QUANTITATIVE CONSTRAINTS ON THE ORIGIN OF STRATIGRAPHIC ARCHITECTURE AT PASSIVE CONTINENTAL MARGINS: OLIGOCENE SEDIMENTATION IN NEW JERSEY, U.S.A.

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ABSTRACT: **The Oligocene of the New Jersey continental margin is divisible into as many as eight sequences and 23 lithofacies associations, documented in a series of seven boreholes across the modern coastal plain. This paper summarizes the sequence architecture of these deposits, interpreted from high-resolution biostratigraphy and Sr-isotope chemostratigraphy, and evaluates the factors that governed patterns of sedimentation, making use of previously published quantitative estimates of water-depth changes and eustasy from 2-D foraminiferal paleoslope modeling and flexural backstripping.**

Each sequence is markedly wedge-shaped, thinning both landward of the rollover in the underlying sequence boundary (the point at which the surface steepens into a clinoform), and seaward of the rollover in the overlying boundary. Each bounding surface is associated with evidence for offlap–onlap geometry and at least locally with benthic foraminiferal evidence for abrupt upward shoaling. Most unconformities merge up dip into a single surface marking the Oligocene–Miocene boundary. Earliest Oligocene unconformities (33.5–31.6 Ma) merge downdip as a result of sediment starvation on the deep shelf. Conventional lithostratigraphic units within the New Jersey Oligocene are highly diachronous. For example, the base of Atlantic City Formation at Cape May (a downdip borehole) is at least 6.6 Myr younger than the top of the same formation at ACGS#4 (an updip borehole).

Factors controlling patterns of sedimentation include: (1) a terraced physiography, with gradients ranging from 1:1,000 (0.06°) on the coastal plain and shallow shelf and 1:500 (0.11°) on the deep shelf to $<$ 1:100 (1.0°) on an intermediate slope; (2) generally low siliciclastic sediment flux, with *in situ* production of authigenic glauconite, especially during times of transgression; (3) a location landward of the hinge zone of the passive margin, with slow tectonic subsidence augmented by compaction and sediment loading; (4) low to moderate amplitudes and rates of eustatic change (10–50 m over spans of $\sim$ 1–2 Myr); and (5) an active wave climate that permitted efficient lateral transport and complete bypass of sediment at paleodepths of at least 20 $\pm$ 10 m.

Sequence architecture in the New Jersey Oligocene differs from that of the standard ''Exxon model.'' Sequences are highstand-dominated, in spite of deposition and preservation largely seaward of the rollover in each underlying sequence boundary. Transgressive systems tracts are thin. Recognizable lowstand units did not form because efficient transfer of sediment across the shallow shelf, combined with the absence of major river systems in the area of study, prevented the reorganization of sedimentation patterns commonly associated with point-source development, in spite of rates of eustatic fall considerably greater than the local rate of tectonic subsidence. Repeated eustatic rises and falls are expressed primarily by variations in paleo-water depth. Although $\sim$ 65–80% of the shallow shelf that had been flooded during each rise became subaerially exposed during the subsequent fall, well developed offlap at each sequence boundary is due primarily to marine bypassing and degradation rather than to ''forced regression.'' Sequence boundaries correspond in time at their correlative conformities not with the onset of falling ''relative'' sea level, but with the start of eustatic rise.

INTRODUCTION

The roles of various factors in governing sedimentation patterns at continental margins have been debated since the early days of modern geology (e.g., Suess 1906; Stille 1924). Of these factors, tectonics, eustasy, and sediment supply have stood out as amongst the most important—tectonics for ultimately making the space needed for sediment to accumulate, and all three factors for potentially influencing the manner in which available space is filled (e.g., Burton et al. 1987; Posamentier et al. 1988; Galloway 1989; Reynolds et al. 1991; Underhill 1991; Plint et al. 1993; Christie-Blick and Driscoll 1995). The emergence of seismic and sequence stratigraphy in the 1970s and 1980s led to the development of new concepts about facies arrangements and stratigraphic architecture and their possible relation to eustatic change (e.g., Vail et al. 1977; Vail et al. 1984; Vail et al. 1991; Haq et al. 1987; Vail 1987; Plint 1988, 1993; Posamentier et al. 1988; Posamentier et al. 1992; Sarg 1988; Van Wagoner et al. 1990; Carter et al. 1991; Christie-Blick 1991; Hunt and Tucker 1992; Karner et al. 1993; Posamentier and James 1993; Schlager 1993; Helland-Hansen and Gjelberg 1994; Christie-Blick and Driscoll 1995; Van Wagoner 1995; Naish and Kamp 1997; Posamentier and Allen 1999; Plint and Nummedal 2000; Posamentier and Morris 2000). The eustatic paradigm has been highly influential, but even as evidence for strong eustatic forcing during times of continental glaciation has solidified (e.g., Naish and Kamp 1997; Miller et al. 1998a), questions have persisted about precisely how patterns of sedimentation respond to changing sea level. In the absence of quantitative stratigraphic constraints, interpretations have largely been qualitative and inseparable from the loosely specified concept of relative sea-level change (Posamentier et al. 1988; Posamentier and Allen 1999).

