# Reciprocal sedimentation and noncorrelative hiatuses in marine-paralic siliciclastics: Miocene outcrop evidence

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**ABSTRACT**

**Deepening-upward paralic sequences present within a thicker record of shallowing-upward shelf and nonmarine sequences in Miocene siliciclastics of Maryland provide rare stratigraphic evidence for (1) coastal trapping of sediment during marine transgression, with simultaneous starvation on the open shelf (recorded by condensed skeletal lags), and (2) reciprocal switching of depositional and nondepositional conditions during regression. It follows that the regressive disconformities that define hemicyclic coastal sequences are not laterally continuous with the transgressive disconformities and condensed lags that define open-shelf hemicyclic sequences, although they are commonly depicted or assumed as such. Nor are these disconformities age correlative: marine-to-nonmarine correlations that assume lateral continuity of small-scale sequences (1 to 10 m thick; seismic parasequences) will err by as much as one-half cycle, restricting the applicability of models of punctuated aggradational cycles. The stratigraphic anatomy of parasequences is most comparable to reciprocal patterns inherent in hierarchically larger scale sequences in passive margins, where subaerial unconformities and submarine condensed intervals have recently been biostratigraphically verified as offset in age.**

## INTRODUCTION

Shallow-marine deposits commonly consist of recurrent, 1- to 10-m-thick, upward-shallowing facies sequences (Fischer, 1961; Ryer, 1977; James, 1984; Goodwin and Anderson, 1985; Grotzinger, 1986). Goodwin and Anderson (1985) and others have maintained that these hemicyclic sedimentary packages, which they called punctuated aggradational cycles (PACs), are laterally continuous across intertidal and subtidal carbonates and provide a basis for high-resolution chronostratigraphic correlation within basins. This application presumes that the sharp base of each PAC records a geologically instantaneous rise in relative sea level, and that subsequent regressive, shoaling-upward deposition is synchronous across a broad swath of environments.

This model has recently been extrapolated to siliciclastic and mixed carbonate-siliciclastic records (Busch and Rollins, 1984; Busch and West, 1987). However, whereas the PAC assumptions might be appropriate for some carbonate systems dominated by locally produced carbonate particles, the approach is questionable for siliciclastic-influenced systems, where sediment must be transported to the depositional site. Holocene studies (Curray, 1964; Wilkinson and Byrne, 1977; Biggs and Howell, 1984; Schubel et al., 1986) indicate that rapid rises in relative sea level have a direct influence on siliciclastic supply to the open shelf by trapping sediment in ephemeral coastal sinks, and this has been a common explanation for upward-shallowing hemicycles in ancient marine records (Swift, 1968; Ryer, 1977; Heckel, 1986). Miocene siliciclastics in Maryland provide rare, direct stratigraphic evidence for coastal sediment sinks during marine transgression and suggest that hemicyclic packages are unreliable for correlation shoreward of open-shelf deposits.

## HEMICYCLIC PATTERNS IN THE MIOCENE OF MARYLAND

Late Burdigalian to Tortonian strata (Melillo and Olsson, 1981; Schreiber, 1984) of the mid-Atlantic Coastal Plain comprise in outcrop ~65 m of richly fossiliferous interbedded

