RADIOLARIANS AND DIATOMS FROM THE POLLACK FARM SITE, DELAWARE: MARINE–TERRESTRIAL CORRELATION OF MIOCENE VERTEBRATE ASSEMBLAGES OF THE MIDDLE ATLANTIC COASTAL PLAIN[1]

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ABSTRACT

The Pollack Farm Site near Cheswold, Delaware, is named for a borrow pit excavated during highway construction. The excavation exposed a portion of the Cheswold sands of the lower Miocene Calvert Formation. Two sand intervals (Cheswold C-3 and C-4) yielded a diverse assemblage of land and marine vertebrate remains and more than 100 species of mollusks. An isolated occurrence of a sandy silt (the radiolarian bed) stratigraphically between the two macrofossil-bearing units yielded only siliceous microfossils—radiolarians, diatoms, and sponge spicules.

Radiolarians from the radiolarian bed identify the *Stichocorys wolffii* Zone, which has an age estimated between 17.3 and 19.2 Ma. This is compatible with the strontium-isotope age estimate of 17.9±0.5 Ma on mollusks from the lower shelly sand bed (Cheswold C-3 sand) at the site. Both age determinations are compatible with the early Hemingfordian North American Land Mammal Age that was assigned to the land mammal fossils recovered from the C-3 sand.

The lower Miocene diatom *Actinoptychus heliopelta* from the radiolarian bed identifies East Coast Diatom Zone (ECDZ) 1. This taxon also occurs within "Bed 3A" of the Calvert Formation, the older part of the highly diatomaceous silty clays of Bed 3 that crop out in the Coastal Plain of Maryland and Virginia.

Correlation of borehole geophysical logs between Delaware and New Jersey places the vertebrate and molluscan assemblages collected from outcrops of the Shiloh marl of the lower Kirkwood Formation of New Jersey stratigraphically below those from the Pollack Farm Site. Estimates between about 19 and 20 Ma are calculated from a published Sr-isotope ratio for one mollusk shell from the Shiloh site. This indicates a possible unconformity between the Shiloh-equivalent beds (Cheswold C-2 sand, not exposed) and the ~18-Ma lower shell bed (Cheswold C-3 sand) at the Pollack Farm Site. The vertebrate assemblage from the Pollack Farm Site is of early Hemingfordian age, but vertebrates from the Shiloh site are not age-diagnostic. Both assemblages occur about 150–200 feet above the base of the Miocene section.

The Farmingdale vertebrate fossils of the northeastern Coastal Plain of New Jersey occur just above the base of the Miocene section (Kirkwood Formation) with an estimated age of 20.5–22.6 Ma based on published strontium-isotope data from boreholes in the vicinity. This age is compatible with the revised interpretation of late Arikareean for the age of the Farmingdale land mammal fossils.

The Popes Creek vertebrate assemblage of Maryland is from beds nearly stratigraphically equivalent to the Pollack Farm Site exposures, which agrees with the close temporal correlation of vertebrate remains from both sites. The Barstovian-age vertebrate assemblages from the Calvert Formation and basal part of the overlying Choptank Formation at the Calvert Cliffs exposures of Maryland are from units equivalent to the early middle Miocene *Dorcadospyris alata* Radiolarian Zone.

Radiolarian criteria that are used to indicate the degree of neritic versus oceanic conditions for the Miocene of the middle Atlantic Coastal Plain show increased neritic influence for the Pollack Farm Site and nearby exposures of beds of the *S. wolffii* Zone in Delaware, as compared with the more oceanic influence interpreted for other occurrences of the zone to the south and west in Maryland. This is consistent with the regional deltaic influence indicated for Delaware and New Jersey during the early Miocene and with the shallow inner neritic to intertidal paleoenvironments interpreted by other contributors to this volume for the Pollack Farm Site.

INTRODUCTION

The Pollack Farm Site is named for a large borrow pit for highway construction that was located near Cheswold, Delaware (Fig. 1). Exposed during the 1991–1992 excavation were two stratigraphically separated shelly sand beds (lower and upper shell beds, Fig. 2) correlated with the Cheswold sands (DGS informal lithostratigraphic unit named for the Cheswold aquifer) of the lower Miocene Calvert Formation. It was mainly the lower shell bed that yielded a diverse assemblage of terrestrial and marine vertebrate remains along with more than 100 species of mollusks plus other invertebrate fossils. The site subsequently was covered and converted to a wetland.

During the early part of the excavation, a small test trench, located several hundred feet east of the main excavation (see Ramsey, 1998, fig. 1), revealed about five feet of a planar-bedded sandy silt (30–35 percent sand), herein called the "radiolarian bed," that yielded abundant radiolarians and diatoms, rare siliceous sponge spicules, and no other fossils from an elevation of about 5 ft below sea level (Fig. 2). On the basis of surveyed elevations in the pit, the trench in the silt bed was just below the stratigraphic level of the upper shell bed (Fig. 2). At the same stratigraphic level in the main part of the pit to the west, a parallel-bedded silty sand yielded rare, poorly preserved diatoms but no radiolarians (Fig. 2). The area of the pit where the radiolarian-bearing silt was

[1] *In* Benson. R.N., ed., 1998, Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 5–19.

trenched was excavated and back-filled prior to my subsequent visits to the Pollack Farm Site; therefore, the extent and stratigraphic relationships of the radiolarian bed to the other units exposed at the site remain unknown. It represents an isolated occurrence, possibly an erosional remnant, of an offshore marine deposit within the predominately inner neritic to estuarine environments interpreted for the sediments at the site by other contributors to this volume.

On the basis of its microfossil content, the radiolarian bed correlates with a fine-grained deposit containing biosiliceous remains that crops out in Maryland west and southwest from the Chesapeake Bay and identified by Andrews (1988) and Wetmore and Andrews (1990) as Bed 3A, after the lower part of Shattuck's (1904) "zone 3" of the Fairhaven Member of the Calvert Formation of Maryland.

The fortuitous occurrence of radiolarians between the two macrofossil-bearing intervals at the Pollack Farm Site provides the means for correlating the vertebrate assemblage to a standard marine radiolarian microfossil zone, namely, the *Stichocorys wolffii* Zone (Riedel and Sanfilippo, 1978). On the bases of geophysical well log correlation and stratigraphic position (150–200 ft above the unconformity at the base of the Miocene section), I have also determined that the vertebrate fossils from the Pollack Farm Site are nearly the same age (early Hemingfordian) but slightly younger than the Shiloh Local Fauna of nearby New Jersey. Both vertebrate assemblages are considerably younger than the Farmingdale Local Fauna (Tedford and Hunter, 1984) of the northeastern Coastal Plain of New Jersey (Fig. 1) which occurs near the base of the Miocene section there.

Acknowledgments

Kelvin W. Ramsey of the DGS provided the composite stratigraphic section of the Pollack Farm Site shown in Figure 2. Ramsey and A. Scott Andres of the DGS measured and described the exposures and tied them to surveyed elevations within the pit as excavation proceeded during 1991 and 1992. Bruce W. Brough and C. Scott Howard of the DGS and Andres measured the natural gamma-ray responses of the exposed units above the lower shell bed with a portable scintillometer and provided the composite gamma-ray log of Figure 2. I thank Thomas G. Gibson, Amanda Palmer Julson, and Thomas E. McKenna for their thoughtful reviews of the manuscript and valuable suggestions for its improvement.

MICROFOSSIL BIOSTRATIGRAPHY

Results reported here of microfossil content refer only to those specimens retained on a 230-mesh (63-micron openings) sieve. Samples were dried, weighed, and washed through the sieve. Sand percentages were calculated, and all counts of microfossils were normalized to number of tests per gram of original sediment (Fig. 2).

Radiolarians and diatoms are common and calcareous microfossils are absent in a sandy silt underlying the upper shell beds at the Pollack Farm Site (Fig. 2). This radiolarian bed was found at only one locality within the excavation, and its lithology and age are representative of Bed 3A of Wetmore and Andrews (1990). At the same stratigraphic level about 500 ft west of the radiolarian bed locality only rare centric diatoms that had been replaced by iron oxides, presumably after pyrite, were recovered from a parallel-bedded sand unit. An increased gamma-ray response at the stratigraphic level of these two units, between about 5 and 10 ft below sea level, is recorded on the composite gamma-ray log of the exposed units above the lower shell bed at the site (Fig. 2).

The lowermost bed exposed at the site, the shelly mud bed underlying the lower shell bed (Fig. 2), yielded rare diatoms, a few radiolarians, and rare to common benthic foraminifers typical of the Chesapeake Group (e.g., *Florilus pizarrensis*, *Caucasina elongata*, *Uvigerina subperegrina*, *Hanzawaia concentrica*, *Bolivina paula*, and *Buliminella elegantissima*). Ward (1998) found scattered *in situ* mollusks, many in living position, in this bed and interpreted this to indicate a nearshore, open-marine, quiet-water setting. The open-marine radiolarian bed ("Bed 3A") differs in microfossil content from this lowermost unit at the site in the absence of calcareous fossils.