Stratigraphic studies of core samples from Oligocene sediments of the New Jersey coastal plain have yielded a remarkably well calibrated record of changing facies and paleo-water depths in eight unconformity-related sequences, from which it has been possible to extract a unique quantitative interpretation of eustatic change on a million-year timescale (Pekar et al. 2000; Pekar et al. 2001; Kominz and Pekar 2001; Pekar and Kominz 2001). Our previously published articles on these sediments focus on high-resolution chronostratigraphy using biostratigraphy (planktonic foraminifers, nannofossils, diatoms, and dinocysts) and Sr-isotope chemostratigraphy; on the development of a quantitative methodology for estimating water-depth changes in two dimensions; and on using flexural backstripping to place constraints on eustatic change. This paper takes stock of how the sequences are put together, and reexamines the factors responsible.

SEQUENCE STRATIGRAPHIC INTERPRETATION

The Oligocene sequence stratigraphy of New Jersey was interpreted from a series of boreholes projected onto a transect across the modern coastal plain (Figs. 1–3; Pekar 1999; Pekar et al. 2000). Sequence boundaries and systems tracts were delineated on the basis of inferred stratal geometry and facies arrangements, and without reference to sea-level change (see Christie-Blick 1991, 2001; Christie-Blick and Driscoll 1995). This distinction, which is consistent with the way in which systems tracts were first defined

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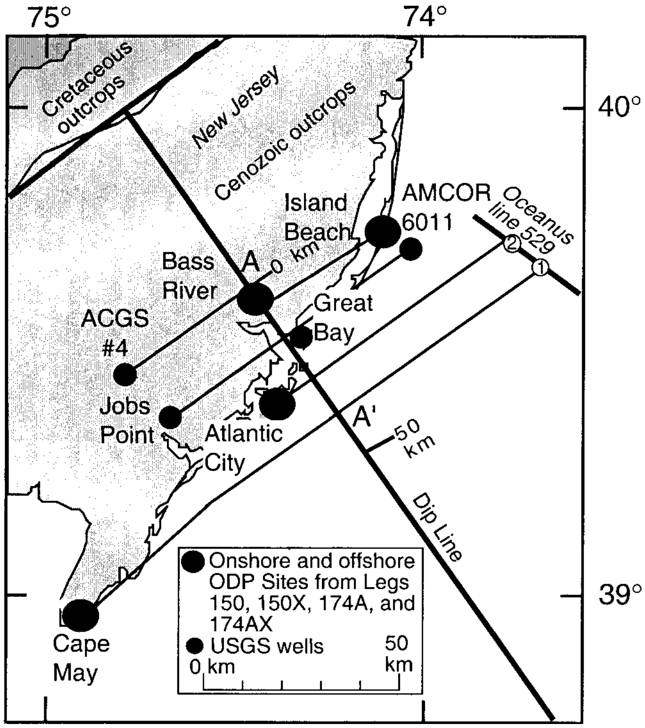

FIG. 1.—Location map. The southern part of New Jersey, eastern United States, is shown with locations of sites used in this study: Island Beach, Atlantic City, Cape May (Leg 150X boreholes); Bass River (Leg 174AX borehole); AMCOR 6011, ACGS#4, Great Bay and Jobs Point (U.S.G.S. onshore and offshore wells). Dip section A–A′ is drawn perpendicular to Cretaceous outcrops; strike lines are projected from boreholes onto that section. Updip part of *Oceanus 270* line 529 is shown with Cape May and Atlantic City sites projected along strike onto that line. Circled numbers 1 and 2 represent location of rollovers for seismic surface m6 (Oligocene–Miocene boundary) and the immediately underlying sequence boundary (Monteverde et al. 2000).

