Outcrop Features and Origin of Basin Margin Unconformities in the Lower Chesapeake Group (Miocene), Atlantic Coastal Plain

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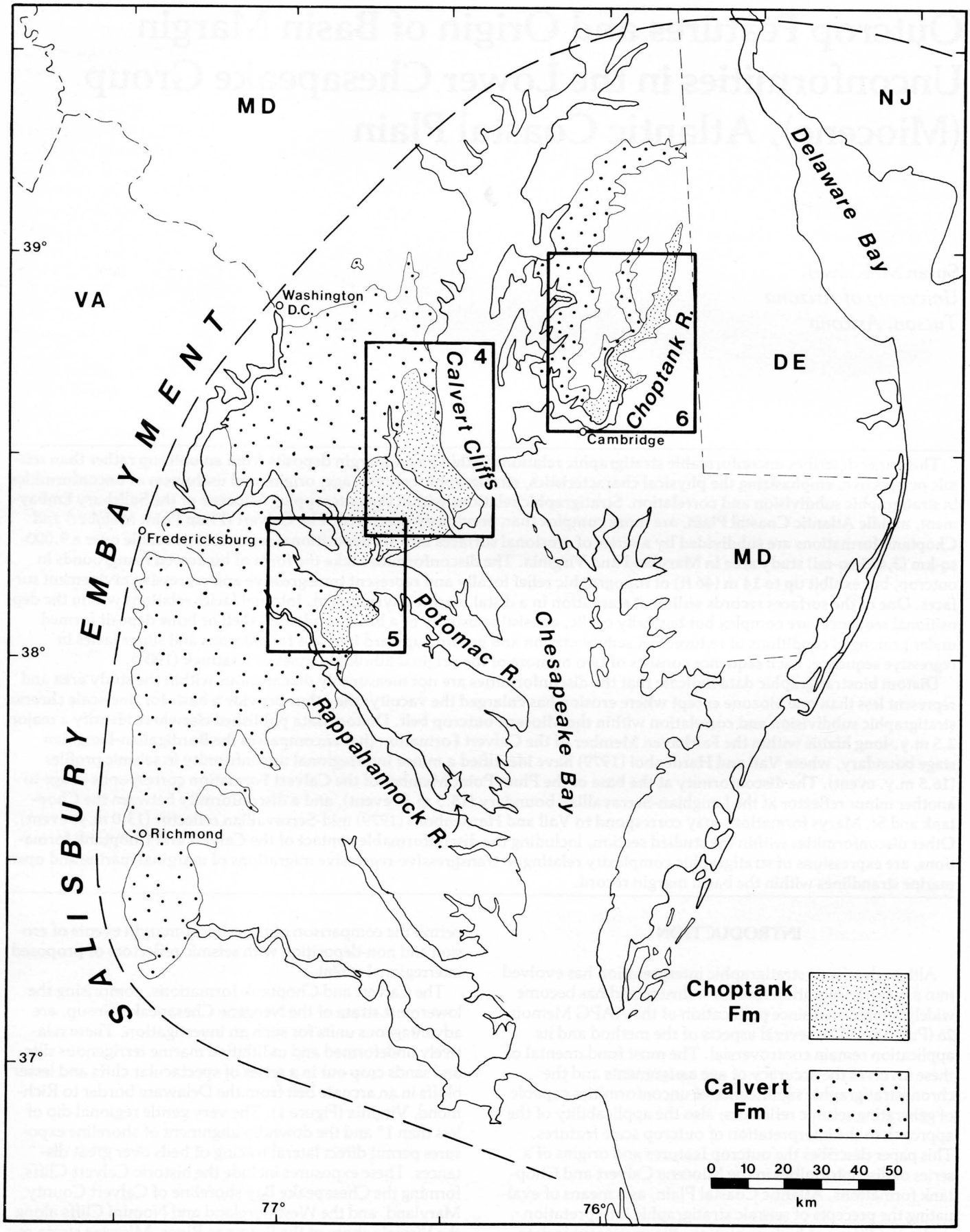
This paper describes unconformable stratigraphic relations within basin-margin deposits from an outcrop rather than seismic perspective, emphasizing the physical characteristics, stratigraphic context, age, origin, and usefulness of unconformities in stratigraphic subdivision and correlation. Stratigraphic relations within the outcropping Miocene of the Salisbury Embayment, middle Atlantic Coastal Plain, are more complex than previously described. The Calvert (Plum Point Member) and Choptank formations are subdivided by a series of erosional surfaces into six depositional sequences traceable over a 9,000-sq-km (3,475-sq-mi) study area in Maryland and Virginia. The disconformities take the form of burrowed firmgrounds in outcrop, but exhibit up to 14 m (46 ft) of topographic relief locally and represent transgressive and regressive ravinement surfaces. One of the surfaces records sediment starvation in a distal marine environment. Internal facies relations within the depositional sequences are complex but basically cyclic, consisting usually of a basal condensed shell or bone deposit formed under prolonged conditions of reduced net sedimentation and grading upward into less fossiliferous and siltier facies in regressive sequence. Each sequence consists of two or more of the original lithologic zones of Shattuck (1904).

Diatom biostratigraphic data indicate that the disconformities are not measurably diachronous within the study area and represent less than one biozone except where erosion has enlarged the vacuity; they thus provide a basis for fine-scale chronostratigraphic subdivision and correlation within the Miocene outcrop belt. Diatom data published elsewhere identify a major, 2.5 m.y.-long hiatus within the Fairhaven Member of the Calvert Formation that encompasses the Burdigalian-Langhian stage boundary, where Vail and Hardenbol (1979) have identified a minor interregional unconformity in seismic profiles (16.5 m.y. event). The disconformity at the base of the Plum Point Member of the Calvert Formation corresponds in age to another minor reflector at the Langhian-Serravallian boundary (15.5 m.y. event), and a disconformity between the Choptank and St. Marys formations may correspond to Vail and Hardenbol's (1979) mid-Serravallian reflector (13.0 m.y. event). Other disconformities within the studied section, including the disconformable contact of the Calvert and Choptank formations, are expressions of stratigraphic complexity relating to transgressive-regressive migrations of marginal marine and open marine strandlines within the basin margin record.

INTRODUCTION

Although seismic stratigraphic interpretation has evolved into a major exploration tool for industry and has become widely appreciated since publication of the AAPG Memoir 26 (Payton, 1977), several aspects of the method and its application remain controversial. The most fundamental of these involves the accuracy of age assignments and the chronostratigraphic significance of unconformities capable of generating seismic reflectors; also the applicability of the approach to the interpretation of outcrop scale features. This paper describes the outcrop features and origins of a series of disconformities in the Miocene Calvert and Choptank formations, Atlantic Coastal Plain, as a means of evaluating the precepts of seismic stratigraphic interpretation under conditions of high resolution. Biostratigraphic data permit the comparison of these basin-margin events of erosion and non-deposition with seismic reflectors of proposed interregional extent.

The Calvert and Choptank formations, comprising the lowermost strata of the Neogene Chesapeake Group, are advantageous units for such an investigation. These relatively undeformed and unlithified marine terrigenous silts and sands crop out in a series of spectacular cliffs and lesser bluffs in an arcuate belt from the Delaware border to Richmond, Virginia (Figure 1). The very gentle regional dip of less than 1° and the downdip alignment of shoreline exposures permit direct lateral tracing of beds over great distances. These exposures include the historic Calvert Cliffs, forming the Chesapeake Bay shoreline of Calvert County, Maryland, and the Westmoreland and Nomini Cliffs along the Virginia shore of the Potomac River. Miocene strata rest


MD
NJ
Delaware Bay
39°
VA
Washington D.C.
SALISBURY EMBAYMENT
4
Calvert Cliffs
Choptank R.
6
Cambridge
DE
Fredericksburg
MD
5
Potomac R.
Chesapeake Bay
38°
Rappahannock R.
Richmond
Choptank Fm
Calvert Fm
0 10 20 30 40 50
km
37°
77°
76°

upon and locally onlap early Tertiary units along the western edge of the Salisbury Embayment, a landward extension of the Baltimore Canyon Trough bounded on the north by the South Jersey High and on the south by the Norfolk High (Poag, 1979)(Figure 1).

The Maryland Miocene is famous for its diverse, well-preserved, and abundant fauna of molluscs, echinoids, bryozoans, cirripeds, brachiopods, corals, reptiles, fish, and marine mammals (Glenn, 1904; Martin, 1904; Ulrich and Bassler, 1904; Gazin and Collins, 1950, Kellogg, 1965-1969, 1969; Gernant, 1970, 1971). The distribution of benthic macroinvertebrates is strongly controlled by lithofacies, but several micropaleontologic zonations permit correlation within the basin and with standard sections (Abbott, 1978; Andrews, 1978; Gibson, 1962; Malkin, 1953). Correlations indicate that the two formations span the Burdigalian, Langhian, and Serravallian stages, and thus have potential to record the 16.5, 15.5, and 13.0 m.y. eustatic events inferred by Vail and others (Vail and Hardenbol, 1979; Vail et al., 1980) from offshore seismic records.

Because the study was designed to analyse the stratigraphic context and origin of molluscan shell beds, the study area was restricted to the northern part of the outcrop belt where fossil preservation and exposures are best. The study therefore concentrated on a 9,000 sq km (3,475 sq mi) area from the Maryland-Delaware border to the Rappahannock River, Virginia (Figure 1). The fossil-poor Fairhaven Member of the Calvert Formation was excluded throughout its outcrop belt. Most of the 194 stratigraphic sections measured for the study are located in Figures 4-6 (locality register available upon request). Informal field units were distinguished on the basis of bioclastic fabric (orientation, close-packing, size distribution and extent of fragmentation) and faunal dominants as well as sedimentary textures, physical and biogenic structures, bedding, and color. These units ranged in thickness from tens of centimeters to a few meters. Field descriptions were supplemented by wet-sieving of approximately 200 sediment samples at 0.5 phi (ϕ) intervals to determine modal sand size and percent admixed mud (less than $^1/_{16}$ mm diameter) for the terrigenous fraction. Ninety large (8 to 10 kg, or 18 to 22 lb) samples collected from the most fossiliferous beds yielded quantitative taphonomic and paleoecologic data on macroinvertebrates, and about 100 sediment samples were analyzed for biostratigraphically significant diatom species by W.H. Abbott (South Carolina Geological Survey). All of these data are tabulated in Kidwell (1982a).

UNCONFORMITIES AND DEPOSITIONAL SEQUENCES

Previous Investigations

Despite a fairly stable nomenclature, stratigraphic relations within the Calvert and Choptank formations have been the subject of continued controversy (Figure 2). Shattuck (1904) interpreted the section as internally conformable with the exception of the Calvert-Choptank formational boundary, which he recognized as unconformable owing to downdip beveling of the Calvert Formation and onlapping relations of Choptank beds. Subsequent workers have employed Shattuck's (1904) subdivision but many have found the formational contact difficult to identify and Shattuck's evidence for an unconformity equivocal (Dryden, 1930; Gibson, 1962; Gernant, 1970, Blackwelder and Ward, 1976). Dryden (1936), Schoonover (1941), and Blackwelder (1981) considered the contact to be conformable. Unconformities have also been recognized between the Fairhaven and Plum Point members of the Calvert Formation (Dryden, 1930, 1936; Gernant, 1971; Blackwelder and Ward, 1976; Andrews, 1978; Blackwelder, 1981), and between the Choptank and St. Marys formations (Gibson, 1971; Gernant, 1970, 1971; Blackwelder and Ward, 1976; Blackwelder, 1981). Newell and Rader (1982) reinterpreted all of these breaks within the lower part of the Chesapeake Group as minor, diastemic features and thus describe the Calvert-Choptank-St. Marys sequences as entirely conformable.

Stratigraphic Methods and Terminology

My initial hypothesis regarding stratigraphic relations was based on a belief that Shattuck's (1904) zones were not lithologically homogeneous layers as traditionally conceived, each recording a unique time interval, but instead were facies arranged within a largely conformable sequence. However, this was largely rejected when field examination revealed a series of erosional surfaces subdividing the section into groups of his zones. These disconformity-bound units are referred to here as depositional sequences (Figure 2). Facies relations as evidenced by lateral gradation, intertonguing, and marker-bed tie-ins could be demonstrated only within single zones and among those zones grouped within a single depositional sequence.

Qualitatively, the Calvert Formation appears to be a siltier and less fossiliferous unit than the Choptank Formation, and quantitative analysis bears this out (Kidwell, 1982a, p. 136). However, each formation contains a similar range of lithologies from silty clays to well-sorted fine sands with 0 to 70% shell carbonate by volume as a distinct coarse mode (Figure 3). The formations are thus distinguished primarily on the basis of proportional representation of sediment types.

Both the Plum Point Member of the Calvert Formation and the Choptank Formation exhibit strong cyclic trends in sediment types, with clean shell-rich sands alternating with shell-poor silty sands, sandy silts, and silty clays (Figure 3). For informal subdivision, an effective solution is to denote four laterally persistent and visually dramatic shell beds and a fifth bone bed as key beds (Figures 2 and 3). The five key beds are assigned geographic names to minimize confusion with existing nomenclatural schemes using numbers and

Figure 1: Outcrop belt of the Calvert and Choptank formations in the Salisbury Embayment, Atlantic Coastal Plain. The study was restricted to the Plum Point Member of the Calvert Formation and Choptank Formation north of the Rappahannock River. Boxes mark location of Figures 4, 5, and 6. Geology based on Cleaves et al (1968) and Calver and Hobbs (1963).