Stichocorys wolffii Radiolarian Zone

The presence of the radiolarian *Spongasteriscus marylandicus* in the radiolarian bed identifies the *Stichocorys wolffii* Zone (Riedel and Sanfilippo, 1978) as defined for the Miocene of the mid-Atlantic Coastal Plain by Palmer (1986b). Other radiolarian species present that have stratigraphic ranges including all or part of the Zone are *Calocycletta virginis* (but not *C. costata*), *Carpocanopsis cingulata*, *Cyrtocapsella cornuta*, *C. elongata*, *C. japonica*, *C. tetrapera*, *Didymocyrtis bassani*, *D. prismatica*, *D. tubaria*, *D. violina* (but not *D. mammifera*), *Dorcadospyris simplex*(?), *Eucyrtidium calvertense*, *E. diaphanes*, *Liriospyris stauropora*, *Stichocorys delmontensis*, *S. diploconus*, and *S. wolffii*.

Actinoptychus heliopelta Diatom Zone (ECDZ 1)

The stratigraphic range of the diatom *Actinoptychus heliopelta* identifies Abbott's (1978) Zone 1 named for that species and referred to as East Coast Diatom Zone (ECDZ)

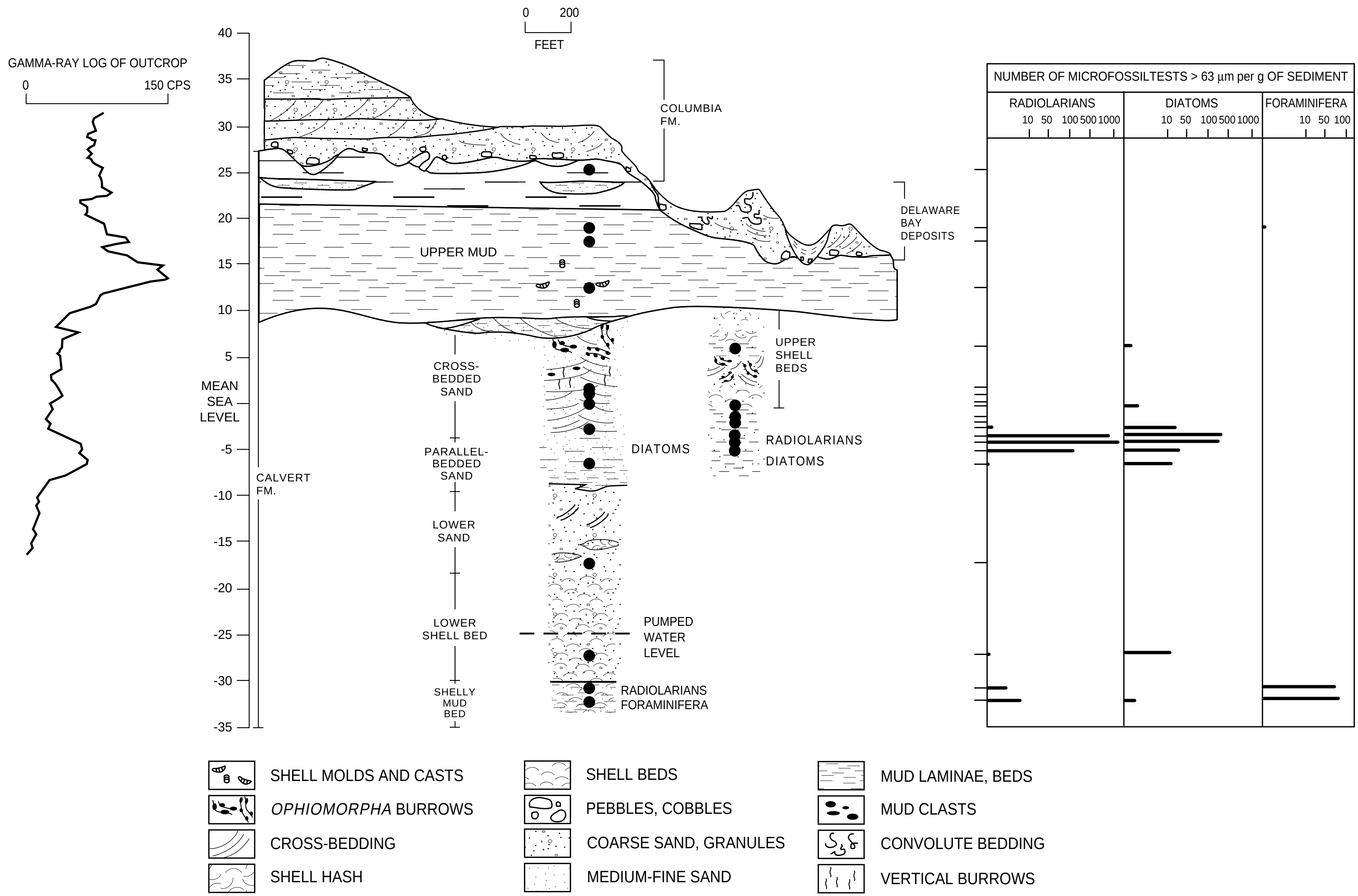

Figure 2. Composite west (on left) to east stratigraphic section of the Calvert Formation (lower Miocene) exposed at the Pollack Farm Site, Delaware (after Ramsey et al., 1992), with composite gamma-ray log of outcrop and results of microfossil counts. Solid circles are microfossil sample locations which correspond to tick marks along the left margin of the fossil count chart. The Columbia Formation and Delaware Bay deposits (Scotts Corners and Lynch Heights formations) are of Quaternary age.

1 by Andrews (1988). Abbott (1978) defined the top of the zone by the extinction of the nominate species but left the base of the zone undefined. A few specimens of this species were found in the radiolarian bed at the Pollack Farm Site. More recent studies by Benson (1990) and Sugarman et al. (1993) show that this species has a long stratigraphic range, almost the entire lower Miocene, and is, therefore, not useful for high resolution biostratigraphy.

CORRELATION

In Delaware, there are two other known exposures of the silts containing radiolarians of the *Stichocorys wolffii* Zone, both of them updip from the Pollack Farm Site (Id11-a). One (Ic22-c) is in a gravel pit located between boreholes 6 and 10 of Figure 3 and the other (Ic14-a) along the southern bank of Garrisons Lake between boreholes 6 and 5. *Spongasteriscus marylandicus* and *Stichocorys wolffii* were found at both sites. The diatom *Actinoptychus heliopelta* was found at the gravel pit site where radiolarians and diatoms are common to abundant, but not at Garrisons Lake where radiolarians and diatoms are rare.

Figure 4 shows the correlation of the increased gamma-ray response of the radiolarian bed on the composite gamma-ray log of the exposures at the Pollack Farm Site (Id11-a) with a similar response on the log of nearby borehole Ic25-12 (6 in Fig. 3). With the Ic22-c gravel pit exposure of the *S. wolffii* radiolarian bed as control, the structural cross section shown in the bottom panel of Figure 5 confirms the correlation of the bed between boreholes 6 and 10 (Ib25-06). The radiolarian bed projected updip from the Pollack Farm Site intersects Garrisons Lake at site Ic14-a as shown in the middle panel of Figure 5.

Downdip from the Pollack Farm Site in boreholes Id31-26 and Je32-04, radiolarians identifying the *Calocycletta costata* Zone, namely *C. costata* and *Didymocyrtis mammifera* (Riedel and Sanfilippo, 1978; Palmer, 1986b), are present in the silty interval above the C-5 sand (Fig. 4). Andrews (1988) and Wetmore and Andrews (1990) identified the biosiliceous interval that correlates to the *C. costata* Zone in Maryland as Bed 3B. On the basis of diatom and silicoflagellate biostratigraphy, Wetmore and Andrews (1990) suggested a hiatus of approximately 1 million years between Bed 3A and Bed 3B. The radiolarian data from Id31-26 and Je32-04 are insufficient to indicate a hiatus between the two successive radiolarian zones. Abbott's (1978) study of diatoms from Je32-04 did not indicate a major hiatus between his diatom zones I (equivalent to ECDZ 1) and II+III (equivalent to ECDZ 2) correlated with beds 3A and 3B, respectively.