(Brown and Fisher 1977; Vail 1987), is necessary to avoid circularity in determining how stratigraphy relates quantitatively to eustasy. In spite of some terminology currently in use (highstand, lowstand, falling stage, forced regressive, etc.; e.g., Vail 1987; Hunt and Tucker 1992; Posamentier et al. 1992; Helland-Hansen and Gjelberg 1994; Naish and Kamp 1997; Plint and Nummedal 2000; Posamentier and Morris 2000), and the apparent intent of some authors, in this paper systems tracts are specifically not interpreted according to whether sea level is thought to have been high, low, or falling, etc. (see below for further discussion). While better terms might be considered, and uncertainties exist in practice about the precise location, continuity, and time significance of systems-tract boundaries, we find the threefold subdivision of sequences into lowstand, transgressive, and highstand systems tracts (Vail 1987) more useful and potentially less subjective than the several variants that have emerged in the past decade. Vail's scheme requires only an assessment of whether the shoreline was moving generally seaward (highstand and lowstand) or landward (transgressive), and of stratigraphic location with respect to the transition from offlap beneath a sequence boundary (highstand) to onlap above (lowstand and transgressive). The transition from highstand to lowstand sedimentation requires a change in the pattern of progradation and, in terrigenous systems, generally begins with the development of point sources. Lowstand systems tracts defined in this way are not present in most sequences, even those overlying prominent unconformities. We note the ill-advised usage by others of the term lowstand for coarse-grained and/or nonmarine lithosomes overlying sequence boundaries, whether or not continued seaward movement of the shoreline can be demonstrated (e.g., Van Wagoner 1995); and for offlapping stratigraphic elements below geometrically delineated sequence boundaries (e.g., Hunt and Tucker 1992; Helland-Hansen and Gjelberg 1994; Posamentier and Allen 1999; Posamentier and Morris 2000). The transition from onlap to offlap is typically associated with the highstand systems tract (Christie-Blick 1991), although the degree to which offlap is developed is highly variable. In some cases, a combination of limited sediment accumulation and degradation beneath a developing surface results in the erosional truncation of already deposited highstand and transgressive units or even the amalgamation of two or more unconformities (e.g., Kidwell 1997).

In our interpretation of the New Jersey Oligocene, each boundary of each sequence is represented by an unconformity that either passes basinward into a correlative conformity, where the associated hiatus is no longer resolvable, or amalgamates with another sequence boundary in an interval of sediment starvation (condensed section). Sequence boundaries are associated with evidence for offlap–onlap geometry (from a comparison of high-resolution chronology in adjacent boreholes), and at least locally with benthic foraminiferal evidence for abrupt upward shoaling, a characteristic feature of this kind of surface (Christie-Blick 1991, 2001). In continuously cored boreholes, unconformities are typically associated with an irregular erosional surface, a marked change in lithofacies and benthic foraminiferal biofacies, hardground development, and a sharp upward increase in gamma-ray log response (features related at least in part to initial marine flooding). In boreholes that were cored discontinuously (at intervals of 5 or 10 feet), unconformities are commonly not recovered but are instead bracketed by samples suggesting the presence of a hiatus and revealing contrasts in lithofacies and/or biofacies. In these cases, the locations of surfaces are interpreted from gamma-ray log data. Condensed sections are typically

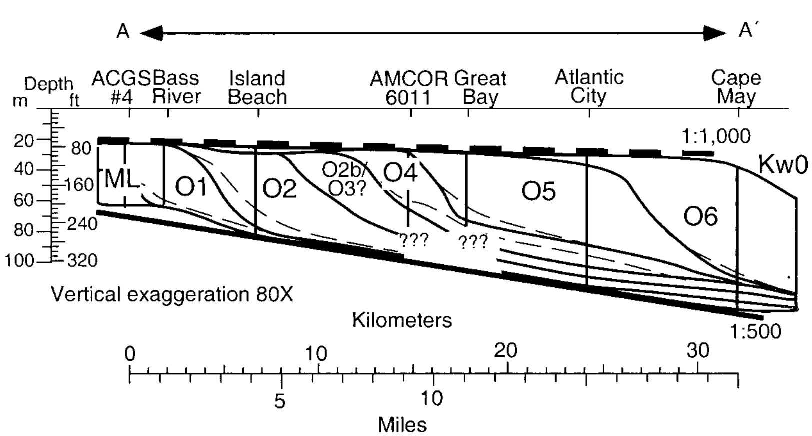

FIG. 2.—Distribution of New Jersey Oligocene sequences projected onto dip section A–A′ (see Fig. 1) at ~ 24 Ma. Sequences ML and O1 through O6 are of Oligocene age. Ties for reconstructed sequence boundaries are depths at each borehole. Clinoforms are required by the data; the sigmoidal shapes are conjectural. Clinoform relief is inferred from two-dimensional flexural backstripping (Kominz and Pekar 2001). Bold line indicates original depth and gradient (1/500) of Eocene–Oligocene surface. Bold dashed line indicates paleoshelf gradient landward of rollover (1/1000).

