

THE JOURNAL OF GEOLOGY

January 1989

STRATIGRAPHIC CONDENSATION OF MARINE TRANSGRESSIVE RECORDS: ORIGIN OF MAJOR SHELL DEPOSITS IN THE MIOCENE OF MARYLAND¹

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ABSTRACT

Cyclic stratigraphic sequences in shallow marine records are commonly characterized by a condensed transgressive lag at the base of thicker, shallowing-upward facies. The standard actualistic model for these thin fossiliferous lags, by which most of the shelf is starved owing to coastal trapping of sediment and fossils are suspected of being reworked because of the association with an erosional ravinement, is contradicted by detailed stratigraphic and taphonomic analysis of Miocene examples in the Maryland coastal plain. The four major shell deposits in the Miocene record are condensed (i.e., demonstrably thin relative to coeval strata), transgressive records of intertidal to subtidal environments (to storm wavebase) and are composed of shells produced locally as transgression proceeded. The complex internal stratigraphies of the shell deposits and the mixture of soft- and shell-bottom faunas indicate condensation under a regime of dynamic bypassing rather than complete sediment starvation; bypassed fine sediments accumulated in deeper water environments below storm wavebase. Deeper, even more basinward parts of the shelf were starved of all sediment size fractions and accumulated shell-poor, bone-rich condensed deposits that lie mid-cycle (bracketing the time of maximum water depth). The base-of-cycle shell deposits and mid-cycle bone bed differ not only in composition and in environment and dynamics of condensation, but also in chronostratigraphic value: the onlapping shell deposits must be diachronous to some degree, whereas the mid-cycle bone bed approximates an isochronous marker for correlation. Thus, in some settings at least, transgressive shelves present a spatial mosaic of condensational and depositional regimes. Regardless of origin, all condensed intervals can time-average assemblages and telescope biostratigraphic datums. They otherwise differ widely, however, in paleontologic attributes and are characterized by highly variable and complex stratigraphic anatomies.

INTRODUCTION

Marine Miocene deposits of the Maryland Coastal Plain include a series of spectacularly fossiliferous sands (fig. 1) whose origins have been debated for over a century. These densely fossiliferous units have served as a cornerstone for lithologic subdivision and correlation of the Chesapeake Group owing to their lateral traceability (Harris 1893; Shattuck 1904; Gernant 1970), have figured prominently in the history of North American

paleontology (see review by Shattuck 1904), and are still a fertile testing ground for paleobiological hypotheses (e.g., Dudley and Vermeij 1978; Stanley and Campbell 1981; Miyazaki and Mickevich 1982; Kelley 1983). Previous workers have stressed the roles of storms and other reworking events, high benthic productivity, ecological succession, and shell transport in the formation of these skeletal concentrations (Mongin 1959; Gernant 1970; Blackwelder and Ward 1976; Moll and Thomas 1979). Detailed stratigraphic and taphonomic re-examination of the entire Miocene section, however, indicates that, while the concentrations clearly reflect repeated short-term reworking and recolonization of the seafloor, they are, when viewed on a broader scale, stratigraphically condensed records of a suite of transgressive shallow

¹ Manuscript received January 21, 1988; accepted July 18, 1988.

[JOURNAL OF GEOLOGY, 1989, vol. 97, p. 1-24]
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0022-1376/89/9701-0001\$1.00



FIG. 1.—Drumcliff Member near Calvert Beach in the Calvert Cliffs, one of four major shell deposits in the Maryland Miocene. Arrow points to burrowed CT-0 disconformity at base of shell deposit.

marine environments (Kidwell 1979, 1982a, 1982b).

Any stratigraphic interval that is demonstrably thinner than coeval strata owing to local failure of sediment accumulation can be regarded as condensed (Heim 1934, 1958; Wendt 1970; Jenkyns 1971). Condensed deposits thus occupy a middle ground between unconformities and thick continuous records, and potentially are equally as significant for the reconstruction of basin histories. Some models for stratigraphic accumulation on passive margins (e.g., Haq et al. 1987) already place equal stress on the identification of mid-cycle (downlapped) condensed intervals as on unconformities for the interpretation of sequences. Few condensed deposits of any sort have been analyzed in detail in North America, however (McGugan and Rapson 1961; Baird and Brett 1981; Maliva 1984; Hattin 1985; Baum in press), and so outcrop-based studies affording high-resolution information on the anatomy and composition of condensed features can provide timely in-

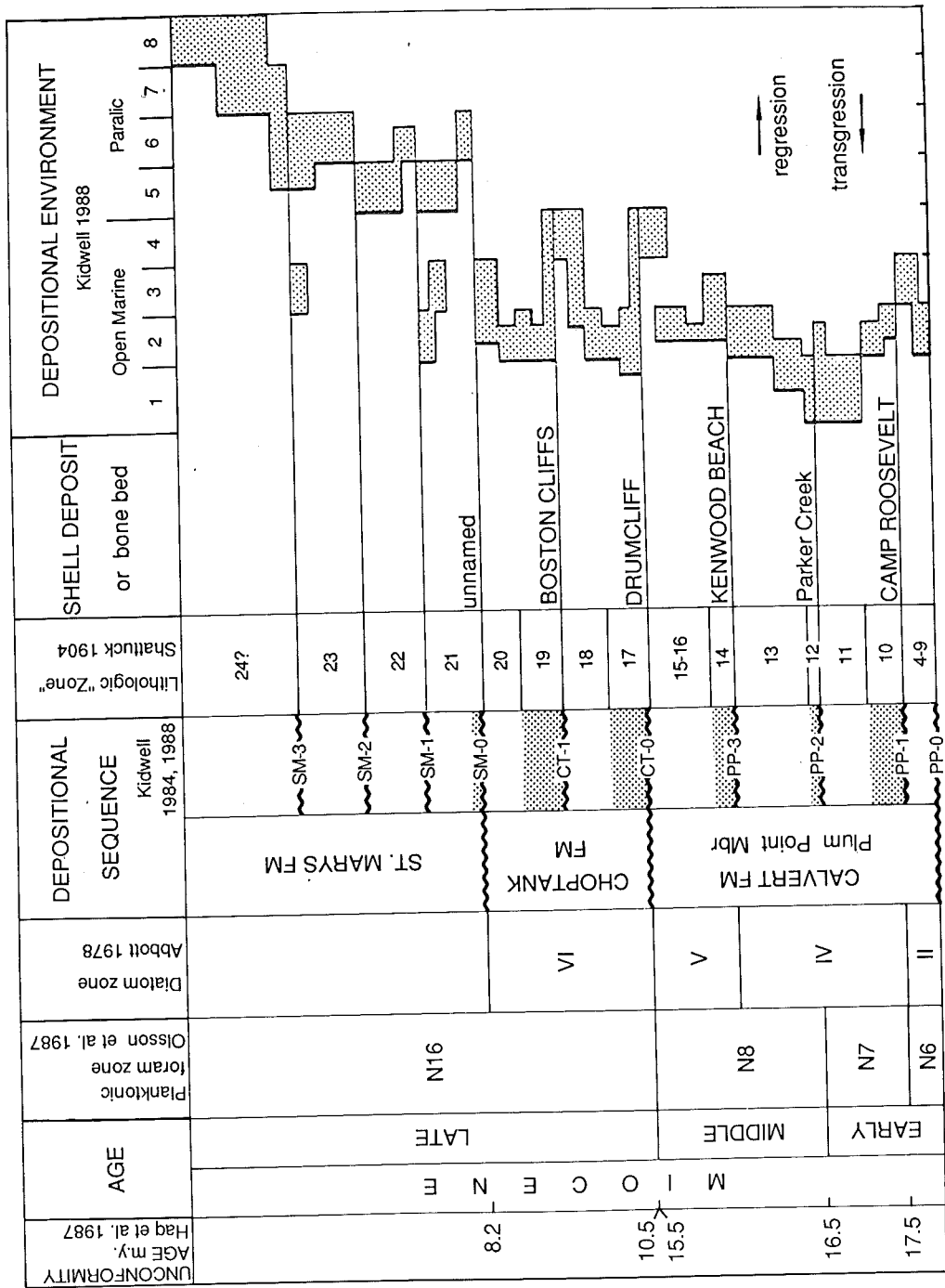
sight at this stage in development of stratigraphic models. The paleontological implications of stratigraphic condensation have been discussed elsewhere (for Maryland Miocene, see Kidwell 1982b, 1986a; Kidwell and Aigner 1985). Here I document the stratigraphy and taphonomy of condensed transgressive lags in particular, using the Miocene of Maryland as a case study of these non-depositional facies in marine siliciclastic records.

FEATURES OF THE MAJOR SHELL DEPOSITS

Lithology and Scale.—The four major “shell beds” of the Maryland Miocene—lithostratigraphic “Zones” 10 and 14 of the Calvert Formation (Plum Point Member), and “Zones” 17 and 19 of the Choptank Formation (Shattuck 1904)—are well-sorted, quartzose, fine sands that contain 40 to 70% shell carbonate by volume. These four units are readily distinguished from other facies in the Miocene section, which tend to be shell-poor ($\leq 10\%$ skeletal carbonate by volume), relatively poorly sorted very fine sands, silty sands, sandy silts, and clays (Kidwell 1984). In addition to the major shell deposits, the Maryland Miocene record includes two comparatively subtle bone beds. The laterally extensive “Zone” 12 contains relatively well-preserved hardparts from marine and terrestrial animals in a glauconitic, shell-poor, very fine sand matrix, whereas the basal lag of the St. Marys Fm is a highly lenticular concentration of comminuted bones, teeth, and phosphatized internal molds of bivalves (fig. 2).