With the stratigraphic control provided by the siliceous microfossil data, the stratigraphic relationships between the vertebrate assemblages of the Pollack Farm Site and the Shiloh marl of New Jersey (Fig. 3) can be established by means of geophysical log correlation. The datum for the stratigraphic correlation shown in Figure 4 is the unconformity at the base of the lower Miocene rocks of Delaware (Calvert Formation) and New Jersey (Kirkwood Formation). Rocks below the unconformity are of middle Eocene age. The unconformity is marked by a distinctive gamma-ray log signature and is documented by microfossil data (Benson et al., 1985; Benson and Spoljaric, 1996). I subdivided the Cheswold sands into five informal, laterally equivalent intervals on the bases of their stratigraphic position above the unconformity and their relationship to the radiolarian zones. Most of the vertebrate and mollusk fossils from the Pollack Farm Site were collected from the lower shell bed which I correlate with the C-3 Cheswold sand. As shown on the structural cross section of Figure 5, this interval is missing by erosional truncation just updip from the Pollack Farm Site and does not crop out as does the overlying *S. wolffii* radiolarian bed. Parallel to strike in New Jersey, the Grenloch Sand Member of the Kirkwood Formation (Isphording, 1970) as indicated in borehole 1 of Figure 4 occupies the same stratigraphic position above the unconformity as the C-1 and C-2 sands in Delaware. Cook (1868) described the several marl pits located along the headwaters of Stow Creek near Shiloh and Jericho, New Jersey. Although his descriptions are not precise, he characterized the fossil-bearing units mined for the marl as generally of gray color and consisting of fine sand and a little clay mixed with varying amounts of calcareous matter. Pit excavations were as deep as 23 feet, and he noted that they are sandier near the bottom. Gibson (1983, Fig. 19) described a well near Shiloh with about 20

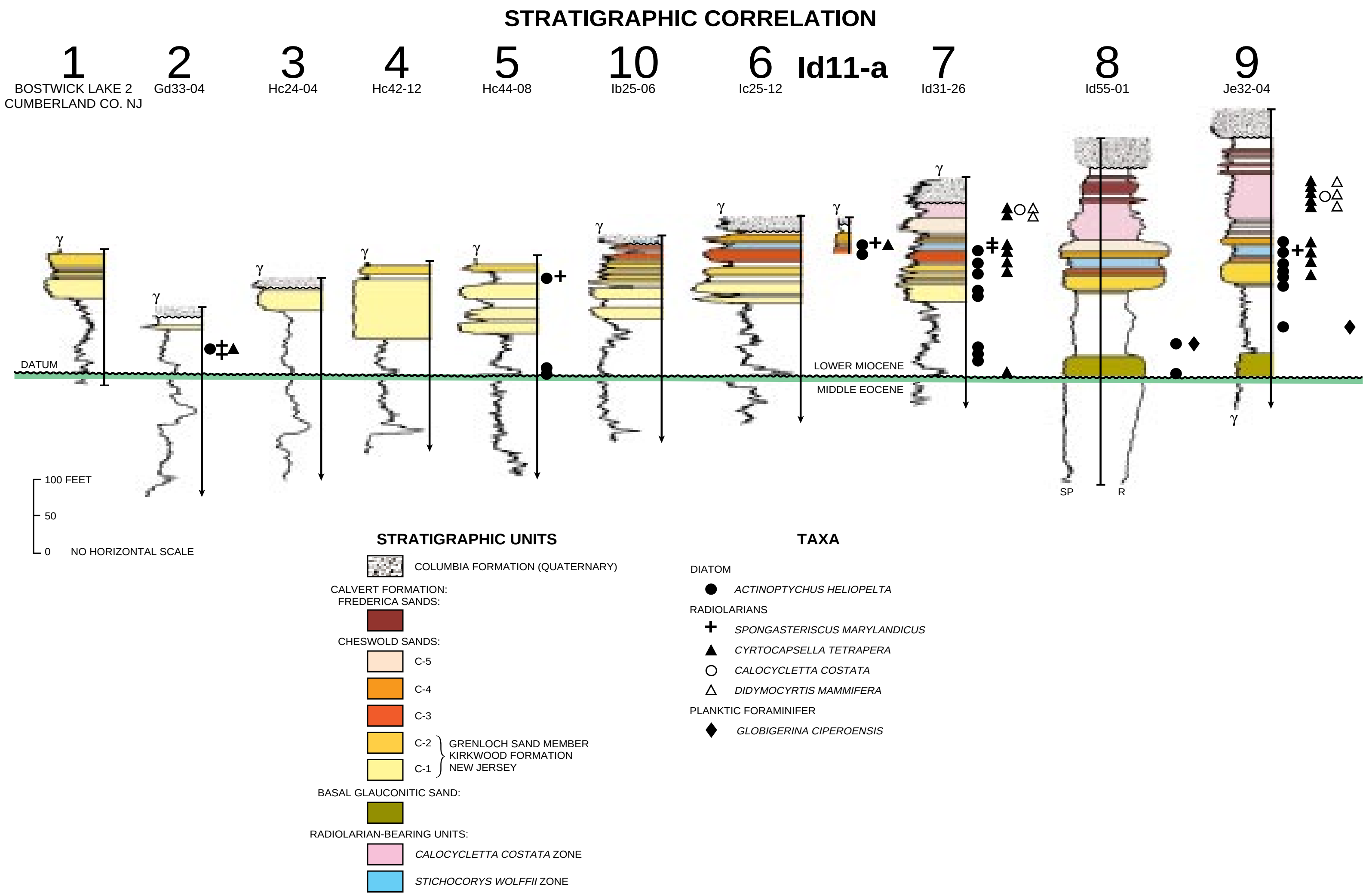

Figure 4. Stratigraphic correlation of geophysical logs of boreholes of Figure 3 and the composite gamma-ray log of the Pollack Farm Site section, Id11-a. DGS alphanumeric designations identify boreholes 2–10. Datum is the middle Eocene-lower Miocene unconformity. Taxa identifying biozones are shown where they were observed. Radiolarian-bearing units identified as representing the *Stichocorys wolffii* and *Calocycletta costata* zones correlate to beds 3A and 3B, respectively, as identified by Andrews (1988) and Wetmore and Andrews (1990). The occurrences of the foraminifer *Globigerina ciperoensis* in sediments dated by radiolarians and diatoms in boreholes 8 (Id55-01) and 9 (Je32-04) as lower Miocene precludes its usefulness as an identifier of Oligocene rocks; therefore, the section indicated as upper Oligocene between 297 and 370 feet in Je32-04 by Benson et al. (1985) is now placed in the lower Miocene (Benson and Spoljaric, 1996). Also in Je32-04, the 34-ft glauconitic sand interval overlying the unconfomity on middle Eocene rocks and indicated as "reworked Piney Point Formation" by Benson et al. (1985) is here considered the basal glauconitic sand of the Calvert Formation that is present in downdip localities (Benson, 1990; Benson and Spoljaric, 1996).

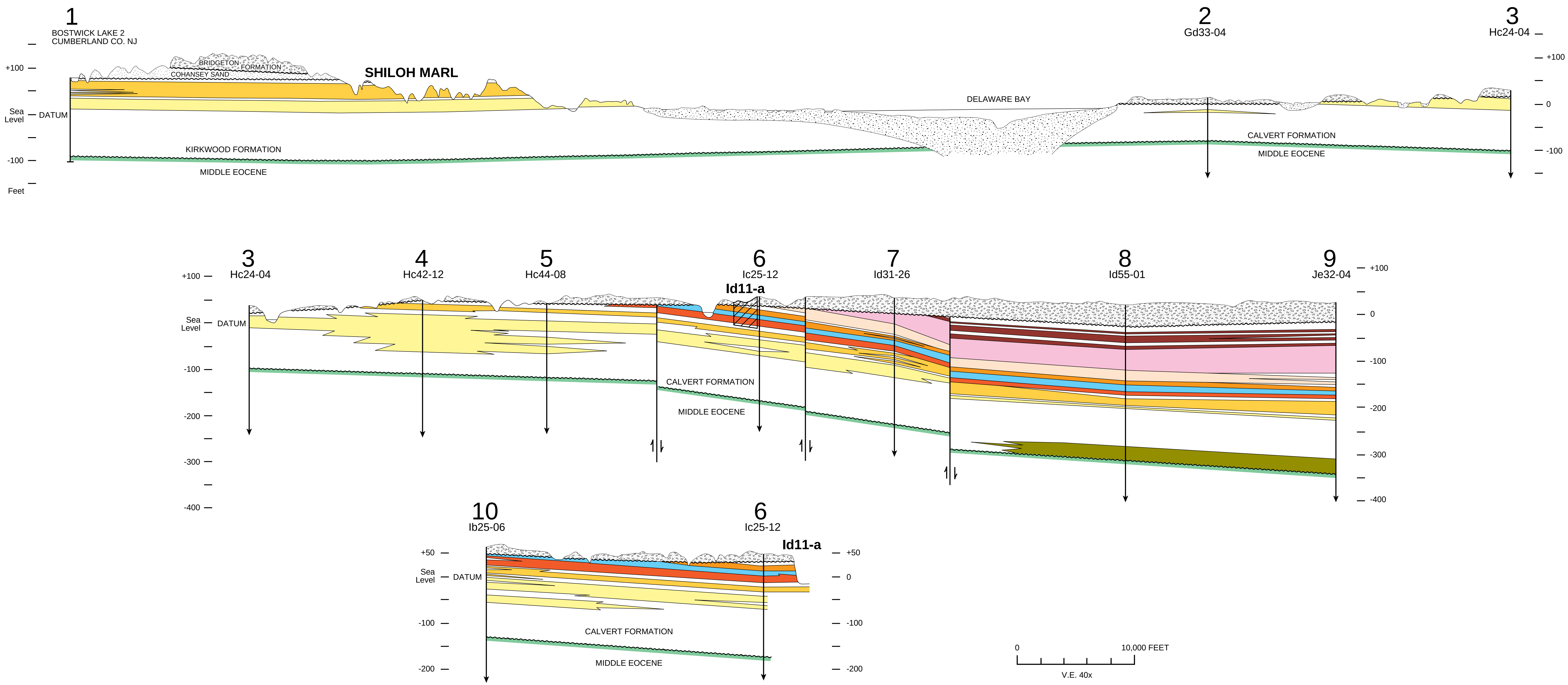

Figure 5. Structural cross section (sea level datum) showing stratigraphic relationships of Miocene rocks of boreholes and outcrops of Figures 3 and 4. See Figure 4 for identification of stratigraphic units.