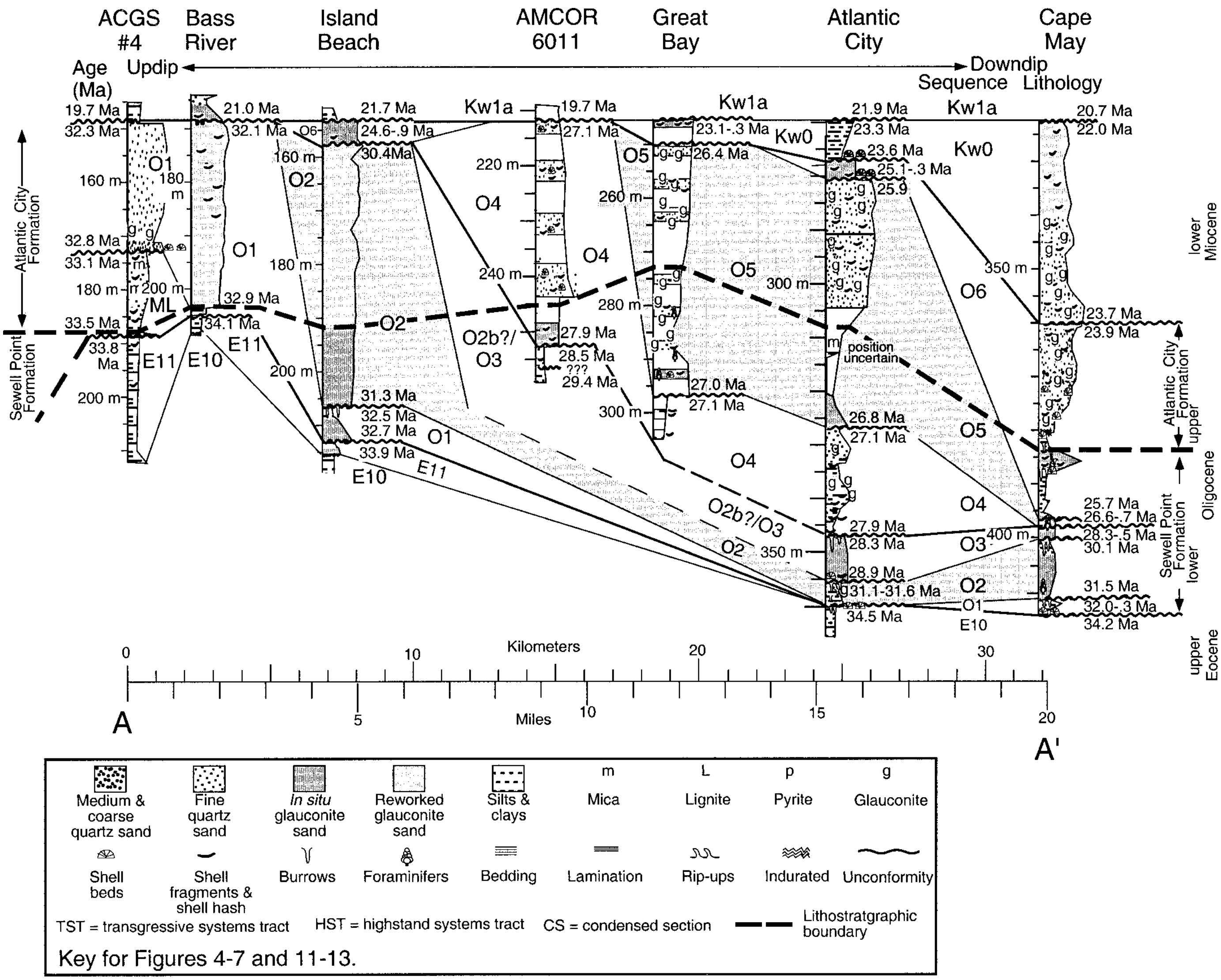

FIG. 3.—Distribution of New Jersey Oligocene sequences and borehole locations projected onto dip section A–A′ (see Fig. 1), with datum at base of sequence Kw1a. Depths are in meters. Ages of sequences: E10 and E11 are latest Eocene (Browning et al. 1997); ML and O1 to O6 are Oligocene (Pekar et al. 2000); and Kw0 and Kw1a are earliest Miocene (Miller et al. 1997). Successive sequences are arranged laterally, with the oldest landward and the youngest seaward. Also shown are lithology, ages of strata immediately below and above sequence boundaries, and lithostratigraphy (from Pekar et al. 1997b). Sequences O2 and O5 are shaded to emphasize correlations between boreholes. Lithologic key applies also to Figures 4–7 and 11–13.

marked by at least one of the following: high concentrations of authigenic glauconite sand (an indicator of low terrigenous input; McRae 1972); abundant benthic foraminifers with peak species abundances of uvigerinids; and a change from upward-deepening to upward-shallowing trends (Pekar 1999; Pekar and Kominz 2001). They are *intervals* of sediment starvation. With few exceptions, maximum flooding surfaces cannot be recognized objectively in our data.