The four shell deposits range up to 6 m in thickness, rest on erosional disconformities, and can be traced continuously over hundreds to thousands of square kilometers in outcrop along the margin of the Salisbury Embayment (fig. 3, table 1). In areal dimensions, these deposits exceed the scale of less fossiliferous facies in the Maryland Miocene—the shell deposits demonstrably cut across tracts of less fossiliferous facies—hence the stratigraphic designation as major skeletal concentrations (Kidwell 1982b).

FIG. 2.—Stratigraphy and paleoenvironments of outcropping Miocene strata in Maryland. The four major shell deposits occur at bases of depositional sequences in the open marine part of the record. The Parker Creek bone bed marks the point of maximum water depth (base of PP-2 sequence), and an unnamed bone sand at the base of the SM-0 sequence marks the transition from open marine to paralic deposition. Key to depositional environments: 1—below storm wavebase open shelf; 2—below fairweather wavebase open shelf; 3—nearshore marine; 4—intertidal marine; 5—below wavebase paralic; 6—above wavebase paralic; 7—intertidal paralic; 8—fluvial channel complex.



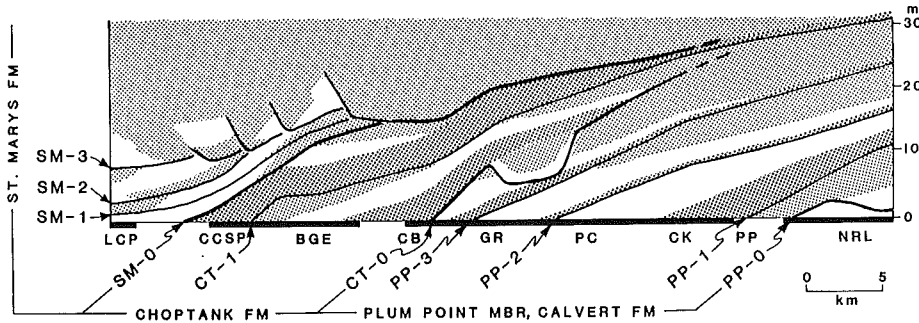


FIG. 3.—Lateral extent and physical stratigraphic relations of major shell deposits and bone beds (dark stipple), poorly sorted, less fossiliferous siliciclastics (white, light stipple), and basin-margin disconformities (numbered successively within formations; fig. 2). Adapted from Kidwell (1988a). Localities in Calvert Cliffs: NRL = Naval Research Lab; PP = Plum Point; CK = Camp Kauffman; PC = Parker Creek; GR = Governor Run; CB = Calvert Beach; BGE = Baltimore Gas & Electric plant; CCSP = Calvert Cliffs State Park; LCP = Little Cove Point.

They are distinguished from minor skeletal concentrations, which never extend beyond the bounds of a single stratigraphic facies (areal extents on the order of cm^2 to few km^2 ; Kidwell 1982b).

Complex Internal Stratigraphy.—In individual measured sections, major shell deposits are not homogeneous but are characterized by a series of subsidiary fossil assemblages (fig. 4). These subdivisions are distinguished by differences in species composition, quality of fossil preservation, bioclastic fabric, and terrigenous matrix, and typically are separated from each other by burrowed or scoured minor discontinuity surfaces. Individual assemblages can contain several dozen species of molluscs; cumulative diversities per major shell deposit can reach ~150 molluscan species, plus echinoids, corals, barnacles, bryozoans, and other benthos (Shattuck 1904; Kidwell 1982a, 1986b) (table 2).

Individual assemblages and shell-rich layers within the major deposit commonly have their own complex microstratigraphy or otherwise reveal complex histories of accumulation. At Kenwood Beach, for example, "Zone" 14 consists of four closely spaced shell-rich sand beds separated by shell-poor silty sands (figs. 5 and 6, locality 12). The second shell band, only 15 cm thick (layer B in fig. 6), consists of (a) a basal lag of disarticulated, convex-up scallops and abraded venerid (infaunal) bivalves, overlain by (b) hashy sand with pods of juvenile *Anomia*, large *Turritella*, and *Glossus* in life

position, topped by (c) a shell-supported, hash-free bed of flat-lying articulated and disarticulated infaunal bivalves. This single layer records at least two episodes of shell reworking with intervening episodes of deposition and recolonization before final burial.

In fact, few microstratigraphic subdivisions or assemblages within the major shell deposits appear to record single, discrete events of shell concentration. The exceptions include shell stringers in the upper part of the Drumcliff shell bed ("Zone" 17, fig. 4) and in subfacies E of the Camp Roosevelt shell bed ("Zone" 10, fig. 7) that have many specimens in life position and ecologically coherent species compositions. Most assemblages instead comprise ecological mixtures of fossils (e.g., both soft-bottom and shell-gravel species) and specimens in different states of preservation, indicating either time-averaging of successive benthic populations or mixing of local and exotic hardparts.

In general, significant transport of shells (i.e., among different habitats; Moll and Thomas 1979) is rejected: skeletal material in the major shell deposits is poorly sorted with respect to size and shape and is not in hydraulic equivalence with the fine sand matrix, nor are fossils associated with high-energy physical sedimentary structures. Moreover, likely sources for shells are lacking. Adjacent and underlying units have sparse, low diversity faunas that simply could not have yielded the high-diversity, large-bodied, predominantly suspension-feeding assemblages that characterize the major shell deposits (Kid-

TABLE 1

SUMMARY OF MAJOR SHELL BED FEATURES

	Camp Roosevelt shell bed (Zone 10)	Kenwood Beach shell bed (Zone 14)	Drumcliff shell bed (Zone 17)	Boston Cliffs shell bed (Zone 19)	Parker Creek bone bed (Zone 12)
Scale and Context: thickness (with paleolow de- posits)	2-6 m	.3-4.5 m	.6-4 m (to 8 m)	.6-3.6 m	.6 m
lateral extent basal contact	400 km ² <i>Thalass.</i> firmground; PP-1 discon. gradational, locally beveled	2000 km ² <i>Thalass.</i> firmground; PP-3 discon. gradational, locally cut out by CT-0 disconformity	2500 km ² <i>Thalass.</i> firmground; CT-0 discon. gradational, locally channeled	3000 km ² <i>Thalass.</i> firmground; CT-1 discon. gradational, widely beveled by SM-0 disconformity	2000 km ² <i>Thalass.</i> firmground; PP-2 discon. <i>Thalass.</i> firmground
upper contact	intertongues basin- ward with thick shell-poor facies basinward thicken- ing; overlapping facies tracts sepa- rated by discon- tinuities	intertongues basin- ward; pinchout landward	pinchout landward	pinchout landward?	splays landward into thick facies
lateral contacts					
geometry & inter- nal relations	transgressive, base-of-cycle	transgressive, base-of-cycle	transgressive, base-of-cycle	transgressive, base-of-cycle	uniformly tabular
position within transgr.-regress. cycle	50-70; locally 20%	20-40; locally more	20-70; $\leq 15\%$ in paleolows	20-70	<10
Bulk Sediment Prop- erties:					
vol % shell car- bonate in bulk sediment	vert. phosph.	vert. phosph., wood	vert. phosph.	vert. phosph.	vert. phosph., trace glauconite
accessory grains	3-5	2-5	3-5	4-5	5
ichnofabric ^a					

(Continued)

TABLE 1 (Continued)

SUMMARY OF MAJOR SHELL BED FEATURES

	Camp Roosevelt shell bed (Zone 10)	Kenwood Beach shell bed (Zone 14)	Drumcliff shell bed (Zone 17)	Boston Cliffs shell bed (Zone 19)	Parker Creek bone bed (Zone 12)
Siliclastic Matrix: mean ϕ sand frac- tion	2.5	3.0	2.0-2.5	2.5-3.0	3.0-3.5
wt % mud (<1/16 mm)	0-12	0-13	0-6	1-11	10-20
Bioclastic Fabric: ^b inclination of large shells to bed- ding	concordant, locally chaotic	concordant, locally edgewise	concordant to chaotic	concordant, locally chaotic	random
frequency of ar- ticulated bi- valves	few artic., rarely in life positions	many artic., in & out of life posi- tions	varies, 0-40% artic.	varies, 0-40% artic.	very low
close-packing of large shells	mostly shell-supp.	matrix- to shell- supp.	mostly shell-supp.	mostly shell-supp.	matrix-supp.
size frequency ^c	large shells in fine hash	large shells, scarce hash	large shells, variable hash	large shells, variable hash	large shells, scarce hash
shell mineralogy	orig. arag. & lesser amts. low-Mg cal- cite	leached arag., scarce calcite	orig. arag. & lesser amts. low-Mg & hi-Mg calcite	orig. arag. & abun- dant calcite	leached arag.

^a Ichnofabric index of Droser and Rotjier (1986) runs from 1 (no disruption of physical bedding) to 5 (complete obliteration of bedding).

^b Bioclastic fabric terminology as in Kidwell et al. (1986).

^c Shell material divided into hash component (whole and fragmental material ≤ 1.5 cm diameter) and large shells (range 2-18 cm).