feet of brown sand at the top of the section overlying about 10 feet of blue clayey sand with shells, the latter corresponding to descriptions of the Shiloh marl. The remaining 130 feet of the Kirkwood Formation below this is predominantly clay with sand interbeds at the top and base. In borehole 1 of Fig. 4, the upper thick portion of the C-2 sand corresponds in position to the brown sand, and the lower siltier portion of the C-2 corresponds to the shelly interval indicated by Gibson (1983). The C-1 sand identified in the well apparently fines to a silt or clay near Shiloh as indicated by Gibson (1983, Fig. 19), although I have shown its stratigraphic position at that locality in Figure 5. Owing to the absence of a prominent sand body (the C-1 sand) below the outcropping Shiloh marl, Isphording (1970) placed the Shiloh marl in the upper part of the Alloway Clay Member of the Kirkwood. As the Shiloh marl correlates with the basal part of or just below the C-2 sand of Delaware, the Shiloh Local (vertebrate) Fauna, therefore, does not correlate with the Chesapeake Bay Fauna of Barstovian Age from the Calvert Cliffs of Maryland as proposed by Tedford and Hunter (1984) but instead is nearly coeval with but slightly older than the Pollack Farm Local Fauna of Delaware. Emry and Eshelman (1998) assign an early Hemingfordian age to the land mammal fossil assemblage from the Pollack Farm Site, but they state that the single specimen of the land vertebrate *Tapirus validus* that constitutes the Shiloh Local Fauna is not age-diagnostic.

Tedford and Hunter (1984) note that the Farmingdale vertebrate collection of O.C. Marsh came from the basal sands of the Asbury Park Member of the Kirkwood Formation of the northeastern Coastal Plain of New Jersey. As the Pollack Farm and Shiloh faunas occur about 150–200 feet above the base of the Calvert and Kirkwood formations, respectively (Fig. 5), the Farmingdale Fauna must be older than those two, assuming the base of the Miocene is of the same age at all three locations. Emry and Eshelman (1998) conclude that the Farmingdale land mammal fossils are of late Arikareean rather than early Hemingfordian age as indicated by Tedford and Hunter (1984).

Figure 6 summarizes the North American land mammal ages assigned to the mid-Atlantic Miocene fossil vertebrate assemblages (Fig. 1) and correlations of the stratigraphic units in which they are found to global and regional Miocene biozones. Berggren et al. (1995) correlated the global planktic foraminiferal and calcareous nannofossil biozones to the geomagnetic polarity time scale of Cande and Kent (1992, 1994). The calibration of the North American land mammal ages to the time scale is that of Tedford et al. (1987). Radiolarian zones are those of Riedel and Sanfilippo (1978), and the ages in Ma of the biostratigraphic datums defining the zonal boundaries are from Hodell and Woodruff (1994, Table 3) who calibrated the datums in cores from DSDP site 289 (western Pacific) to their composite strontium seawater curve for the Miocene using the time scale of Cande and Kent (1992). Riedel and Sanfilippo (1978) define the base of the *Stichocorys wolffii* Radiolarian Zone by the first appearance datum (FAD) of *S. wolffii* and also indicate the last appearance (LAD) of *Dorcadospyris ateuchus* as coincident with the FAD of *S. wolffii*. Hodell and Woodruff (1994) do not give an age for the FAD of *S. wolffii* but do indicate the LAD of *D. ateuchus* at DSDP site 289 as 19.22 Ma. The top of the *S. wolffii* Zone is defined by the FAD of *Calocycletta costata* which Hodell and Woodruff (1994) give as 17.30 Ma. The radiolarians at the Pollack Farm Site, therefore, indicate the age of the fossil beds there as between 17.3 and 19.2 million years old. From analyses of strontium-isotope ratios of marine mollusks from the lower shell bed (C-3 sand) at the site, Jones et al. (1998) determined the mean age of the shells as 17.9±0.5 Ma, which is consistent with the age determined by the radiolarians and with the early Hemingfordian age assigned by Emry and Eshelman (1998) to the Pollack Farm Site vertebrate fossils (although 17.9 Ma is within the earliest late Hemingfordian according to Tedford et al., 1987).

As discussed previously, the Shiloh marl of nearby New Jersey is stratigraphically below the shell beds of the Pollack Farm Site. Sugarman et al. (1993, Table 1) determined a $^{87}Sr/^{86}Sr$ ratio of 0.708499±7 for one mollusk shell from the outcropping Shiloh marl and estimated its age using three different regression equations to correlate to the geomagnetic polarity time scale of Berggren et al. (1985) as 20.3, 20.1 and 20.0 Ma (solid dots in Shiloh marl column of Figure 6). The two open dots for the Shiloh marl in Figure 6 show that same ratio calibrated to the time scale of Cande and Kent (1992), giving age estimates of (1) about 19 Ma as read from Hodell and Woodruff's (1994, Fig. 10) composite strontium seawater curve for the Miocene, and (2) about 20 Ma as read from the linear regression line of Oslick et al. (1994, Fig. 6). This range in the age estimates for the Shiloh Local Fauna as shown in Figure 6 is consistent with either a latest Arikareean or an early Hemingfordian age. The strontium-isotope age estimates for the Delaware and New Jersey sites indicate a possible unconformity between the 19–20-Ma Shiloh-equivalent beds (Cheswold C-2 sand, not exposed) and the ~18-Ma lower shell bed (Cheswold C-3 sand) at the Pollack Farm Site.

As noted previously, the Farmingdale land vertebrate fossils occur in the basal sands of the Kirkwood Formation. Strontium-isotope age estimates of the basal Kirkwood located closest to the Farmingdale sites are from the Berkeley and Lacey wells reported by Sugarman et al. (1993, Fig. 3, Table 1) who estimated ages of 22.2, 22.0, and 21.7 Ma for the former and 22.6, 22.3, and 22.0 Ma for the latter (solid dots in Figure 6) by using three different regression equations to correlate to the geomagnetic time scale of Berggren et al. (1985). The total range of 20.5–22.6 Ma for the age estimate for the Farmingdale Fauna shown in Figure 6 was determined in the same manner as that for estimating the age of the Shiloh mollusk: strontium-isotope ratios reported by Sugarman et al. (1993, Table 1) for the Berkely and Lacey wells calibrated to the time scale of Cande and Kent (1992) by means of Hodell and Woodruff's (1994) curve give age estimates of about 20.5 and 21 Ma for the Berkeley and Lacey wells, respectively, and by means of the regression line of Oslick et al. (1994) give estimates of about 21.9 and 22.2 Ma, respectively (open dots in Figure 6). The age estimates thus determined give the Farmingdale Local Fauna a late Arikareean land mammal age (Fig. 6), which is consistent with that age interpretation by Emry and Eshelman (1998) and confirms that the Shiloh and Pollack Farm vertebrate faunas are stratigraphically higher (by 150–200 ft?) than the Farmingdale Fauna.

The ages of the Miocene vertebrate fossils from Maryland can be bracketed by means of correlation with the