Lithofacies and Age Control

The strata have been divided into 23 lithofacies associations on the basis of grain size, mineral abundance (mainly quartz and glauconite), whether the glauconite is *in situ* or detrital (reworked or transported), diagnostic microfauna, and the presence of shells and associated sedimentary structures (Table 1; summarized from lithologic descriptions in Miller et al. 1994; Pekar et al. 1997a; Pekar 1999). *In situ* glauconite typically forms in quiescent, sediment-starved, low-oxygen middle neritic and deeper paleoenvironments (McRae 1972). Detrital glauconite is suggested by: (1) abraded, cracked, and broken grains; (2) mixed populations of green and brown grains (weathered to goethite); (3) an association with abundant quartz; (4) an association with inner neritic benthic foraminiferal taxa (Pekar et al. 1997a). Cumulative weight percentage data were collected for the medium to coarse and fine quartz sand fractions, silt–clay, glauconite sand, and shell material. (For the purpose of simplification in this paper, the term fine sand includes fine- and very fine-grained sand on the Wentworth scale, or 63 to 250 μm; and the term coarse sand includes coarse- and very coarse-grained sand on the Wentworth scale, or 500 to 2,000 μm.) In intervals with glauconite, abundances of other components were visually estimated from the greater than 63 μm size fraction. In intervals without glauconite and shell material, the percentages of fine versus medium to coarse sand were obtained by dry sieving and weighing.

An age model was developed for New Jersey Oligocene strata by integrating planktonic foraminiferal, dinocyst, diatom, and nannofossil biostratigraphy, Sr-isotopic chemostratigraphy, and limited magnetostratigraphy