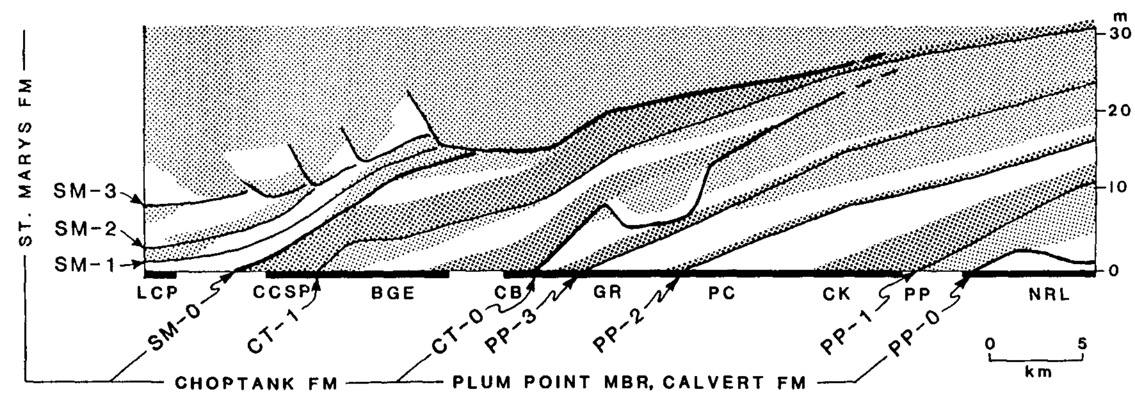


**Figure 1. Offlapping patterns of Miocene sequences in Calvert Cliffs, Calvert County, Maryland. Basal disconformities, with varied erosional relief, are labeled successively as PP-0, PP-1, etc. Dark stipple = transgressive shell- and bone-rich sand facies; light stipple and white = sparsely fossiliferous sand/silty sand and sandy silt/clay facies, respectively, arranged regressively within upper part of Calvert and Choptank sequences, and arranged transgressively within lower three sequences of St. Marys Formation. Horizontal datum is mean sea level; thick line segments along base of cross section mark continuous exposures. From north to south in Calvert Cliffs: NRL = Naval Research Labs, PP = Plum Point, CK = Camp Kauffman, PC = Parker Creek, GR = Governor Run, CB = Calvert Beach, BGE = Baltimore Gas and Electric plant, CCSP = Calvert Cliffs State Park, LCP = Little Cove Point.**

siliciclastic sands, silty sands, and clays of the Plum Point Member of the Calvert Formation, the Choptank Formation, and the St. Marys Formation (Shattuck, 1904). The offlapping strata are best exposed along dip-trending tributaries of the Chesapeake Bay in southern Maryland, where they can be traced for tens of kilometres (Fig. 1). Detailed analysis (Kidwell, 1982, 1984, 1986) indicates that the overall regressive record is subdivided by basin-margin disconformities and discontinuity surfaces into ten depositional sequences, each of which records a shorter term (about 0.5 to 1.0 m.y.) transgressive-regressive cycle (Fig. 2).

Cyclic depositional sequences in the open-marine Plum Point–Choptank interval (PP-0 to SM-0 surface; Figs. 1 and 2) are 7–10 m thick and extend over several thousand square kilometres in outcrop. In general, each sequence fines and then coarsens upward and rests on a *Thalassinoides*-burrowed disconformity. Sequences typically consist of a basal, densely fossiliferous (20% to 70% skeletal material by volume), comparatively thin, well-sorted fine sand that is overlain by sparsely fossiliferous, coarsening-upward facies of sand, silty sand, sandy silt, or clay (Figs. 2 and 3). Up-dip sandy facies grade into and extend over down-dip, finer grained, less well-bedded facies in regressive relation (Fig. 1). Deepest water conditions in each sequence were attained during the final stages of accumulation of the basal shell and bone sands, which also exhibit sedimentologic and paleontologic evidence of slow accumulation and stratigraphic condensation (Kidwell and Jablonski, 1983; Kidwell, in prep.). These basal sands are thinner or subequal to the overlying regressive facies; each disconformity-bounded sequence is therefore a predominantly upward-shallowing record of a transgressive-regressive cycle (Fig. 2).

In contrast to repetitive upward-shallowing open-marine hemicycles in the Plum Point–Choptank interval, upward-deepening hemicycles constitute the SM-0, SM-1, and SM-2 sequences of the lower St. Marys Formation (Fig. 2). These sequences are 3–7 m thick, can be traced only within the Calvert Cliffs, and consist largely of shell-poor, laminated to massive, sandy silt and clay facies. The sharp sequence boundaries are burrowed firmgrounds characterized by *Gyrolithes* and small, 2-cm-diameter *Thalassinoides*. Abundant carbonized wood and a mixture of polyhaline (e.g., *Isognomon*, *Corbula*, tellinid bivalves) and euryhaline mollusks suggest fresh-water influence. Bipolar orientations of elongate shells indicate reversing, probably tidal, currents (Nagle, 1967) in down-dip facies, which contain more diverse and stenohaline fauna.

These features, plus relatively rapid lateral facies changes (Fig. 1) and along-dip reversals from bedded to bioturbated to bedded structures (and from better to poorer to better sorted sediment) indicate accumulation in low-energy, subtidal coastal environments. Facies are arranged in transgressive order within each sequence, opposite to the predominant pattern in Plum Point–Choptank sequences. Shallow-marine silty sand and polyhaline clay facies are present in down-dip exposures, and when traced up dip they grade into and extend over onshore polyhaline facies of silty clay and silty sand (Fig. 1). There are no shallowing-upward regressive beds in these three sequences: net regression in this part of the St. Marys Formation is a result of basinward shifting of successive deepening-upward hemicycles.