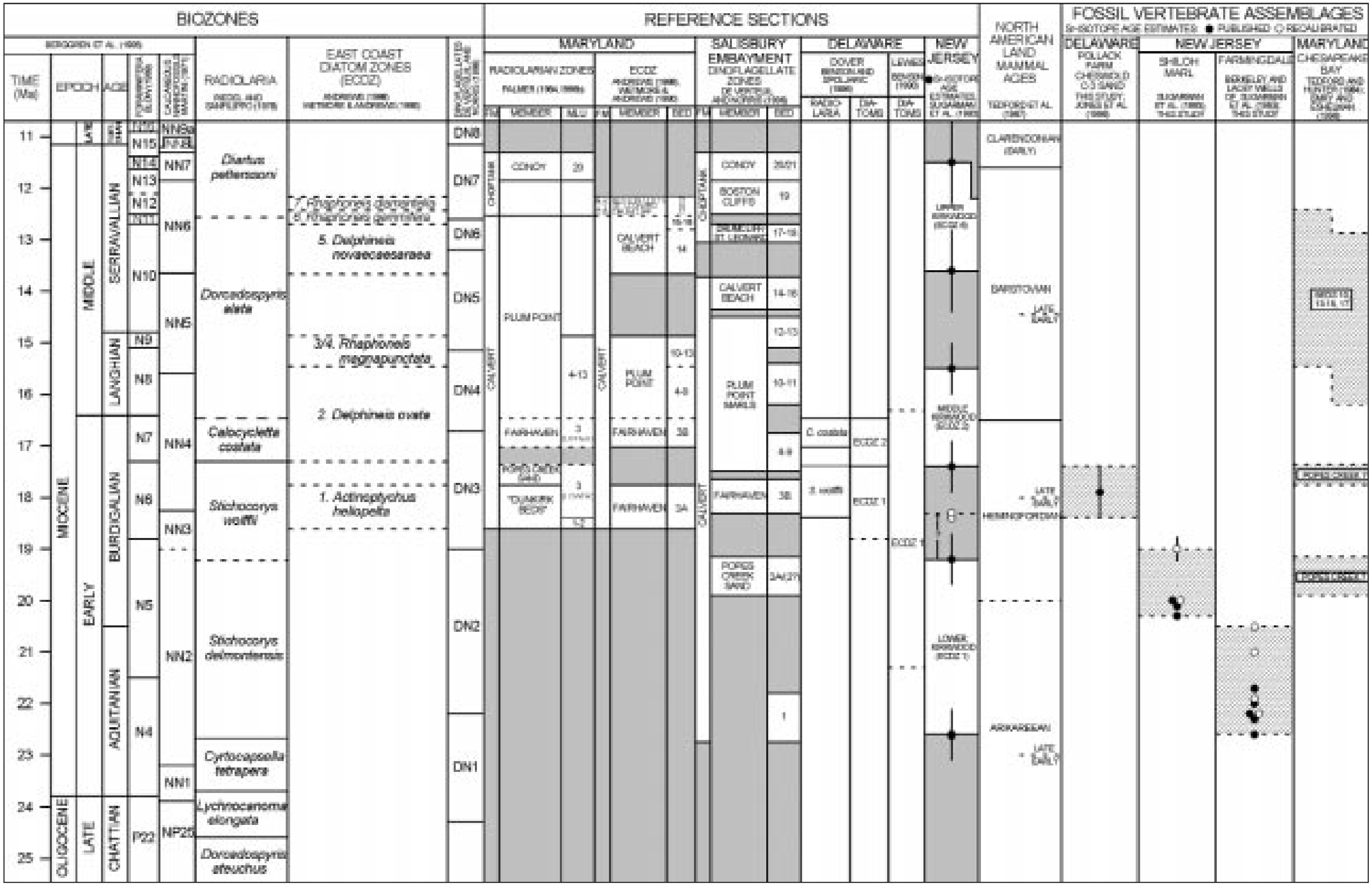

Figure 6. Correlation of the stratigraphic units containing the mid-Atlantic Miocene fossil vertebrate assemblages to global foraminiferal, calcareous nannofossil, and radiolarian biozones and regional diatom and dinoflagellate biozones calibrated to the geomagnetic polarity time scale of Cande and Kent (1992, 1994). Diagonal ruling indicates the maximum range of the age estimate for each fossil vertebrate assemblage. Solid dots are strontium-isotope age estimates for the New Jersey assemblages and Kirkwood sequences published by Sugarman et al. (1993), and open dots are my recalibrations of their published isotope ratios. Dashed lines indicate uncertainty in correlations by authors cited and in this study. See text for further explanation.

global radiolarian biozones shown in Figure 6. Palmer (1984, 1986b) identified the biozones in her study of mid-Atlantic Miocene radiolarian occurrences and correlated them to the "zones" of Shattuck (1904), which she referred to as Miocene Lithologic Units (MLU) as recommended by Andrews (1978). Andrews (1988) and Wetmore and Andrews (1990) likewise correlated the East Coast Diatom Zones (ECDZ) and silicoflagellate zones to the MLUs.

Palmer (1984) assigned the highly diatomaceous clayey silts of the Dunkirk beds of Gibson (1982) to the *Stichocorys wolffii* Radiolarian Zone (Fig. 6). They are the lowermost outcropping beds of the Calvert Formation in Maryland but are not present in surface sections at Calvert Cliffs on the western shore of Chesapeake Bay (Fig. 1). Palmer (1984) identified the entire Fairhaven Member of the Calvert Formation at the base of the Calvert at Calvert Cliffs as MLU 3 and assigned it to the *Calocycletta costata* Zone, but Andrews (1988) and Wetmore and Andrews (1990) indicate this as their Bed 3B (Fig. 6). Following the analysis of Gibson (1982), Palmer (1984) states that the Dunkirk beds correspond to MLU 1, MLU 2, and the lower part of MLU 3. The Dunkirk beds, therefore, are equivalent, at least in part, to Bed 3A, recognized as the lower part of the Fairhaven Member of the Calvert Formation by Andrews (1988) and Wetmore and Andrews (1990), and to the radiolarian bed at the Pollack Farm Site in Delaware (Fig. 6). Gibson (1982) identified the Popes Creek sand as occurring stratigraphically between the Dunkirk beds and the Fairhaven Member but also not present at Calvert Cliffs. Emry and Eshelman (1998) compared peccary fossils from the Popes Creek locality along the lower Potomac River to a small peccary from the Pollack Farm Site and concluded that there is a close temporal correlation between the sites (early? to late? Hemingfordian); therefore, the Popes Creek vertebrate assemblage is considered approximately coeval with part of the *Stichocorys wolffii* Zone (Fig. 6). Palmer's (1984, 1986b) correlation of the Popes Creek sand follows that of Gibson (1982) who placed the Popes Creek stratigraphically between the Dunkirk (*S. wolffii* Zone) and the Fairhaven Diatomaceous Earth Member (*Calocycletta costata* Zone) of the Calvert Formation. The Popes Creek sand, therefore, is coeval or nearly so with the Cheswold sands exposed at the Pollack Farm Site (Fig. 6). On the other hand, on the basis of their dinoflagellate biostratigraphy de Verteuil and Norris (1996) correlate the Popes Creek sand with foraminiferal zone N5 and calcareous nannofossil zone NN2 as shown in figure 6. This places the Popes Creek in the early Hemingfordian; therefore, two possibilities for the age of this unit are shown in the Chesapeake Bay column of Figure 6.

Andrews (1988) and Wetmore and Andrews (1990) assigned Bed 3A to ECDZ 1 and observed the extent of this diatom zone into New Jersey. Strontium-isotope dating of ECDZ 1 (lower Kirkwood) in New Jersey by Sugarman et al. (1993) indicates that its upper limit is older than 19.2 Ma, therefore, older than the upper limit of the ECDZ 1 interval (and *Stichocorys wolffii* Zone) in Maryland and Delaware, although the error bars for the strontium-isotope age estimates shown in Figure 6 for the New Jersey reference section and the Pollack Farm Site (also ECDZ 1) nearly overlap. The strontium-isotope ratios that yielded minimum age estimates of 19.2 Ma for ECDZ 1 in New Jersey (Sugarman et al., 1993, Table 1) when calibrated to the time scale of Cande and Kent (1992) using the composite strontium seawater curve of Hodell and Woodruff (1994) yield age estimates of about 18.3–18.4 Ma (open dots in Figure 6), closer to the age estimate for the Pollack Farm Site. In borehole Oh25-02 near Lewes, Delaware, Benson (1990) found *Actinoptychus heliopelta*, the identifying taxon for ECDZ 1, above the highest occurrence of planktic foraminiferal Zone N7 (16.7–16.4 Ma: Berggren et al., 1995), which is stratigraphically higher than indicated by Sugarman et al. (1993) for ECDZ 1 in New Jersey (Fig. 6). Sediments of the *S. wolffii* Zone in the Dover Air Force Base well Je32-04 correlate with the same interval at the Pollack Farm Site (Fig. 5). In that well, the top of the *S. wolffii* Zone occurs at the top of ECDZ 1 (Benson and Spoljaric, 1996), but the base of the latter extends below the base of the radiolarian zone (Fig. 6). Also in Je32-04, radiolarians that identify the *Calocycletta costata* Zone occur only in the upper half of the interval assigned to ECDZ 2 (Benson and Spoljaric, 1996).

Emry and Eshelman (1998) summarize the occurrences of fossil land mammals from the Calvert Cliffs as from beds 10 and 13–15 of the Calvert Formation and the basal part of the overlying Choptank Formation (bed 17, see Andrews, 1988). The left half of the Chesapeake Bay column of Figure 6 shows the correlation of these beds to the radiolarian zones after Palmer (1984, 1986b), and the right half shows de Verteuil and Norris's (1996) slightly different correlation of beds 10–17 based on dinoflagellate biostratigraphy. Palmer (1984) assigned the Plum Point Member of the Calvert (MLU 4–13) to the lower part of the *Dorcadospyris alata* Zone, older than the LAD of *Calocycletta costata* (14.46 Ma as given by Hodell and Woodruff, 1994) as that species occurs within the stratigraphic interval. Palmer (1984) noted that radiolarians are sparse in MLU 14 through 19, and, therefore, no zonal assignment could be made for that interval, although she does suggest that it may correspond to the *D. alata* Zone. Whether they are correlated by radiolarian or dinoflagellate biostratigraphy, the beds containing the Calvert Cliffs land mammal fossils correspond to the *D. alata* Zone and span the early to late Barstovian, which conforms to the age assigned to the vertebrate fossils by Tedford and Hunter (1984) and Emry and Eshelman (1998).

The only other radiolarian zone in Maryland identified by Palmer (1984) is the *Diartus petterssoni* Zone for MLU 20 (Conoy Member) of the Choptank Formation.

PALEOENVIRONMENTAL INTERPRETATION

The high numbers of radiolarians and diatoms in the radiolarian bed at the Pollack Farm Site (Fig. 2) reflect open marine, biologically productive, relatively low-energy conditions. The presence of 30–35 percent fine sand in this silt bed, however, indicates that the environment was near a source of sand. This contrasts with the lithology of Bed 3A in Maryland, part of which is coeval with the radiolarian bed. Bed 3A is a diatomaceous silt with some included clay but very little fine sand that Wetmore and Andrews (1990) interpret as having been deposited in a shallow marine environment with no apparent influence from rivers supplying clastic sediments and fresh water.