TABLE 1.—*Summary of late Paleogene (34.2–23.9 Ma) lithofacies in New Jersey.*

Lithofacies Code	Description	Type Location	Depositional Environment
Medium to coarse quartz association			
C1	Dark olive gray (5GY 4/1) coarse to gravelly glauconitic (10–20%) quartz sand; massive, microfossils are sparse.	Uppermost sequence O6 at Cape May	Inner neritic
C2	Dark greenish gray (5GY 4/1) to olive gray (5Y 4/2) slightly glauconitic (<10%), shelly, medium to coarse quartz sand. Microfossils are sparse to absent; typically massive.	Sequence O5 at Atlantic City	Inner to inner middle neritic
C3	Dark greenish gray (5GY 4/1) to dark green (5GY 4/1), glauconitic (10–30%), medium to coarse quartz sand, mostly massive with occasional thin parallel bedding. Microfossil are sparse to moderate.	Sequence O6 at Cape May	Inner neritic
C4	Light gray (5Y 7/1) to gray (5Y 6/1) medium to coarse quartz sand, shells present, microfossils are sparse to absent.	Sequence O1 at ACGS#4; Sequence O4 at AMCOR	Inner neritic
C5	Olive (5Y 4/3) slightly glauconitic (<10%) medium to coarse quartz, with abundant shell fragments, abundant foraminifers.	Sequence O5 at Great Bay	Inner to middle neritic
Detrital glauconite			
DG1	Dark olive green (5Y 2.5/2) reworked glauconite (goethite, 40–70%) with medium to coarse quartz sand (10–25%). Little clay, barren to sparsely fossiliferous, massive with occasional subparallel bedding.	Sequence O1 at Bass River	Inner to middle neritic
DG2	Dark olive green (5Y 2.5/1) clayey (40–60%), detrital glauconite. Occasional shell fragments, slightly sandy (<10%), sparsely fossiliferous, commonly massive.	Sequence O2 at Island Beach	Inner to middle neritic
Fine quartz sand association			
F1	Very dark gray (5Y 3/1) to dark olive gray (5Y 3/2) silty micaceous fine quartz sand, barren to sparsely fossiliferous.	Sequence ML (upper part) at ACGS#4	Inner middle to middle neritic
F2	Olive gray (5Y 3/2) to dark olive gray (5G 4/1) Silty glauconitic (~10%) fine quartz sand, abundant shell fragments, moderate to high microfossil abundances, laminated to occasionally massive.	Sequence O6 at Cape May	Middle neritic
F3	Very dark gray (5Y 3/1) silty glauconitic (<10%) fine to medium quartz sand, abundant shells.	Between 865 & 845 ft at Great Bay	Middle neritic
Silt association			
S1	Dark olive gray (5Y 3/2) to olive gray (5Y 4/2) micaceous sandy silt, massive, microfossils absent.	Sequence ML (lower part) at ACGS#4	Inner middle neritic
S2	Dark olive gray (5Y 3/2) clayey sand silt, slightly glauconitic (<5%), abundant microfossils.	Sequence O3 at AMCOR 6011 & sequence O4 at Great Bay	Middle neritic
S3	Dark gray (5Y 4/1), clayey glauconitic silts, slightly sandy. Occasional burrows, abundant microfossils, mostly laminated to thinly bedded.	Sequence O4 at Atlantic City (1140–1130 ft)	Middle neritic
Clay association			
Cl1	Dark greenish gray (5G 4/1) glauconitic (20–40%) clays sparsely to moderately fossiliferous, occasional shells	Sequence O1 at Island Beach, Sequence O2 at Atlantic City (1181–1170 ft)	Middle to outer middle neritic
Cl2	Dark olive gray (5Y 2.5/2 to 5Y 3/2) sandy silty, glauconitic (10–20%) clay. Often burrowed, occasional thin walled shells; laminations present.	Sequence O6 at Cape May (1324–1314 ft)	Outer middle neritic
Cl3	Dark olive gray (5Y 3/3 to 5Y 3/2), massive clay, very slightly glauconitic (<5%), occasional laminae of fine sand. Sand filled burrows; occasional thin-walled shells.	Sequence O6 at Cape May (1260–1250 ft)	Middle neritic
Cl4	Grayish brown (2.5Y 5/2) clays, slightly micaceous. Slightly sandy to silty, occasionally very slightly glauconitic (<5%), abundant microfossils, extensive bioturbation.	Sequence E11 at ACGS#4 and at Bass River	Outer neritic
In situ glauconite association			
G1	Very thin, very dark grayish brown (2.5Y 3/2) to black (2.5Y 2.5/1) mostly clayey *in situ* glauconite sand, abundant shells fragments.	Sequence ML at ACGS#4 (615–613 ft)	Inner middle neritic
G2	Dark olive gray (5Y 3/2) clayey *in situ* glauconite (~50%); sparsely to moderately fossiliferous; commonly burrowed, occasional shell fragments.	Sequence O1 at Bass River	Middle to outer neritic
G3	Dark olive gray (5Y 3/2) to dark gray (5Y 4/1) *in situ* clayey glauconite (~50), occasional very fine quartz sand, abundant microfossils.	Sequence O2 at Cape May and Atlantic City	Outer neritic
G4	Dark olive green (5Y 3/2) sandy (fine to medium, 10–30%) clayey shelly glauconite sand, abundant microfossils.	O6 at Island Beach & Atlantic City	Inner to inner middle neritic
G5	Dark olive gray (5Y 2.5/2) to dark gray (5G 4/1) *in situ* clayey (30–50%) glauconite sand, fine quartz sand (<20%).	Sequence O2 at Island Beach	Outer middle to outer neritic
Shell association			
SH1	Glauconitic sandy shell bed or shell hash.	Base of Sequence O6 (923–922 ft) at Atlantic City	Inner neritic

Note: Underlined words indicate unique characteristics for a given lithologic association.

(Pekar et al. 2000) using the Berggren et al. (1995) timescale. Sr-isotopic ages were calibrated to the timescale using regressions of Reilly et al. (1996). Age uncertainties related to these regressions are approximately ± 0.6 Myr for the late Oligocene and ± 0.7 Myr for the early Oligocene. Integrating these age data results in absolute uncertainties of the order of ± 0.3 to ± 0.7 Myr for individual ages. However, combining age data and sequence stratigraphic framework yields age estimates with a relative precision of about ± 0.1 Myr. This high precision was accomplished by tracing sequence boundaries and the condensed sections (proxies for time surfaces) among the seven sites. Relative sedimentation rates above and below condensed sections were estimated using sedimentation rates determined from five parasequences identified in the Cape May borehole that

