marked "F" is an auger hole site where late middle Miocene beds also were encountered. Circles labeled "C" are known localities of the upper Choptank Formation. The triangle marked "B, C?" is an area in Bon Air where the eastern Piedmont upland gravel unit overlies weathered clayey and silty very fine sands that are probably referable to the upper Choptank Formation. The circle marked "C?" is a region in Lunenburg County underlain by Caroline coastal plain soils (McDaniel and others, 1981). Circle marked "S" is the westernmost known outcrop of the St. Marys Formation. Triangles labeled "B" are representative localities of the eastern Piedmont upland gravel unit. Dashed lines show the approximate updip limit of the middle Eocene Piney Point Formation and the lower Miocene Popes Creek Sand Member of the Calvert Formation.

through a sandy phase of the eastern Piedmont upland gravel unit yielded clayey, very fine sandy silt at about 270 feet elevation that contained dinoflagellates. Dinoflagellate data, derived from both of these localities, strongly suggest that the likely age of the eastern Piedmont upland gravel unit is late middle Miocene.

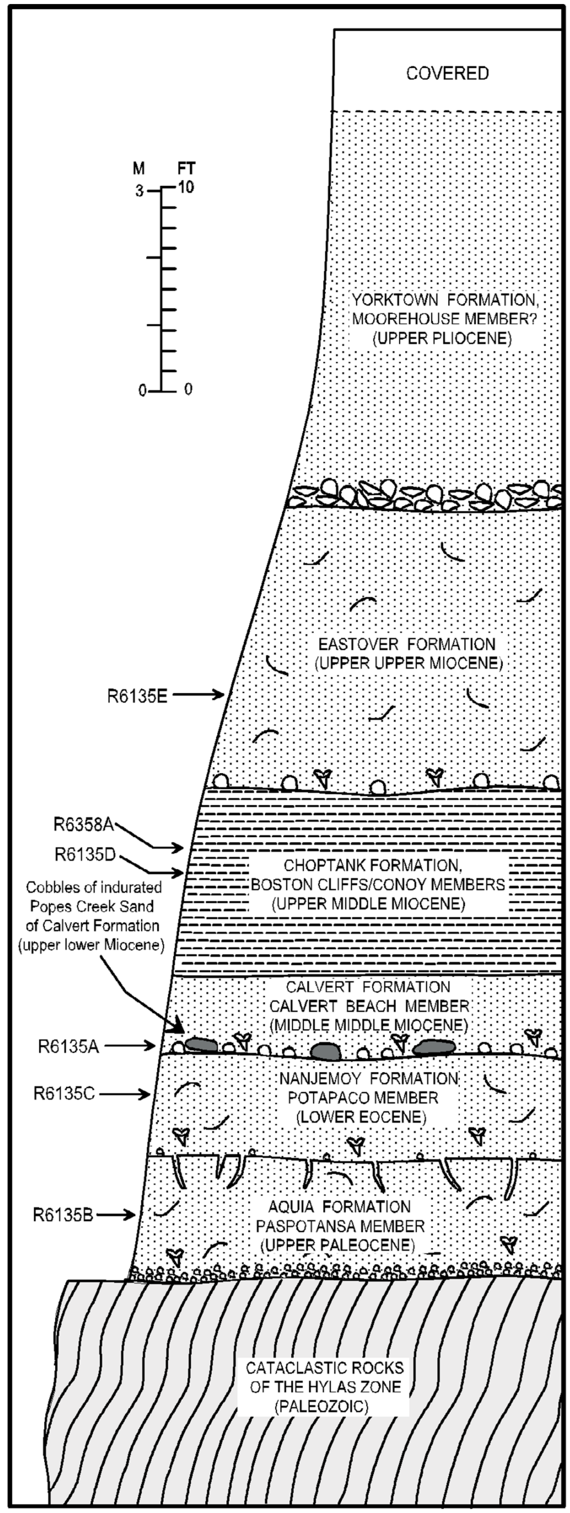
PRESENT WORK

The strata preserved at the Caroline Stone Quarry are summarized in text-figure 2 and placed chronostratigraphically in text-figures 3 and 4. The dinoflagellate assemblages are shown in Table 1. The preserved sequence includes the upper Paleocene Paspotansa Member of the Aquia Formation, the lower Eocene Potapaco Member (Bed A) of the Nanjemoy Formation (not the Woodstock Member as indicated by Marr and Ward 1987), the middle middle Miocene Calvert Beach Member of the Calvert Formation, the upper middle Miocene Boston Cliffs Member of the Choptank Formation as indicated by Marr and Ward (1987) (not the St. Marys Formation as suggested by Barnes and others, 2004), the upper upper Miocene Eastover Formation, and nearshore strata of the upper Pliocene Yorktown Formation. All of these units formed in marine environments, though the Yorktown sediments grade upward and laterally in areas near the quarry into onshore deltaic deposits of the Brandywine Member of the Yorktown (Weems 1986).

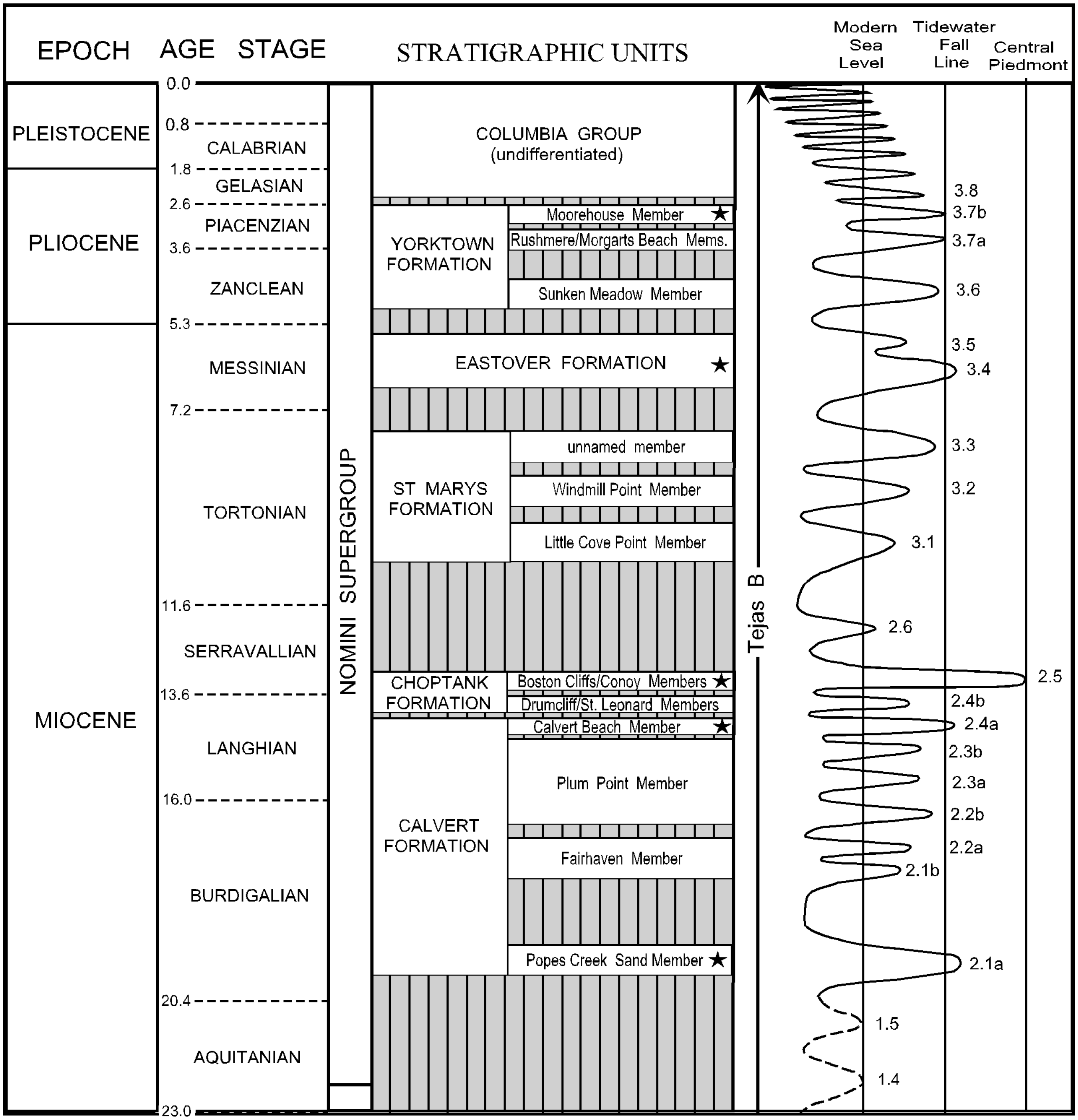
Dinoflagellate cysts in sediments are useful for both biostratigraphy and paleoecology. Because dinoflagellates are planktonic organisms, the patterns of cyst distribution do not reflect water depth. Their patterns of occurrence, however, do relate to factors such as sea-surface temperature, nutrient supply, and fluctuating salinity. In general, nearshore dinoflagellate assemblages have low diversity and are strongly dominated by one or only a few species. Offshore dinoflagellate assemblages tend to be much more diverse and not to be dominated by any particular taxon.