The Cheswold sands that predominate at the Pollack Farm Site are evidence of a deltaic influence. Gibson (1982, 1983) shows the regional paleoenvironments for the lower half of the Plum Point Member of the Calvert Formation and its equivalents (early middle Miocene) throughout the middle Atlantic Coastal Plain and indicates the area of deltaic influence from the north into New Jersey and the northern Delmarva Peninsula as shown in Figure 7. That same area of deltaic influence likely prevailed during the early Miocene in central New Jersey where the Grenloch Sand Member of the Kirkwood Formation dominates the Coastal Plain section (Isphording, 1970, Fig. 1) and during the later early Miocene when the Cheswold sands prograded into Delaware. To the west of the area of deltaic influence, Gibson (1982, 1983) shows a protected embayment in which biosiliceous remains, particularly diatoms, accumulated in numbers sufficient to produce diatomites. To the south in Virginia and North Carolina, phosphatic to carbonate, inner to middle shelf environments predominated.

Ramsey (1998) interprets the depositional environments represented by the sediments exposed at the Pollack Farm Site (see Figure 2): (1) shelly mud bed–marine inner shelf; separated by a disconformity from (2) lower shell bed and lower sand–tidal channel; separated by a ravinement surface or disconformity from (3) parallel-bedded sand (in which I found rare centric diatoms and which is at the same stratigraphic level in the pit as the radiolarian bed about 500 ft to the east)–subtidal channel margin; (4) cross-bedded sand–subtidal sand flat shoaling upward to a subtidal to intertidal flat with channel axis and channel-margin facies identified by Miller et al. (1998) on the basis of relative densities of *Ophiomorpha nodosa* burrows; separated by a ravinement surface from (5) upper mud–intertidal to supratidal flat.

A sandy silt with abundant radiolarians and diatoms representing biologically productive open marine waters in close proximity to the environments just listed in which the mix of marine, brackish-water, fresh-water, and terrestrial fossils were deposited presents a challenge to interpretation. An added difficulty is that the area in the pit where the test trench uncovered the radiolarian bed was excavated and back-filled prior to subsequent visits to the site for study; therefore, the stratigraphic relationships of the radiolarian bed to the other units exposed at the Pollack Farm Site could not be determined. As the silts containing the radiolarians of the *Stichocorys wolffii* Zone are widespread as shown in Figures 4, 5, and 7, the Cheswold sands can be considered as the deposits of a delta prograding into the widespread open marine environment supporting production of biogenous silica, and the radiolarian bed at the Pollack Farm Site represented an isolated area such as an interdistributary bay where sand influx was minimal. Alternatively, the radiolarian bed may have been an erosional remnant of the biosiliceous unit "Bed 3A" that was preserved in one small area of the Pollack Farm Site, surrounded by younger marginal marine deposits. A third interpretation is that the radiolarian bed represents a deeper water deposit than the rest of the sediments at the Pollack Farm Site and that its base (not observed) may represent a flooding surface—one separating younger from older strata across which there is evidence of an abrupt increase in water depth, thus defining a parasequence boundary (Van Wagoner, 1995). The fact that the parallel-bedded sand/radiolarian bed interval has a gamma-ray log response correlatable over a large area (Figs. 4 and 5) supports the interpretation that it represents a parasequence, at least the deeper-water basal part of one.

Radiolarians, which are generally associated with the oceanic realm, are not usually found in abundance in shelf environments. Palmer (1984, 1986a) investigated the radiolarians in diatomaceous Miocene shelf sediments of the mid-Atlantic region and was able to apply criteria from her and others' studies to show the potential value of these siliceous microfossils as indicators of neritic versus oceanic conditions. In her model, she infers that radiolarians were trans-

Figure 8. Maps of contoured data from Table 1 showing radiolarian criteria indicating oceanic versus neritic conditions.

ported to the Virginia to New Jersey shelf (Salisbury Embayment) from slope waters by warm-core rings (eddies) spawned from the Miocene Gulf Stream and to the phosphate-rich North Carolina shelf by upwelling from or intrusion by the ancient Gulf Stream (Palmer, 1988). The early Miocene shelf edge off New Jersey and Delmarva (Fig. 7) was 50–100 km landward of the modern shelf edge as inferred from analysis of offshore seismic reflection data by Roberts (1988) and Poag (1992); therefore, the source of oceanic slope waters was that much closer to the Pollack Farm Site than it is today.

Palmer (1984, 1986a) reasoned from her results of quantitative analyses of the radiolarian assemblages that radiolarian populations transported into shelf waters would encounter ecologic stresses, particularly in the vicinity of the mouths of large rivers. These stresses would result in a decrease in overall diversity, with increased dominance by taxa more tolerant of shelf conditions. The emphasis in her study was determining the changes in oceanic versus neritic conditions through time. In this study, in order to characterize the regional paleoenvironmental setting of the Pollack Farm Site, I have analyzed the assemblages only of the *Stichocorys wolffii* Zone. Known (presence of *Spongasteriscus marylandicus* with other zonal markers) and probable (by correlation) occurrences of the zone in the mid-Atlantic Coastal Plain are shown in Figure 7.

Table 1A lists the radiolarian counting groups of Palmer (1984, 1986a) which I used in analyzing the Delaware assemblages of the *Stichocorys wolffii* Zone and the one sample of the zone from the Hammond well of Maryland. Palmer's (1984, Appendix C) data from Maryland outcrop and well samples of the zone are included in the table. Criteria derived from the data (Table 1B) that indicate the degree of neritic versus oceanic influence (Palmer 1984, 1986a) are contoured in Figure 8.

The assemblages at the Pollack Farm Site (Id11-a) and the two nearby outcrop sites Ic14-a and Ic22-c are nearly the same. Three combined counting groups (Table 1) dominate, all spumellines: 1) actinommids, averaging 29.1% for the three sites; 2) spongodiscids + coccodiscids, spongy taxa considered by Palmer (1984) to contain symbiotic algae, averaging 29.4%; and 3) litheliids, averaging 26.3%. The next most abundant groups include one spummelline family —phacodiscids (2.9%)—and two nasselline genera—*Cyrtocapsella* (3.4%) and *Stichocorys* (2.6%).

Only one core sample from Je32-04 (depth 197–199 ft) and one sample from the Hammond well (depth 1100–1110 ft) yielded rare tests of *Spongasteriscus marylandicus*. Only 34 radiolarian tests were found in the Je32-04 sample, a diatomite, because of their dilution by diatoms, particularly *Actinoptychus heliopelta*; therefore, results of counts in Table 1 for that sample are not statistically significant. The sample examined from the Hammond well is a float sample of poorly washed drill cuttings; radiolarians likewise are not clean but most counting groups could be identified under a low power binocular microscope. I suspect that counts of that sample may be biased (perhaps by the laboratory flotation process or by the sample being of drill cuttings rather than of core or outcrop) as actinommids account for 88.4% of the assemblage, which seems too high for its offshore (more oceanic) location compared to the Pollack Farm Site. The low diversity of the sample (Shannon-Wiener index, H(S), of 0.90, Table 1B) likewise does not fit a more nearly oceanic setting.

Palmer's (1986a) outcrop samples from the Dunkirk beds of Maryland (LC-2, K-1, and J-1 in Fig. 7) are highly diatomaceous silts and diatomites containing hundreds to thousands of radiolarians per gram of sediment. Radiolarians are well preserved (grades 2 to 3 of Westberg and Riedel, 1978). From her interpretation, high rates of biological productivity with little dilution by clastic sediments yielded the large concentrations of diatoms in a shallow, open-marine environment in a quiet aerobic setting below storm-wave base. Closer to or within the area of deltaic influence, the two well samples from the Maryland Eastern Shore (Qa-63 and TAL-30, Fig. 7) are from less diatomaceous and sandier sediments with higher amounts of carbonate and organic matter. Radiolarians are more poorly preserved (grade 4 of Westberg and Riedel, 1978), less abundant, and less diverse than those from the Dunkirk outcrops (Palmer, 1986a). Likewise, I interpret radiolarian preservation at the Pollack Farm and nearby sites as grade 4 on the basis of the dominance of the assemblages by robust tests (thick test walls and pore bars) and the paucity of delicate forms. The robust tests, however, may reflect uptake of high dissolved silica concentrations brought into the area by nearby rivers and may not represent pronounced distortion of the assemblage by dissolution of the more delicate forms which characterizes grade 4 preservation (Westberg and Riedel, 1978). The robust tests are generally well-preserved and do not show much evidence of pitting by dissolution.

Results of radiolarian counts of the Delaware samples continue the trend of increasing neritic influence from the open marine embayment as exemplified by the Dunkirk beds northeastward to the region of deltaic influence. Diversity as measured by the Shannon-Wiener information function (Gibson and Buzas, 1973) decreases in that direction (Table 1B, Fig. 8A). Equability, which equals 1.0 when all taxa are equally distributed (Gibson and Buzas, 1973), likewise is much less in the Delaware samples than those from Maryland (Table 1B) and reflects the dominance of just a few taxa that could flourish in the stressed nearshore environment of the Pollack Farm and nearby sites.