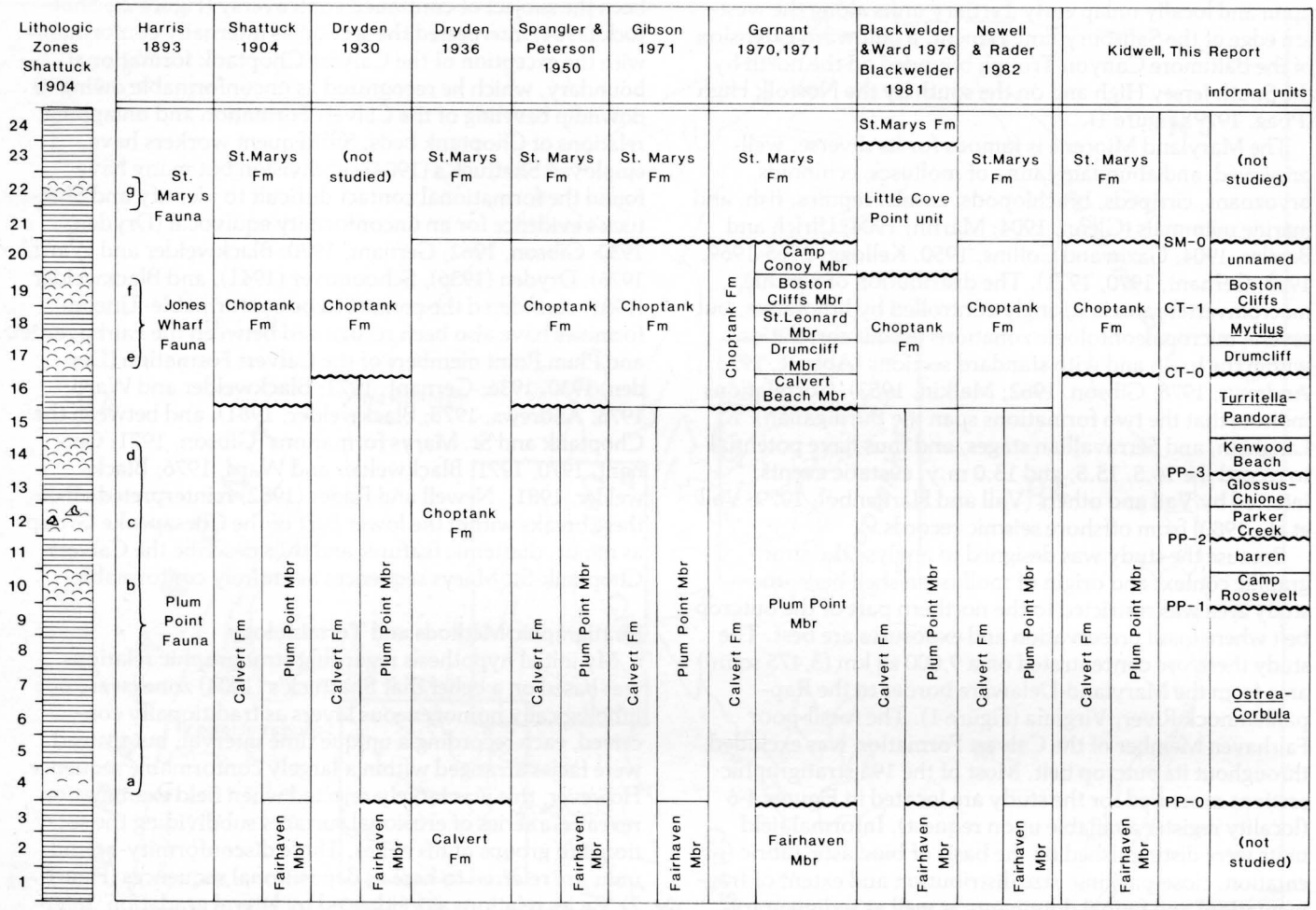


Figure 2: Nomenclature and stratigraphic relations of the Maryland Miocene. Column at far right summarizes informal lithostratigraphic nomenclature used in this paper, consisting of highly fossiliferous key beds with geographic names and sparsely fossiliferous silty intervals with taxonomic (generic) names. Disconformities in the section are numbered sequentially within each formal unit (PP = Plum Point Member of Calvert Formation; CT = Choptank Formation; SM = St. Marys Formation). The informal alpha-numeric name of each disconformity also denotes the immediately overlying depositional sequence, all but one of which consist of a key bed and its succeeding interval. Lithologic column not to thickness scale.

letters (Harris, 1893; Shattuck, 1904; Dryden, 1930, 1936; Abbott, 1978; Andrews, 1978). The geographic names of the two key beds in the Choptank Formation, coinciding approximately with Zones 17 and 19 of Shattuck (1904), are the same as those used by Gernant (1970) when he elevated these units to formal member status; these are the Drumcliff and Boston Cliffs shell beds. Key beds in the Plum Point Member of the Calvert Formation, corresponding closely to Zones 10, 12, and 14 of Shattuck (1904), are assigned new geographic names; these are the Camp Roosevelt shell bed, Parker Creek bone bed, and Kenwood Beach shell bed. These units are not proposed as members or submembers; such formalization would unnecessarily fragment the firmly established nomenclature of the Plum Point Member, whose lithologic heterogeneity is already accepted by regional workers.

Shell-poor strata lying between key beds are assigned to informal intervals. These are named for abundant and distinctive macroinvertebrate genera in Calvert Cliffs exposures in order to avoid redundant lithologic terms among sequences. Geographic names were rejected in order to avoid confusion with key-bed nomenclature. In ascending order, the Plum Point and Choptank intervals are designated: *Ostrea-Corbula*, barren, *Glossus-Chione*, *Turritella-Pandora*, and *Mytilus* intervals (Figures 2 and 3). The interval whose base is defined by the Boston Cliffs shell bed remains unnamed pending further investigation of the Choptank-St. Marys transition.

Shattuck's (1904) scheme of informal zones, utilized by most previous workers, is not used in this report for several reasons. Most importantly, because the units recognized in this field study do not correspond exactly to Shattuck's zones in all situations. In addition, previous workers have had difficulty identifying Shattuck's zones in localities away from his 12 reference sections as well as in some reference sections (Dryden, 1930; Schoonover, 1941; Blackwelder and Ward, 1976); and finally, the zonal scheme carries the connotation of a layer-cake series of laterally invariant strata inconsistent with the findings of this study.

Facies are designated within intervals exhibiting notewor-

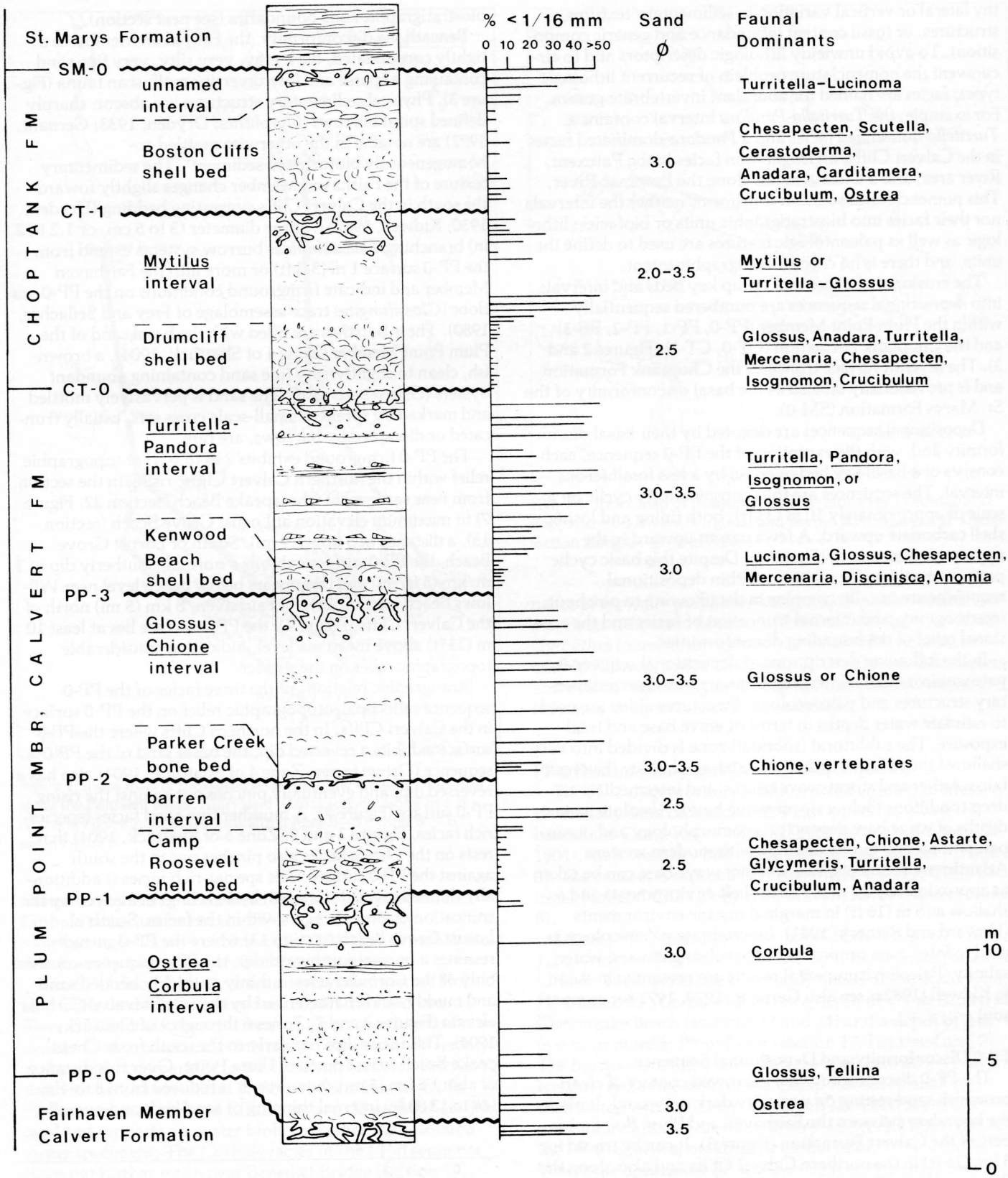


Figure 3: Composite stratigraphic column of the Plum Point Member and the Choptank Formation. The disconformities are burrowed firmgrounds in individual exposures and, with the exception of the PP-0 surface, are overlain by a richly fossiliferous clean sand that grades into much less fossiliferous and usually silty sediments. Only the most abundant taxa in faunal assemblages are noted; key shell beds usually contain 40 or more species. Sediment and faunal data are tabulated in Kidwell (1982a).

thy lateral or vertical variation in sedimentary textures, structures, or fossil content (abundance and generic composition). To avoid unwieldy lithologic descriptors and to circumvent the nomenclature problem of recurrent lithologic types, facies are named for abundant invertebrate genera. For example, the *Turritella-Pandora* interval contains a *Turritella*-dominated facies and a *Pandora*-dominated facies in the Calvert Cliffs, an *Isognomon* facies in the Patuxent River area, and a *Glossus* facies along the Potomac River. This nomenclatural solution transforms neither the intervals nor their facies into biostratigraphic units or biofacies: lithologic as well as paleontologic features are used to define the units, and there is no chronostratigraphic intent.

The erosional surfaces that group key beds and intervals into depositional sequences are numbered sequentially within the Plum Point Member (PP-0, PP-1, PP-2, PP-3) and the Choptank Formation (CT-0, CT-1) (Figures 2 and 3). The seventh surface truncates the Choptank Formation and is provisionally labeled as the basal disconformity of the St. Marys Formation (SM-0).

Depositional sequences are denoted by their basal disconformity and, with the exception of the PP-0 sequence, each consists of a basal key bed overlain by a less fossiliferous interval. The sequences are thus conspicuously cyclic on a scale of approximately 10 m (33 ft), both fining and losing shell carbonate upward. A few coarsen upward in the uppermost meter or so (Figure 3). Despite this basic cyclic pattern, stratigraphic relations within depositional sequences are usually complex in detail owing to pinchout, intertonguing, and internal truncation of facies and the erosional relief of the bounding disconformities.

In the following descriptions of depositional sequences, paleoenvironmental interpretations are based on sedimentary structures and paleoecology. Structures alone are used to estimate water depths in terms of wave base and tidal exposure. The sublittoral (subtidal) zone is divided into very shallow (above fair-weather wave base), shallow (between fair-weather and storm-wave bases), and intermediate-to-deep conditions (below storm-wave base). Absolute water depths of wave base depend on geomorphology and oceanographic facing, but by analogy with modern western Atlantic environments, fair-weather wave base can be taken as approximately 20 m (66 ft) in shelf environments and as shallow as 5 m (16 ft) in marginal marine environments (Howard and Reineck, 1981). Invertebrate paleoecology is used to infer mass properties of the substratum and water salinity. Paleoenvironmental results are presented in detail in Kidwell (1982a; see also Gernant, 1970, 1971 for comparison).

PP-0 Disconformity and Depositional Sequence

The PP-0 disconformity is a burrowed contact of clean brownish sand resting on very silty dark gray sand. It marks the boundary between the Fairhaven and Plum Point members of the Calvert Formation (Figure 3). It can be traced for 5 km (16 ft) in the northern Calvert Cliffs and also along the Patuxent River (Figures 7 and 8). Evidence for the disconformity includes truncation of Fairhaven beds, lithologic change and presence of a firmground along the contact, topographic irregularity of the surface, distribution of overlying facies with respect to the surface, and coincidence with biostratigraphic zone boundaries (see next section).

Beneath the disconformity, the Fairhaven Member is a tightly consolidated, dark gray, very silty, very fine sand containing a sparse and low-diversity molluscan fauna (Figure 3). Physical sedimentary structures are absent; sharply defined spiral burrows (*Gyrolithes*; Dryden, 1933; Gernant, 1972) are notable in the otherwise mottled-to-homogeneously bioturbated sediment[1]. The sedimentary texture of the Fairhaven Member changes slightly toward the south in the Calvert Cliffs suggesting bedding (Dryden, 1930; Kidwell, 1982a). Large diameter (3 to 5 cm, or 1.2 to 2 in) branching *Thalassinoides* burrow systems extend from the PP-0 surface 1 m (3.3 ft) or more into the Fairhaven Member and indicate firmground conditions on the PP-0 sea floor (*Glossifungites* trace assemblage of Frey and Seilacher, 1980). These burrows are filled with the basal sand of the Plum Point Member (Zone 4 of Shattuck, 1904), a brownish, clean to slightly-silty fine sand containing abundant oysters (*Ostrea percrassa*). The sand is pervasively mottled and marked by spreiten; small-scale cross sets, usually truncated or disrupted by burrows, are rare.

The PP-0 firmground exhibits 2 m (6.6 ft) of topographic relief within the northern Calvert Cliffs, rising in the section from near sea level at Chesapeake Beach (section 22, Figure 7) to maximum elevation at Locust Grove Beach (section 13), a distance of 3 km (1.9 mi). South of Locust Grove Beach, the PP-0 surface exhibits a normal, southerly dip of 1 m/km (5 ft/mi) and disappears below beach level near Willows Beach (section 16). At Fairhaven, 8 km (5 mi) north of the Calvert Cliffs (Figure 4), the PP-0 surface lies at least 10 m (33 ft) above mean sea level, indicating considerable topographic relief on the surface.

Stratigraphic relations of the three facies of the PP-0 sequence reflect paleotopographic relief on the PP-0 surface in the Calvert Cliffs. In the northern Cliffs where the PP-0 surface exhibits a reversed dip, the basal sand of the PP-0 sequence (*Ostrea* facies; Zone 4 of Shattuck, 1904) also has a reversed dip, and eventually pinches out against the rising PP-0 surface (Figure 7). A muddier fine-sand facies (species-rich facies, Figures 3 and 7; Zone 5 of Shattuck, 1904) that rests on the *Ostrea* facies also pinches out to the south against the PP-0 surface. The species-rich facies is additionally thinned toward the south by beveling, evidenced by the truncation of shell stringers within the facies. South of Locust Grove Beach (section 13) where the PP-0 surface resumes a normal southward dip, the PP-0 sequence consists only of the *Corbula* facies, a thinly to thickly bedded sand and muddy sand characterized by the small bivalve *Corbula elevata* (Figures 3 and 7; Zones 6 through 9 of Shattuck, 1904). This facies dips regularly to the south from Chesapeake Beach to just north of Plum Point. Over this distance of about 8 km (5 mi), however, it is reduced from 8 to 4 m (26 to 13 ft) by internal thinning of sand beds and overall

[1]The term burrow denotes fully three-dimensional biogenic sedimentary structures with distinctive outlines. All other penetrative biogenic structures, including mottled and homogeneous fabrics, are described by the general term bioturbation. Burrowed contacts are thus well-defined but microtopographically complex surfaces; bioturbated contacts will be gradational.