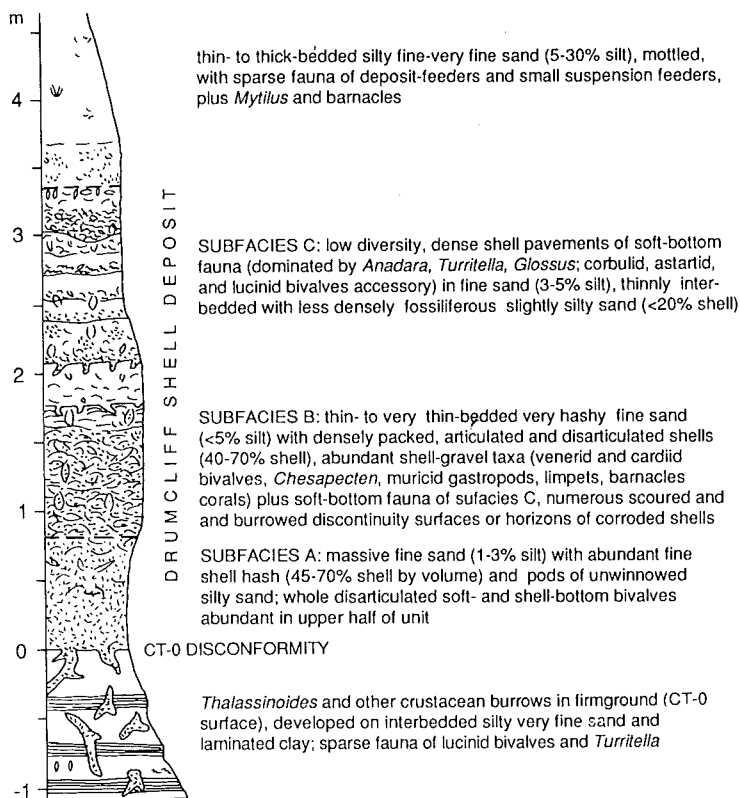


FIG. 4.—Example of complex internal stratigraphy within a major shell deposit. Measured section 35 (same as fig. 1).

well 1982a, 1984). Even the Kenwood Beach shell bed ("Zone" 14), which contains a relatively low diversity fauna dominated by venerids, could at most have acquired only a few of its less abundant species from surrounding facies (e.g., *Chione*, *Glossus*, *Turritella*, *Isognomon*, lucinids).

All four major shell deposits show similar trends in sedimentology and taphonomy consistent with decreasing water energy. Usually the fine sand matrix becomes less well sorted up-section, and winnowed sand beds become fewer and thinner with increasingly thick intercalated muddy sands (observed down-dip toward the basin axis as well as up-section in the Camp Roosevelt shell deposit; fig. 7). In the Camp Roosevelt, Drumcliff, and Boston Cliffs shell deposits, a well-winnowed, basal finely fragmental shelly sand grades upward into assemblages with larger numbers of large (>2 cm) unbroken bivalves, and the percentage of infaunal bivalves in life positions also increases, both indicating less frequent and

less vigorous physical reworking over the course of accumulation (fig. 8). The Kenwood Beach shell deposit does not have a basal hash, but shell beds in the lower part of the deposit are more likely to contain fragmental shell hash than higher shell beds. In combination with the nearshore to shallow shelf, open marine fauna, these features suggest accumulation of each shell deposit over a spectrum of depths ranging from above fair-weather wavebase to near storm wavebase.

Stratigraphic context also indicates that the major shell deposits accumulated during periods of deepening water and marine transgression. Each shell deposit rests on an erosional disconformity (usually *Thalassinoides*-burrowed; Kidwell 1984) that cuts across intertidal or subtidal facies that are shallower or more onshore than those represented by the shell deposit itself (fig. 2). For example, the Camp Roosevelt shell deposit rests on freshwater-influenced silty sands (*Corbula* facies of underlying PP-0 sequence;

TABLE 2

COMMON OR CHARACTERISTIC MACROINVERTEBRATE GENERA IN MAJOR SHELL BEDS

	Camp Roosevelt shell bed (Zone 10)	Kenwood Beach shell bed (Zone 14)	Drumcliff shell bed (Zone 17)	Boston Cliffs shell bed (Zone 19)	Parker Creek bone bed (Zone 12)
Shell Gravel Taxa					
<i>Anadara</i>	X		X	X	
<i>Glycymeris</i>	X				
<i>Mytilus</i>	X		X	X	
<i>Isognomon</i>	X	X	X	X	
<i>Crassostrea</i>				X	
<i>Chesapecten</i>	X	X	X	X	
<i>Anomia</i>	X	X	X		
<i>Carditamera</i>	X		X	X	
<i>Astarte</i>	X	X	X	X	
<i>Laevicardium</i>	X	X	X	X	
<i>Semele</i>	X		X	X	
<i>Callista</i>	X		X	X	
<i>Mercenaria</i>	X	X	X	X	X
" <i>Petricola</i> "	X		X	X	
<i>Hiatella</i>		X	X		
<i>Diodora</i>	X		X		
<i>Calliostoma</i>	?		X	X	
" <i>Vermetus</i> "	X		X		
<i>Crucibulum</i>	X		X	X	
<i>Crepidula</i>	X		X		
<i>Ecphora</i>	X	X	X	X	X
<i>Discinisca</i>		X	X	X	X
Endo- & Epibionts					
" <i>Martesia</i> "	?		X	X	
<i>Concavus</i>	X	X	X	X	X
bryozoa	X		X	X	
<i>Hydractinia</i>	X				
<i>Astrhelia</i>			X	X	
" <i>Astrangia</i> "	?		?		
<i>Cliona</i>	X	X	X	X	
<i>Polydora</i>	X	X	X	X	
Soft-Bottom Taxa					
<i>Modiolus</i>	X		X	X	
<i>Pinna</i>	X		X	X	
<i>Lucina</i>	X	?	X	X	
<i>Miltha</i>		X	X	?	X
" <i>Diplodonta</i> "			X	X	
<i>Cyclocardia</i>	X		X		
<i>Eucrassatella</i>	X	X	X	X	
<i>Spisula</i>	X	X	X	X	
<i>Tellina</i>	X		X		
<i>Macoma</i>			X	X	X
<i>Glossus</i>		X	X		X
<i>Pitar</i>			X	X	
<i>Dosinia</i>	X	X	X	X	
<i>Chione</i>	X	X			X
<i>Clementia</i>		X	X		
<i>Corbula</i>	X	X	X	X	
<i>Panopea</i>	X	X	X	X	
<i>Kuphus</i>	X				
<i>Turritella</i>	X	X	X	X	X
naticid spp.	X	?	X	X	
<i>Busycon</i>	X		X	X	
" <i>Voluta</i> "	X		X		
<i>Terebra</i>	X		X		
<i>Cadulus</i>	X		X		
<i>Abertella</i>		X	X		

NOTE.—Rank and relative abundance vary laterally and microstratigraphically within each shell bed (see Kidwell 1982a for more complete compilation). Substratum tolerances of genera assigned as in Kidwell (1986b); shell gravel taxa = living on or within dead hardparts or hardpart-rich sediment; soft-bottom taxa = living on or within soft, hardpart-poor sand or silt. Commensals (e.g., kelliid and leptonid bivalves) excluded.

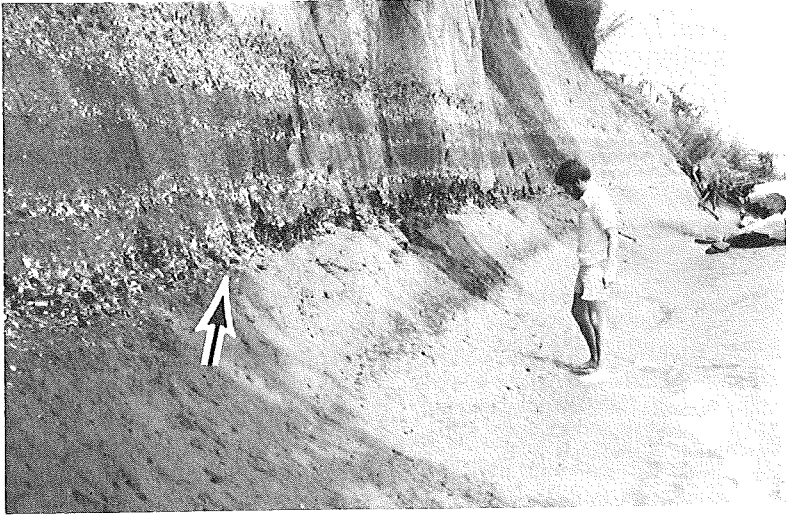


FIG. 5.—The Kenwood Beach shell deposit at Kenwood Beach in the Calvert Cliffs (loc. 12 in fig. 6) consists of a series of shell-rich beds. Each bed is actually an amalgam of several distinct assemblages. Arrow points to burrowed PP-3 disconformity at base of shell deposit.

fig. 7); the Kenwood Beach shell deposit rests on a regressive *Chione* facies and beds containing *Ocyropsis*-type burrows (fig. 6); the Drumcliff shell deposit onlaps an intertidal *Pandora*-dominated facies (fig. 9); and the Boston Cliffs shell deposit is in extensive contact with *Mytilus*-dominated intertidal facies (Kidwell 1982a, 1984).

Except for the Camp Roosevelt shell deposits, maximum water depths attained by each transgression are recorded in the upper part of the major shell deposit or along its upper contact with overlying shell-poor beds (Kidwell 1984, 1988). The major shell deposits thus record the transgressive phase and

mid-point (turn-around point) of each disconformity-bound, transgressive-regressive cycle (fig. 2). The Camp Roosevelt shell deposit records only the shallowest, early phase of transgression, since it is overlain by even deeper water, below storm wavebase deposits ("Zone" 11 = barren interval). Maximum water depths are not attained until "Zone" 12 (= Parker Creek bone bed), which is then overlain by a shallowing-upward, regressive facies tract like those that directly overlie the other major shell deposits.

Lateral Variability.—In detail, the basically tabular shell deposits are observed to thin toward the depositional margins of the

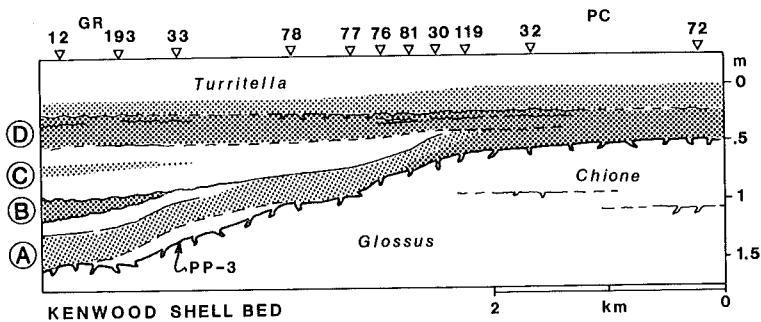


FIG. 6.—Stratigraphic pinchout and convergence of discrete shell beds within the Kenwood Beach shell deposit over a paleotopographic high in the basal PP-3 disconformity, Calvert Cliffs. The thin, condensed record over the paleohigh preserves the microstratigraphic sequence of assemblages observed in thicker sections, and is characterized by taphonomic and sedimentologic features indicating physical reworking and winnowing. Shell abundance varies from <10% by volume (white) and 10–40% (light stipple) to >40% (dark stipple). Numbered localities from Kidwell (1984); lettered localities as in figure 3.