Three other criteria that Palmer (1984, 1986a) used to indicate neritic versus oceanic conditions are shown in Figures 8B–D. All three show the trend of increased neritic conditions from the area of the Dunkirk outcrops toward the area of deltaic influence to the northeast. Palmer's (1984) oceanic radiolarian index of Figure 8B increases away from the deltaic region as the oceanic-enhanced families theoperids and phacodiscids increase in relative abundance. A similar trend is shown by the percentage of nasselline tests (Fig. 8C) which also are more indicative of oceanic conditions. Palmer (1984) cites several studies by Casey and his students (e.g., Casey et al., 1982) that report the presence of symbiotic algae in shallow-water-dwelling spongy taxa, the spongodiscids and coccodiscids, which dominate in shelf waters of tropical and temperate regions. Figure 8D shows the shoreward increase to nearly 60 percent domination by these groups which are indeed excellent indicators of neritic conditions.

Palmer (1984) did not find a clear pattern of abundance distribution for the actinommids and litheliids in her study of Coastal Plain assemblages. These groups occur at similar levels of abundance at all sites she studied. At the Pollack Farm and nearby Delaware sites, however, these two groups (plus the spongy taxa) dominate the assemblages and have greater abundances than in the Maryland samples to the west (Table 1B). They may be useful in indicating environments closer to ancient shores than those paleoenvironmental settings sampled by Palmer (1984).

SUMMARY AND CONCLUSIONS

Radiolarians recovered from the Pollack Farm Site provided the means to correlate the rich molluscan and vertebrate fossil remains found there to the record of global marine biostratigraphic zones and the geomagnetic polarity time scale. The early Miocene *Stichocorys wolffii* Radiolarian Zone (17.3–19.2 Ma) identified at the site is compatible with the 17.9±0.5 Ma age of mollusks as determined from strontium-isotope ratios (Jones et al., 1998) and with the early Hemingfordian age of the fossil land mammal remains (Emry and Eshelman, 1998). The close temporal relationships between the Popes Creek vertebrate remains of Maryland and the vertebrates and mollusks from the Pollack Farm Site of Delaware and the Shiloh marl of New Jersey as determined from analyses by Emry and Eshelman (1998) and Ward (1998) are supported by radiolarian studies of Palmer (1984, 1986b) and by stratigraphic correlation of borehole geophysical logs in this study.

TABLE 1

Results of counts of radiolarian assemblages of the *Stichocorys wolffii* Zone, Delaware and Maryland. Abundances are percentages of the total number of tests counted for each site (P=present).

A. COUNTING GROUPS	**Id11-a**	**Ic14-a**	**Ic22-c**	**Tal-30**	**Qa-63**	**J-1**	**K-1**	**LC-2**	**Je32-04**	**Hammond**
SPUMELLINE TAXA:										
CUBOTHOLIIDS:										
Cubotholus			0.16							
COLLOSPHAERIDS	0.04									
ACTINOMMIDS:										
Hexacontium	6.30	8.14	5.67	23.00	8.70	1.40	19.10	13.60		1.62
Stylosphaera	2.70	6.70	9.49							6.94
other actinommids	14.20	17.46	16.65			5.00	1.20		26.50	79.86
PHACODISCIDS	2.80	2.87	3.13	6.40	8.70	1.40	3.20	0.70	2.90	1.39
COCCODISCIDS:										
Didymocyrtis	3.10	5.02	4.19	3.20	2.40	5.80	6.90	4.30	5.90	0.46
SPONGODISCIDS:										
Dictyocoryne	2.80	4.07	2.55	9.70	7.90	11.50	7.30	7.90		0.46
Porodiscus -narrow rings	1.60		1.11	7.20	13.40	2.90	4.50	2.90		
Porodiscus -wide rings	0.60	0.24	0.74	0.80			0.40			
Spongasteriscus	0.60	0.72	0.16	1.60	5.50	2.90	2.00	2.90	2.90	0.46
Spongodiscus	15.20	18.42	16.97	6.40	19.70	2.90	8.50	1.40		3.01
Stylodictya	0.20	0.24	0.11	0.80	7.10		0.80	1.40	8.80	
spongodiscid group A	2.00	2.87	3.82				0.40	0.70	5.90	0.46
spongodiscid group B	0.10	0.24	0.16							
other spongodiscids	0.50		0.05						5.90	
PYLONIIDS	1.20	1.91	0.53			0.70				
LITHELIIDS:										
Lithelius	20.40	18.42	22.38	12.90	11.00	0.70	7.30	3.60		0.46
Pylospira	1.90	0.72	0.16	0.80	2.40	7.20	3.20	4.30		
other litheliids	12.10	1.20	1.75							
NASSELLINE TAXA:										
SPYRIDS:										
Dendrospyris	2.20	0.72	1.22	1.60	1.60	0.70	1.20	10.00	2.90	
Desmospyris	0.20		0.05			0.70				
Liriospyris	0.04									
other spyrids										
PLAGONIIDS:										
Ceratospyris group A	0.10	0.96	0.32	3.20	1.60	19.40	3.20	11.40		
Ceratospyris group B	0.10	0.24								
Lithomelissa	0.30	0.72	0.74			5.00	3.70	11.40	26.50	
Pseudocubus										
Pseudodictyophimus						2.90	0.40	0.70		
plagoniid group A				1.60		1.40	0.80	2.90		
other plagoniids	0.10	0.24	0.16		0.70	4.30				
THEOPERIDS:	0.10									
Bathropyramis	0.10	P								
Cyrtocapsella	3.20	4.31	2.55	4.80	3.90		0.80		5.90	4.17
Eucyrtidium group A	0.90	1.20	1.17	4.00	0.70	2.90	2.80	3.60		
Eucyrtidium group B	0.20	0.24	0.16							
Gondwanaria	0.04	P	0.16	2.40		15.80	19.10	10.00	2.90	
Lithopera										
Lychnocanoma	0.10		0.11							0.23
Stichocorys	3.10	2.15	2.44	4.80	3.90	2.20	0.80	2.10	5.90	0.23
other theoperids	0.04						0.40			
CARPOCANIIDS	0.10	P								
PTEROCORYTHIDS	0.40	P	0.69		1.60		0.40			0.23
ARTOSTROBIIDS				1.60			0.40	0.70		
CANNOBOTRYIDS	0.04	P				0.70	0.40			
INCERTAE SEDIS:										
Carpocanarium	0.50	P	0.21							
Tepka							P	P		
UNIDENTIFIED NASSELLINES			0.27							

B. DATA SUMMARY	**Id11-a**	**Ic14-a**	**Ic22-c**	**Tal-30**	**Qa-63**	**J-1**	**K-1**	**LC-2**	**Je32-04**	**Hammond**
NUMBER COUNTED	2505	418	1886	124	127	139	246	140	34	432
NUMBER OF GROUPS	38	25	32	19	17	23	27	21		14
NO. OF SPUMELLINE GROUPS	19	16	19	11	10	11	13	11		10
NO. OF NASSELLINE GROUPS	19	9	13	8	7	12	14	10		4
PERCENT NASSELLINE TESTS	12.20	10.80	10.23	27.20	13.20	57.60	36.00	56.30		4.86
PERCENT ACTINOMMIDS	23.15	32.30	31.81	23.00	8.70	6.40	20.30	13.60		88.43
PERCENT SPONGODISCIDS	23.60	26.62	25.67	26.50	53.60	20.20	23.90	17.20	23.50	4.39
PERCENT LITHELIIDS	34.40	20.34	24.29	13.70	13.40	7.90	10.50	7.90		0.46
PERCENT THEOPERIDS	7.68	7.90	6.59	16.00	8.50	20.90	23.90	15.70	14.70	4.63
OCEANIC RADIOLARIAN INDEX	0.39	0.34	0.33	0.75	0.31	0.86	0.88	0.76	0.60	1.24
H(S)	1.82	2.29	2.33	2.48	2.50	2.66	2.62	2.69		0.90
E (equability)	0.16	0.40	0.32	0.63	0.72	0.62	0.51	0.70		0.18
PRESERVATION	4	4	4	4	4	2	2	2		

In the northeastern Coastal Plain of New Jersey, the stratigraphic position of the Farmingdale vertebrate assemblage just above the base of the Miocene section (Kirkwood Formation) indicates that it is older than the Pollack Farm and Shiloh fossils which occur 150–200 feet stratigraphically higher, assuming the base of the Miocene is of the same age at all three locations. This is supported by the late Arikareean age assigned to the Farmingdale vertebrates by Emry and Eshelman (1998) and by strontium-isotope age estimates of 20.5–22.6 Ma, based on data by Sugarman et al. (1993), for the basal Kirkwood near the Farmingdale locality.

Radiolarian and dinoflagellate biostratigraphy support the Barstovian age (Tedford and Hunter, 1984; Emry and Eshelman, 1998) of the vertebrate assemblages from the Calvert Formation and basal part of the overlying Choptank Formation at the Calvert Cliffs exposures along the western shore of the Chesapeake Bay in Maryland.