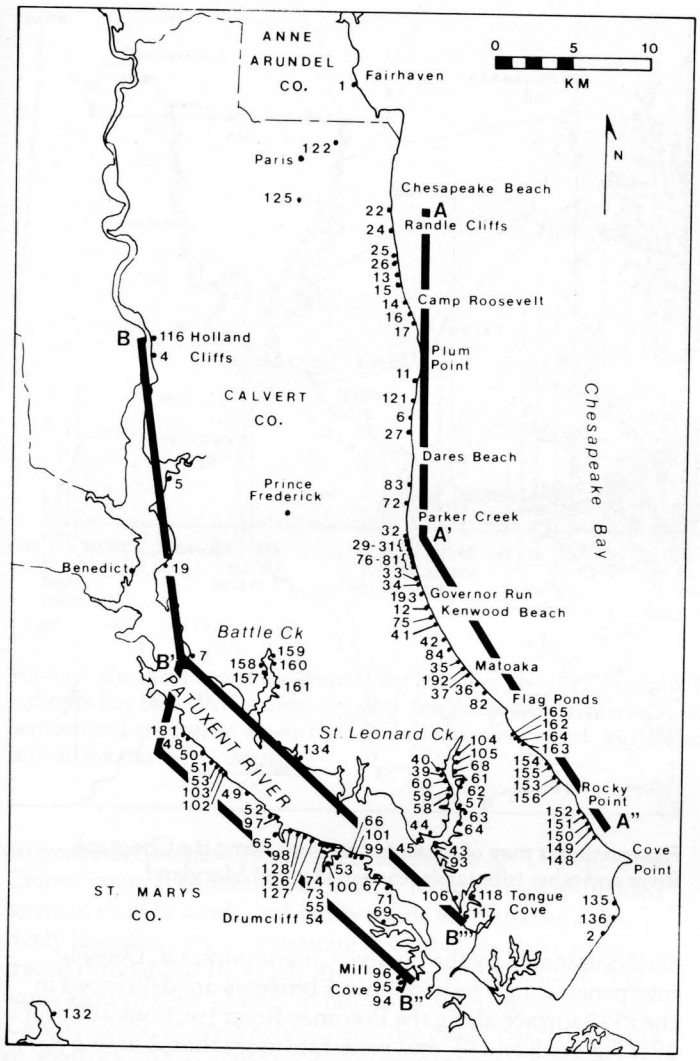


Figure 4: Index map of measured sections in the Calvert Cliffs and along the Patuxent River, Maryland. Cross section along line A - A′′ is in Figure 7; cross sections along lines B - B′′ and B′ - B′′′ are in Figure 8.

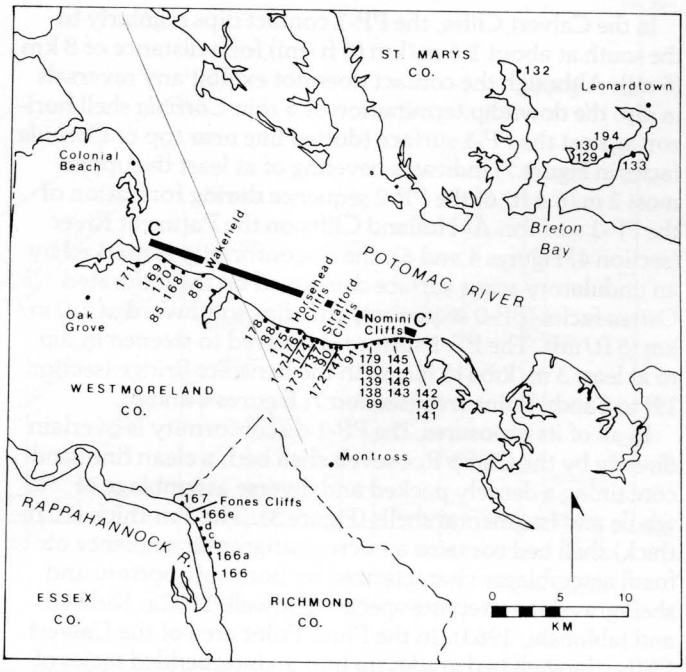


Figure 5: Index map of measured sections along the Potomac and Rappahannock rivers, Virginia, and Breton Bay, Maryland. Cross section along C - C′ is in Figure 9.

truncation by the PP-1 surface. The dotted contact in the *Corbula* facies just below the PP-1 surface in Figure 7 marks a shell stringer (Zone 9 of Shattuck, 1904) that demonstrates this downdip truncation of the PP-0 sequence.

The PP-0 disconformity is tentatively identified at Holland Cliffs (section 4, Figures 5 and 8) on the Patuxent River. There, it also has the form of a burrowed, sand on muddy sand contact and is inferred to dip relatively steeply to the south, comparable to the PP-0 surface from Fairhaven south to the Calvert Cliffs. The basal *Ostrea* facies of the PP-0 sequence at Holland Cliffs is a very clean, lithified fine sand and supports an oyster bioherm rather than isolated oyster specimens. The *Corbula* facies of the PP-0 sequence crops out further south near Benedict Bridge (section 19).

The PP-0 sequence records a variety of polyhaline environments from very shallow (*Ostrea* facies and upper part of the *Corbula* facies) to shallow (lower *Corbula* facies) and intermediate sublittoral water depths (species-rich facies). A freshwater influence is indicated by the numerical dominance of typically polyhaline genera such as *Ostrea* and its associates (*Martesia*, *Mytilus*), *Corbula*, and the trace fossil *Gyrolithes* found in the species-rich facies (see references cited in Kidwell, 1982a; Gernant, 1972). Sand-mud couplets and overall coarsening up within the *Corbula* facies might indicate a delta-influenced environment.

PP-1 Disconformity and Depositional Sequence

The PP-1 disconformity is a burrowed contact of massive clean shelly sand on bedded silty sand, and lies along the base of the Camp Roosevelt shell bed (Zone 10 of Shattuck, 1904), the lowest key bed of the Plum Point Member (Figure 3). The contact is exposed in the northern Calvert Cliffs and in the Holland Cliffs along the Patuxent River (Figures 7 and 8).

Like the PP-0 disconformity, large diameter (3 to 5 cm, or 1.2 to 2 in) the *Thalassinoides* burrows characterize the PP-1 surface. These penetrate the muddy sands of the underlying PP-0 sequence (*Corbula* facies) to a depth of 0.7 m (2.3 ft) at Chesapeake Beach (sections 22 and 24) and a depth of 2 m (6.6 ft) or more at Plum Point (section 17; Figures 4 and 7). The burrows are filled with the very shelly (to 40 percent by weight), clean fine sand of the Camp Roosevelt shell bed; shell material in the Camp Roosevelt shell bed is always more abundant and far more diverse in species than that of the PP-0 sequence, making the contact easy to recognize. Where the uppermost PP-0 sequence is very sandy (for example, at Holland Cliffs and at Chesapeake Beach), pods of diverse shells in the upper 2 m (6.6 ft) of the sequence impart a gradational appearance to the PP-1 contact. However, on closer inspection these pods are clearly part of *Thalassinoides* burrows originating at the PP-1 surface.

In the Calvert Cliffs, the PP-1 contact dips regularly to the south at about 1.6 m/km (8 ft/mi) for a distance of 8 km (5 mi). Although the contact does not exhibit any reversals in dip, the downdip termination of a thin *Corbula* shell horizon against the PP-1 surface (dotted line near top of *Corbula* facies in Figure 7) indicates beveling of at least the uppermost 2 m (6.6 ft) of the PP-0 sequence during formation of the PP-1 surface. At Holland Cliffs on the Patuxent River (section 4, Figures 4 and 8), the disconformity is marked by an undulatory scour surface developed on the indurated *Ostrea* facies (PP-0 sequence), and dips southward at 1.0 m/km (5 ft/mi). The PP-1 surface is inferred to steepen in dip to at least 3 m/km (15 ft/mi) in the Benedict Bridge (section 19) to Sandy Point area (section 7; Figures 4 and 8).

In all of its exposures, the PP-1 disconformity is overlain directly by the Camp Roosevelt shell bed, a clean fine sand containing a densely packed and diverse assemblage of whole and fragmental shells (Figure 3). The 3 m-thick (10 ft-thick) shell bed contains a microstratigraphic sequence of fossil assemblages characterized by both soft-bottom and shell-gravel invertebrate species (Kidwell, 1982a; Kidwell and Jablonski, 1983). In the Plum Point area of the Calvert Cliffs, the shell bed grades up into an interbedded facies of clean fine sand and muddy sand with thin shell layers and clay bands (transitional sand facies, Figure 7). Further north in the Camp Roosevelt and Chesapeake Beach area, this transitional sand facies is absent and the Camp Roosevelt shell bed is overlain immediately by a barren clay interval (Zone 11 of Shattuck, 1904) (Figure 3). Unlike other intervals of the Calvert and Choptank formations, the barren interval cannot be subdivided into facies but is a massive, blue-gray sandy clay throughout its exposed extent in the study area (to the Virginia shore of the Potomac River). With the exception of rare, poorly-preserved shell fragments and echinoid spines, its fauna consists only of traces: color and textural mottling; small-diameter (1 to 2 cm, or .4 to .8 in) unbranched burrows with clay fill; and 5 cm (2 in) diameter pods of clay packed with dark fecal pellets.

The PP-1 sequence records fully marine depositional conditions in shallow sublittoral (Camp Roosevelt shell gravel) and deep sublittoral water depths (barren interval). An open-shelf setting is indicated both by the fauna and the sheet-like geometry of the units.

PP-2 Unconformity and Depositional Sequence

The PP-2 surface is a burrowed contact along which the brownish, slightly muddy to clean fine sand of the Parker Creek bone bed (Zone 12 of Shattuck, 1904) is juxtaposed against the blue-gray sandy clay of the barren interval (Figure 3). The disconformity and overlying depositional sequence can be traced throughout the study area with the exception of the eastern shore of Maryland (Figures 7, 8, and 9).

Burrows in the PP-2 surface tend to be short (15 cm, or 6 in, maximum length), less than 2 cm (.8 in) in diameter, unlined simple tubes oriented either vertically or at a steep angle to bedding. The burrows are distinguished by the brownish, loosely-packed sand of the Parker Creek bone bed that fills them. This sand contains sparsely disseminated bone and teeth and local concentrations of poorly preserved

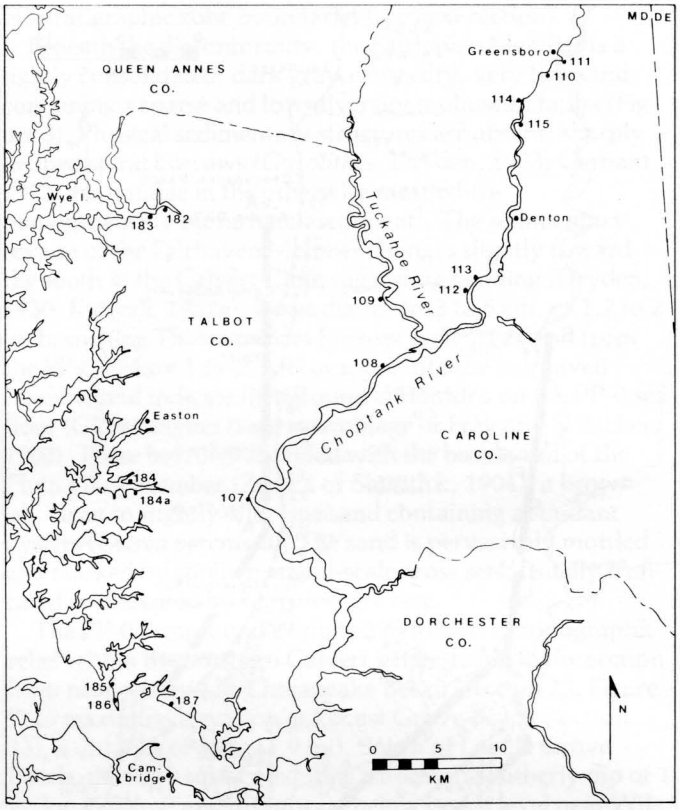


Figure 6: Index map of measured sections along the Choptank River and other tributaries, eastern shore of Maryland.

shell dominated by the bivalve *Chione parkeria*. Densely interpenetrating *Thalassionoides* burrows are developed in the PP-2 surface along the Potomac River (sections 169 and 171; Figures 5 and 9), and penetrate more than 2 m (6.6 ft) into the underlying barren interval. The PP-2 contact is gradational in extreme northern Calvert Cliffs outcrops (sections 25 and 26) owing to bioturbation.

The PP-2 surface dips at a uniform rate of 1 m/km (5 ft/mi) in the Calvert Cliffs, where it is most continuously exposed, and is probably best described as an omission or non-depositional surface inasmuch as it lacks evidence of sea-floor erosion. Channel-shaped features and sharp changes in dip are lacking, and, because the underlying barren interval is massive, erosional beveling cannot be demonstrated. The only suggestion of erosional truncation is thinning of the PP-1 barren interval in the northern part of the Calvert Cliffs. Evidence for stratigraphic omission, either by sediment starvation or dynamic bypassing, includes the concentration of fossil vertebrate bones and teeth and the presence of authigenic glauconite in the winnowed quartz sand of the Parker Creek bone bed. In his detailed taphonomic analysis of the bone bed in the Potomac River exposures, Myrick (1979) concluded that the marine mammal assemblage of the bed is a condensed record of at least two ecologically distinct faunas, and resulted from reduced sedimentation over a period of thousands to tens-of-thousands of years.

The PP-2 depositional sequence consists of the thin (0.6 m, or 2 ft) Parker Creek bone bed and the lithologically het-

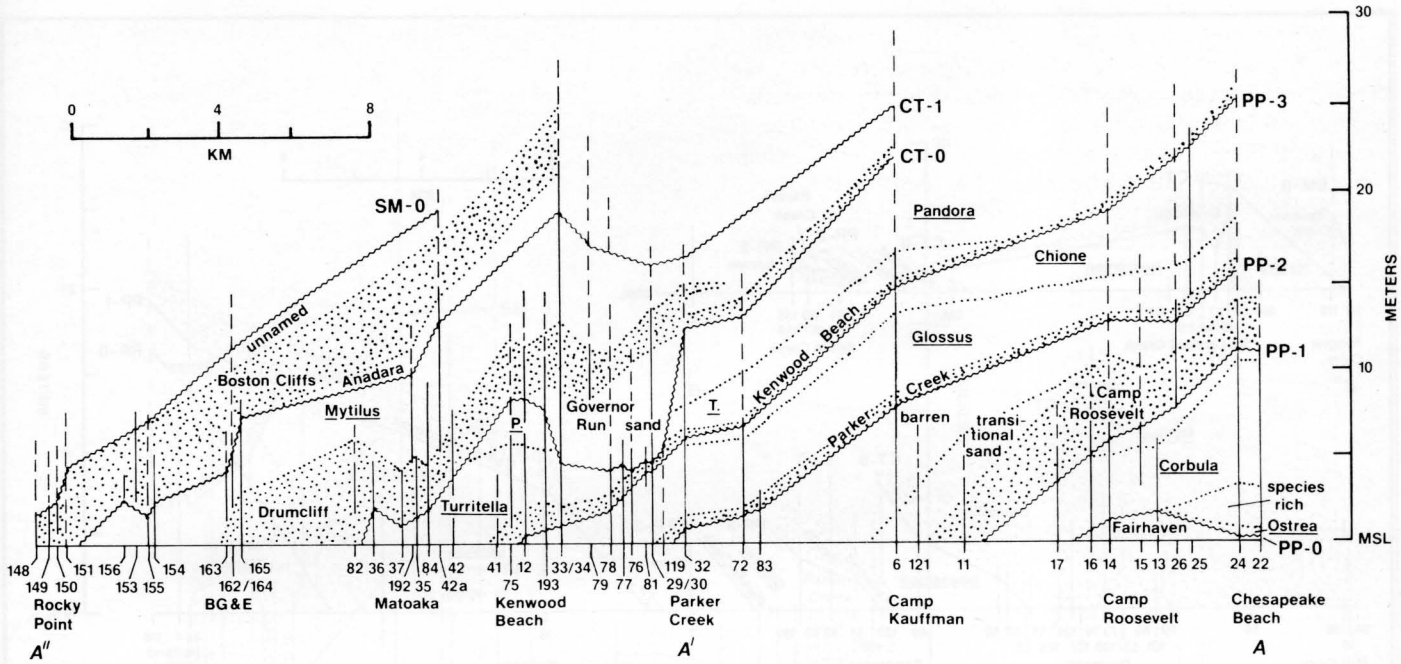


Figure 7: Cross section of the Plum Point Member and the Choptank Formation in Calvert Cliffs, Maryland (see Figure 4). Stippled pattern indicates key beds. White areas are silty, less fossiliferous intervals; taxonomic terms indicate facies names; vertical lines mark measured sections and are dashed where elevation data are estimated. Vertical exaggeration is 250:1. True dips range from 0.4 to 5 m/km (2 to 25 ft/mi); all are less than 1 degree.

erogeneous *Glossus-Chione* interval (Figure 3). The *Glossus-Chione* interval consists of a thickly- to very thickly-bedded series of muddy sands and sandy muds with sparse, relatively low-diversity invertebrate assemblages and can be traced throughout the study area (Figures 7, 8, and 9). It is equivalent to zone 13 and, in northern outcrops of the Calvert Cliffs, to both zone 13 and the lower part of zone 14 of Shattuck (1904). Two facies are recognized within the interval in the Calvert Cliffs. The *Glossus* facies consists of massive sandy mud and muddy sand with disarticulated specimens of the bivalve *Glossus fraterna* arranged in widely-spaced shell stringers. The stratigraphically higher and overlapping *Chione* facies consists of thickly- to very thickly-bedded muddy sand characterized by the small bivalve *Chione parkeria*. *Chione* specimens tend to be clumped within the sandier layers rather than uniformly disseminated, and common associates include the gastropod *Turritella plebeia*, *Glossus fraterna*, and the scallop *Chesapecten nefrens*. This stratigraphic pattern of a basal clayey facies and an upper sandier and shellier facies recurs in the few exposures of this interval along the Patuxent River, although shell preservation there is poor.