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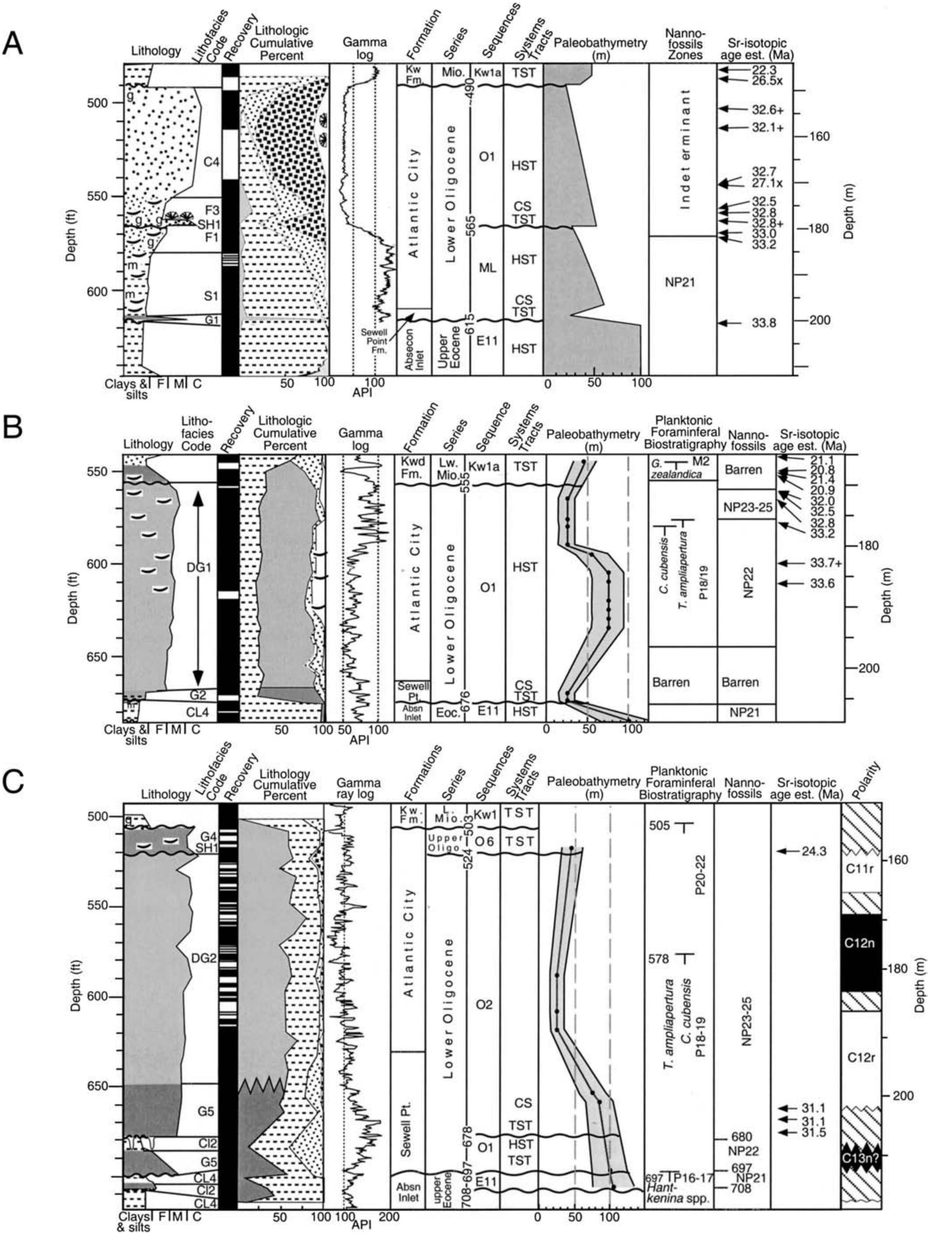
FIG. 4.—Summary diagrams for boreholes at **A)** ACGS#4, **B)** Bass River, and **C)** Island Beach. See Figure 3 for lithologic key, and Table 1 for lithofacies codes. Lithologic cumulative percents are from Pekar (1999). Depths of sequence boundaries are in feet. Systems-tract terminology is from Vail (1987). Paleobathymetric estimates, with uncertainty, are from Pekar and Kominz (2001). Sr-isotopic age estimates with a + symbol indicate an average age for that depth interval; x represents age estimates that are stratigraphically inconsistent (Pekar 1999).


A
Lithology
Lithofacies Code
Recovery
Lithologic Cumulative Percent
Gamma log
Formation
Series
Sequences
Systems Tracts
Paleobathymetry (m)
Nannofossils Zones
Sr-isotopic age est. (Ma)
Depth (ft)
Depth (m)
Kw Fm.
Atlantic City
Sewell Point Fm.
Absecon Inlet
Mio.
Lower Oligocene
Upper Eocene
Kw1a
O1
ML
E11
TST
HST
CS
Indeterminant
NP21
Clays & silts F M C
API
B
Litho-facies Code
Planktonic Foraminferal Biostratigraphy
Kwd Fm.
Sewell Pt.
Absn Inlet
Lw. Mio.
Eoc.
DG1
G2
CL4
Barren
NP23-25
NP22
C
Gamma ray log
Polarity
Upper Oligo
upper Eocene
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C12n
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C13n?