The dinoflagellate floras recovered from the Paspotansa member of the Aquia and the Potapaco (Bed A) member of the Nanjemoy both have moderately high diversity and are not dominated by any single species. This suggests accumulation in offshore (though not far offshore) environments of deposition. At the time these deposits were accumulating, the sea must have transgressed onto the eastern portion of the present Piedmont well beyond the present outcrop limit.

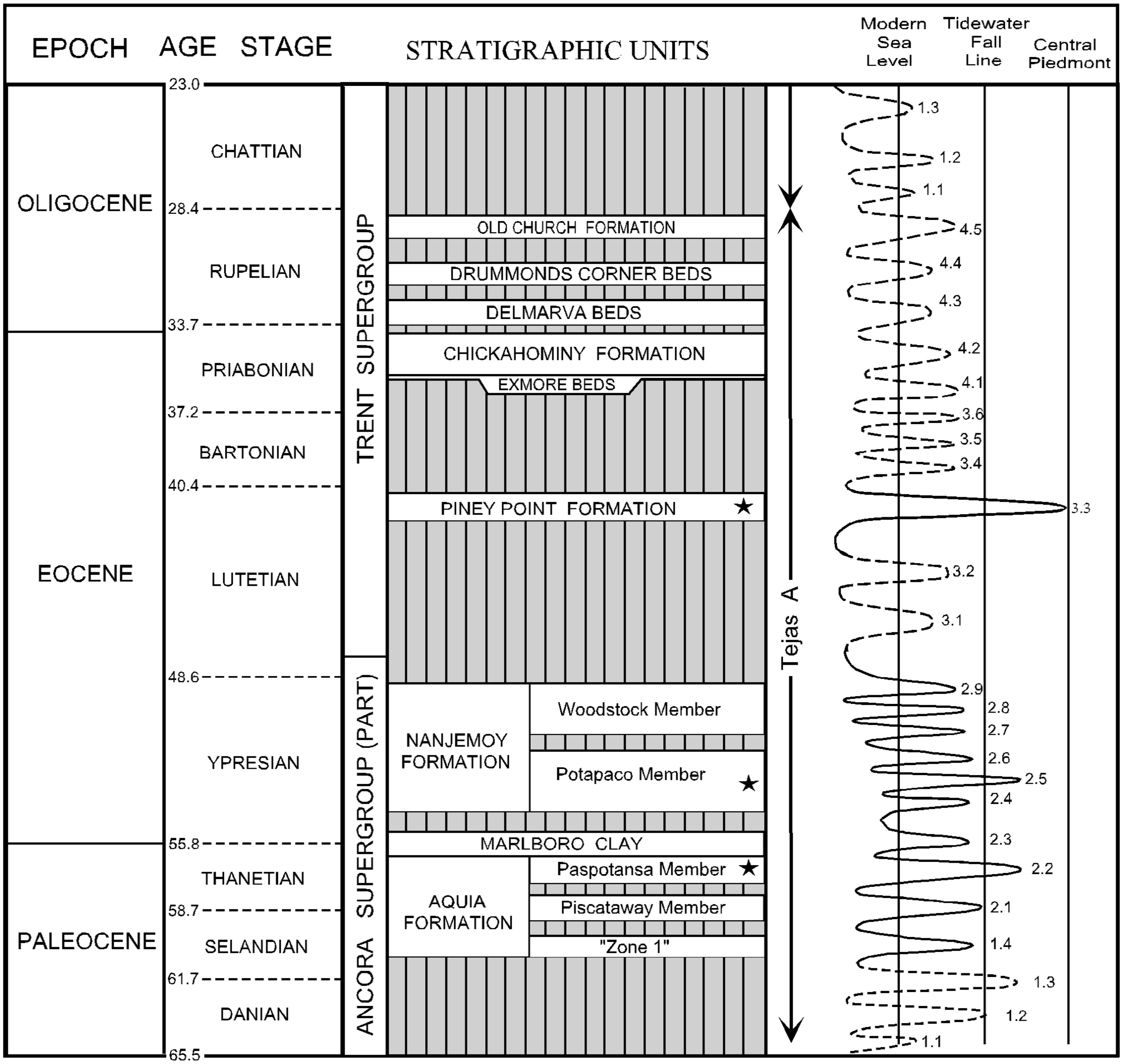
At the base of the Calvert Beach Member, numerous rounded and reworked calcareous sandstone pebbles and cobbles are present that contain unidentified molds of mollusks. A sample from one of these clasts contains dinoflagellate assemblages of at least two different ages (Table 1, R6135 A). *Cerebrocysta satchelliae* de Verteuil and Norris 1996 indicates that material from the early Miocene zone DN2 of de Verteuil and Norris (1996) is included. The only units of this age known from the central and western Virginia Coastal Plain are the Popes Creek Member of the Calvert Formation (Gibson 1983) and the probably coeval Newport News beds of Powars and Bruce (1999). An older assemblage is also present. Its age is restricted to the range of *Corrudinium incompositum* (Drugg 1970) Stover and Evitt 1978, which is middle Eocene to early Oligocene. The only unit of this age known from the central and western Coastal Plain is the middle Eocene Piney Point Formation (Ward 1985). Neither the Piney Point nor the Popes Creek are known within twenty miles of this locality at the present time



TEXT-FIGURE 2
Columnar section of sediments exposed in the Caroline Stone Quarry, adapted from Marr and Ward (1987) with the following revisions and additions: 1) The Nanjemoy Formation is represented by the Potapaco Member (Bed A) and not by the Woodstock Member as previously reported. 2) The Calvert Beach Member of the Calvert Formation is recognized (Dooley, 1993). 3) The basal lag bed of the Calvert Beach Member of the Calvert Formation contains reworked indurated clasts of the Popes Creek Sand Member of the Calvert Formation. 4) The clasts from the Popes Creek Member also contain reworked dinoflagellates from the Piney Point Formation.