A third, sandier facies represents the *Glossus-Chione* interval in the Potomac region. This facies consists of noncyclic alternations of bioturbated thickly- to very thickly-bedded sand, sandy clay, and clayey sand, and contains relatively abundant wood and vertebrate material. The facies takes its name from burrows attributable to ghost crabs (*Ocypode*; see Radwanski, 1977) found along some bedding planes in the uppermost part of the interval. Clay-rich beds often contain abundant fecal pellets within small burrows; surficial gypsum crystals and yellow sulfurous crusts, and fetid odor of fresh cuttings indicate finely-disseminated pyrite.

The deep sublittoral water depths responsible for the barren interval (PP-1 sequence) persisted at least until the initial phases of Parker Creek bone bed accumulation. In addition to taphonomic and paleoecologic evidence within the bed itself, the context of the bone bed between the assuredly deep-water barren interval and the intermediate sublittoral *Glossus* facies also indicates a deep depositional environment more distal from source areas than any other Plum Point or Choptank unit. The shallow sublittoral *Chione* facies succeeds the *Glossus* facies everywhere but in the Potomac region, where the very shallow sublittoral to littoral *Ocypode* facies constitutes the upper PP-2 sequence.

PP-3 Disconformity and Depositional Sequence

The PP-3 surface is an erosional surface in the Calvert Cliffs, but is a simple bedding plane elsewhere in the study area. The shelly sand on silty sand contact is burrowed and marks the base of the Kenwood Beach shell bed, the stratigraphically highest key bed of the Calvert Formation (Zone 14 of Shattuck, 1904; Figures 3, 7, 8, and 9).

The surface dips southward with a uniform dip of 1.2 m/km (6 ft/mi) in the Calvert Cliffs. North of Parker Creek (section 32, Figures 4 and 7), burrows are unbranched, small diameter (less than 3 cm, or 1.2 in), and sharply defined vertical tubes extending less than 20 cm (8 in) into underlying strata. However, south of Parker Creek as far as Kenwood Beach where the PP-3 surface drops below beach level, burrows are larger in diameter, branched, and penetrate 1 m (3.3. ft) or more into the *Glossus-Chione* interval. These

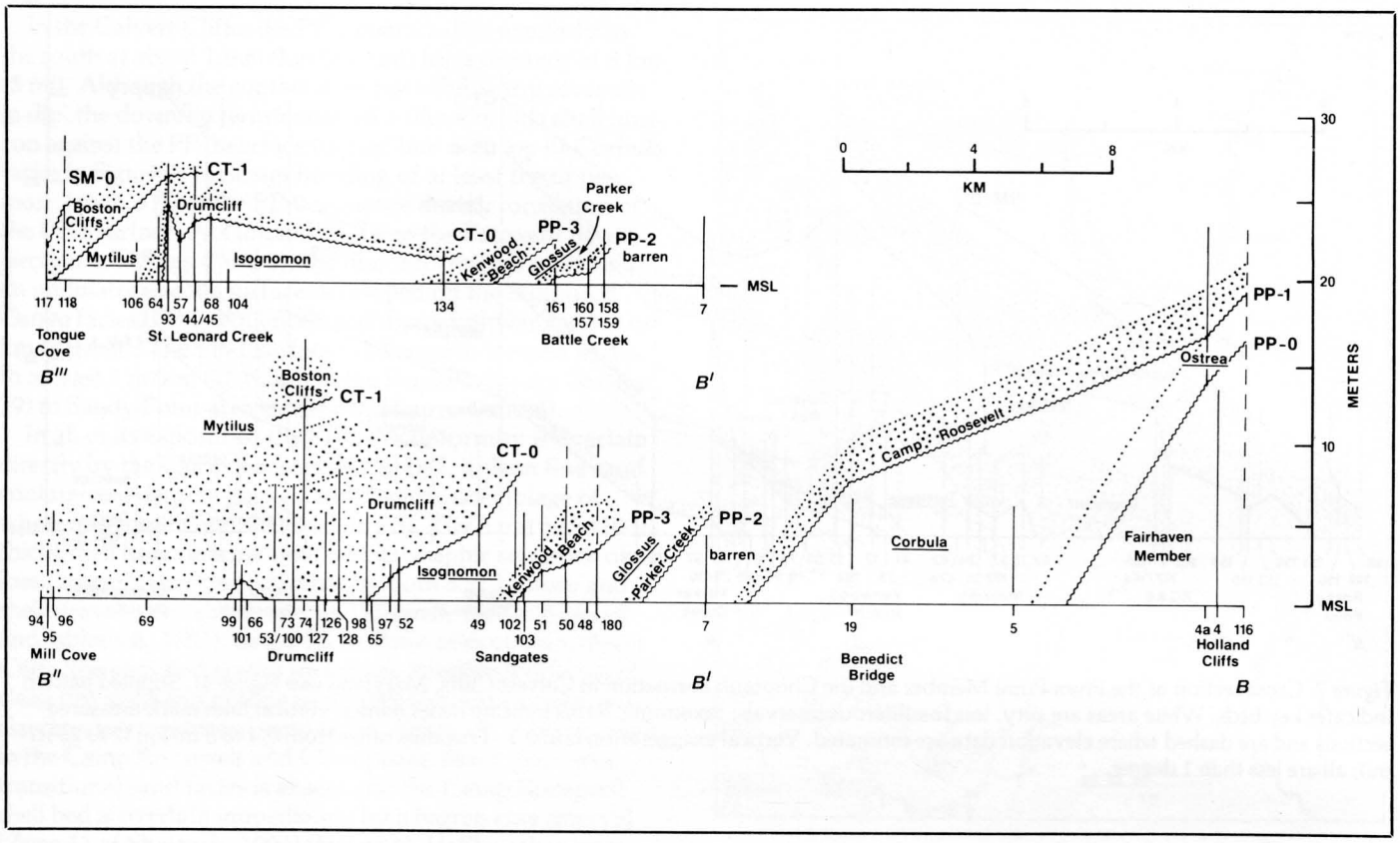


Figure 8: Cross section constructed from Patuxent River sections, Maryland. Segment B′ - B′′ is along the west bank of the river; segment B′ - B′′′ describes the east bank (Figure 4). Conventions as in Figure 7.

Thalassinoides burrows are accompanied by *Gyrolithes* burrows, especially in the Kenwood Beach area. An erosional origin for the PP-3 surface is indicated by: (1) truncation of bedding and downdip beveling of the *Glossus-Chione* interval (Figure 7); and, (2) by the appearance in the base of the Kenwood Beach shell bed of specimens of *Chione parkeria* reworked from the PP-2 sequence, especially in the Parker Creek to Kenwood Beach area. Elsewhere in the study area, the PP-2 and PP-3 depositional sequences are entirely conformable and it is difficult to identify a single bedding surface as the basal PP-3 contact.

The PP-3 depositional sequence consists of the Kenwood Beach shell bed and the several facies of the *Turritella-Pandora* interval (Figure 3). In the northern Calvert Cliffs (Chesapeake Beach to Parker Creek; Figure 7), the Kenwood Beach shell bed is a thin (0.5 m, or 1.6 ft) densely-packed shell accumulation having a clean fine sand matrix. It is equivalent to only the upper 0.5 m (1.6 ft) of strata assigned by Shattuck (1904) to Zone 14. South of Parker Creek, the shell bed is thicker (to 2 m, or 6.6 ft) and contains interbeds of less fossiliferous, muddy fine sand. Burrowed discontinuities with firmground trace assemblages separate as many as four discrete shell layers within the bed. The Kenwood Beach shell bed is thicker (to 7 m, or 23 ft) in the Patuxent region (Figure 8) where it includes a greater number of shell layers interbedded with muddy sand. Identification of the bed is only tentative in the Potomac region because of poor shell preservation and great lithologic variability throughout the entire upper part of the Calvert Formation. There, the shell bed consists of a 7-m-thick (23-ft-thick) unit distinguished from adjacent units by its more diverse fossil assemblage and by the less silty matrix found in its thin shell layers (Figure 9).

Throughout the study area, the Kenwood Beach shell bed grades up into the *Turritella-Pandora* interval, a coarsening-up sequence of thin interbedded sands, muddy sands, and clays with a sparse and low diversity fauna that is typically concentrated into thin shell bands within sandy layers (Figure 3). The interval includes Zones 15 and 16 of Shattuck (1904), except in updip outcrops of the Calvert Cliffs where it includes only the lower portion of the great thickness of strata assigned by Shattuck to Zone 15 (1904; his reference sections 5, 7, and 8).

Four laterally disposed facies are present in the *Turritella-Pandora* interval. In the southern Calvert Cliffs, including the type section for these strata (Gernant, 1970; sections 35, 36, and 37; Figures 4 and 7), the interval consists of thickly-bedded and bioturbated muddy, very fine sand with 8- to 10-cm-thick (3.2- to 3.9-in-thick) bands of homogeneous clay. The top surfaces of the clay bands are bored, and are usually overlain by a thin stringer of the gastropod *Turritella plebeia* (Figure 3). This *Turritella* facies grades into, and in the northern Calvert Cliffs outcrops is entirely replaced by, a thin bedded muddy sand with sand-laminated clay bands (*Pandora* facies, Figure 7). The small inequivalve bivalve *Pandora crassidens* occurs as fine fragmental shell

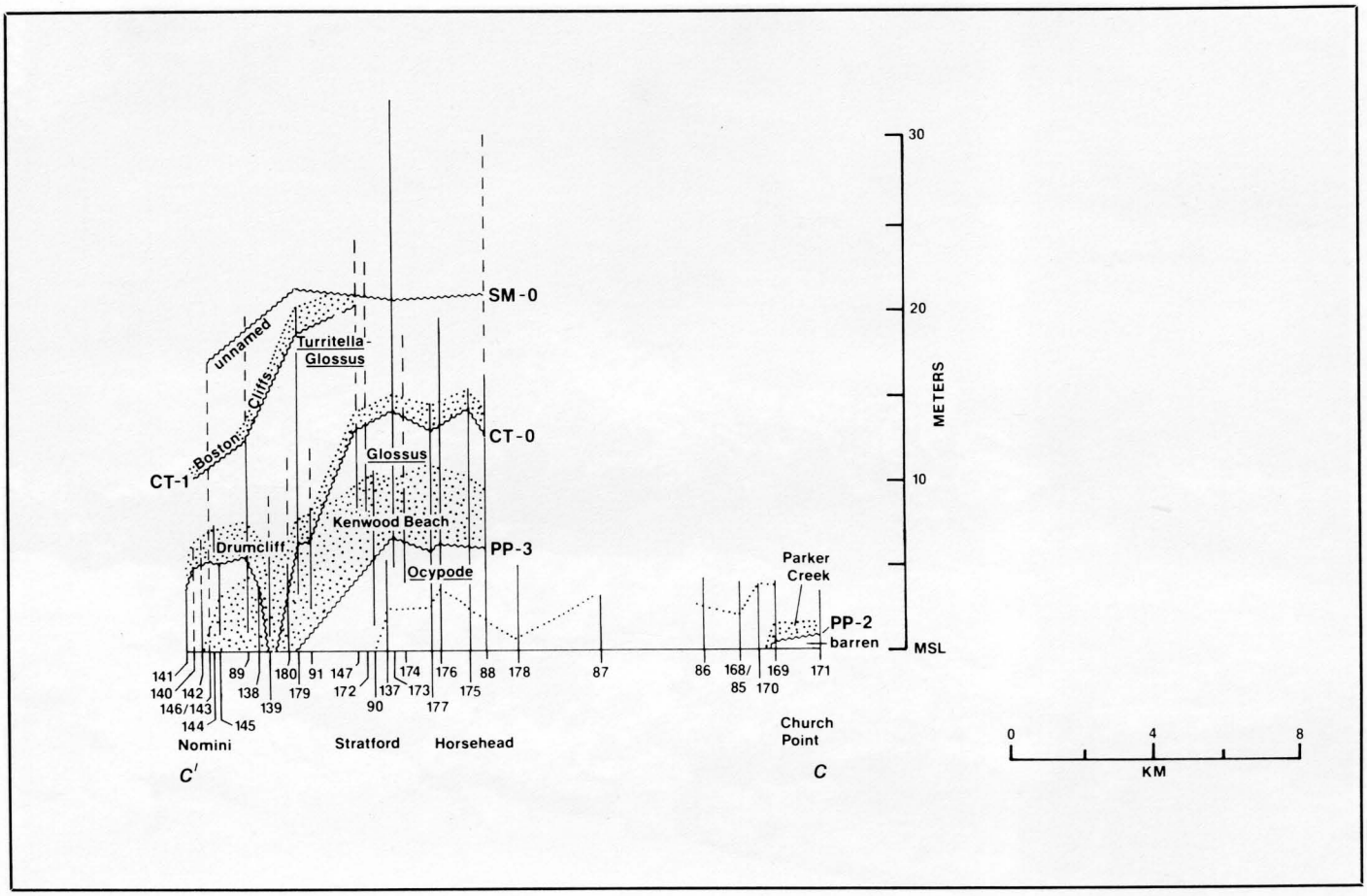


Figure 9: Cross section along the Virginia shore of the Potomac River. Conventions as in Figure 7.

material in the sand layers of that facies along with other small-sized species.

The *Turritella-Pandora* interval is indicated in Patuxent River exposures by interbedded silty- to very-silty very-fine sand with widely-spaced bored-clay bands. The large bivalve *Isognomon maxillata* dominates the macrofauna and occurs primarily in shell pavements. In the St. Leonard Creek region along the Patuxent (Figure 8), *I. maxillata* is densely packed into a clean fine sand (mistakenly assigned to the CT-0 sequence in Kidwell, 1982a). Finally, in the Potomac area, the *Turritella-Pandora* interval consists of massive clay and sandy mud that coarsen upward by the inclusion of muddy sand layers (*Glossus* facies, Figure 9). Shell material is very sparse except for thin, laterally discontinuous shell stringers dominated by *Glossus fraterna*.