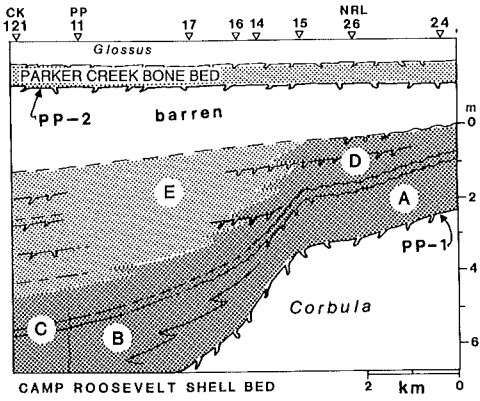


FIG. 7.—Condensation (internal thinning) of Camp Roosevelt shell deposit in the Calvert Cliffs. See text for description of subfacies A–E.

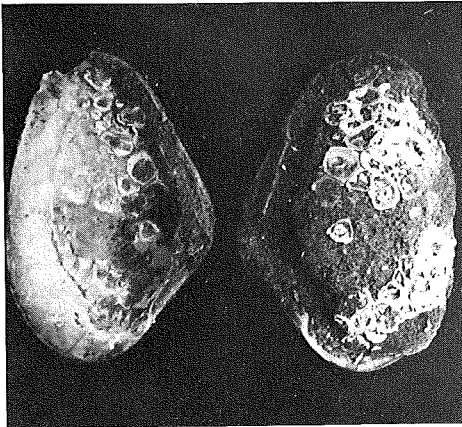


FIG. 8.—Barnacles (*Concavus chesapeakensis* Zullo) encrusting the interior surface of *Eucrassatella melina* (Conrad) found in life position within Camp Roosevelt shell deposit. Valves are 8 cm. long.

basin (e.g., fig. 3), and are inferred to inter-tongue with thicker, less fossiliferous deposits toward the axis. Within the outcrop belt, the internal stratigraphy and overall thickness of the major shell deposits can vary considerably owing to the intergradation, pinch-out, and erosional truncation of subsidiary assemblages.

Most of these lateral changes in microstratigraphy, along with changes in thickness, correspond to paleorelief on the basal erosional disconformity. In each instance, paleorelief was determined independently of shell deposit geometry by using flat-bedding in underlying and overlying units as datums (Kidwell 1984). In general, each major shell deposit is thickest over paleotopographic lows, where it consists at least in part of intercalated shell-rich and shell-poor layers. The shell-poor beds, which commonly have a silty sand silt matrix, pinchout (or are cut out) toward paleohighs. Shell-rich layers converge stratigraphically on the paleohighs, where they are amalgamated into a single thinner and microstratigraphically more complex shell deposit.

Thin stratigraphic sections usually preserve the order of subsidiary assemblages observed in thicker paleolow sections: thinning of each major shell deposit is internal, not by erosional beveling of the entire deposit. Subsidiary assemblages commonly have a better sorted sand matrix over paleohighs, higher shell packing densities, and poorer quality of shell preservation (greater fragmentation, disarticulation, abrasion, bioerosion). The proportion of fauna requiring or preferring shell-gravel habitats is typically higher, consistent with a biological response by benthos

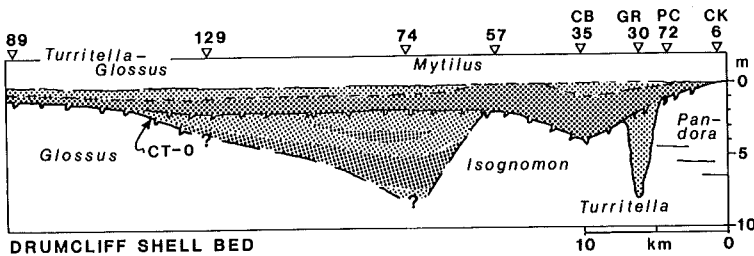


FIG. 9.—Stratigraphic condensation is evident within the main body of the Drumcliff shell deposit (upper darkly stippled unit), which truncates less densely fossiliferous sand fill of paleotopographic lows in the CT-0 surface. Cross-section drawn along dip from CK to CB in the Calvert Cliffs; drawn along strike from Calvert Cliffs to Patuxent River (localities 57 and 74), Breton Bay (129), and Virginia shore of Potomac River (89).

to the accumulation of skeletal material in the habitat (i.e., taphonomic feedback; Kidwell and Jablonski 1983; Kidwell 1986b).

The Kenwood Beach shell deposit in the Calvert Cliffs illustrates these concurrent trends in sedimentology, microstratigraphy, and paleontology. Over a distance of ~5 km, the shell deposit thins by 65% to 0.5 m (fig. 6), a thickness it then maintains to its erosional updip limit 15 km to the north (fig. 3). Thinning is accomplished internally by pinchout and erosional beveling of both shell-rich and shell-poor interbeds; over the paleohigh, discrete, internally complex shell-rich layers are amalgamated into a single complex shell deposit. Articulated infaunal bivalves are less common in the upper part of the shell bed over the paleohigh than over the adjacent paleolow, and disarticulated specimens are oriented edgewise as well as in the more typical convex-up position, suggesting more vigorous or protracted exposure at the seafloor. Average shell packing density is higher in the thin paleohigh sections than in the thicker sections over paleolows, but the faunal composition of the bed is comparable (Kidwell 1982a). The only change in the sequence of assemblages is the addition of a thin (5 cm) basal hashy sand over the paleohigh, containing abraded specimens of *Chione parkeria* that have clearly been erosionally recycled from underlying beds (*Chione* facies, PP-2 sequence). The Kenwood Beach fauna otherwise appears to be local in origin and to post-date formation of the basal PP-3 disconformity.

Traced westward along strike from the Calvert Cliffs, the shell deposit thickens to 4.5 m and contains a larger number of shell-rich beds that are separated by thicker shell-poor interbeds (Kidwell 1984). The microstratigraphic complexity of the shell-rich beds and the close-packing of shells is lower than in Calvert Cliffs sections; in addition, contacts between shell-rich and shell-poor beds tend to be gradational rather than sharp. This lateral change in internal bed contacts parallels the along-strike transition of the basal PP-3 disconformity into conformable bedding planes (Kidwell 1984).

The Camp Roosevelt shell deposit has a small outcrop area owing to post-Miocene erosion, but still exhibits significant lateral variability (fig. 7). It is divisible into five sub-

units or subfacies: (A) a dense, basal shell hash with horizons of heavily bored and abraded shell-gravel taxa, especially bivalves; downdip, this intergrades with (B) a hashy sand containing a larger portion of whole bivalves, both articulated and disarticulated; species relative abundance varies among a series of 10 cm-thick amalgamated shell-rich layers; (C) a thin (0–30 cm), undulatory layer composed almost exclusively of *Turritella variabilis* in good condition, in scour contact with subfacies A and rapidly gradational with subfacies B; (D) hashy, slightly silty fine sand with abundant articulated and disarticulated bivalves, similar to subfacies B; and (E) thinly interbedded shell-rich sand and shell-poor silty sand dominated by soft-bottom infauna.

Thinning of the deposit by more than 50% over 10 km distance reflects thinning along minor discontinuity surfaces and some beveling of the upper contact over a paleotopographic high in the PP-1 disconformity (dated to Parker Creek bone bed = "Zone" 12) (fig. 7). Thin sections over the paleohigh consist of the most densely fossiliferous subfacies (A and D); post-mortem modification of shells (e.g., fig. 8) is most pervasive in these subfacies, particularly damage accrued through prolonged or repeated exposure on the seafloor. Assemblages include a mixture of soft-bottom infaunal and shell-bottom epifaunal species (table 2) consistent with taphonomic feedback (for data see Kidwell 1982a; Kidwell and Jablonski 1983).

The well-exposed Drumcliff shell bed ("Zone" 17) reveals the anatomy of major skeletal deposits at a larger scale (fig. 9). It consists of a series of localized, lenticular sand bodies that fill channel-shaped paleolows of the CT-0 disconformity, overlain by a roughly tabular body of densely fossiliferous, well-sorted fine sand (= main body of shell deposit). Paleolow fills are variable in composition and distinct from the rest of the shell deposit. The "Governor Run sand" (Kidwell 1984) (figs. 3 and 9) in the Calvert Cliffs, for example, comprises intertidal flat and channel facies of laminated clay, cross-bedded sand, and interbedded sand and clay, and local concentrations of mussels, barnacles, and the irregular echinoid *Echinocardium*. At Drumcliff on the Patuxent River (locality 74

in fig. 9), paleolow deposits are faunally diverse, well-sorted fine sands with alternating thick beds of abundant coarse shell hash and sparsely disseminated fine shell hash. Biostratigraphically, all of these paleolow fills are identical to the main body of the Drumcliff shell bed and distinct from strata below the CT-0 surface, and so are included with the Drumcliff (Kidwell 1984).