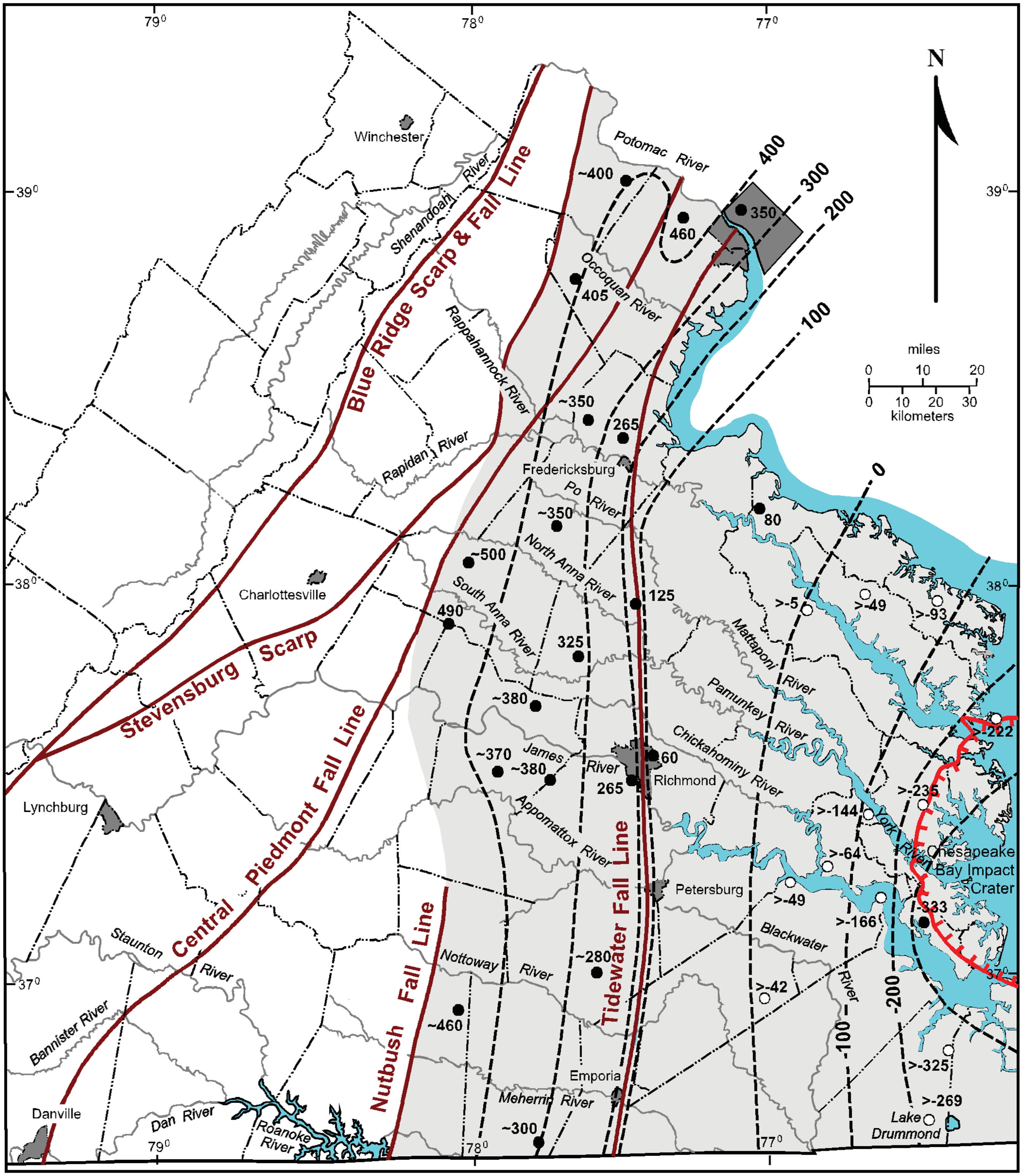
TEXT-FIGURE 3
Neogene stratigraphic units known from the central Virginia Coastal Plain. Units marked with a star are represented at the Caroline Stone Quarry. Based on presence or absence of units at this site, and evidence for distance to shore from contained dinoflagellate floras, a curve of relative transgression distances has been created indicating times of maximal inundation. The single strongest transgression that can be documented directly is the upper Choptank transgression about 12-13 Ma. Strong transgressions are inferred also at about 14 Ma and 20 Ma. Solid curves are from evidence available in the western Coastal Plain of central Virginia. Dashed lines are inferred from work done in and near the Chesapeake Bay Crater (Powars and Bruce 1999) for the lower Miocene interval. Numerical ages are from Gradstein and others (2004). Curve numbers are from Haq and others (1988), but their ages and intensities have been modified to fit newer data presented in Billups and Schrag (2002) and Gradstein and others (2004).



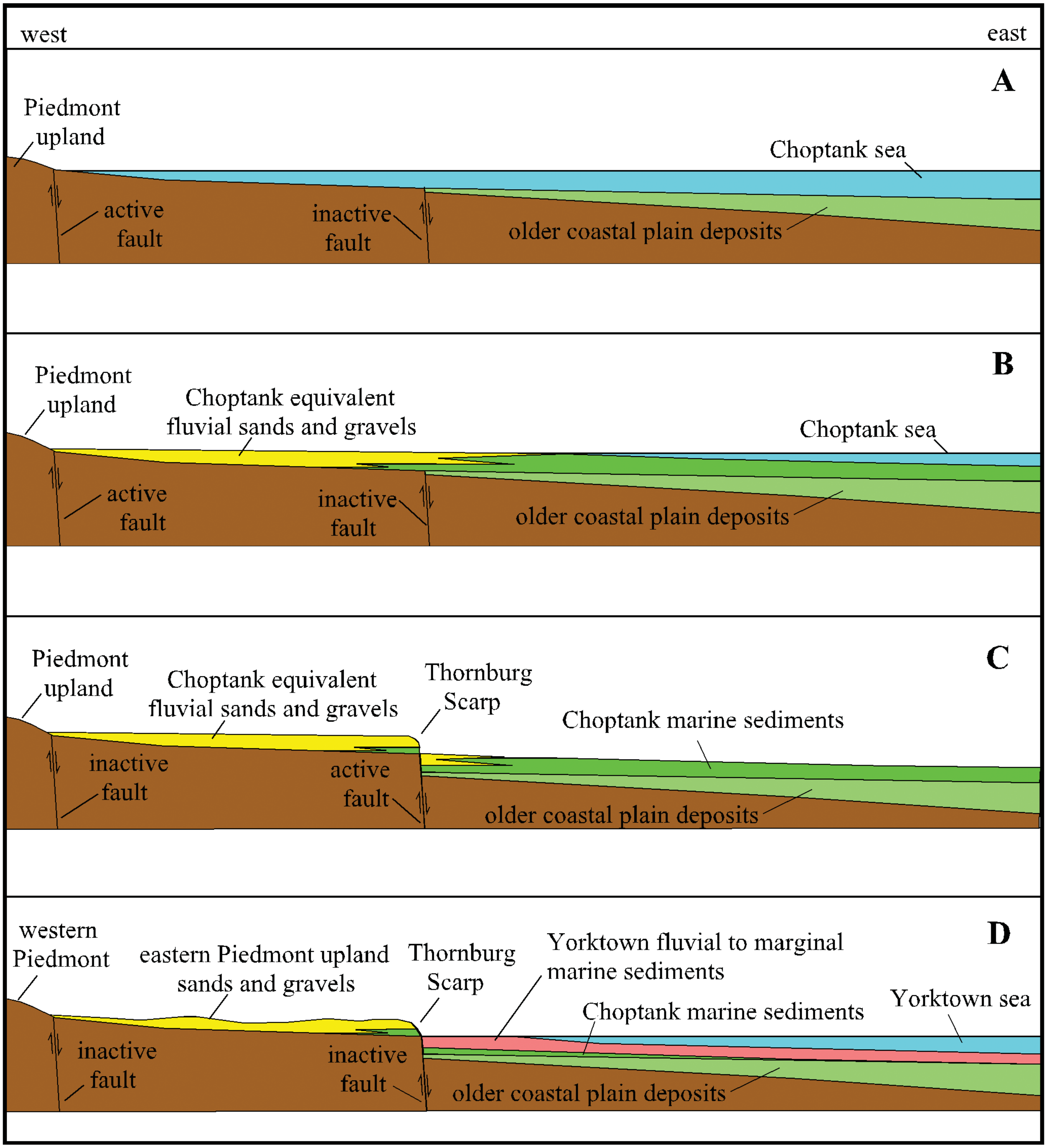
TEXT-FIGURE 4
Paleogene stratigraphic units known from the central Virginia Coastal Plain. Units marked with a star are represented at the Caroline Stone Quarry. Based on presence or absence of units at this site, and evidence for distance to shore from contained dinoflagellate floras, a curve of relative transgression distances has been created indicating times of maximal inundation. An especially strong transgression is inferred at about 42 Ma (Cabe 1984; Ward 1992). Solid curves are from evidence available in the western Coastal Plain of central Virginia. Dashed lines are inferred from work in South Carolina and Georgia (Edwards 2001) and work done in and near the Chesapeake Bay Crater (Powars and Bruce 1999) for the middle Eocene through Oligocene interval. Numerical ages are from Gradstein and others (2004). Curve numbers are from Haq and others (1988).