Shallow sublittoral, polyhaline conditions are indicated for the Kenwood Beach shell bed by its trace- and body-fossil assemblage of venerid, lucinid, and corbulid bivalves, and *Gyrolithes*. The *Turritella-Pandora* facies tract includes: a littoral-to-sheltered, very shallow sublittoral *Pandora* facies; a soft-bottom, shallow sublittoral but fully marine *Turritella* facies; a firm bottom, shallow sublittoral polyhaline(?) *Isognomon* facies (both sandy shoal and adjacent muddy sea floor); and a soft-bottom, intermediate sublittoral marine *Glossus* facies.

CT-0 Disconformity and Depositional Sequence

The CT-0 disconformity is a burrowed firm ground, developed on the dark-gray silty fine sands of the *Turritella-Pandora* interval (PP-3 sequence) and overlain by the very shelly, well-sorted fine sand of the Drumcliff shell bed (Zone 17 of Shattuck, 1904; Figure 3). The burrowed surface coincides with an unconformity recognized by Shattuck (1904) between his Zones 15 and 17 in the Parker Creek area of the Calvert Cliffs, and used by him to define the Calvert-Choptank formational contact. The CT-0 disconformity is exposed over a distance of 15 km (9.3 mi) in the Calvert Cliffs, and along the Patuxent, Potomac, Rappahannock, and Choptank rivers (Figures 7, 8, and 9; Kidwell, 1982a).

Throughout much of its geographic extent, the CT-0 disconformity supports large-diameter (3 to 5 cm, or 1.2 to 2 in), interbranching *Thalassinoides* burrows that penetrate 0.7 to 2 m (2.3 to 6.6 ft) into underlying PP-3 strata (Figure 11). Exceptionally, the disconformity is an unburrowed scour surface in a 4-km (2.5-mi) stretch of the Calvert Cliffs between Parker Creek and Governor Run (sections 32 and 193 respectively; Figure 7). In that area, the disconformity describes a broad channel that cuts as much as 7 m (23 ft) into the underlying *Turritella-Pandora* interval and, at its lowest point, truncates the upper part of the Kenwood Beach shell bed. The erosional origin of this feature is evi-

Figure 10: Bedding plane exposure of the burrowed PP-0 disconformity at Chesapeake Beach (section 22, Figure 4). Waves have preferentially removed the basal, oyster-bearing sand of the Plum Point Member from *Thalassinoides* burrows developed in the top of the tightly consolidated Fairhaven Member. Shells of *Ostrea percrassa* in photograph are up to 20 cm (7.9 in) in length.

denced by the truncation of beds in the PP-3 sequence, lithofacies variation in the lower CT-0 sequence, and a thin (10 to 30 cm, or 4 to 12 in) basal lag of reworked calcitic shell debris and bone. The channel is filled with a body of interbedded clean fine sand and sandy clay informally named the Governor Run sand—clay interbeds characterized by the mussel *Mytilus incurvus* and the barnacle *Balanus concavus* thicken and become more closely spaced almost to the exclusion of sand beds along the flanks of the channel.

The basal lag of fragmental shells is immediately overlain by as much as 1 m (3.3 ft) of muddy sediments characterized either by algal laminations (?) or by the irregular urchin *Echinocardium cordatum* and its feeding traces. As a result, the CT-0 disconformity is marked by a notch of easily eroded sand between two muddy units in this Parker Creek to Governor Run stretch of the Calvert Cliffs, where workers most frequently choose to study and sample the formations. Truncation of bedding, development of a basal lag, and lithologic and paleontologic dissimilarity indicate that the relief on the CT-0 surface and the Governor Run sand resulted from primary erosion and deposition on the Miocene sea floor (Dryden, 1930; Kidwell, 1982a), not from post-depositional sagging of the section (Dryden, 1936) or diagenetic alteration of the PP-3 sequence (Gernant, 1970). Shattuck (1904) and subsequent workers have interpreted the Governor Run sand as a sandy updip facies of the *Turritella-Pandora* interval of the PP-3 sequence (that is, Zone 16).

South of Governor Run in the Calvert Cliffs, the CT-0 surface has its usual burrowed appearance and is immediately overlain by the Drumcliff shell bed (Figure 11). North of Parker Creek, the Drumcliff shell bed interfingers with an updip facies of the *Mytilus* interval of the CT-0 sequence (Figure 7). The CT-0 disconformity in these northern Calvert Cliffs exposures is overlain by a 0.7 m-thick (2.3 ft-thick) fine sand containing only scattered shell material.

The CT-0 depositional sequence consists of the very shelly, well-sorted sand of the Drumcliff shell bed and the several sparsely fossiliferous facies of the *Mytilus* interval (Zone 18 of Shattuck, 1904; Figure 3). In the Calvert Cliffs, the lower part of the *Mytilus* interval is a massive, mottled, very muddy fine sand to sandy clay, and contains typically deposit-feeding bivalve species. It grades into a muddy to sightly muddy, thickly-bedded sand facies containing sparsely disseminated shell and shell lenses dominated by the bivalves *Mytilus incurvus* and *Anadara staminea*. In

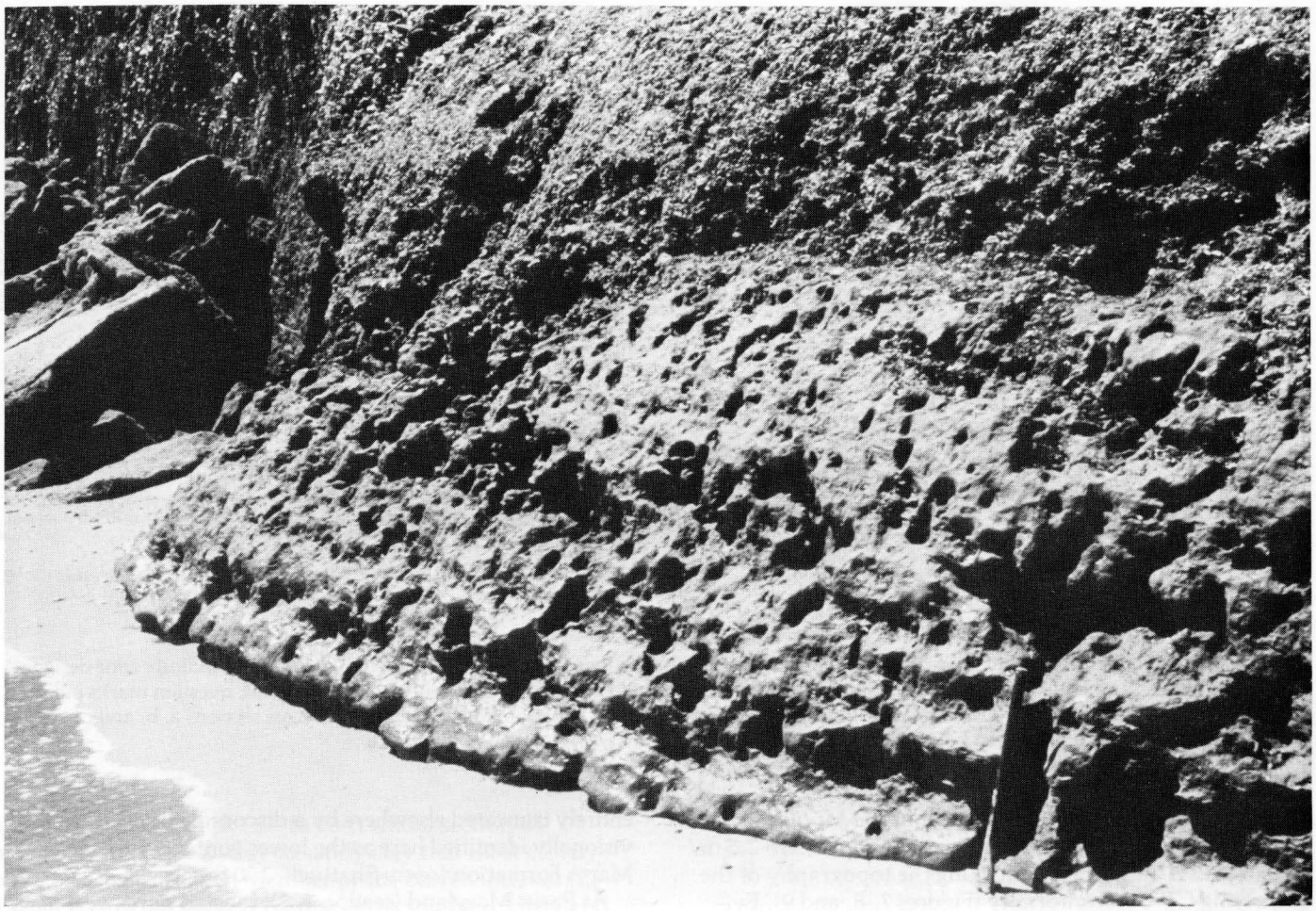


Figure 11: Weathered exposure of *Thalassinoides* burrow systems originating from the CT-0 disconformity at Matoaka, Calvert Cliffs of Maryland (section 35). The large diameter burrows are filled with loosely-consolidated, well-sorted shelly sand from the Drumcliff shell bed. Chisel at lower right is 45 cm (17.7 in) long.

extreme downdip exposures in the Calvert Cliffs (Figure 7; sections 165 and 154), the exposed interval consists of a clean, very bluish and unfossiliferous sand. Clean sand containing abundant calcitic shell hash characterizes the *Mytilus* interval along the Patuxent River and infills 2 m-deep (6.6 ft-deep) channels cut into the Drumcliff shell bed. The fossil assemblage, consisting of both whole and broken specimens of *Balanus concavus*, *Chesapecten nefrens*, *Ostrea* sp., *Abertella aberti* (sand dollar), and bryozoans, closely resembles the calcitic portion of the upper sand facies of the *Mytilus* interval in Calvert Cliffs. The cliffs along the Potomac River expose a fourth facies consisting of bioturbated, muddy very fine sand and sandy mud dominated by *Turritella plebeia*, which occurs in thin lenses as much as 0.5 m (1.6 ft) long.

The characteristically littoral (*Mytilus-Balanus*; algal mats) to very shallow sublittoral (*Echinocardium*) assemblages and sedimentary structures of the Governor Run sand, as well as reworked *Mytilus* along the base of the Drumcliff shell bed, indicate extremely shallow conditions during initial accumulation of the CT-0 sequence. The Drumcliff shell bed itself contains a stratigraphically condensed series of polyhaline and fully-marine, shallow- to very shallow-sublittoral, soft-bottom, and shell-gravel molluscan assemblages (Kidwell, 1979; 1982a). The overlying *Mytilus* interval consists of a progradational sequence of intermediate sublittoral (deposit-feeding fauna) to very shallow sublittoral to littoral facies (*Anadara* and *Mytilus* sands), with the exception of the *Turritella-Glossus* facies in the Potomac region, which arose in open-marine, shallow- to intermediate-sublittoral depths.

CT-1 Disconformity and Depositional Sequence

The CT-1 disconformity is a burrowed firmground along which the very shelly sands of the Boston Cliffs shell bed (Zone 19 of Shattuck, 1904) are superposed upon the lithologically variable sediments of the *Mytilus* interval of the CT-0 sequence (Figure 3). The surface can be traced in the Calvert Cliffs and along the Patuxent and Potomac rivers (Figures 7, 8, and 9).

In the southern Calvert Cliffs and along the Patuxent River, *Thalassinoides* burrows characterize the CT-1 disconformity. Smaller diameter but similarly deep (2 m, or 6.6 ft) burrows are present in the northern Calvert Cliffs, and in Potomac River exposures, non-branching small-diameter

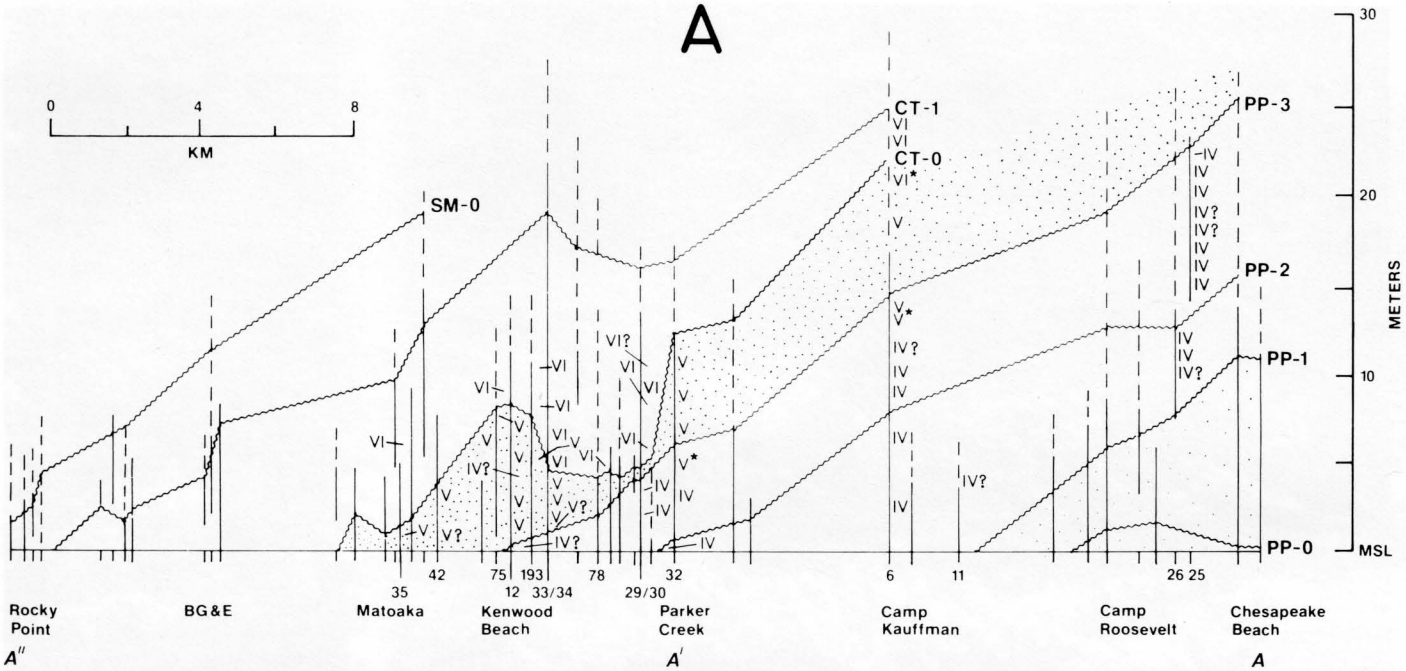


Figure 12: Correspondence of East Coast diatom zones (Abbott, 1978) and depositional sequences. Roman numerals indicate zone designations of individual samples. Asterisked samples are probably contaminated by burrow piping of younger material; question marks indicate doubt in zone assignment for some other reason. Zones II and V are stippled. Location and conventions of cross sections a, b, and c are identical to those in Figures 7, 8, and 9.

tubes penetrate less than 1 m (3.3 ft) into the *Mytilus* interval. The disconformity steepens locally in dip to 2 to 2.5 m/km (10 to12 ft/mi), often mimicking the topography of the underlying CT-0 disconformity (Figures 7, 8, and 9). Evidence for the erosional origin of the CT-1 surface includes the truncation of beds and facies of the underlying CT-0 sequence, and channel-like irregularities in the CT-1 surface. In addition, the Boston Cliffs shell bed varies in thickness and shell-packing density with topographic irregularities in the CT-1 surface. This variation is less well established than that of the Drumcliff shell bed because the CT-1 disconformity is exposed over a smaller outcrop area than the CT-0 surface, and secondly, the shell bed is often inaccessible in high cliffs.