These deepening-upward hemicycles could be loosely called estuarine (e.g., criteria of Frey and Howard, 1986), although valley walls cannot be confidently identified; a leaky tidal lagoon (e.g., Kjerfve, 1986) or embayment formed by coastal-plain submergence is inferred. This interpretation is in substantive agreement with previous workers (Gernant et al., 1971; Gibson, 1983; McCartan et al., 1985) and is consistent with the stratigraphic position of these strata between Plum Point–Choptank beds of undoubted fully marine origin and stratigraphically higher beds of the St. Marys Formation (SM-3 sequence), which are predominantly nonmarine (Fig. 2).

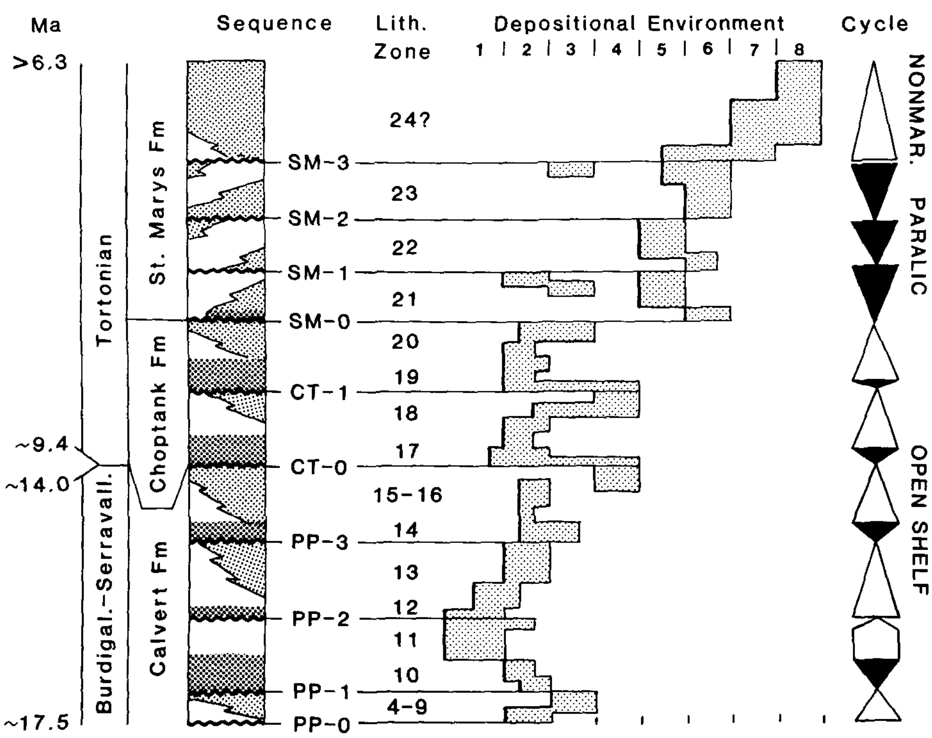


**Figure 2. Each sequence records small-scale transgressive-regressive cycle within overall regressive Maryland Miocene record; triangles on right indicate relative water-depth trends through each cycle. Open-shelf Calvert-Choptank sequences are predominantly shallowing-up hemicycles in which regressive deposits are thicker than transgressive shell and bone beds, whereas subtidal paralic St. Marys sequences (SM-0, SM-1, SM-2) are deepening-upward hemicycles. Numbered lithologic zones of Shattuck (1904) provided for reference; sequence subdivision and placement of formational boundaries follows Kidwell (1982, 1984, 1986). Chronostratigraphy based on foraminiferal biostratigraphy of Melillo and Olsson (1981) and Schreiber (1984), calibrated to time scale of Haq et al. (1987). Depositional environments: 1—below storm wave base open shelf; 2—below fair-weather wave base open shelf; 3—nearshore marine; 4—intertidal marine; 5—below wave-base paralic; 6—above wave-base paralic; 7—intertidal paralic; 8—fluvial channel complex.**