(text-fig. 1), but the preserved clast indicates that both units once were widespread up to the Tidewater Fall Line.

It is difficult to evaluate the depositional environment of the dinoflagellate flora recovered from the indurated nodules of the Popes Creek Sand Member of the Calvert Formation, because this flora includes reworked taxa probably from the Piney Point Formation. Even so, diversity is moderate and no single species dominates the composite assemblage. Therefore, part or all of the eastern Piedmont also probably was covered by these transgressions. This conclusion is supported by data gathered for an extensive middle Eocene transgression in North Carolina southeast of Raleigh (Cabe 1984; Ward 1992), and by data gathered for an early Miocene transgression in the District of Columbia (Fleming and others 1994), and in southern Maryland (Gibson 1983). These data collectively suggest that both the Piney Point and the Popes Creek depositional events represent times of major westward transgression of the Atlantic Ocean across the Coastal Plain and onto the eastern Piedmont (text-fig. 3, text-fig. 4).



TEXT-FIGURE 5
Approximate structure contour map of the base of the upper Choptank/Bryn Mawr depositional package. Despite sparse data points, a prominent flexure is apparent along the Tidewater Fall Line. This indicates 100-200 feet of tectonic offset on the base of the unit along this feature some time after the middle Miocene, probably during the late Miocene. The slope of the base of this unit averages about 7 feet per mile eastward, both east and west of the Tidewater Fall Line, indicating that most of the tectonic motion was vertical. Steepened gradients in the vicinity of the Chesapeake Bay impact crater may be due to the effect of long-term differential settling and dewatering within the crater fill. Structure contours beneath the Coastal Plain are partially constrained by localities from Powars and Bruce (1999) (white circles), which give current elevations of tops of units that are older than the upper Choptank (usually the top of the Calvert Formation). The base of the upper Choptank must have lain at elevations higher (i.e., greater than) the top of units that lay beneath it. Thus, except in the vicinity of the Watkins School core where the upper Choptank is still preserved, the approximated structure contours could lie east of where they have been placed, but they could not lie much farther west.



TEXT-FIGURE 6
Diagram showing the stages in the development of the modern eastern Piedmont landform in the middle Miocene and Pliocene. A – Late Serravallian transgression of the Choptank sea covers all pre-existing Coastal Plain units in eastern Virginia and spreads far westward into the Piedmont up to a fault-bounded rising upland. B – Late Serravallian deposition partly fills the Choptank sea in the east, and fluvial-deltaic deposits spread eastward across the Choptank marine deposits from a rising fault-bounded upland within the Piedmont. C – Choptank sea retreats eastward, and a reactivation of fault motion occurs along the Thornburg Scarp and the future position of the Tidewater Fall Line. D – Late Pliocene Yorktown sea spreads westward up to the Thornburg scarp, largely reworking the Choptank (and also Eastover) marine deposits east of the Thornburg Scarp and depositing its own sediments in their stead.

TABLE 1
Stratigraphic distribution of dinoflagellates observed in samples from the Caroline Quarry (locality CQ in Fig. 1, 37.9067° N, 77.4797° W). Sample positions shown in text-figure 2. X = present, R = present but presumably reworked.

Dinoflagellate taxa	Eastover Formation R6135E	Choptank Formation R6358A R6135D	Calvert Fm. Popes Creek Sand Mem. R6135A	Piney Point Fm. (reworked into Popes Creek Sand) R6135A	Nanjemoy Fm. Potapaco Mem. (Bed A) R6135C	Aquia Fm. Paspotansa Mem. R6135B
Achomosphaera andalousiensis Jan du Chene 1977	X					
Habibacysta tectata Head et al. 1989	X	X				
Invertocysta lacrymosa Edwards 1984	X	X				
Labyrinthodinium truncatum Piasecki 1980 subsp. *truncatum*	X	X				
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967	X	X	X	X		X
Nematosphaeropsis Deflandre & Cookson 1955 sp.	X					
Operculodinium Wall 1967 sp.	X	X			X	
Operculodinium ?eirikianum Head et al. 1989	X					
Reticulatosphaera actinocoronata (Benedek 1972) Bujak & Matsuoka 1986	X	X				
Spiniferites elongates Reid 1974	X					
Spiniferites Mantell 1850 spp.	X	X	X	X	X	X
Tectatodinium pellitum Wall 1967	X	X				
Tuberculodinium vancampoae (Rossignol 1962) Wall 1967	X	X	X			
Areoligera group	R					
Batiacasphaera sphaerica Stover 1977		X				
Dapsilidinium pseudocolligerum (Stover 1977) Bujak et al. 1980		X				
Hystrichosphaerosis obscura Habib 1972		X				
Impagidinium Stover & Evitt 1978 sp.		X				
Lejeunecysta Artzner & Dorhofer 1978 sp.		X				
Operculodinium centrocarpum (Deflandre & Cookson 1955) Wall 1967		X				X
Palaeocystodinium golzowense Alberti 1961		X	X	X	X	X
Selenopemphix brevispinosa Head et al. 1989 subsp. *brevispinosa*		X				
Selenopemphix quanta (Bradford 1975) Matsuoka 1985		X				
Sumatradinium druggii Lentin et al. 1994		X				
Sumatradinium soucouyantiae de Verteuil & Norris 1996		X				
Apteodinium spiridoides Benedek 1972			X			
Batiacasphaera hirsuta Stover 1977			X			
Brigantedinium cariacoense (Wall 1967) Lentin & Williams 1993			X			
Cerebrocysta satchelliae de Verteiul & Norris 1996			X			
Pentadinium sp. cf. *P. laticinctum granulatum* Gocht 1969			X			
Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1970			X			
Corrudinium incompositum (Drugg 1970) Stover & Evitt 1978				X		

All of these stratigraphic intervals mark major transgressions across the Coastal Plain and onto the eastern edge of the Piedmont. Even so, the flora from the upper Choptank Formation (i.e., strata laterally equivalent to the Boston Cliffs Member and (or) the Conoy Member of the Choptank Formation in Maryland) has a higher diversity of dinoflagellates than any of the other units present at this site. This implies that, during the late middle Miocene (about 12-13 Ma), the Atlantic Ocean transgressed farther across the eastern portion of the Piedmont than at any other time that can be documented adequately at the Caroline Stone Quarry site. Because beds of this age are rarely encountered, occurring in Virginia only as localized remnants (text-fig. 1) near Newport News (Watkins School site; Edwards and others, 2004), near Oak Grove (Gibson and others 1980), and in Shockoe Valley in Richmond (de Verteuil and Norris 1996), it has not been appreciated in the past that this was one of the major trangressive events in Coastal Plain history. However, the diverse dinoflagellate flora preserved in this unit at the Caroline Stone Quarry site, as well as the consistently very fine-grained, silty, and diatomaceous texture of this unit up to its westernmost preserved edge, attest that this transgression extended farther into the Piedmont than any other transgression that can be documented in the stratigraphic column of the Virginia Coastal Plain.