The Boston Cliffs shell bed usually rests directly on the CT-1 disconformity (Figures 7, 8, and 9). From Matoaka (section 35) north to at least Governor Run (section 193) in the Calvert Cliffs, however, a lensoidal sand body (*Anadara* sand; Figure 7) intervenes. Unlike the Governor Run sand, which lies between the CT-0 surface and the Drumcliff shell bed, the *Anadara* sand does not appear to be a channel fill but simply rests on a stretch of the burrowed CT-1 surface, and grades upward into the Boston Cliffs shell bed.

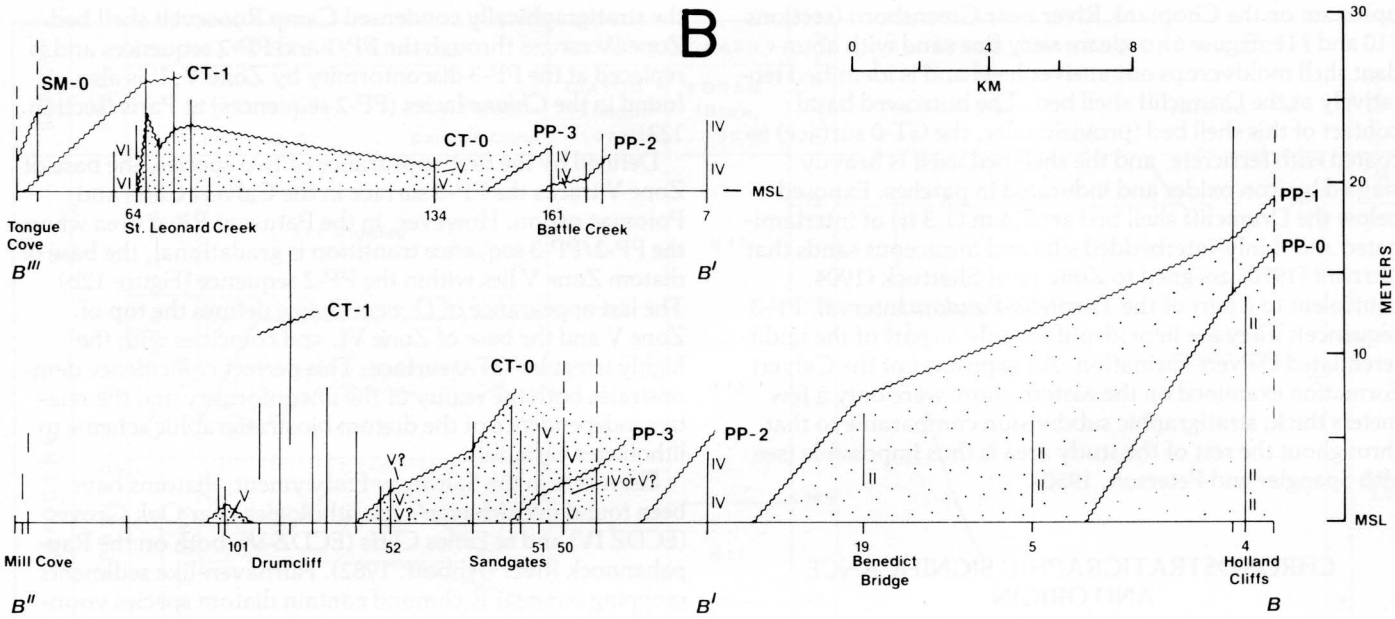
The Boston Cliffs shell bed grades upward into a less fossiliferous, very muddy unnamed interval (Figure 3). The interval has a *Turritella*-dominated facies in the Calvert Cliffs (Figure 7) and a *Glossus*-dominated facies in the Potomac region (Figure 9). These massive sediments are a portion of the strata assigned by Shattuck (1904) and Gernant (1970) to Zone 20 of the Choptank Formation. Although relatively thick in Potomac outcrops (3 to 5 m, or 10 to 16 ft; Figure 9), this part of the Choptank Formation is largely or entirely truncated elsewhere by a disconformity (SM-0) provisionally identified here as the lower contact of the St. Marys Formation (*sensu* Shattuck, 1904).

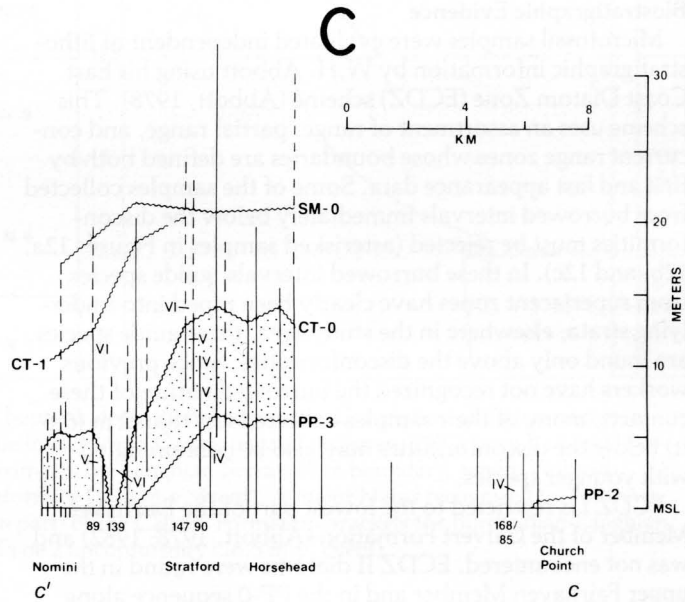
At Paris, Maryland (section 122), located northwest of the Calvert Cliffs (Figure 4), the CT-1 depositional sequence rests on or very near strata assigned with certainty to the *Glossus-Chione* interval (PP-2 sequence, Calvert Formation). The *Chione* facies is exposed in the extreme headwaters of a branch of Fishing Creek; nearby exposures of the Boston Cliffs shell bed are indicated by float specimens of indurated sandstone containing a Boston Cliffs fauna. These float specimens could not be derived from strata more than 3 m (10 ft) above the highest *Chione* exposure because of topographic constraints. The absence, or minimal thickness, of PP-3 and CT-0 strata in this area indicates that these strata were truncated during CT-1 erosion or were never deposited in this northern part of Calvert County. Shattuck (1904) and Gernant (1969, 1970) made similar observations in this area, interpreting the stratigraphic relations as evidence of unconformable Choptank onlap of Calvert strata.

The Boston Cliffs shell bed accumulated in shallow to very shallow sublittoral environments; the abundance of *Ostrea*, *Martesia*, *Isognomon*, and *Gyrolithes* suggests at least intermittent polyhaline conditions. The shell bed grades up into the fully marine shallow to intermediate sublittoral *Turritella* facies and intermediate sublittoral *Glossus* facies of the unnamed interval.

Rappahannock and Choptank River Exposures

In Fones Cliffs along the northern bank of the Rappahannock River (Figure 5), the exposed Calvert Formation con-





sists of a 3- to 4-m-thick (10- to 13-ft-thick) section of massive diatomaceous clay to sandy clay that most closely resembles the Fairhaven Member or the barren interval (PP-1 sequence) of the Calvert Formation in southern Maryland. Its upper contact is heavily burrowed by interpenetrating, sub-horizontal *Thalassinoides* filled with clean, very fine sand. This contact and infilling sand are nearly identical to the CT-0 surface and lower Drumcliff shell bed in the extreme eastern end of Nomini Cliffs, Potomac River (sections 140 and 141; Figure 9). The "Drumcliff" sand that rests on this burrowed surface at Fones Cliffs is leached of skeletal carbonate, varies from 2.7 to 2.9 m (8.9 to 9.5 ft) in thickness along the 5-km-long (3.1-mi-long) exposure and grades rapidly into 14 m (46 ft) of thickly- to very-thickly-bedded muddy fine sand with thin shell bands. Tentatively identified as undifferentiated Choptank Formation, this thick interval is truncated by a sharp burrowed surface and overlain by clayey sediments of the Eastover Formation (stratigraphically above the St. Marys Formation; see Ward and Blackwelder, 1980; Newell and Rader, 1982). The contact is marked by a lag of bone, wood, and phosphatic debris.

In the Rappahannock River area, it thus appears that the PP-0 (or possibly PP-2) through CT-0 surfaces are combined into a single unconformity that represents a large part of the Plum Point Member as developed in southern Maryland. Determining the precise nature of stratigraphic relations within the Choptank-St. Marys-Eastover interval here will require additional fieldwork. Preliminarily, the simplest interpretation is that the lag-marked lower contact of the Eastover Formation incorporates the CT-1, SM-0, and any intraformational discontinuities that might be present within the St. Marys Formation in the Potomac region. The convergence of the CT-1 and SM-0 disconformities in Nomini and Stratford Cliffs along the Potomac River (Figure 9) points to such a relationship.

The scarcity and small size of outcrops on Maryland's eastern shore hinder stratigraphic subdivision and analysis of Calvert-Choptank strata. Of the six depositional sequences, the CT-1 sequence can be identified with greatest confidence based on exposures of the Boston Cliffs shell bed along the Choptank River (section 107; Figure 6). The CT-1 surface itself is not exposed. Further north along the Choptank River are a series of small outcrops of homogeneous clay which may be a facies of the *Mytilus* interval of the CT-0 sequence (sections 108, 112, and 113; Figure 6). Maximum exposed thickness of the clay is 5 m (16.4 ft); neither the upper nor the lower contact is exposed; fossils consist only of the bivalve molds not identifiable to species level. Further

upstream on the Choptank River near Greensboro (sections 110 and 111; Figure 6), a clean, very fine sand with abundant shell molds crops out at river level and is identified tentatively as the Drumcliff shell bed. The burrowed basal contact of this shell bed (provisionally, the CT-0 surface) is coated with ferricrete, and the shell bed itself is heavily stained by iron oxides and indurated in patches. Exposed below the Drumcliff shell bed are 0.4 m (1.3 ft) of interlaminated and thinly-interbedded silts and micaceous sands that Gernant (1970) assigned to Zone 16 of Shattuck (1904; equivalent to a part of the *Turritella-Pandora* interval, PP-3 sequence). They are here identified only as part of the undifferentiated Calvert Formation. All exposures of the Calvert Formation examined on the eastern shore were only a few meters thick; stratigraphic subdivision comparable to that throughout the rest of the study area is thus impossible (see also Spangler and Peterson, 1950).

CHRONOSTRATIGRAPHIC SIGNIFICANCE AND ORIGIN

Biostratigraphic Evidence

Microfossil samples were evaluated independent of lithostratigraphic information by W.H. Abbott using his East Coast Diatom Zone (ECDZ) scheme (Abbott, 1978). This scheme uses an assortment of range, partial range, and concurrent range zones whose boundaries are defined both by first and last appearance data. Some of the samples collected from burrowed intervals immediately below the disconformities must be rejected (asterisked samples in Figures 12a, 12b, and 12c). In these burrowed intervals, guide species from superjacent zones have clearly been piped into underlying strata; elsewhere in the study area, these guide species are found only above the disconformities. Since previous workers have not recognized the burrowed nature of these contacts, many of their samples collected less than 2 m (6.6 ft) below the disconformities may also be contaminated with younger species.

ECDZ I is restricted to the lowest part of the Fairhaven Member of the Calvert Formation (Abbott, 1978; 1982) and was not encountered. ECDZ II diatoms were found in the upper Fairhaven Member and in the PP-0 sequence along the Patuxent River (Figure 12b) and in the Calvert Cliffs (Abbott, 1978). ECDZ III diatoms were not recovered in the course of this study, possibly because of the scarcity of any diatoms within the Camp Roosevelt shell bed. However, Abbott (1982) identified them in the top of the PP-0 sequence at Chesapeake Beach (section 22, Figure 12a; burrow piping?), and in the Camp Roosevelt shell bed at Plum Point (sections 11 and 121, Figure 4) and the Baltimore Gas and Electric Company well core taken at Flag Pond (near section 163, Figure 4). He also records Zone III from the Plum Point Member along the Pamunkey River in Virginia (Abbott, 1982).

ECDZ IV, V, and VI characterize the studied strata above the PP-1 disconformity, and their boundaries coincide with disconformities recognized by physical stratigraphic evidence (Figure 12a, 12b, and 12c). The base of Zone IV, defined by the last appearance of *Delphineis ovata*, lies at or less than 1 m (3.3 ft) above the PP-1 disconformity within the stratigraphically condensed Camp Roosevelt shell bed. Zone IV ranges through the PP-1 and PP-2 sequences and is replaced at the PP-3 disconformity by Zone V. It is also found in the *Chione* facies (PP-2 sequences) at Paris (section 122).

Defined by the first appearance of two species, the base of Zone V tracks the PP-3 surface in the Calvert Cliffs and Potomac region. However, in the Patuxent River area where the PP-2/PP-3 sequence transition is gradational, the base of diatom Zone V lies within the PP-2 sequence (Figure 12b). The last appearance of *D. penelliptica* defines the top of Zone V and the base of Zone VI, and coincides with the highly irregular CT-0 surface. This perfect coincidence demonstrates both the reality of the unconformity and the relative independence of the diatom biostratigraphic scheme to lithofacies variation.

Elsewhere in the Salisbury Embayment, diatoms have been found in Fairhaven-type lithologies near Oak Grove (ECDZ IV) and at Fones Cliffs (ECDZ V), both on the Rappahannock River (Abbott, 1982). Fairhaven-like sediments cropping out near Richmond contain diatom species younger than Zone VI (that is, above the last appearance of *Distephanus stauracanthus*; Abbott, 1982). These data indicate that the Fairhaven paleoenvironment migrated southward with time, being replaced in Maryland by Plum Point and Choptank lithologies.

Chronostratigraphic Utility

The disconformities provide a reasonable basis for chronostratigraphic subdivision and correlation within the study area. Available biostratigraphic data indicate that the disconformity-bounded depositional sequences are not diachronous within the limits of resolution of diatom zonation, although the top of each depositional sequence must vary somewhat in age locally owing to erosional relief (Figure 13). Depositional sequences, or sets of two depositional sequences, occupy unique time intervals (that is, correspond to single biozones). Inasmuch as exposures limit the evaluation of diachroneity over down-dip distances of less than 30 km (18.6 mi) in a structural embayment of very slight initial dip, this result should not be too surprising. The fortunate consequence for regional geologic interpretation, however, is that the depositional sequences delimit a series of facies tracts that can be used to reconstruct depositional systems for six relatively brief time periods (see Kidwell, 1982a).

Ages and Magnitudes of Hiatuses

Each of the disconformities formed over a period of time less than the duration of a single diatom zone (Figure 13). Locally and in updip areas, however, erosion enlarged some breaks in the record to equal or exceed one zone in duration. The CT-0 disconformity, for example, encompasses all or almost all of Zone V time where it cuts deeply into the PP-3 depositional sequence in the Calvert Cliffs and along the Potomac River (Figures 12a and 12c). Traced updip, the CT-1 hiatus expands to represent late Zone IV and all of Zone V time as well as Zone VI time by merging with the CT-0 and PP-3 disconformities in northern Calvert County; and along the Potomac River, the SM-0 hiatus progressively encompasses the larger part of Zone VI time by merging with the CT-1 surface.