The main body of the shell deposit is separated from the paleolow fills by a burrowed surface, and rests directly on paleohighs in the CT-0 surface (fig. 9). It has a three-part microstratigraphy, exemplified by measured sections in the Calvert Cliffs (fig. 4), that persists throughout the outcrop belt. These three subfacies thin toward pinchout of the entire Drumcliff shell deposit in the northern Calvert Cliffs (fig. 3), where they interfinger with a thin (0.3 m) medium sand that is virtually unfossiliferous (Kidwell 1984).

In contrast, the Boston Cliffs shell deposit (= "Zone" 19) is remarkably uniform in thickness and composition among its farflung exposures (Kidwell 1984) (table 1). In physical appearance it is very similar to the main body of the Drumcliff shell deposit: densely fossiliferous, hashy, clean to slightly silty fine sand with diverse, predominantly aragonitic molluscs. The microstratigraphy is quite different, however, with two main subdivisions, each consisting of a basal hash and an upper, hash-poor shell-supported fabric dominated by large infaunal bivalves or admixed infauna and disarticulated *Chesapeake* (Kidwell 1982a). Compared to the Drumcliff shell deposit, the Boston Cliffs deposit accumulated in a more onshore, freshwater-influenced setting (addition of "*Crassostrea*", rarity of stenohaline corals and echinoids).

CONDENSED ORIGIN OF MAJOR SHELL DEPOSITS

Evidence for Condensation.—The stratigraphic convergence and amalgamation of discrete beds into locally thin, microstratigraphic records provides straightforward evidence for condensation of the Camp Roosevelt and Kenwood Beach shell deposits (figs. 6 and 7). Even within relatively small outcrop belts, these shelly sands are reduced by several fold into microstratigraphically complex deposits less than 1 m thick over paleohighs and along the margin of the basin (table 1). There is a true condensation of

geological and paleontological information in the relatively thin records preserved over paleohighs, rather than only culling.

Other taphonomic and sedimentologic features of these strata, consistent with slow net accumulation, are strong correlates of stratigraphic condensation in shallow water. [They are neither necessary nor sufficient evidence for condensation, however, since they can also characterize shallow-water deposits that are not condensed (e.g., shelly shoals; and see Kidwell 1988b).] These features include: (1) well-sorted, winnowed sand matrix (compared with silty sand sheltered under concave-down shells); (2) complex microstratigraphy including multiple scoured and burrowed contacts; (3) dense packing of apparently untransported shells, especially infaunal shells packed beyond likely living densities; (4) articulated specimens rotated out of life positions and containing unwinnowed matrix or draft-fills (specimens rotated within the substratum by bioturbators would not have traction-laminated sediment fills); (5) mixture of specimens in different states of preservation and having different ecologies, indicating time-averaging of successive death assemblages (faunal condensation of Fürsich 1978); and (6) bioerosion of infaunal shells, including encrustation of interiors of infaunal bivalves still in life position (fig. 8). In addition, correlations between skeletal abundance and faunal composition, with shell-rich layers characterized by significantly higher proportions of species adapted to shell-bottom habitats, show that skeletal material was not rapidly buried but accumulated post-mortem on the seafloor where it could drive a biological response (i.e., taphonomic feedback; Kidwell 1986b). Combined, these features indicate exhumation and post-mortem residence of shells at or near the seafloor, and repeated physical and biological reworking of sedimentary increments during formation of the major shell deposits.

Both the main body of the Drumcliff shell deposit and the Boston Cliffs shell deposit have complex microstratigraphies, winnowed matrices, faunal compositions, and shell taphonomies consistent with stratigraphic condensation in shallow water. They deepen upward like the other two major shell deposits, are comparable in scale, and subsurface data suggest that coeval strata thicken mark-

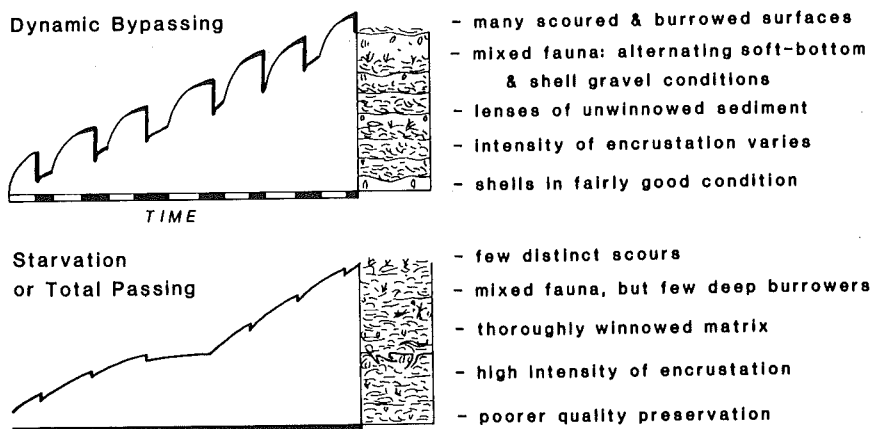


FIG. 10.—Taphonomic and microstratigraphic criteria for interpreting sedimentary dynamics of condensational regimes from shallow-water shell concentrations (adapted from Kidwell and Jablonski 1983; Kidwell and Aigner 1985). Horizontal axis: elapsed time; black segments are periods when dead shell is exposed at seafloor, white segments when seafloor is shell-poor, soft sediment. Drumcliff and Kenwood Beach shell deposits indicate accumulation by dynamic bypassing, with alternating soft- and shell-bottom conditions, whereas the Camp Roosevelt and upper Boston Cliffs shell deposits have features more consistent with starvation and only intermittent sediment coverage of dead shells.

edly toward the basin axis (e.g., Olsson et al. 1987), so they would conform to a broad definition of condensation. Unlike the other two shell deposits, however, stratigraphic condensation *sensu stricto* cannot be demonstrated unequivocally within the available outcrop belt. In the Drumcliff shell deposit, for example, the main body shows features consistent with condensation but is not demonstrably the product of thinning of thicker coeval strata: paleolow fills are truncated by, rather than stratigraphically telescoped and incorporated into, the main body of the shell deposit (fig. 9).

Short-term Physical and Biological Dynamics.—Restated in terms of process, condensed stratigraphic intervals reflect locally low rates of aggradation, that is, low net rates of sediment accumulation. Net rates of autochthonous sediment accumulation (mineral authigenesis, benthic production of carbonate) must be low, because of either low production or high removal, but net rates of allochthonous (siliciclastic) sediment accumulation must also be low. Locally low rates of allochthonous accumulation can arise in several ways, including: (1) sediment starvation (failure of sediment delivery to site); (2) total passing (sediment delivered to site but maintained as suspended load and not deposited); and (3) dynamic bypassing (sediment delivered to site but deposited only tem-

porarily; depositional increments balanced or nearly balanced by episodes of erosion).

Each dynamic condition implies different short-term patterns of seafloor aggradation—monotonic accumulation *vs.* sawtoothed—and these are distinguishable on the basis of sedimentologic and paleontologic features of the resulting condensed deposit (e.g., Kidwell and Aigner 1985). The detailed dynamics of a period of condensation are implicit from the type and spacing of discontinuity surfaces, thoroughness of winnowing, state of shell preservation, bioclastic fabric, and paleoecology of fossil assemblages (fig. 10). Thickness, mass properties, and persistence of depositional increments are reflected in the ecology and state of preservation of infauna; the timing and duration of intervening periods of shell exposure at the seafloor are indicated by colonization by epifaunal and semi-infaunal taxa.

For example, individual shell beds within the Kenwood Beach shell deposit are composed predominantly of soft-bottom molluscan assemblages in partially winnowed fine sands (Kidwell 1982a) (table 2). Infaunal bivalves are commonly articulated but rotated out of life positions; shells are generally in good condition, suggesting minimal post-mortem exposure of exhumed death assemblages after concentration into discrete layers. The low diversity and scarcity of

shell-bottom species are consistent with rapid burial of shells once concentrated: with few exceptions, dead shells did not significantly alter mass properties of the substratum, nor were they available as substrata for epifaunal attachment. Scarcity of evidence for shell exposure suggests immediate reburial of concentrated shells, but the newly deposited sediment cover was not always thick. Relatively deep-burrowing forms such as *Panopea* and the lucinid *Miltha* are found in life position abutting the top of some shell-rich beds, which apparently were barriers to bivalve penetration. In addition, shell-gravel species such as *Isognomon*, *Chesapecten*, and *Anomia*, when present, are associated with shell-rich beds. This suggests an ecological association with shell material on or just below the seafloor, rather than a random post-mortem distribution.

The Drumcliff shell deposit also accumulated through alternating deposition and erosional winnowing of the seafloor, but skeletal material resided at the seafloor for longer periods of time before reburial. Soft-bottom infauna are abundant throughout the deposit and include numerous relatively deep-burrowing forms; their abundance and adult size indicates repeated deposition of relatively thick increments of silty sand (remnants preserved under large shells, and as a few shell-poor interbeds) that permitted intensive infaunal colonization during Drumcliff history. Disarticulation, reorientation, extensive fragmentation, and bioerosion indicate post-mortem exhumation and exposure of infaunal specimens, probably by storm reworking, that repeatedly transformed the seafloor into a shell-paved surface favoring colonization by shell-gravel-dwelling epifauna and semi-infaunal species (table 2). Similar patterns are observed in the lower part of the Boston Cliffs shell deposit. Together with sedimentologic and physical stratigraphic features described earlier, the paleoecology and taphonomy suggest accumulation under a regime of dynamic by-passing.

The more thoroughly winnowed matrix, greater abundance of shell-gravel dwellers (particularly encrusters), and fewer large-bodied soft-bottom infauna in the Camp Roosevelt shell deposit suggest thinner depositional increments and more continuous

shell-gravel conditions (also seen in upper part of Boston Cliffs shell deposit). Shell-gravel dwellers include very shallow burrowing to semi-infaunal taxa that tolerate or prefer living in the interstices of shelly bottoms, and epifauna requiring hard substrata for attachment or support (e.g., byssate bivalves, limpets, borers and encrusters, sessile free-living benthos; table 2). These features indicate accumulation under either total passing or complete starvation of terrigenous sediment. Vertical gradation of the Camp Roosevelt shell deposit into a deeper-water (below storm wavebase) sandy clay suggests total passing of mud and virtual starvation of sand only.