Above the Choptank, the assemblage from the Eastover Formation is moderately diverse but dominated by a single species (*Operculodinium* Wall 1967 sp.). This pattern indicates that the Eastover transgression was far less expansive westward than the earlier transgressions documented in this area. The highly oxidized upper Yorktown beds were not successfully sampled for dinoflagellates, but the presence of *Ophiomorpha* burrows, me-

TABLE 1
continued.

Dinoflagellate taxa	Eastover Formation R6135E	Choptank Formation R6358A R6135D	Calvert Fm. Popes Creek Sand Mem. R6135A	Piney Point Fm. (reworked into Popes Creek Sand) R6135A	Nanjemoy Fm. Potapaco Mem. (Bed A) R6135C	Aquia Fm. Paspotansa Mem. R6135B
Heteraulacacyata pustulosa Jan du Chene & Adediran 1985				X		
Histiocysta sp. of Stover and Hardenbol (1993)				X		
Lentinia serrata Bujak 1980				X	X	X
Phthanoperidinium stockmansii (de Coninck 1975) Lentin & Williams 1977				X		
Saturnodinium sp. Brinkhuis et al. 1992				X		
Apectodinium homomophum (Deflandre & Cookson 1955) Lentin & Willliams 1977					X	X
Catillopsis abdita Drugg 1970					X	
Cribroperidinium Neale & Sarjeant 1962 sp.					X	
Deflandrea phosphoritica/oebisfeldensis complex					X	X
Diphyes colligerum (Deflandre & Cookson 1955) Cookson 1965					X	
Eocladopyxis peniculata Morgenroth 1966					X	
Fibrocysta radiata (Morgenroth 1966) Stover & Evitt 1978					X	
Fibrocysta Stover & Evitt sp.					X	
Hafniasphaera septata (Cookson & Eisenack 1967) Hansen 1977					X	X
Heteraulacacysta Drugg & Loeblich 1967 sp.					X	
Hystrichosphaeridium tubiferum (Ehrenberg 1838) Deflandre 1937					X	X
Kallosphaeridium brevibarbatum de Coninck 1969 (2 var.)					X	X
Muratodinium fimbriatum (Cookson & Eisenack 1967) Drugg 1970					X	
Wilsonidium tabulatum (Wilson 1967) Lentin & Williams 1976					X	
miscellaneous areoligeracean forms					X	X
miscellaneous cladopyxiaceaen forms					X	X
Amphorosphaeridium multispinosum (Davey & Williams 1966) Sarjeant 1981						X
Cordosphaeridium fibrospinosum Davey & Williams 1966						X
Fromea fragilis (Cookson & Eisenack 1967) Stover & Evitt 1978						X
Hystrichokolpoma Klumpp 1953 sp.						X
Phelodinium Stover & Evitt 1978 sp.						X
Spinidinium Cookson & Eisenack 1962 sp.						X
Turbiosphaera sp. aff. *T. magnifica* of Edwards 1989						X
small peridiniacean forms					X	X

dium-grained sands, and prominent cross-bedding all indicate a nearshore depositional environment during a transgression that peaked in the late Pliocene about at the present Tidewater Fall Line. No later transgressions are known that extended this far inland (Weems 1986).

In the northwest corner of the Fredericksburg, Virginia 7.5-minute quadrangle (text-fig. 1, locality F), an auger hole through the Piedmont upland gravel unit yielded a sample of clayey, very fine sandy silt at approximately 270 feet elevation that contains dinoflagellates (Table 2, right column) characteristic of the same upper Choptank interval (upper middle Miocene, DN7) encountered in the Caroline Stone Quarry at an elevation of approximately 125 feet (Table 1, Choptank Formation column). The high diversity of the sample comes from a large number of protoperidiniacean species (presumed to be heterotrophic), so this sample may represent a nearshore, nutrient-rich environment. This updip occurrence demonstrates directly that the Piedmont upland gravel unit of the eastern Piedmont cannot be any older than the 12-13 Ma upper Choptank unit exposed at the Caroline Quarry, and additionally suggests that the deposits near Fredericksburg have been uplifted 100-200 feet relative to the Caroline Stone Quarry site due to post-depositional tectonism (text-fig. 5). Weathered unfossiliferous very fine-grained strata, of very similar lithology and at a nearly identical elevation, lie beneath the Piedmont upland gravel unit in Bon Air (Johnson and others 1987). These deposits here are referred to the upper Choptank (text-fig. 1, circle marked B, C?). The eastern Piedmont upland gravel unit at the Fredericksburg site is more sandy than gravelly and contains several subtle fining upward sequences that suggest the fluvial sands lie with some degree of unconformably upon the marine sandy silts. This apparent angularity could suggest a much younger age for the Piedmont upland gravel unit, but it is just as plausible that the observed unconformable relationships simply reflect the relatively rapid meanderings of delta distributary channels within an offlap depositional sequence, where fluvio-deltaic sands and gravels were prograding into a shallow, high-stand sea. Thus, based only on lithologic criteria, the Piedmont upland gravel unit could be either onshore fluvio-deltaic deposits coeval with the upper Choptank Formation or a distinctly younger unit resting unconformably upon the upper Choptank.

If the eastern Piedmont upland gravel unit is significantly younger than the Choptank, only laterally equivalent marine units older than the upper Yorktown Formation need to be considered as possible correlatives. This is because, by the time that the upper Yorktown deposits at the Caroline Quarry accumulated, the Thornburg Scarp was already in existence and blocked the upper Yorktown transgression from extending any farther inland except for fluvial/estuarine deposits that extend westward along the major rivers (Weems 1998). Where such deposits have been mapped along the James River (Goodwin 1970) they clearly extend up a broad river valley that was already deeply incised into the Bon Air uplands and thus represent deposits distinctly younger than the eastern Piedmont upland gravel unit. Additionally, the gravels associated with the late Yorktown transgression are composed almost entirely of very stable quartzite and vein quartz clasts that appear to have been reworked from the older eastern Piedmont upland gravel unit. The eastern Piedmont upland gravel unit contains ghosts of many other kinds of igneous and metamorphic clasts that are extremely leached and weathered, so those clasts did not survive reworking (Weems 1986). As incisement of the eastern Piedmont upland was already well under way by the time of the late Yorktown (late Pliocene), only units younger than the upper Choptank and older than the upper Yorktown are possible candidates for offshore equivalents to the eastern Piedmont upland gravel. These candidates are, from oldest to youngest, the St. Marys Formation (early late Miocene), the Eastover Formation (late late Miocene), and the Sunken Meadow Member of the Yorktown Formation (early Pliocene).