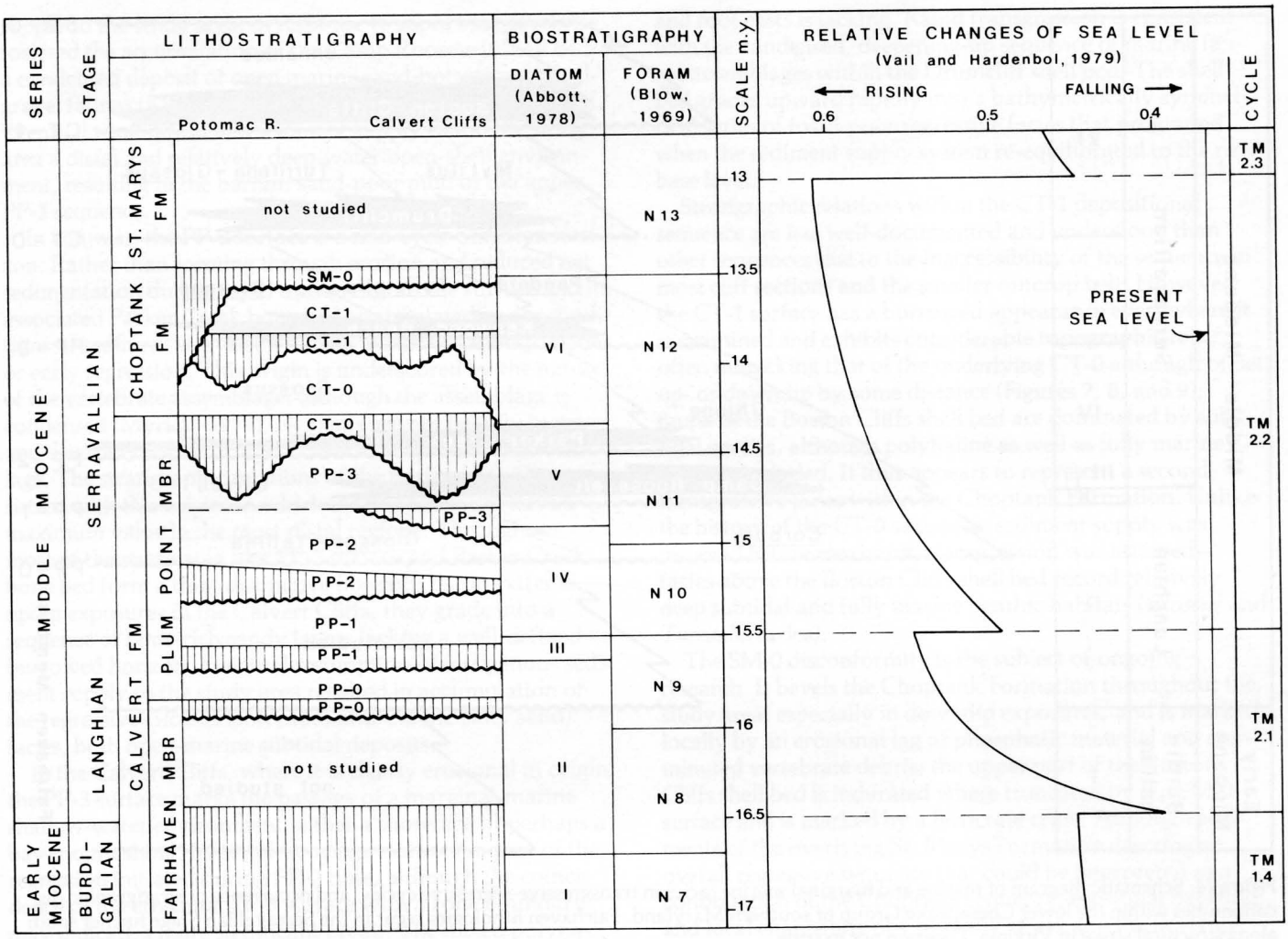


Figure 13: Biostratigraphic correlation and geochronology of Calvert-Choptank depositional sequences. Correlation of diatom and Neogene foraminiferal zones from Abbott (1978, 1982); geochronologic scale in m.y. (van Couvering and Berggren, 1977) from Vail and Hardenbol (1979). The PP-1 disconformity of the Calvert Formation approximates the Langhian-Serravallian boundary, where Vail and Hardenbol (1979) have recognized a minor, Type 2 interregional unconformity (15.5 m.y. event). A major hiatus recognized by Andrews (1978) and Abbott (1978, 1982) within the Fairhaven Member (shown in part) of the Calvert Formation brackets the Burdigalian-Langhian boundary, where Vail and Hardenbol (1979) identified another minor Type 2 unconformity (16.5 m.y. event).

To evaluate the disconformities in terms of absolute age, the diatom zones are correlated (Abbott, 1978, 1982) to the standard Neogene foraminiferal scheme of Blow (1969), which in turn has recently been calibrated to a geochronologic scale (van Couvering and Berggren, 1977; Vail and Hardenbol, 1979). As summarized in Figure 13, several diatom zones span one or more erosional surface, thus limiting the accuracy of age estimates. For example, the PP-0 disconformity lies somewhere within diatom Zone II, the PP-2 surface within Zone IV, and the CT-1 surface within Zone VI. Also diatom zone boundaries coinciding with erosional surfaces do not all coincide with well-dated boundaries of standard foraminiferal zones for the Neogene; for example, the bases of diatom Zones V and VI fall within foraminiferal zones N11 and N12. Perhaps the best constrained erosional surface is the PP-1 surface, which truncates diatom Zone II and lies very near the top of Zone III, the shortest of all of Abbott's (1978) East Coast Diatom Zones. The diatom information places the Langhian-Serravallian stage boundary just above the PP-1 surface within the Camp Roosevelt shell bed. The age of the SM-0 surface is not as well-constrained owing to the absence of diatoms in the overlying St. Marys Formation. However, it must lie near the foraminiferal zone N12-N13 boundary (Figure 13) based on diatoms found in the underlying CT-1 sequence (Abbott, 1982).

Both Andrews (1978) and Abbott (1978, 1982) have recognized a major hiatus between Abbott's Zones I and II within the Fairhaven Member of the Calvert Formation (Figure 13). This hiatus, which includes the Burdigalian-Langhian stage boundary, has a minimum duration of 2.5 m.y. (in the work cited). In contrast, disconformities in the Plum Point Member, Calvert Formation, all represent hiatuses less than 0.5 m.y. in magnitude. This includes the PP-1 surface and associated Camp Roosevelt shell bed, which coincide with the Langhian-Serravallian stage boundary.

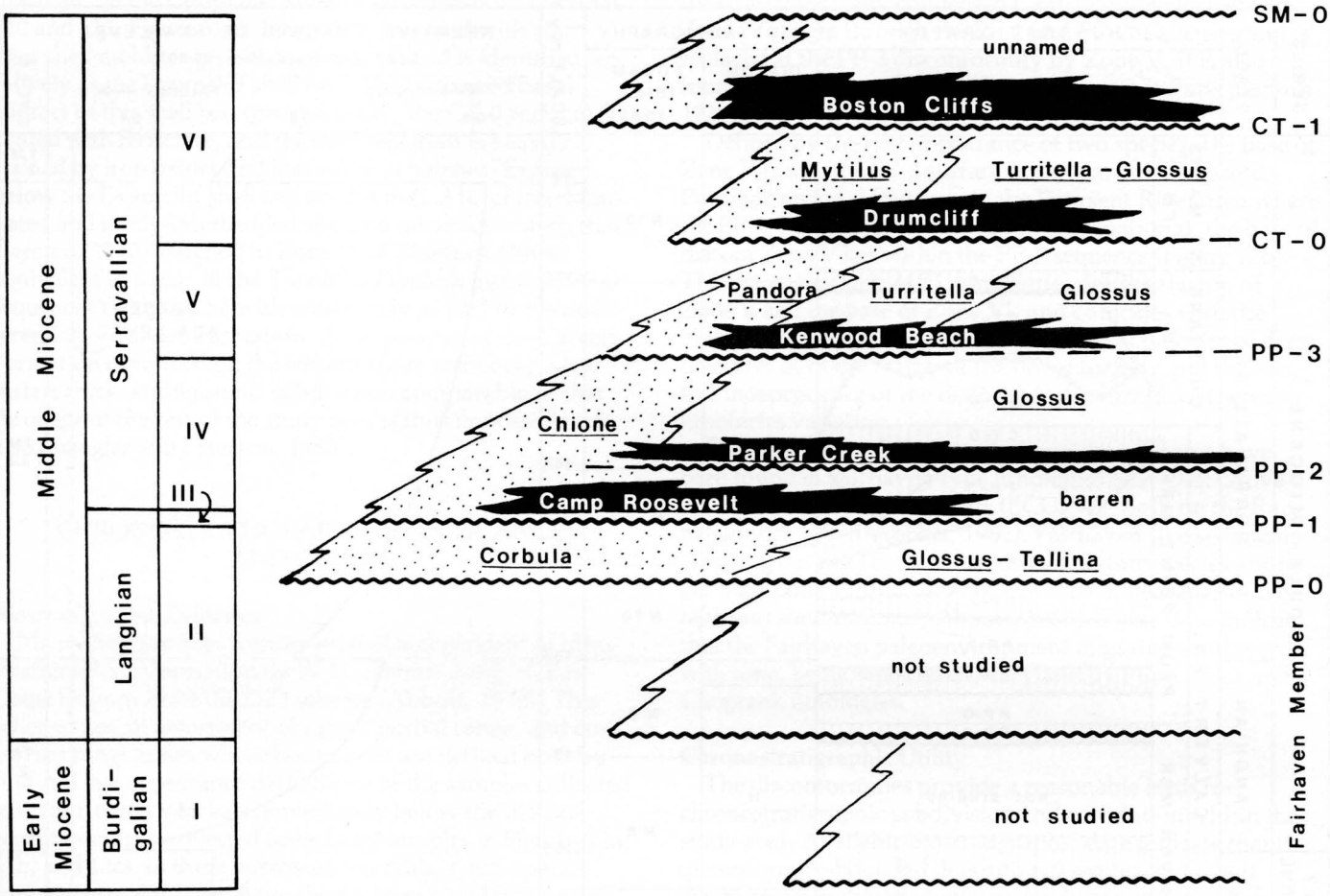


Figure 14: Schematic diagram of marine and marginal marine facies in transgressive-regressive cycles, and occurrence of stratigraphic discontinuities within the lower Chesapeake Group of southern Maryland. Fairhaven lithologies recur in the Serravallian Stage further south along structural strike in Virginia. Diagram not to scale.

Finally, disconformities within the Choptank Formation and at the base of the St. Marys Formation represent at least 0.5 m.y. each over most of their geographic extent, and considerably more locally (Figure 13).

Origin

Paleoenvironmental interpretation of the Plum Point and Choptank strata indicates a series of transgressive-regressive cycles with asymmetric facies records (Figure 14). This evidence, along with limited available information on onlapping relations between Burdigalian, Langhian, and Serravallian strata in the Salisbury Embayment, can be used to infer the origin and stratigraphic significance of the described surfaces. Unfortunately, published information on the mid-Fairhaven hiatus, not included in this study but probably the most significant break in the Maryland Miocene section, is insufficient to permit interpretation of its origin.

The lower Plum Point Member records a transgressive phase of deposition, with maximum open-shelf water depths attained in the massive barren interval of the PP-1 depositional sequence. Above the PP-2 surface and Parker Creek bone bed, the Plum Point and Choptank strata record an overall regressive phase punctuated by transgressive pulses and condensed shell deposits. Within this context, most of the disconformities represent ravinement surfaces formed erosionally during early transgression or late regression.

The PP-0 firmground, dominated by crustacean burrows including the typical marginal-marine form *Gyrolithes*, records the transgression of a marginal marine shoreface across older Fairhaven strata. The most conservative interpretation, consistent with the associated fauna, considerable erosional relief, and placement within a single biozone, is that the PP-0 surface is a submarine ravinement surface. However, because the paleoenvironmental significance of the underlying Fairhaven is unknown and owing to the limited exposures of the PP-0 surface, an earlier, possibly prolonged interval of subaerial exposure cannot be ruled out. The burrowed shoreface was followed in transgression by shallow-water oyster-bearing sands, including small reef bodies on paleohighs (Holland Cliffs), soft-bottom muds dominated by deposit-feeding communities and storm-transported skeletal debris from shallower areas (species-rich facies), and episodically prograding, polyhaline disturbed mud and sand habitats dominated by *Corbula*.

The PP-1 surface records rapid transgression of an open-marine shoreface across the prograding marginal marine system. Shutdown or slowdown of terrigenous sediment

supply to the study area, in response to rapid base-level rise, fostered the accumulation of the Camp Roosevelt shell bed, a condensed deposit of open marine sand-bottom and shell-gravel faunas (Kidwell 1982a; Kidwell and Jablonski, 1983). Eventual resumption of a sediment supply found the study area a distal and relatively deep-water open-shelf environment, resulting in the barren, sand-poor mud of the upper PP-1 sequence.

In contrast, the PP-2 surface is a mid-cycle omission horizon. Rather than forming through erosion and reduced net sedimentation during rapid transgression, the surface and its associated Parker Creek bone bed accumulated under conditions of sediment starvation during maximum transgression or early regression. This origin is underscored by the nature of the vertebrate assemblage: although the assemblage is condensed (Myrick, 1979), elements are not heavily worn and disarticulated as is typical of erosional bone and teeth lags. The stratigraphic relations of the horizon are also consistent with this origin, in which the hiatus should have a maximum value in the most distal regions. Throughout most of the study area, the PP-2 surface and Parker Creek bone bed form a thin, distinctive horizon, but in extreme updip exposures in the Calvert Cliffs, they grade into a sequence of bone-rich sandy layers lacking a well-defined burrowed horizon. Eventual resumption of terrigenous sediment supply to the study area resulted in accumulation of the regressive *Glossus* (soft mud) and *Chione* (silty sand) facies, both open-marine subtidal deposits.

In the Calvert Cliffs, where it is clearly erosional in origin, the PP-3 surface marks the passage of a marginal-marine shallow-water environment, either a shoreface or perhaps a bay-mouth shoal. Its simplest interpretation is a part of the regression initiated during PP-2 time, although the coincidence of the erosional PP-3 surface with a zone boundary may indicate a more significant break. The mixed polyhaline and open-marine fauna of the Kenwood Beach shell bed is succeeded by a regressive series of subtidal facies (*Glossus*, *Turritella*, and *Isognomon*) culminating in the very shallow subtidal to intertidal *Pandora* facies.

The CT-0 disconformity marks the termination of the Plum Point transgressive-regressive cycle and initiation of a new pulse of transgression within the study area. Much of the topographic relief on this surface, as much as 14 m (46 ft) locally, probably dates to late, erosional stages of the Plum Point regression—sediments immediately below the disconformity accumulated in intertidal flat and marsh environments (*Pandora* facies of the Calvert Cliffs, and *Ocypode* facies along the Potomac River, Virginia) characterized by channel systems, and it is not improbable that they were succeeded by fully supratidal coastal conditions. Topographic relief of this magnitude is not uncommon along modern coastlines and in Holocene transgressive records (Reineck and Singh, 1975). The intertidal origin of sediments resting directly upon the CT-0 disconformity (basal *Mytilus* assemblages within the Drumcliff shell bed and mussel-barnacle-echinoid assemblages and algal mats of the Governor Run sand (Kidwell, 1982a) underscores the probability of subaerial conditions during some period of CT-0 formation, and that much of the erosional paleotopography is regressive rather than transgressive in origin. Direct evidence of subaerial exposure such as paleosol development and root casts is lacking. Rapid transgression is consistent with the condensed, deepening-up sequence of marine faunal assemblages within the Drumcliff shell bed. The shell bed grades upward rapidly into a bathymetrically symmetrical series of fossil-poor regressive facies that prograded when the sediment supply system re-equilibrated to the new base level.