## SIGNIFICANCE OF DEEPENING-UPWARD HEMICYCLES

Asymmetrical, hemicyclic sequences are not distributed randomly. Deepening-upward hemicycles, which have a depositional record of transgression but none of regression, are encountered only in the part of the Miocene record that samples paralic environments. Shallowing-upward hemicycles, which have stratigraphically condensed records of transgression and fully depositional records of regression, characterize the open-marine part of the record (Fig. 3). The presence of deepening-upward coastal hemicycles within a thicker section of shallowing-upward open-marine and nonmarine hemicycles has several implications. (1) Deepening-upward metre-scale hemicycles, although rarely documented in the stratigraphic record, can occur with shallowing-upward hemicycles of the same scale. They can occur within overall regressive series, just as shallowing-upward hemicycles can occur within generally transgressive series (e.g., Ryer, 1977). (2) The scarcity of deepening-upward hemicycles in the larger record may reflect an inherent temporal and spatial patchiness of estuarine and siliciclastic lagoon environments of accumulation relative to more persistent and widespread environments such as the open shelf. (3) Coastal environments acted as sinks during successive marine transgressions. Deepening-upward paralic hemicycles in the Miocene section provide direct evidence of trapping during rises of relative sea level; Holocene analogues do not have to be presumed. With continued sediment supply and a stable or falling relative sea level, coastal sinks must have aggraded (or prograded) to base level and released progressively coarser grained siliciclastics to the open shelf, both by bypassing previously intercepted river supply and by relinquishing stored sediment. Former areas of sediment starvation on the shelf could then be replaced by shallowing-upward deposition, completing the open-shelf hemicycle (Fig. 3, top half). (4) Sediment accumulation in paralic and open-marine areas thus was not simultaneous, but reciprocal, and it alternated with periods of nondeposition which must also have been nonsimultaneous across the area (Fig. 3, bottom half). Discontinuity surfaces encountered in the two areas cannot be age-correlative, but will be offset by as much as one-half cycle.

The more basinward of the two hiatuses, formed subtidally in open-shelf environments during transgression, extends landward only as far as the maximum incursion of the marine shoreface (Fig. 3, bottom half). It has two components: (1) a diachronous erosional interval ($E_1$), represented by the basal transgressive disconformity and produced by landward migration of marine shoreface and shoal environments along the leading (landward) edge of the open shelf, and (2) an omissional interval, marked by condensed skeletal material and produced by nearshore bypassing ($P_1$) and/or offshore starvation of siliciclastics ($S_1$). Nearshore and offshore condensed deposits can be separated by intervening deposits (Fig. 3; exemplified by combined PP-1 and PP-2 sequences, Fig. 2) or can be combined into a single horizon. Starved conditions persist until deposition resumes on the shelf at maximum transgression or later. The total duration of the transgressive hiatus thus increases from a minimum value at the landward edge to a maximum value basinward (this excludes time value of eroded sediments).

The more landward hiatus, formed subtidally to subaerially in coastal environments during regression, can extend basinward over areas formerly occupied by marine deposition (Fig. 3, lower half). Hypothetically, the hiatus has a maximum value landward and decreases in magnitude toward its basinward edge, and it marks the transition of coastal sinks into surfaces of net transport (bypassing; $P_2$ in Fig. 3) and/or erosional entrenchment (if relative sea level falls) during regression ($E_2$). Erosion can remove all or part of the late shallowing-upward phase of deposition in coastal sinks; this may explain why Miocene paralic sequences consist only of deepening-upward strata.

The disconformities and condensed deposits that mark these hiatuses in the marine-paralic record are thus distinct in age, distribution, and history of formation. Despite their different ages and origins, the surfaces can nonetheless appear to be laterally continuous. Given adequate rates of erosion and some areal overlap with previous regressive disconformities, for example, a transgressive shoreface could cut through section and literally connect with an older regressive paralic disconformity. Conversely, the basinward edge of a regressive paralic disconformity could cut through regressive shelf deposits and converge stratigraphically with an older transgressive disconformity. When complete hemicyclic sequences are only metres thick, misleading convergence and anastomosing of surfaces is expected.

## CONSEQUENCES FOR DEPOSITIONAL MODELS

The asymmetry of facies sequences varies among environments as a function of sediment supply and other physical environmental features, so that the assumptions of the PAC model (as well as its depiction of hemicycle composition) are valid only in a narrow range of shallow-marine deposits. For example, in Devonian strata of New York, Brett and Baird (1986) have traced shallowing-upward shelf hemicycles into symmetrical, deepening and then shallowing cycles in coeval slope deposits, where they inferred greater subsidence (see Kradyna, 1987). Thus, a single fluctuation in relative sea level can generate cyclic sequences