The early late Miocene, when the St. Marys Formation was deposited (text-fig. 4), was a time of relatively low global sea levels (Haq and others 1988; Miller and others, 2005). The westernmost St. Marys deposit found in this general area, a clayey silt sampled at a site seven miles northeast of Petersburg in Chesterfield County (elevation about 80 feet above sea level, labeled S in text-fig. 1), contains an inshore dinoflagellate flora with abundant pollen and plant debris that accumulated in a low-energy, nearshore depositional setting (Table 2, right column). Therefore, the St. Marys is not a reasonable candidate for correlation with the Piedmont upland gravel unit, because it cannot be associated with a depth of transgression great enough to flood or back up sediment across the eastern Piedmont. In the very late Miocene, global sea levels rose again, and this rise in global eustatic sea level correlates well with the Eastover transgression that produced nearshore deposits at the Caroline Stone Quarry site in the vicinity of the Tidewater Fall Line. Again, however, the near-shore nature of these deposits at the Caroline Quarry does not indicate a depth of transgression great enough to have allowed a regional accumulation of the widespread eastern Piedmont upland gravels. Although no deposits remain in the area, it is worth considering the early Pliocene Sunken Meadow Member of the Yorktown Formation. Gibson (1967) has provided evidence that the Sunken Meadow transgression was more widespread than its present distribution would suggest, but even so he considered its maximum depth of transgression to be no more than 250 feet above modern sea level. This is slightly less than the maximum depth of the later Yorktown transgression that was blocked by the Thornburg Scarp, and again is insufficient to allow a regional accumulation of the widespread eastern Piedmont upland gravels.

The relatively nearshore flora and depositional fabric in all younger candidate units leaves the upper Choptank unit as the only plausible equivalent to the eastern Piedmont upland gravel unit, because patches of eastern Piedmont upland gravel and sand are found across the Piedmont up to 35 miles west of the Tidewater Fall Line (text-fig. 1, triangles labeled "B") and this westward extent is comparable only to the degree of westward transgression suggested by dinoflagellates for the late middle Miocene upper Choptank transgression.

The abundance and thickness of the upland gravels seem somewhat anomalous when compared to the energy of the depositional regime that formed the very fine grained marine deposits of the upper Choptank, but it needs to be kept in mind that only the lower portion of the original upper Choptank Formation remains east of the Tidewater Fall Line, and that any still-stand progradational deposits that once may have overtopped this sequence are long since gone. Thus, due to the local depositional geometry and setting, toward the east (seaward) only early transgression deposits are preserved and toward the west (landward) mostly progradational still-stand deposits of slightly younger age are preserved. The westernmost extent of these gravel outliers presently is constrained by portions of three geomorphic features, the Nutbush Fall Line, the Central Piedmont Fall Line, and the Stevensburg Scarp (text-fig. 1). As the Piedmont upland gravel unit locally is incised into the Piedmont upland surface west of the Nutbush Fall Line along major rivers such as the Roanoke, it seems likely that these features already existed in the late middle Miocene and constrained the inland extent of the late middle Miocene transgression. The presence of such uplands to the west would help to explain the large volume of pebbles and cobbles in the upland gravel unit, especially those that once were metamorphic or igneous rocks now completely saprolitized. This scenario is compatible with what little is known from the heavy minerals in this part of the section. At the Haynesville core in Richmond County, Virginia the upper Choptank unit is absent, but the immediately underlying Calvert Beach Member of the Calvert Formation is present, as is the immediately overlying St. Marys Formation. In the upper Calvert, hornblende and epidote are only about half as abundant as they are in the St. Marys, indicating a significant influx of first-cycle metamorphic and igneous minerals immediately after the middle Miocene (McCartan, 1989). This indicates that at least the western part of the Piedmont must have been tectonically reactivated during or right after the time of the upper Choptank transgression.

Further support for the association of the eastern Piedmont upland gravel unit with the middle Miocene comes from studies much farther south in Georgia. There, a unit called the Screven Member of the Altamaha Formation (Huddlestun 1988) appears to be of the same age and to have the same characteristics as the eastern Piedmont upland gravel unit in Virginia. The Screven Member, unlike the eastern Piedmont upland gravels, is in the western Atlantic Coastal Plain Province, but this is in an area where the coastal plain deposits have undergone significant up-

TABLE 2
Stratigraphic distribution of dinoflagellates observed in samples from Chesterfield County (locality S in text-fig. 1, 37.3290° N, 77.3629° W) and from Stafford County, Virginia (locality F in text-fig. 1, 38.3709° N, 77.4982° W).

Dinoflagellate taxa	Chesterfield County (St. Marys Fm.)	Stafford County (Choptank Fm.)
Achomosphaera andalousiensis Jan du Chene 1977	X	
Achomosphaera Evitt 1963 sp.	X	
Bitectatodinium tepikiense Wilson 1973/ *Betectatodinium raedwaldii* Head 1997	X	
Brigantedinium simplex Wall 1965	X	
Cyclopsiella Drugg & Loeblich 1967 sp.?	X	
Impagidinium Stover & Evitt 1978 sp.	X	
Polykrikos Butschli 1873 sp.?	X	
Sumatradinium Lentin & Wiliams 1976 sp.	X	
Trinovantedinium papula de Verteuil & Norris 1992	X	
Batiacasphaera hirsuta Stover 1977	X	X
Erymnodinium delectabile (de Verteuil & Norris 1992) Lentin et al. 1994	X	X
Geonettia clinae de Verteuil & Norris 1996	X	X
Habibacysta tectata Head et al. 1989	X	X
Labyrinthodinium truncatum Piasecki 1980 subsp. *truncatum*	X	X
Lejeunecysta Artzner & Dorhofer 1978 sp.	X	X
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967	X	X
Nematosphaeropsis Deflandre & Cookson 1955 sp.	X	
Operculodinium centrocarpum (Deflandre & Cookson 1955) Wall 1967	X	X
Quadrina? *condita* de Verteuil & Norris 1992	X	
Reticulatosphaera actinocoronata (Benedek 1972) Bujak & Matsuoka 1986	X	X
Selenopemphix brevispinosa Head et al. 1989 subsp. *brevispinosa*	X	X
Spiniferites Mantell 1850 spp.	X	X
Tectatodinium pellitum Wall 1967	X	X
Trinovantedinium harpagonium de Verteuil & Norris 1992	X	X
Tuberculodinium vancampoae (Rossignol 1962) Wall 1967	X	X
Barssidinium evangelineae Lentin et al. 1994		X
Batiacasphaera sphaerica Stover 1977		X
Brigantedinium Reid 1977 sp.		X
Cannosphaeropsis passio de Verteuil & Norris 1996		X
Cerebrocysta poulsenii de Verteiul & Norris 1996		X
Dapsilidinium pseudocolligerum (Stover 1977) Bujak et al. 1980		X
Hystrichosphaeropsis obscura Habib 1972		X
Operculodinium piaseckii Strauss & Lund 1992		X
Palaeocystodinium golzowense Alberti 1961		X
Selenopemphix dionaeacysta de Verteuil & Norris 1992		X
Sumatradinium druggii Lentin et al. 1994		X
Sumatradinium soucouyantiae de Verteuil & Norris 1996		X
Trinovantedinium glorianum de Verteuil & Norris 1992		X

lift and warping west of the Orangeburg Scarp similar to the pattern seen for the upland gravel unit. Lithologically, the two units are quite similar. Huddlestun (1988) described the Screven as a prominently cross-bedded, feldspathic, pebbly sand that locally contains gravel beds with cobbles up to 7 inches (18cm) in diameter. In Georgia, the Screven Member overlies deposits of the Meigs and the Berryville Clay members of the Coosawhatchie Formation, which Huddlestun assigned to the lower Serravallian. Huddlestun noted that the Screven often lay unconformably upon the Coosawhatchie, but he considered this to be the result of lateral channel migrations that occurred very shortly after deposition of the underlying estuarine to shallow marine strata. In other places, he noted that the Screven sequence seems to be conformable with underlying strata, and also that the fluvial Screven deposits seemed to grade down dip into deposits of either the Meigs Member or the Berryville Member. The Meigs Member and much of the Berryville Clay Member are lower Serravallian in age (containing a DN5 dinoflagellate flora), but it since has been established that there are very similar-looking diatomaceous deposits that are slightly younger and upper Serravalian in age, based on the DN7 dinoflagellate flora that they contain (Weems and Edwards, 2001). We suggest that it is this upper Berryville Member with which the Screven Member intertongues, and that the Screven is time-equivalent to the eastern Piedmont upland gravel unit, with which it is so very similar lithologically and in its depositional setting.