Stratigraphic relations within the CT-1 depositional sequence are less well-documented and understood than other sequences due to the inaccessibility of the sequence in most cliff sections and the smaller outcrop belt. However, the CT-1 surface has a burrowed appearance everywhere it is examined and exhibits considerable topographic relief, often mimicking that of the underlying CT-0 although offset up- or downdip by some distance (Figures 7, 8, and 9); fauna of the Boston Cliffs shell bed are dominated by subtidal species, although polyhaline as well as fully marine taxa are included. It thus appears to represent a second transgressive pulse within the Choptank Formation. Unlike the history of the CT-0 sequence, sediment supply was resumed before maximum transgression was attained—facies above the Boston Cliffs shell bed record relatively deep subtidal and fully marine benthic habitats (*Glossus* and *Turritella* facies).

The SM-0 disconformity is the subject of ongoing research. It bevels the Choptank Formation throughout the study area, especially in downdip exposures, and is marked locally by an erosional lag of phosphatic material and comminuted vertebrate debris; the upper part of the Boston Cliffs shell bed is indurated where truncated by the SM-0 surface and is marked by a ferricrete crust. Although sediments of the overlying St. Marys Formation describe an overall regressive sequence that could be interpreted as a continuation of the Choptank sequence, erosional beveling and local channeling of Choptank strata and the development of a phosphatic lag suggest disconformity and a significant episode of submarine and possibly subaerial erosion and non-deposition.

The physical features and paleontology of the Calvert-Choptank section are consistent with deposition along a non-deltaic coastline that experienced several cycles of rapid, erosional and non-depositional transgression and progradational regression (see Kraft, 1978). The features do not fit a deltaic model (see Miall, 1979). Facies sequences consistently fine rather than coarsen upward, and the section lacks distributary channel and bar sands, delta front sands, and delta-plain deposits even though several depositional sequences shallow-up into intertidal and possibly subaerial environments. The sedimentary structures and context of sub-wave base marine deposits are inconsistent with accumulation on prodeltaic slopes. It is thus unlikely that the disconformity-bounded depositional sequences owe their origin to alternating conditions of erosion and progradation related to delta-lobe switching. Moreover, the condensed shell beds associated with the erosional surfaces accumulated in open-marine, subtidal environments under conditions of prolonged low net sedimentation rather than erosional reworking (Kidwell, 1982a, 1982b). They are thus better explained in terms of marine transgression of non-deltaic coastlines following base-level rise, than by the erosional reworking of delta-front and plain environments in

response to sediment cutoff alone.

Relations to Interregional Unconformities

In the absence of seismic profiles for direct tracing of offshore subsurface reflectors into the Salisbury Embayment, determining the relationship of recognized interregional unconformities to the basin margin disconformities described here is limited to similarities in geologic age and onlap relations. Possible correlations are discussed without presupposing any eustatic or relative sea level significance for the interregional unconformities.

Biostratigraphic correlation places a 2.5 m.y. hiatus within the Fairhaven Member of the Calvert Formation at the Burdigalian-Langhian stage boundary (Abbott, 1978, 1982; Andrews, 1978), approximately 16.5 m.y. ago (Figure 13). In seismic records, Vail and Hardenbol (1979) have dated a minor, Type 2 unconformity at this same boundary (Type 2 unconformities are thought to result from a rapid rise in sea level following a period of stillstand or slow fall, inferred from onlap over a progradational sequence). Younger, Langhian aged strata of the Fairhaven Member should significantly onlap older strata if this major hiatus is related to this unconformity. Unfortunately, information on onlap-offlap relations, physical characteristics, and paleoenvironmental context for the mid-Fairhaven unconformity is unavailable for evaluation.

Within the studied Plum Point-Choptank section, which is Langhian to Serravallian in age, several laterally persistent erosional surfaces have been identified. Elsewhere, Vail and Hardenbol (1979) have identified only two unconformities of interregional significance, at the Langhian-Serravallian boundary at 15.5 m.y., and within the Serravallian stage at approximately 13.0 m.y. (Figure 13). Both are minor, Type 2 unconformities.

The 15.5-m.y.-ago event correlates closely with the PP-1 disconformity and its basal condensed shell bed (Figure 13). The PP-1 disconformity, however, is a marine ravinement surface rather than a major unconformity. Its stratigraphic position 10 m (33 ft) or less above the geologically more significant PP-0 surface, however, is beyond the resolution of typical seismic reflection data, and so the disconformable base of the Plum Point Member (PP-1 to PP-2 package) might represent the basin margin extension of Vail and Hardenbol's (1979) 15.5 m.y. sequence boundary. Available data for Langhian and Serravallian strata do indicate onlapping relations. Langhian-age strata, represented in Maryland by the upper part of the Fairhaven Member (Abbott, 1978; 1982; Figure 13), have not yet been recognized in Virginia, but Serravallian age strata extend throughout southern Maryland and as far south as Richmond, Virginia. In Maryland they are represented by the Plum Point Member of the Calvert Formation and the Choptank Formation (Figure 13); in Virginia they consist of Fairhaven-type diatomaceous sediments referred to as the Calvert Formation (Abbott, 1982).

The mid-Serravallian, 13.0 m.y. Type 2 unconformity is too young to correspond to any of the Plum Point or Choptank erosion surfaces, but may correlate with the SM-0 surface at the Choptank-St. Marys formational contact. Additional biostratigraphic evidence will be required, however, to determine whether the SM-0 hiatus was sufficiently long to encompass this event and whether regional stratigraphic relations are consistent with an onlapping record. Marine depositional environments do regress during St. Marys accumulation, but marginal marine strata can be traced further updip even in the Calvert Cliffs than previously reported (Kidwell, work in progress), and the extent of non-marine coastal onlap has not yet been established. Blackwelder (1981) and Newell and Rader (1982) have discussed unconformities and onlap relations for Chesapeake Group strata younger than the St. Marys Formation and their possible sea level significance.

CONCLUSIONS

Three hiatuses within the Maryland Miocene correlate with minor, Type 2 interregional unconformities recognized in seismic sections elsewhere by Vail and Hardenbol (1979). These are found: (1) within the Fairhaven Member of the Calvert Formation (16.5 m.y. event at Burdigalian-Langhian stage boundary); (2) at the approximate base of the Plum Point Member of the Calvert Formation (15.5 m.y. event at Langhian-Serravallian stage boundary); and (3) at the contact of the Choptank and St. Marys formations (13.0 m.y. event within the Serravallian stage). The disconformable contact of the Calvert and Choptank formations (CT-0 surface) also indicates a period of subaerial erosion and possibly onlap. It dates at approximately 14.5 m.y. (Figure 13), but does not correlate with any published interregional reflector. Correlation of Calvert-Choptank disconformities with offshore subsurface reflectors using geologic age and correspondence in onlap relations should be relatively straightforward, since the complications of delta-lobe switching that characterize some basin margins are absent in this situation.

The other disconformities of the Plum Point-Choptank section are transgressive or regressive ravinement surfaces or distal omission horizons associated with stratigraphically condensed fossil accumulations. These relations are an expression of stratigraphic complexity within larger-scale, interregionally significant depositional sequences, and would be beyond the resolution of most seismic reflection data. The isochroneity of the Plum Point-Choptank disconformities over down-dip distances on a regional scale requires further documentation, but the surfaces should grade into conformable sections within the shallow subsurface given their origins, and within the outcrop belt the disconformities are not measurably diachronous. They thus provide a valuable basis for chronostratigraphic subdivision and correlation within the study area and demonstrate the applicability of depositional sequence analysis to outcrop scale features. The practical consequences for the Maryland Miocene include the identification of facies tracts for paleogeographic reconstruction of the Salisbury basin margin (see Kidwell, 1982a) and a chronostratigraphic framework for paleobiologic analysis of its diverse and historically important faunas.

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REFERENCES CITED

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

——, 1982, Diatom biostratigraphy of the Chesapeake Group, Virginia and Maryland, *in* T.M. Scott and S.B. Upchurch, eds., Miocene of the southeastern United States: Special Publication, n. 25, Florida Bureau of Geology, p.

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

Blackwelder, B.W., 1981, Late Cenozoic marine deposition in the United States Atlantic Coastal Plain related to tectonism and global climate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 34, p. 87-114.

——, and L.W. Ward, 1976, Stratigraphy of the Chesapeake Group of Maryland and Virginia: Geological Society of America Southeast Section Field Trip Guidebook, 55 p.

Blow, W.H., 1969, Late middle Eocene to Recent planktonic foraminiferal biostratigraphy: Geneva, Proceedings, First International Conference on Planktonic Microfossils, p. 199-421.

Calver, J.L., and C.R.B. Hobbs, Jr., eds., 1963, Geologic Map of Virginia: Virginia Division of Mineral Resources, Scale 1:500,000.

Cleaves, E.T., J. Edwards, Jr., and J.D. Glaser, eds., 1968, Geologic Map of Maryland: Maryland Geological Survey, Scale 1:250,000.

Dryden, A.L., Jr., 1930, Stratigraphy of the Calvert Formation at the Calvert Cliffs, Maryland: Unpublished Ph.D. Dissertation, John Hopkins University, 235 p.

——, 1933, *Xenohelix* in the Maryland Miocene: Proceedings, National Academy of Science, v. 19, p. 139-143.

——, 1936, The Calvert Formation in southern Maryland: Proceedings, Pennsylvania Academy of Science, v. 10, p. 42-51.

Frey, R.W., and A. Seilacher, 1980, Uniformity in marine invertebrate ichnology: Lethaia, v. 13, p. 183-207.

Gazin, C.L., and R.L. Collins, 1950, Remains of land mammals from the Miocene of the Chesapeake Bay region: Smithsonian Miscellaneous Collections, v. 16, n. 2, 21 p.

Gernant, R.E., 1970, Paleoecology of the Choptank Formation (Miocene) of Maryland and Virginia: Maryland Geological Survey Report of Investigations, v. 12, 90 p.

——, 1971, Invertebrate biofacies and paleoenvironments, *in* R.E. Gernant, T.G. Gibson, and F.C. Whitmore, Jr., eds., Environmental history of Maryland Miocene: Maryland Geological Survey Guidebook, v. 3, p. 19-30.

——, 1972, The paleoenvironmental significance of *Gyrolithes* (Lebensspur): Journal of Paleontology, v. 46, p.735-741.

Gibson, T.G., 1962, Benthonic foraminifera and paleoecology of the Miocene deposits of the middle Atlantic Coastal Plain: Unpublished Ph.D. Dissertation, Princeton University, 198 p.

——, 1971, Miocene of the middle Atlantic Coastal Plain, *in* R.E. Gernant, T.G. Gibson, and F.C. Whitmore, Jr., eds., Environmental history of Maryland Miocene: Maryland Geological Survey Guidebook, v. 3, p. 1-15.

Glenn, L.C., 1904, Systematic paleontology, Miocene Pelecypoda: Maryland Geological Survey, Miocene Volume, p. 274-401.

Harris, G.D., 1893, The Tertiary geology of Calvert Cliffs, Maryland: American Journal of Science, 3rd Series, v. 45, p. 21-31.

Howard, J.D., and H.-E. Reineck, 1981, Depositional facies of high-energy beach-to-offshore sequence: Comparison with low-energy sequence: AAPG Bulletin, v. 65, p. 807-830.

Kellogg, R., 1965-1969, Fossil marine mammals from the Miocene Calvert Formation of Maryland and Virginia: U.S. National Museum Bulletin, n. 247, parts 1-9, 197 p.

Kellogg, R., 1969, Cetothere skeletons from the Miocene Choptank Formation of Maryland and Virginia: U.S. National Museum Bulletin, n. 294, parts 1 and 2, 39 p.

Kidwell, S.M., 1979, Stratigraphic condensation and the formation of major shell beds in the Miocene Chesapeake Group: Geological Society of America Abstracts, v. 11, p. 457.

——, 1982a, Stratigraphy, invertebrate taphonomy, and depositional history of the Miocene Calvert and Choptank formations, Atlantic Coastal Plain: Unpublished Ph.D. Dissertation, Yale University, 514 p.

——, 1982b, Time scales of fossil accumulation——patterns from Miocene benthic assemblages: Proceedings, Third North America Paleontology Convention, v.1, p. 295-300.

——, and D. Jablonski, 1983, Taphonomic feedback; ecological consequences of shell accumulation, *in* M.J.S. Teresz and P.L. McCall, eds., Biotic interactions in Recent and fossil benthic communities: New York, Plenum Press, p. 195-248.

Kraft, J.C., 1978, Coastal stratigraphic sequences, *in* R.A. Davis, Jr., ed., Coastal sedimentary environments: New York, Springer-Verlag, p. 361-383.

Malkin, D.S., 1953, Biostratigraphic study of Miocene Ostracoda of New Jersey, Maryland, and Virginia: Jour-

nal of Paleontology, v. 27, p. 761-799.
Martin, G.C., 1904, Systematic paleontology, Miocene Gastropoda: Maryland Geological Survey, Miocene Volume, p. 131-270.
Miall, A.D., 1979, Facies Models 5—deltas, *in* R.G. Walker, ed., Facies models: Geoscience Canada Reprint Series, v. 1, p. 43-56.
Myrick, A.C., Jr., 1979, Variation, taphonomy, and adaptation of the Rhabdosteidae (=Eurhinodelphidae) (Odontoceti, Mammalia) from the Calvert Formation of Maryland and Virginia: Unpublished Ph.D. Dissertation, University of California, 411 p.
Newell, W.L., and E.K. Rader, 1982, Tectonic control of cyclic sedimentation in the Chesapeake Group of Virginia and Maryland: Geological Society of America Northeastern-Southeastern Section Guidebook Field Trip No. 1, p. 1-27.
Payton, C.E., ed., 1977, Seismic stratigraphy -- applications to hydrocarbon exploration: AAPG Memoir 26, 516 p.
Poag, W.C., 1979, Stratigraphy and depositional environments of Baltimore Canyon Trough: AAPG Bulletin, v. 63, p. 1452-1466.
Radwanski, A., 1977, Burrows attributable to the Ghost Crab *Ocypode* from the Korytnica Basin middle Miocene (Holy Cross Mountains, Poland): Acta Geologica Polonica, v. 27, p. 217-225.
Reineck, H.-E., and I.B. Singh, 1975, Depositional sedimentary environments. Berlin, Springer-Verlag, 439 p.
Schoonover, L.M., 1941, A stratigraphic study of the mollusks of the Calvert and Choptank formations of southern Maryland: Bulletin of American Paleontology, v. 25, 94B, p. 169-199.
Shattuck, G.B., 1904, Geological and paleontological relations, with a review of earlier investigations: Maryland Geological Survey, Miocene Volume, p. 33-137.
Spangler, W.B., and J.J. Peterson, 1950, Geology of Atlantic Coastal Plain in New Jersey, Delaware, Maryland, and Virginia: AAPG Bulletin, v. 34, p.1-99.
Ulrich, E.O., and R.S. Bassler, 1904, Systematic paleontology, Miocene Bryozoa: Maryland Geological Survey, Miocene Volume, p. 404-429.
Vail, P.R., and J. Hardenbol, 1979, Sea level changes during the Tertiary: Oceanus 22, v. 71-79.
——, et al, 1980, Unconformities of the North Atlantic: Philosophical Transactions, Royal Society of London, v. A294, p. 137-155.
van Couvering, J.A., and W.A. Berggren, 1977, Biostratigraphical basis of the Neogene time scale, *in* E.G. Kauffman and J.E. Hazel, eds., Concepts and methods of biostratigraphy: Stroudsburg, PA, Dowden, Hutchinson, and Ross, p. 283-306.
Ward, L.W., and B.W. Blackwelder, 1980, Stratigraphic revision of upper Miocene and lower Pliocene beds of the Chesapeake Group, middle Atlantic Coastal Plain: U.S. Geological Survey Bulletin, v. 1482-D, 61 p.