Criteria derived from radiolarian abundance data that Palmer (1984, 1986a) used to determine the degree of oceanic versus neritic influence in radiolarian-bearing deposits of the middle Atlantic Coastal Plain were applied in this study of the radiolarian assemblages of the *Stichocorys wolffii* Zone in Delaware, including the Pollack Farm Site. Results indicate a more neritic influence at the Delaware sites than the open-marine, quiet-water offshore environments to the west and south in Maryland that Palmer's data, in comparison, indicate as more oceanic and less neritic. The increasing neritic trend toward the Pollack Farm and nearby sites from the Maryland sites is shown by decreases in (1) diversity (Shannon-Wiener information function), (2) Palmer's (1984) oceanic radiolarian index, and (3) the percentage of nasselline tests, and (4) an increase in the percentage of spongy taxa with algal symbionts. These results support the shallow inner neritic to marginal marine interpretation for the strata at the Pollack Farm Site and also the deltaic influence indicated for this area and New Jersey by Gibson (1982, 1983) as exemplified by the Cheswold sands of the Calvert Formation in Delaware and the Grenloch Sand Member of the Kirkwood Formation of New Jersey.

REFERENCES CITED

Abbott, W.H., 1978, Correlation and zonation of Miocene strata along the Atlantic margin of North America using diatoms and silicoflagellates: Marine Micropaleontology, v. 3, p. 15–34.

Andrews, G.W., 1978, Marine diatom sequence in the Chesapeake Bay region, Maryland: Micropaleontology, v. 24, p. 371–406.

___1988, A revised marine diatom zonation for Miocene strata of the southeastern United States: U.S. Geological Survey Professional Paper 1481, 29 p., 8 pls.

Benson, R.N., 1990, ed., Geologic and hydrologic studies of the Oligocene–Pleistocene section near Lewes, Delaware: Delaware Geological Survey Report of Investigations No. 48, 34 p., 4 pls.

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. 3 pls.

Benson, R.N., and Spoljaric, Nenad, 1996, Stratigraphy of the post-Potomac Cretaceous–Tertiary rocks of central Delaware: Delaware Geological Survey Bulletin No. 20, 28 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.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy, *in* Berggren, W. A., Kent, D. V., Aubry, M.-P., and Hardenbol, Jan, eds., Geochronology, time scales and global stratigraphic correlation: SEPM (Society for Sedimentary Geology) Special Publication No. 54, p. 129–212.

Blow, W.H., 1969, Late middle Eocene to Recent planktonic foraminiferal biostratigraphy: Proceedings First International Conference on Planktonic Microfossils, Geneva, 1967, v. 1: Leiden, E. J. Brill, p. 199–422, 54 pls.

Cande, S.C., and Kent, D.V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 97, p. 13,917–l3,951.

___1994, Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 100, p. 6093–6095.

Casey, R.E., Spaw, J.M., and Kunze, F.R., 1982, Polycystine radiolarian distributions and enhancements related to oceanographic conditions in a hypothetical ocean: Transactions Gulf Coast Association of Geological Societies, v. 32, p. 319–332.

Cook, G.H., 1868, Geology of New Jersey: Newark, N.J., Daily Advertiser Office, 898 p.

de Verteuil, Laurent, and Norris, Geoffrey, 1996, Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia, Part I, Dinoflagellate cyst zonation and allostratigraphy of the Chesapeake Group: Micropaleontology, v. 42, supplement, p. 1–82.

Emry, R.J., and Eshelman, R.E., 1998, The early Hemingfordian (early Miocene) Pollack Farm Local Fauna: First Tertiary land mammals described from Delaware, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 153–173.

Gibson, T.G., 1982, Depositional framework and paleoenvironments of Miocene strata from North Carolina to Maryland, *in* Scott, T.M., and Upchurch, S.B., eds., Miocene of the southeastern United States: Florida Bureau of Geology Special Publication No. 25, p. 1–22.

___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, I: Smithsonian Contributions to Paleobiology, no. 53, p. 35–80.

Gibson, T.G., and Buzas, M.A., 1973, Species diversity: Patterns in modern and Miocene Foraminifera of the eastern margin of North America: Geological Society of America Bulletin, v. 84, p. 217–238.

Hodell, D.A., and Woodruff, Fay, 1994, Variations in the strontium isotopic ratio of seawater during the Miocene: Stratigraphic and geochemical implications: Paleoceanography, v. 9, p. 405–426.

Isphording, W.C., 1970, Petrology, stratigraphy, and re-definition of the Kirkwood Formation (Miocene) of New Jersey: Journal of Sedimentary Petrology, v. 40, p. 986–997.

Jones, D.S., Ward, L.W., Mueller, P.A., and Hodell, D.A., 1998, Age of marine mollusks from the lower Miocene Pollack Farm Site, Delaware, determined by $^{87}Sr/^{86}Sr$ geochronology, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 21–25.

Martini, Erlend, 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation, *in* Farinacci, Anna, ed., Proceedings of the II Planktonic Conference, Roma, 1970: Roma, Edizioni Tecnoscienza, p. 739–785.

Miller, M.F., Curran, H.A., and Martino, R.L., 1998, *Ophiomorpha nodosa* in estuarine sands of the lower Miocene Calvert

Formation at the Pollack Farm Site, Delaware, *in* Benson. R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 41–46.

Oslick, J.S., Miller, K.G., and Feigenson, M.D., 1994, Oligocene–Miocene strontium isotopes: stratigraphic revisions and correlations to an inferred glacioeustatic record: Paleoceanography, v. 9, p. 427–443.

Palmer, A.A., 1984, Neogene radiolarians of the U. S. mid-Atlantic Coastal Plain: Biostratigraphic and paleoenvironmental analysis, and implications to shelf paleoceanography and depositional history: Princeton, N.J., Princeton University, Ph.D. dissertation, 281 p.

___1986a, Cenozoic radiolarians as indicators of neritic versus oceanic conditions in continental margin deposits: U.S. mid-Atlantic Coastal Plain: Palaios, v. 1, p. 122–132.

___1986b, Miocene radiolarian biostratigraphy, U.S. mid-Atlantic Coastal Plain: Micropaleontology, v. 32, p. 19–31.

___1988, Radiolarians from the Miocene Pungo River Formation of Onslow Bay, North Carolina continental shelf, *in* Snyder, S. W., ed., Micropaleontology of Miocene sediments in the shallow subsurface of Onslow Bay, North Carolina continental shelf: Cushman Foundation for Foraminiferal Research Special Publication No. 25, p. 163–178.

Poag, C.W., 1992, U. S. middle Atlantic continental rise: Provenance, dispersal, and deposition of Jurassic to Quaternary sediments, *in* Poag, C.W., and de Graciansky, P.C., eds., Geologic evolution of Atlantic continental rises: New York, Van Nostrand Reinhold, p.100–156.

Ramsey, K.W., 1998, Depositional environments and stratigraphy of the Pollack Farm Site, Delaware, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 27–40.

Ramsey, K.W., Benson, R.N., Andres, A.S., Pickett, T.E., and Schenck, W.S., 1992, A new Miocene locality in Delaware [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 69.

Riedel, W.R., and Sanfilippo, Annika, 1978, Stratigraphy and evolution of tropical Cenozoic radiolarians: Micropaleontology, v. 24, p. 61–96.

Roberts, J.H., 1988, Post-rift sediments of the United States middle Atlantic margin and speculations regarding tectonics in the source area: Newark, Del., University of Delaware, M.S. thesis, 157 p.

Shattuck, G.B., 1904, Geological and paleontological relations, with a review of earlier investigations: Maryland Geological Survey, Miocene volume, p. xxxiii–cxxxvii.

Sugarman, P.J., Miller, K.G., Owens, J.P., and Feigenson, M.D., 1993, Strontium-isotope and sequence stratigraphy of the Miocene Kirkwood Formation, southern New Jersey: Geological Society of America Bulletin, v. 105, p. 423–436.

Tedford, R.H., and Hunter, M.E., 1984, Miocene marine–nonmarine correlations, Atlantic and Gulf Coastal Plains, North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 47, p. 129–151.

Tedford, R.H., Skinner, M.F., Fields, R.W., Rensberger, J.M., Whistler, D.P., Galusha, Theodore, Taylor, B.E., Macdonald, J.R., and Webb, S.D., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene epochs) in North America, *in* Woodburne, M.O., ed., Cenozoic mammals of North America: Berkeley and Los Angeles, University of California Press, p. 153–210.

Van Wagoner, J.C., 1995, Overview of sequence stratigraphy of foreland basin deposits: Terminology, summary of papers, and glossary of sequence stratigraphy, *in* Van Wagoner, J.C., and Bertram, G.T., Sequence stratigraphy of foreland basin deposits: American Association of Petroleum Geologists Memoir 64, p. ix–xxi.

Ward, L.W.,1998, Mollusks from the lower Miocene Pollack Farm Site, Kent County, Delaware: A preliminary analysis, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 59–131.

Westberg, M.J., and Riedel, W.R., 1978, Accuracy of radiolarian correlations in the Pacific Miocene: Micropaleontology, v. 24, p. 1–23.

Wetmore, K.L., and Andrews, G.W., 1990, Silicoflagellate and diatom biostratigraphy in successive Burdigalian transgressions, middle Atlantic Coastal Plain: Micropaleontology, v. 36, p. 283–295.