Short-term Dynamics vs. Stratigraphic Context.—In terms of the short-term dynamics of skeletal accumulation evident within individual outcrops, the diverse interpretations of previous workers can readily be combined into a single "polygenetic" model. With the exception of Moll and Thomas (1979) and possibly Mongin (1959), who stressed shell transport, there is general agreement that these are within-habitat accumulations. Repeated storm-reworking as envisioned by Gernant (1970) is implicit in the complex internal stratigraphy and exhumed infauna; moreover, individual shell-rich beds within the major deposit underwent repeated reworking by storms and bioturbators such that few taphonomically simple concentrations are preserved within the major deposits. The major shell deposits also reflect continuous recolonization of shell accumulation sites by benthos (Moll and Thomas 1979), benthos that influenced, as well as were influenced by, patterns of dead shell accumulation (taphonomic feedback), and that changed in composition over time as water depths increased (Kidwell and Jablonski 1983). In composition and physical features, the major shell deposits reflect a broad array and complex history of short-term post-mortem phenomena in shallow subtidal, storm-dominated marine environments.

An explanation for the major shell deposits nonetheless requires more than the sum of the microstratigraphic parts. Had all of these short-term processes of skeletal concentration and modification not occurred during a regime of condensation, the stratigraphic record of transgression would more closely

resemble the record of regression, which consists only of sparsely fossiliferous facies. The shell-rich transgressive deposits clearly are not products of simple environmental tracking of isobaths, since environments of comparable bathymetry (intertidal to storm-wavebase subtidal) are recorded by shell-poor regressive facies tracts (fig. 2; Kidwell 1984, 1988a). Instead, regimes of slow terrigenous accumulation and condensation must be invoked during successive marine transgressions in order to telescope short-term skeletal concentrations into a series of complex deposits.

Blackwelder and Ward (1976) suggested that the major shell deposits record the migration of a particularly productive environment. Miocene waters of the Atlantic continental margin may well have been highly productive (e.g., Gibson 1983): extensive phosphate deposits in North Carolina are roughly correlative, diatomaceous facies are found throughout the Miocene section, and the gigantism seen in a number of younger Chesapeake Group mollusks may be attributable to superabundant resources. The major shell beds cannot be explained in terms of high productivity alone, however, particularly high benthic productivity in a circumscribed environment. Each major shell deposit incorporates several biologically and taphonomically distinct subfacies, and lateral variation in composition indicates accumulation over a range of habitats. In addition, major shell beds are not directly associated with the diatomaceous beds linked with highly productive upwelling events (Palmer 1986).

More importantly, high hardpart input alone cannot account for direct, independent sedimentologic and stratigraphic evidence for condensation. Thus, if high productivity figured into the formation of the major shell deposits, it must have coincided with periods of condensation (e.g., Kidwell 1986a). Environments (or periods) of elevated hardpart production could be linked to regimes of stratigraphic condensation: (1) as a direct response to low terrigenous sedimentation itself; (2) as a response to the post-mortem accumulation of hardparts at or near the seafloor, fostered by low sedimentation (situations 1 and 2 both favor suspension-feeding, typically large-bodied mollusks); or (3) as a direct or indirect consequence of marine

transgression (e.g., hardpart production and preservation enhanced by warmer water, improved circulation or deeper water).

Time Scale of Condensation.—Biostratigraphic and other lines of evidence indicate that each major shell deposit accumulated over a period of several thousands to a few ten thousands of years (Kidwell 1982b). The amalgamation of many minor shell concentrations, each recording accumulation over ecological time scales of 10^0 to 10^2 years, suggests condensation over several hundreds of years at the very least. At the other extreme, major shell deposits are clearly formed over time periods shorter than the average duration of Neogene biostratigraphic zones: molluscan, diatom, and planktic foraminiferal interval zones all range through stratigraphic intervals that include one or more major shell deposits (fig. 2). Stanley et al. (1980) determined average durations of Neogene mollusk species on the order of 8 m.y. (gastropods) and 14 m.y. (bivalves); average duration of transgressive-regressive cycles represented by depositional sequences appears to be on the order of 1 m.y. (fig. 2).

The major shell deposits thus represent accumulation over 10^5 years at most. Such an estimate seems reasonable: the glacioeustatically-driven Holocene transgression, for example, has generated extensive shelly sand deposits on starved continental shelves over the past 18,000 years. Given independent oxygen isotope evidence for high-frequency fluctuations in ocean temperature (Savin et al. 1985), the Maryland Miocene sequences were likely glacioeustatically-driven as well (Kidwell 1984). One of the best Recent analogs for the major skeletal deposits may be a microstratigraphically complex concentration off Mauritania that is similar in scale and faunal composition to the Miocene shell beds. Radiocarbon dates indicate that the accumulation of just one subsidiary assemblage within that transgressive deposit records a thousand years of elapsed time (5 to 6 kyr B.P.; Einsele et al. 1977).

PARADOX OF PRESERVATION

The association of slow net terrigenous sedimentation and enhanced hardpart concentration is somewhat paradoxical: conventional wisdom holds that good fossil preservation requires rapid burial, and numerous

experiments have documented the rapid destruction of carbonate shells exposed on or only shallowly buried beneath the seafloor (e.g., Peterson 1976; Aller 1982; Cummins et al. 1986).

Several ongoing processes during stratigraphic condensation could, however, mitigate against shell destruction. First, during condensation by dynamic bypassing or even by starvation in agitated shallow water, shells are not necessarily continuously exposed to destructive agents. Exposure may be only brief and episodic, alternating with relatively prolonged periods of burial below the surficial zone of traction and active bioturbation. A history of intermittent exposure would reduce shell loss from physical abrasion, algal boring, chemical dissolution, and biofragmentation. High energy events such as storms need not be invoked: Johnson (1957) demonstrated the rapid burial of shells even under fairweather conditions of ripple migration, and several authors have postulated rapid burial of shells by conveyor-belt burrowers (e.g., Van Straaten 1952; Rhoads and Stanley 1965; Cadée 1976; Meldahl 1987).

Second, winnowing of terrigenous material generates a porous sand matrix whose porewaters would have freer exchange with overlying seawater, which is generally saturated or oversaturated with respect to carbonate. Also, once concentrated, shells could contribute to their own favorable chemical microenvironment by buffering porewaters and would discourage its disruption by forming a barrier to at least some bioturbators. In terrigenous muds, high porewater acidities documented by Aller (1982) are anathema to carbonate preservation, but if shells are introduced during seasons of low acidity (e.g., a time lag exists between carbonate addition and aerobic decay or sulfide oxidation), or if they are advected down through the acidic or undersaturated horizon sufficiently rapidly, shell preservation would be possible.

Third, episodic exposure of shells and their progressive accumulation within surficial sediments creates a favorable habitat for colonization by typically larger-bodied, epifaunal suspension-feeding organisms. These benthos not only contribute hardparts to the initial concentration, but further decrease its erodibility and seal off some shells from destructive agents.

Fourth, all experiments on shell destruction in marine environments show a strong size dependency, implicitly or explicitly, with highest rates of shell loss among the smallest and thinnest specimens (but see Pip 1988 for opposite pattern in freshwater environments). Staff and Powell (1988) have shown that these "lost" individuals represent the ecologically least persistent components of benthic communities—the opportunists and exotic spatfalls—and that shells above a threshold size at the time of death have a comparatively high potential for entering the permanent fossil record. Sand substrata that favor colonization by suspension-feeders might therefore from the very outset have a higher likelihood of yielding a preservable condensed shell deposit.

Finally, the persistence of Quaternary surficial shell gravels indicates that skeletal material can survive even continuous exposure on the seafloor longer than experimentally determined half-lives would suggest, and that shells are also more durable to repeated cycles of exhumation and burial than would be predicted from lab simulations. Some of these shells yield very old radiocarbon dates (e.g., 1000 yrs BP on British Columbian shelf, Young and Nelson 1985; 2200 to 4200 yrs BP for intertidal of Gulf of California, Meldahl 1987; see Sutherland 1986 for evaluation of mollusc-based dates). Possible explanations may lie in (1) very early diagenetic stabilization (e.g., partial mineralization of organic matrix or "case-hardening" that change skeletal composition), (2) ionic poisoning of the shell surface that changes the kinetics of dissolution (comparable to Mg^{+} poisoning of calcareous microfossils in the deep sea, related to point 1), or (3) protection of dead shell by organic chelates, or by a "slime coat" of algae or bacteria (e.g., Henrich and Wefer 1986). This latter mechanism would be effective only if decomposers and shell-rasping grazers could not keep up with coating of all dead shell material.

These observations suggest that hardparts in concentrations have greater potential for preservation than hardparts that are sparsely dispersed: there appears to be a positive feedback between skeletal concentration and skeletal preservation (Kidwell 1986a). Regardless of why skeletal material persists during hiatuses in sediment accumulation, however, the observation that few of the assemblages

contained within major shell deposits resemble the simpler assemblages from minor shell concentrations in regressive facies tracts (Kidwell 1982a, 1982b; discussion above) testifies to the cascading effects of condensation on the sedimentology, paleoecology, and taphonomy of the final deposit. During condensation, the products of short-term events (minor precursor concentrations of shells) are not only stratigraphically amalgamated and telescoped by the regime of slow net sedimentation, but they are also modified and supplemented by biological and physical (and no doubt biogeochemical) conditions inherent to slow stratigraphic accumulation.