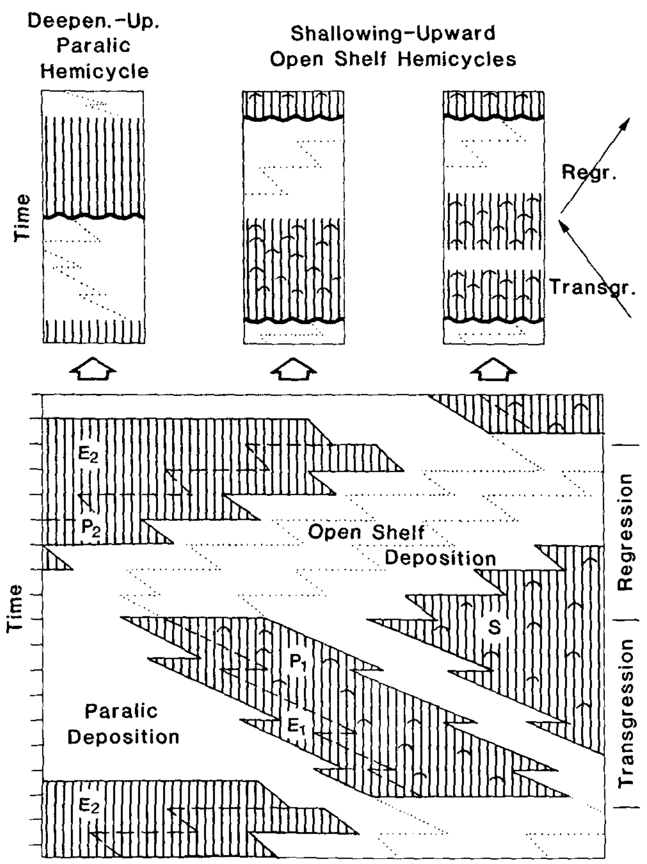


**Figure 3. Upper half: Relative ages of siliciclastic deposits (white) within paralic and open-shelf hemicycles, showing noncorrelation of hiatuses (vertical lines; shell symbol indicates accumulation of condensed shell- or bone-rich lag in absence of siliciclastic deposition). Lower half: Idealized distribution of depositional and nondepositional (E = erosion, P = dynamic or total passing, S = starvation of siliciclastic sediment) conditions across marine-paralic transect, reconstructed for single transgressive-regressive cycle. Fossil-lagged, basal disconformity ($E_1 + P_1 + S$ hiatus) of shallowing-upward shelf hemicycle correlates with deepening-upward deposition in paralic setting, not with hiatuses ($E_2 + P_2$) at either top or bottom of paralic hemicycle. Assumptions of lateral continuity and chronostratigraphic identity of sequence-bounding surfaces across marine-nonmarine transitions lead to age miscorrelations of as much as one-half cycle.**

that vary laterally in timing and composition: from deepening-upward paralic hemicycles, to shallowing-upward shallow shelf hemicycles, to symmetrical cycles in deeper shelf (e.g., combined Miocene PP-1 and PP-2 sequences) and slope settings.

Correlations that assume lateral continuity of small-scale sequences can err by as much as one-half cycle. This error is not the result of unrecognized diachroneity in basal disconformities (e.g., Johnson, 1987, and others), although this can be a factor locally. Instead, it results from the mistaking of paralic disconformities as identical with marine disconformities, when these surfaces in fact record different, even mutually exclusive periods of nondeposition within a cycle of relative sea-level change, and are probably not laterally continuous with each other. The rationale that sequences correlate because similar numbers are encountered in different areas is invalid; Figure 3 shows how relative sea-level fluctuations could produce identical numbers of disconformity-bounded sedimentary packages in paralic as in open-shelf settings, and yet none would correlate precisely with the other.

A half-cycle error in correlating sedimentary deposits may be inconsequential for some purposes—e.g., in the evolutionary analysis of faunas whose morphologies are static over periods greater than the duration of entire transgressive-regressive cycles. However, the procedural error in correlation is more insinuative than operational error: if the rationale of correlation does not permit reciprocity in deposition, discontinuity-bounded units must correlate precisely across a wide range of environments, and it becomes impossible to identify more than one (nonreciprocal) model of sediment accumulation. As the procedure is used to correlate finer and finer scaled units, the error becomes increasingly intractable: age distinctions within fourth, fifth, and higher order cycles (durations less than 1 m.y.) commonly exceed the resolving power of independent biostratigraphic and radiometric techniques.

Maryland Miocene patterns indicate the complex stratigraphic relations present within hierarchically larger scale depositional sequences in passive margins. In addition, the inferred dynamics of sediment accumulation and hiatus formation are analogous to the reciprocal relations inherent within first-, second-, and third-order onlap-offlap cycles. For example, seismically recognized basin-margin unconformities and basin-axis condensed intervals (downlap surfaces) that previously were correlated (e.g., Vail et al., 1984) have now been verified biostratigraphically to be offset in age (Haq et al., 1987). A priori, patterns of sediment accumulation observed within small-scale transgressive-regressive cycles need not resemble patterns evidence at the scale of continental margins, but it appears that they do, despite differences in depositional environments and in the time scales and driving mechanisms of fluctuations in relative sea level.

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