As noted by Huddlestun (1988), the Screven is lithologically very unusual for an Atlantic Coastal Plain unit because it is so predominantly fluvial in character and so areally wide-spread. Except for a few Cretaceous deposits, such as the Patuxent and Potapsco formations in Maryland and Virginia, and the Cape Fear and Tuscaloosa (s.l.) formations in Georgia and the Carolinas, Atlantic Coastal Plain deposits almost all formed in marine shelf environments. Fluvial deposits landward of these units either never formed or were quickly eroded away, leaving only a sparse record of onshore deposition, especially in the Cenozoic. Thus, while the strongly fluvial character of the eastern Piedmont upland gravels in Virginia might suggest that they represent a deposit distinctly different in age than the upper Choptank marine beds, the occurrence of very similar deposits of the same age in Georgia and South Carolina, with a similarly contrasting onshore and offshore character, indicates that the contrast in depositional setting of the onshore and offshore components of the eastern Piedmont upland gravel and upper Choptank depositional packages occurred elsewhere at that time.

The deposition of a widespread, feldspathic fluvial unit across the southern Atlantic Coastal Plain and the eastern Piedmont of Virginia at the same time that a strong late Serravallian transgression was occurring, suggests that this transgression coincided with the beginning of a significant uplift in the entire Appalachian interior region that ultimately produced the modern Southern Appalachians. The abrupt appearance of abundant labile heavy minerals in the sands of the immediately younger (Tortonian) St. Marys Formation (McCartan 1989) also supports this age for the beginning of uplift in the interior modern Appalachian region. This transgression, in conjunction with the presence of the uplifted Thornburg Scarp by 3.5 Ma (Mixon and others 1989), brackets the interval of major modern Appalachian uplift to between 13 Ma and 3.5 Ma, or the latest Middle Miocene to early Pliocene.

This same time interval also brackets the timing of uplift of the eastern Piedmont in Virginia. Interestingly, the presence of a sand and gravel unit up to 70 feet thick across the eastern Piedmont during the early phase of this uplift meant that the river and stream systems that formed after the Choptank regression in this area were incised into an unconsolidated, broadly planar-bedded substrate. This resulted in a linear, down-slope stream-drainage pattern that is nearly identical to the stream flow patterns developed on the Atlantic Coastal Plain farther east. The total amount of uplift, while sufficient to block any further marine transgressions across this region, has been insufficient to allow most of the drainage patterns to adjust to the structural grain of the Piedmont rocks that lie beneath the Coastal Plain cover that once blanketed the region. This explains why the stream drainage patterns in the eastern Piedmont of Virginia are very much like the stream drainage patterns found in the Coastal Plain and contrast sharply with the predominantly bedrock-adjusted drainage patterns found in the western Piedmont of Virginia.

CONCLUSIONS

Based on available direct evidence, a major marine trangressive event in the late middle Miocene (late Serravallian) resulted both in the deposition of the upper Choptank Formation and the onshore to nearshore deposits of the eastern Piedmont upland gravel unit in Virginia. This transgression was the most westward that can be documented so far for any time interval within the Cenozoic Era. Remnant patches of these gravels extend westward far enough to indicate that the eastern Piedmont of Virginia at one time was completely buried beneath these deposits. During the subsequent regression, the eastern Piedmont region developed a linear, down-slope stream-drainage pattern on this thick gravel deposit that is similar to that seen throughout the Coastal Plain. This sand and gravel depositional event, and the subsequent stream flow pattern developed upon it, best explains the strong geomorphic contrast between the eastern and western Piedmont regions of Virginia and the lack of geomorphic contrast between the eastern Piedmont and Coastal Plain. If the upper Choptank Formation is age equivalent to the eastern Piedmont upland gravel unit, then the present geomorphology of the eastern Piedmont in Virginia must have developed between 13 Ma and 3.5 Ma. This matches the timeframe for uplift of the modern Appalachian Mountains in the southeastern United States.

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REFERENCES

BARNES, L., DOOLEY, A. C., Jr. and FRASER, N. C., 2004. A new Miocene sperm whale (Cetacea; Physeteridae) from Virginia. *Journal of Vertebrate Paleontology,* 24 (supplement):36A.

BILLUPS, K. and SCHRAG, D. P., 2002. Paleotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and $^{18}O/^{16}O$ measurements on benthic foraminifera. *Paleoceanography*, 17(1):1-11.

CABE, S., 1984. "Cretaceous and Cenozoic stratigraphy of the upper and middle Coastal Plain, Harnett County area, North Carolina."

Ph.D. dissertation, University of North Carolina at Chapel Hill, 101 pp.

DE VERTEUIL, L. and NORRIS, G., 1996. Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. *Micropaleontology*, 42 (supplement):1-172.

DISCHINGER, J. B., Jr., 1987. Late Mesozoic and Cenozoic stratigraphic and structural framework near Hopewell, Virginia. *United States Geological Survey Bulletin,* 1567:1-48.

DOOLEY, A. C., Jr., 1993. The vertebrate fauna of the Calvert Formation (middle Miocene) at the Caroline Stone Quarry, Caroline County, Va. *Journal of Vertebrate Paleontology,* 13 (supplement):33A.

DRAKE, A. A., Jr. and FROELICH, A. J., 1997. *Geologic map of the Falls Church quadrangle, Fairfax and Arlington Counties and the City of Falls Church, Virginia, and Montgomery County, Maryland.* United States Geological Survey Geologic Quadrangle Map GQ–1734 with text, scale 1:24,000.

EDWARDS, L. E., 1989, Dinoflagellate cysts from the lower Tertiary formations, Haynesville cores, Richmond County, Virginia. In: Mixon, R.B., Ed., *Geology and Paleontology of the Haynesville cores — Northeastern Virginia Coastal Plain*, C1-C12. U.S. Geological Survey Professional Paper 1489.

———, 2001. *Geology and paleontology of five cores from Screven and Burke Counties, eastern Georgia.* United States Geological Survey Professional Paper 1603.

EDWARDS, L. E., POWARS, D.S., GOHN, G.S., HORTON, J.W., JR., LITWIN, R.J. AND SELF-TRAIL, J.M., 2004. Inside the crater, outside the crater: comparison of two cores from the Chesapeake Bay impact structure. G*eological Society of America Abstracts with Programs,* 36:266.

FLEMING, A. H., DRAKE, A. A., JR. and MCCARTAN, LUCY, 1994. *Geologic map of the Washington West quadrangle, District of Columbia, Montgomery and Prince Georges counties Maryland, and Arlington and Fairfax counties Virginia.* United States Geological Survey Geologic Quadrangle Map GQ-1748, with text, scale 1:24,000.