TRANSGRESSION: SPATIAL MOSAIC OF CONDENSATION AND SKELETAL ACCUMULATION

"Condensed transgressive lags" are commonly invoked to describe thin conglomeratic, glauconitic, or fossiliferous beds at the base of shallowing-upward marine sequences. The major shell deposits of the Maryland Miocene, although locally quite thick owing to paleotopographic relief on the transgressed surface, would fall within this class. They are transgressive records of successively deeper and more offshore environments, are demonstrably (or, in two cases, arguably) condensed stratigraphically, are truly thin (0.5–2 m) over much of their areal extents (Kidwell 1984), show independent sedimentologic and paleontologic evidence of having formed under conditions of negligible siliciclastic accumulation (bypassing and starvation), and are each overlain by an equivalent or greater thickness of regressive, shallowing-upward strata. Had net carbonate production (autochthonous sedimentation) been lower, these transgressive records would be even thinner, inasmuch as skeletal carbonate composes 40 to 70% of their volume.

The composition, stratigraphic anatomy, and context of the Miocene shell deposits suggest that conceptual models for the origins of transgressive lags need to be enlarged if they are to characterize the diversity of condensed features in the stratigraphic record. During transgression, condensed lags do not necessarily extend across the entire shelf, and even shallow-water winnowed lags need not be dominated by material reworked from older strata (and thus predating the hiatus itself). Moreover, not all condensed transgres-

sive deposits provide isochronous markers for correlation.

Mosaic of Erosional, Condensational, and Depositional Regimes during Transgression.—The stratigraphic interval from the Camp Roosevelt shell deposit to the Parker Creek bone bed ("Zones" 10–12 of Shattuck 1904) provides the best evidence for a spatial mosaic of sedimentary regimes during transgression. This interval consists of: (1) an erosional disconformity (PP-1 surface); (2) the condensed Camp Roosevelt shell deposit, recording a transgressive suite of subtidal shelf environments, all above storm-wavebase; conformably overlain by (3) a massive sandy clay ("Zone" 11) virtually barren of macroinvertebrate fossils, recording shelf environments below storm-wavebase; and (4) the condensed (Myrick 1979; Kidwell 1982a) Parker Creek bone bed, a thin (≤ 0.5 m; table 1) laterally extensive sand associated with a series of closely spaced burrowed firm grounds. The Parker Creek bone bed is overlain by a regressive, shallowing-upward tract of shell-poor facies, and records the deepest water conditions in the Miocene section (Kidwell 1984; figs. 2 and 3).

This sequence suggests the co-existence during transgression of (1) an onshore, presumably shoreface environment of erosional ravinement, (2) a nearshore (above storm-wavebase) area starved of sand and bypassed by mud, generating the base-of-cycle shell accumulation, (3) a below storm-wavebase area serving as a sink for bypassed mud, and (4) a more distal shelf area starved even of fine-grained siliciclastics, generating the mid-cycle bone bed (see schematic bathymetric profile, top of fig. 11). Although the upper part of the Camp Roosevelt shell bed and the Kenwood Beach shell bed clearly grade laterally into thicker, less fossiliferous sediments (figs. 6 and 7; Kidwell 1984), the complete onshore-offshore pattern of fig. 11 cannot be observed directly in the Miocene outcrop belt but instead must be reconstructed from vertical facies sequences.

Because the maximum water depth attained in a single transgressive-regressive cycle decreases landward, local stratigraphic records will vary in facies composition. Records of relatively basinward sites (e.g., position B in fig. 11; exemplified by the Camp Roosevelt-Parker Creek interval just described) where maximum water depths are

great can include two condensed stratigraphic intervals, that is both a base-of-cycle shell deposit and a mid-cycle bone bed. More landward sites (e.g., position A in fig. 11; exemplified by the CT-0 Drumcliff sequence and CT-1 Boston Cliffs sequence) where the maximum water depths attained may be well above storm-wavebase display only one condensed (shell-rich) deposit, which spans the entire period from initial to maximum transgression. Presumably, at sites more basinward than B in fig. 11 where waters never *shallowed* above storm-wavebase, stratigraphic records of transgression-regression should also contain only one condensed interval and this will be a mid-cycle bone bed rather than a base-of-cycle shell deposit. These mid-cycle bone beds are functional analogs of the starved, deep-water, down-lapped, pelagic-rich condensed sequences that now figure largely in the Exxon model of passive margin depositional sequence (e.g., Haq et al. 1987).

Chronostratigraphic Attributes of Condensed Deposits.—Hypothetically, each of the major shell deposits must be diachronous on some scale (lower part of fig. 11). This deduction is not based on the possible diachroneity of the disconformities, but instead follows from the apparent onlapping relation of the shell deposits themselves against the disconformities (best seen in the Camp Roosevelt shell deposit; fig. 7). Diachroneity is also implicit in the conclusion that condensed shell deposits were not accumulating across the entire shelf at once, but only in the above storm-wavebase area: the landward migration of this area during the course of transgression must make the final shell deposit diachronous. Future subsurface work may demonstrate this diachroneity. To date, however, closely spaced biostratigraphic sampling has failed to detect any measurable time-transgressiveness within the outcrop belt, where beds can be traced over several tens of kilometers perpendicular to depositional strike. Thus, in the specific case of the Maryland Miocene, the condensed base-of-cycle shell deposits do provide practical chronostratigraphic markers for paleogeographic reconstruction and paleobiologic analysis (Kidwell 1984).

In contrast, the mid-cycle Parker Creek bone bed, formed by sediment starvation

of the distal shelf, brackets the isochronous "moment" of maximum transgression throughout the basin and thus should provide a dependable marker for time-correlation wherever present. The duration of the period of starvation, and thus the resolution with which the bone bed approximates an instantaneous time-horizon, should, however, vary laterally. Maximum duration of starved conditions—and thus poorest chronostratigraphic resolution—will characterize the bone bed in the most basinward sites, which are first to experience starvation during transgression and last to receive siliciclastics during regression. Nearer the basin margin, more proximal to siliciclastic supply, the period of starvation will be relatively shorter, chronostratigraphic resolution will improve, and the bone bed should splay into a series of simple bedding plane accumulations. Biostratigraphic zonation of the Maryland Miocene is not sufficiently fine to distinguish lateral variation in the period of starvation over the outcrop belt of the Parker Creek bone bed. In extreme updip exposures in the Calvert Cliffs, however, the bed does change into a series of very thin, closely spaced sand beds (Kidwell 1982a). Unlike the base-of-cycle shell deposits, the bone bed does not interfinger basinward with thicker deposits.

The expected age relations of erosion surfaces, noncondensed deposits, and both base-of-cycle and mid-cycle condensed deposits are summarized in fig. 11 (lower part) for a Maryland Miocene type of system. It is conceivable that, in settings where absolutely no siliciclastic sediment escapes the coastal region and the entire width of the shelf is starved during transgression, a laterally continuous condensed skeletal deposit could arise. This situation in fact describes many modern continental shelves today in temperate latitudes, where rates of benthic carbonate production are low (and/or rates of carbonate destruction are high). This type of "condensed transgressive lag," occupying a base-of-cycle position, would have the chronostratigraphic attributes of a mid-cycle shell bed described above.

Controls on Development of Shell-Rich vs. Bone-Rich Deposit.—Base-of-cycle and mid-cycle condensed deposits can differ significantly in fossil abundance and taxonomic composition. In the Maryland

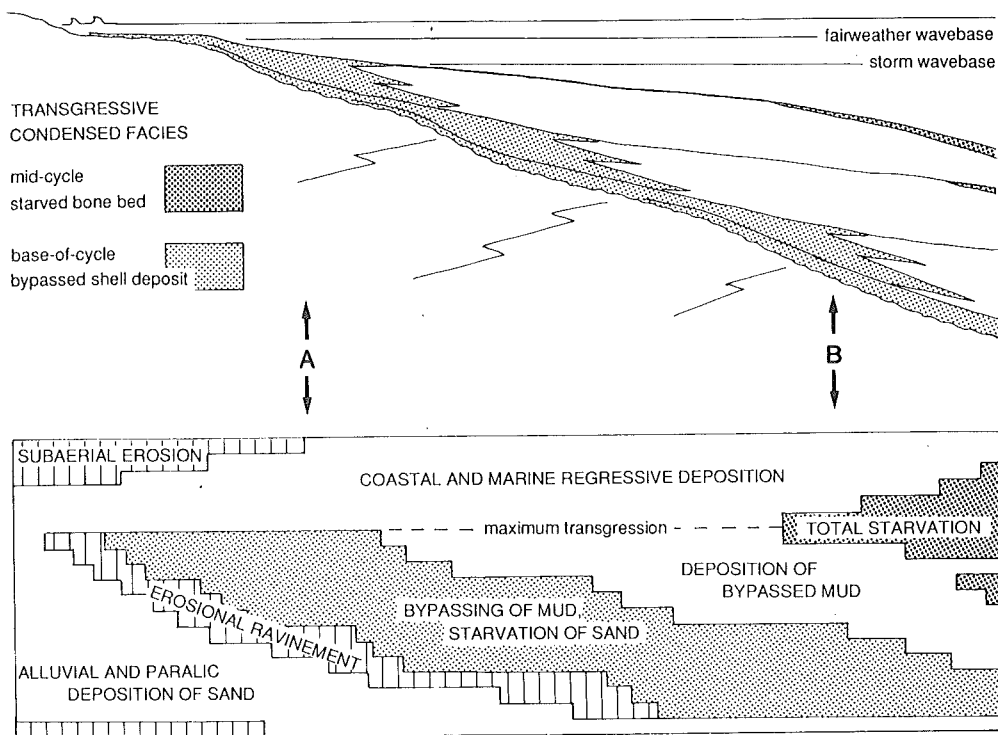


FIG. 11.—Idealized shelf transect during transgression, with contemporaneous onshore and offshore areas of condensation; vertical axis scaled to thickness (top) and to time (bottom). The onshore belt, characterized by winnowing and bypassing of fines above storm-wavebase, accumulates a shell-rich deposit condensed over paleohighs on the transgressive disconformity. This paleontologically complex condensed interval lies at the base of the depositional sequence, overlies the erosional disconformity, and thus is diachronous in nature. The offshore belt, separated by an area of deposition (white), is starved of all allochthonous sediment supply, and accumulates a glauconitic bone sand; macroinvertebrate shells are poorly preserved. This condensed interval brackets maximum water depths in the cycle and thus provides an isochronous marker for correlation, even though the period of condensation varies in duration laterally. The local record of marine transgression can include one (location A) or both (location B) condensed intervals.

Miocene, base-of-cycle, shallow-water condensed deposits are dominated by shell carbonate but also contain abundant vertebrate material, whereas the mid-cycle, deep-water condensed deposit is rich in bones and poor in shells. Other examples of this same pattern are known from the Cenozoic record. The pattern is not necessarily general, however: many deep-water mid-cycle starved intervals are poor in macroscopic fossils of any type [e.g., glauconite-rich intervals such as the Mississippian Rockford Limestone (Maliva 1984) and various Paleogene examples of Baum (1988)].

There are several possible explanations for the shell-poor condition of mid-cycle condensed deposits.

1) Ecology.—Quiet water, fine-grained substrata commonly support a lower biomass of benthos with mineralized hardparts; those benthos with hardparts tend to be small-bodied, thin-shelled, aragonite-secreting species. Opportunistic settlement would also be less frequent and populations in general more stable, so that total carbonate production is lower than onshore. If oxygen levels were depressed, even sporadically, this would further lower secondary benthic production.

2) Taphonomy.—Mobile deposit-feeders and other burrowers typical of fine-grained substrata acidify porewaters by irrigating reduced organic-rich sediments and disrupt (or vertically advect) skeletal concentrations which might otherwise provide refuges for

carbonate preservation, thus lowering carbonate preservation potential relative to coarser grained substrata (see discussion in previous section). These ecological and taphonomic conditions would explain the virtually barren sandy clay between the Camp Roosevelt and Parker Creek condensed deposits in the Maryland Miocene, as well as the sparse fauna of the Parker Creek bone bed itself (table 2).

3) Duration of hiatus.—Slow siliciclastic accumulation favors the passive concentration of shells because shells are less diluted. At the same time, however, delayed burial may increase the probability of shell destruction by various physical, chemical and biological processes active at the seafloor. The shell-poor nature of mid-cycle condensed deposits thus to some extent could reflect periods of low sedimentation in excess of some threshold, beyond which the disadvantages to shell preservation outweigh the advantages. In the Maryland Miocene, there is no evidence that the Parker Creek bone bed accumulated over a longer period of time than any of the major shell deposits, and so this factor can probably be rejected. The hypothesis would be worth testing, however, in other settings with better biostratigraphic control and a wider range of hiatus lengths to examine. The series of starved mid-cycle condensed intervals indicated by seismic surveys of passive continental margins (Haq et al. 1987) would provide an ideal setting to test for microfossil concentration and preservation as a function of length of hiatus, since these condensed intervals contain planktic as well as benthic species.

The presence of a phosphatic, bone- and tooth-rich lag at the base of the St. Marys Formation (fig. 2) suggests a second kind of bone sand, formed in very shallow water and found at the end (top) of transgressive-regressive cycles. This very patchily preserved accumulation consists of comminuted vertebrate fossils and phosphatic molds of small bivalves (e.g., *Caryocorbula*), rests on the erosionally beveled top of the Choptank Formation (SM-0 disconformity) and coincides with a major regression in the Miocene record. Facies in stratigraphically higher sequences are predominantly paralic in origin (marginal marine bays and lagoons, marshes, intertidal flats, and fluvial coastal plain

deposits; Kidwell 1988a and references therein). In taphonomy, sedimentology, and stratigraphic context, this skeletal concentration is most similar to European bone sands such as the Ludlow and Rhaetic bone beds and other placers formed by sediment winnowing and exhumation of prefossilized hardparts (see Reif 1982 for review). It suggests a broader picture of environmental variation in skeletal composition during condensation, with two belts of bone rich deposits—one marginal marine, the other deep or distal shelf—flanking a shallow shelf belt of shell carbonate accumulation.

Why don't the St. Marys depositional sequences (fig. 2) contain major shell deposits or bone beds? An initial hypothesis, difficult to test, invoked low carbonate production and/or rapid carbonate destruction in marginal marine environments. To some degree, such ecological and taphonomic controls, linked with fine-grained substrata plus physical environmental stress, probably apply. Detailed stratigraphic analysis of these beds, however, suggests a more straightforward, geological explanation. Depositional sequences of the St. Marys Fm consist of transgressive tracts of "normal" siliciclastic facies without any evidence of condensation: these marginal marine and coastal environments apparently were the sinks that starved the inner shelf of sand, allowing condensed shell deposits to accumulate there (Kidwell 1988a). It is conceivable that shell-rich deposits might have accumulated during regression when these former sinks became sites of sediment transport (bypassing), but erosion has removed entirely any regressive record that might once have accumulated in these environments and has left only burrowed disconformities without any skeletal lag. Intuitively, end-cycle condensed deposits should have low preservation potential, and perhaps this explains in part the very localized distribution of the end-cycle SM-0 bone sand.

CONCLUSIONS

Each of the major shell deposits of the Maryland Miocene is truly unique, stratigraphically and paleontologically. This variability among examples, as well as lateral and microstratigraphic complexity within each deposit, is probably a hallmark of stratigraphic condensation in shallow marine set-

tings. The deposits are nonetheless similar in origin: all are condensed over sub-zonal time scales, are composed of skeletal material produced during the period of condensation rather than reworked from older strata, and accumulated in a suite of subtidal environments above storm wavebase during marine transgression. Their complex internal stratigraphies moreover indicate dynamic bypassing rather than complete starvation of siliciclastics, and pervasive biotic interactions between benthos and accumulating dead shells.

The link between assemblage composition and sediment shelliness is strong. In fact, many species have spotty but highly systematic stratigraphic distributions, occurring only within major shell deposits (Shattuck 1904; Gernant 1970; Kidwell 1982*a*). Regardless of whether this pattern in species distribution is controlled by ecology or taphonomy (e.g., positive feedback between shell abundance and the likelihood of shell preservation), it suggests another level of influence that condensed intervals exert on biostratigraphic data, at least for benthic organisms. Such gaps within species ranges increase error bars associated with range endpoints (first and last appearance datums) and thus reduce confidence in the stratigraphic ordering of those datums (e.g., Springer and Leje 1988). This complication is distinct from the commonly cited telescoping of species ranges by condensed intervals.

Also, because base-of-cycle and mid-cycle condensed deposits are stratigraphically distinct from one another, the Maryland Miocene record verifies significant differences between these two types of accumulations in terms of sedimentary dynamics, paleontology, and chronostratigraphic utility. Mid-cycle condensed deposits—here, bone-rich, shell-poor sands—bracket isochrons but will have variable duration when traced laterally and bear the paleoecological and taphonomic imprint of starvation. Base-of-cycle shell-rich condensed deposits, on the other hand, can have similar duration but different ages when traced laterally and reflect the complicated dynamics of bypassing of fines and starvation of coarser sediment size fractions. Differences in the environments of accumulation of shell-rich and bone-rich deposits also argues for two bathymetrically

distinct but contemporaneous areas of stratigraphic condensation, and thus a spatial mosaic of depositional, condensational, and erosional regimes on shelves during transgression.

Thus, the standard actualistic model for condensed transgressive lags (Swift 1976), in which most of the shelf is starved owing to coastal trapping of sediment and fossils are suspected of being reworked because of the association with an erosional ravinement, is contradicted by the detailed stratigraphic anatomy and taphonomy of Miocene examples and by their distribution with respect to transgressive-regressive cycles. The discrepancy between this stratigraphic case study and the actualistic model may be attributed to differences in the rate of transgression. For example, Swift (1976) notes that during slow transgression, coastal sinks will bypass the finer fraction to the shelf for wide dispersal in suspended load and will only trap the coarser fraction for permanent burial in channel axes. If the Miocene "spatial mosaic" is in fact due to slower transgression, the shell deposits underscore the range of sea level histories under which demonstrably condensed lags form, in addition to the already discussed range of environments, dynamics, and time-scales.

In terms of condensed deposits, recent seismic-based models for the accumulation of passive margin sequences focus exclusively on mid-cycle starved intervals (work in press summarized by Haq et al. 1987; Van Wagoner et al. 1987). The model, which involves landward and seaward switching of depositional sites during eustatic sea level fluctuations, has great deductive appeal and is amenable to outcrop tests. However, condensed intervals in the general, traditional sense—i.e., records that are thinner than coeval sections owing to persistent low net sedimentation—are more diverse in features, genesis, and stratigraphic distribution than allowed for in the present model. This diversity should not be neglected in pursuit of a general hypothesis for stratigraphic accumulation, nor should the diversity of condensed features be swept aside by operational redefinitions of the term. Instead, seismic perspectives on the architecture of passive margins should provide an impetus and a framework for critical, systematic surveys of condensed

facies, with the aim of better understanding the broad biological and geological controls on the nature of the record.

ACKNOWLEDGMENTS.—R. D. Kidwell, N. Landman, D. Gibson, and L. O. Cox are thanked for canoe-borne field assistance, and C. E. Brett, D. Jablonski, and an anonymous

reviewer for their comments on the manuscript. Work was supported by Sigma Xi, Geological Society of America, and Women's Seamens Friend Society (1978–1980 field work), and by ARCO Oil and Gas Company, Shell Foundation, Amoco Production Company, and the National Science Foundation (Grant EAR85-52470-PYI), which are gratefully acknowledged.

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