GIBSON, T. G., 1983. Stratigraphy of Miocene through Lower Pleistocene Strata of the United States central Atlantic Coastal Plain. In: Ray, C. E., Ed., Geology and Paleontology of the Lee Creek Mine, North Carolina, Part 1. S*mithsonian Contributions to Paleobiology*, 53:35-80.

GIBSON, T. G., ANDREWS, G. W., BYBELL, L. M., FREDERIKSEN, N. O., HANSEN, T., HAZEL, J. E., MCLEAN, D. M., WITMER, R. J. and NIEUWENHUISE, D. S. VAN, 1980. Biostratigraphy of the Tertiary strata of the core. In: *Geology of the Oak Grove core,* 14-30*.* Virginia Division of Mineral Resources Publication, 20(2).

GOODWIN, B.K., 1970. Geology of the Hylas and Midlothian quadrangles, Virginia. *Virginia Division of Mineral Resources Report of Investigations,* 23:1-51, 2 maps.

GRADSTEIN, F. M., OGG, J. G., SMITH, A. G., BLEEKER, WOUTER and LOURENS, L.J., 2004. A new geologic time scale, with special reference to Precambrian and Neogene. *Episodes*, 27:83-100.

HAQ, B. U., HARDENBOL, J. AND VAIL, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C. K., Hastings, B. S., Ross, C. A., Posamentier, H. W., Van Wagoner, J., and Kendall, C.G. St. C., Eds., *Sea-level changes; an integrated approach*, 72-108. Society of Economic Paleontologists and Mineralogists Special Publication, 42.

HUDDLESTUN, P. H., 1988. A revision of the lithostratigraphic units of the Coastal Plain of Georgia; the Miocene through Holocene. *Georgia Geologic Survey Bulletin,* 104:1-162.

JOHNSON, G. H., GOODWIN, B. K., WARD, L. W. and RAMSEY, K.W., 1987. Tertiary and Quaternary stratigraphy across the Fall Zone and western Coastal Plain, southern Virginia. In: Whittecar, G. R., Ed., *Geological excursions in Virginia and North Carolina. Southeastern Section*, 87-144. Geological Society of America 36th Annual Meeting. Norfolk, Virginia, Department of Geological Sciences, Old Dominion University.

LEWIS, H. C., 1881. The Trenton gravel and its relation to the antiquity of man. *Proceedings of the Academy of Natural Sciences of Philadelphia,* 32:296-309.

MARR, J. D., Jr. and WARD, L. W., 1987. Geology of the Caroline Stone Quarry. *Virginia Minerals,* 33(4):29-33.

MATHEWS, H. L., HODGES, R. L. AND AMOS, D. F., 1965. Some geological and geomorphical observations of Chesterfield County.*Virginia Journal of Science,* 16:380-381.

MCCARTAN, L., 1989. Mineralogy of the Haynesvile, Virginia, cores. In: Mixon, R.B., Ed., *Geology and Paleontology of the Haynesville cores – Northeastern Virginia Coastal Plain*, B1-B9. United States Geological Survey Professional Paper, 1489.

MCDANIEL, J. C., GILLISPIE, H. L. and ALI, JAMES, 1981. *Soil survey of Lunenburg County, Virginia.* United States Department of Agriculture, Soil Conservation Service: 1-109.

MILLER, K. G., KOMINZ, M. A., BROWNING, J. V., WRIGHT, J. D., MOUNTAIN, G. S., KATZ, M. E., SUGARMAN, P. J., CRAMER, B. S., CHRISTIE-BLICK, NICHOLAS and PEKAR, S. F., 2005. The Phanerozoic record of global sea-level change. *Science*, 310:1293-1298.

MIXON, R. B., BERQUIST, C. R., Jr., NEWELL, W. L., JOHNSON, G. H., POWARS, D. S., SCHINDLER, J. S. and RADER, E. K., 1989. *Geologic map and generalized cross sections of the coastal plain and adjacent parts of the Piedmont, Virginia.* United States Geological Survey, Report of Investigations I-2033, 2 map sheets and text.

MIXON, R. B. and NEWELL, W. L., 1977. Stafford fault system; structures documenting Cretaceous and Tertiary deformation along the Fall Line in northeastern Virginia. *Geology*, 5(7):437-440.

NEWELL, W. L. and RADER, E. K., 1982. Tectonic control of cyclic sedimentation in the Chesapeake Group of Virginia and Maryland. In: Lyttle, P.T., Ed., *Central Appalachian geology*, 1-27. Falls Church, Virginia: American Geologic Institute.

OWENS, J. P. and MINARD, J. P., 1979. *Upper Cenozoic sediments of the lower Delaware Valley and the northern Delmarva Peninsula, New Jersey, Pennsylvania, Delaware, and Maryland.* United States Geological Survey Professional Paper, 1067-D, 47p.

PAZZAGLIA, F. J., 1993. Stratigraphy, petrography, and correlation of late Cenozoic middle Atlantic Coastal Plain deposits: implications for late-stage passive-margin geologic evolution. *Geological Society of America Bulletin,* 105:1617-1634.

PAZZAGLIA, F. J. and GARDNER, T. W., 1993. Fluvial terraces of the lower Susquehanna River. *Journal of Geomorphology,* 8:83-113.

POWARS, D. S. and BRUCE, T. S., 1999. *The effects of the Chesapeake Bay Impact Crater on the Geological framework and correlation of* *hydrogeologic units of the lower York-James Peninsula, Virginia.* United States Geological Survey Professional Paper, 1612, 82p.

REINHARDT, JUERGEN, NEWELL, W.L. and MIXON, R.B., 1980. Tertiary lithostratigraphy of the core. In: Geology of the Oak Grove core. *Virginia Division of Mineral Resources Publication,* 20(1):1-13.

SPANGLER, W. P., PETERSON, J. J., 1950. Geology of the Atlantic Coastal Plain in New Jersey, Deleware, Maryland, and Virginia. *American Association of Petroleum Geologists,* 34:1-99.

STOVER, L. E., and HARDENBOL, JAN, 1993. Dinoflagellates and depositional sequences in the lower Oligocene (Rupelian) Boom Clay Formation, Belgium. *Bulletin de la Société Belge de Géologie* 102 (1-2):5-77.

WARD, L. W., 1985. *Stratigraphy and characteristic mollusks of the Pamunkey Group (lower Tertiary) and the Old Church Formation of the Chesapeake Group, Virginia coastal plain*. United States Geological Survey Professional Paper, 1346, 78p.

———, 1992. Middle Eocene and upper Pliocene sea level events; maximum high-stands during the Tertiary. In: Zullo, V.A., Harris, W.B. and Price, V. Jr., Eds., *Proceedings of the Bald Head Island Conference on Coastal Plains Geology.* Wilmington, University of North Carolina: 2:143.

WEEMS, R. E., 1986. Geology of the Ashland quadrangle, Virginia. *Virginia Division of Mineral Resources Publication 64*, text and 1:24,000 scale map.

———, 1998. *Newly recognized* en echelon *fall lines in the Piedmont and Blue Ridge provinces of North Carolina and Virginia, with a discussion of their possible ages and origins*. United States Geological Survey, Open-File Report 98-0374, 40p.

WEEMS, R. E., and EDWARDS, L. E., 2001. Geology of Oligocene, Miocene, and younger deposits in the coastal area of Georgia. *Georgia Geologic Survey Bulletin,* 131:1-124.

WENTWORTH, C. K., 1930. Sand and gravel resources of the Coastal Plain of Virginia. *Virginia Geological Survey Bulletin,* 32:1-146.

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