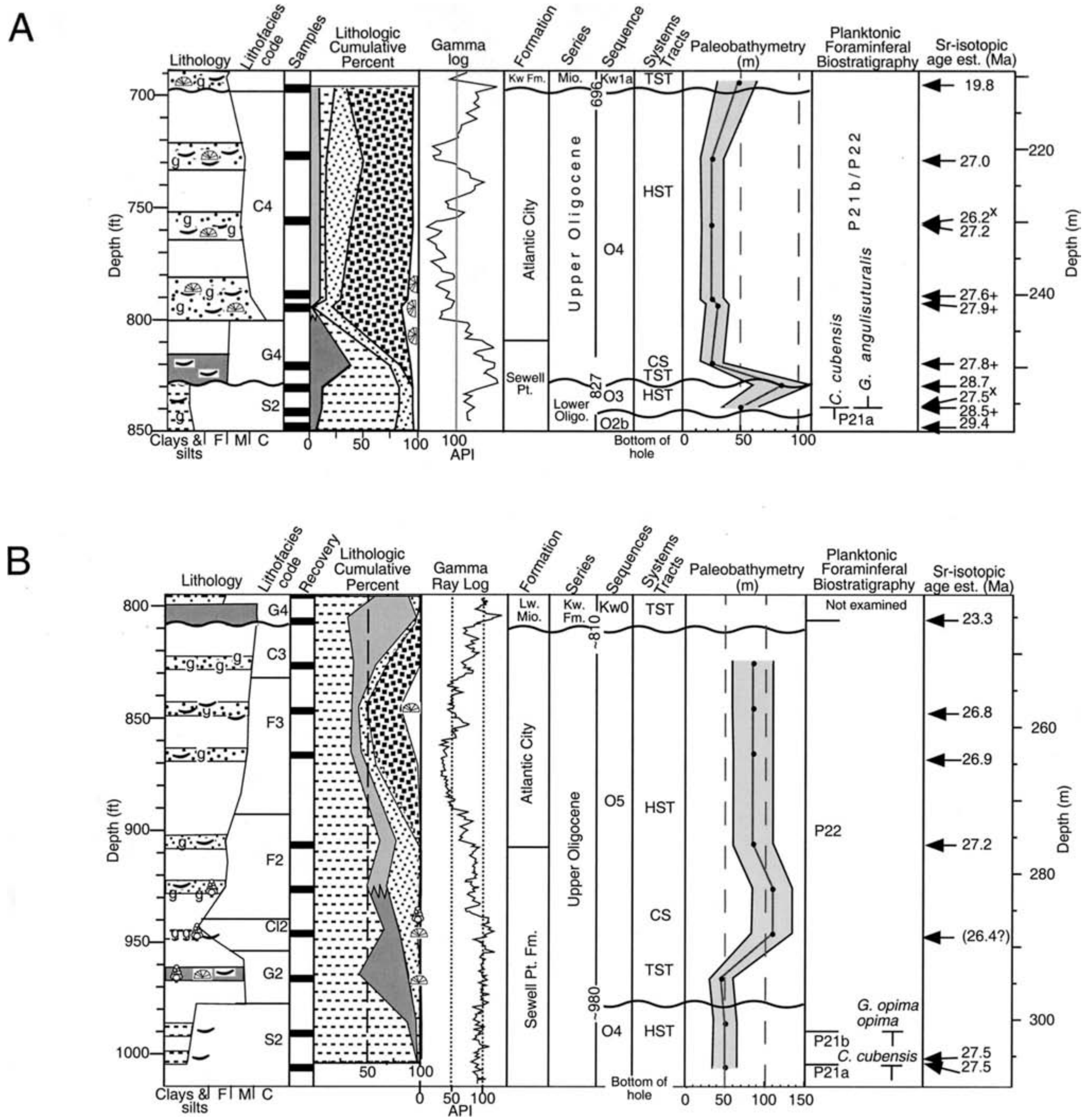


FIG. 5.—Summary diagrams for boreholes at **A)** AMCOR 6011 and **B)** Great Bay. See captions to Figures 3 and 4 for additional explanation.

correspond to five 400 ky cycles from isotopic records from ODP Site 929 (Pekar 1999). This provided estimates of sedimentation from ~ 10 m/Myr for glauconite-rich sediments to ~ 40 m/Myr for quartz-rich sediments. Thus, while the observed absolute age estimate may shift by as much as ± 0.7 Myr within any given sequence, the correlated relative ages are considerably more precise. In the absence of seismic reflection data through the boreholes, high-resolution chronology is critical for locating stratigraphic discontinuities and for establishing offlap and onlap geometry at sequence boundaries.

OLIGOCENE SEQUENCE ARCHITECTURE OF THE NEW JERSEY COASTAL PLAIN

Oligocene strata of the New Jersey coastal plain are divisible into as many as eight sequences (Figs. 3–6; see Appendix 1). Reconstructions of the stratal geometry indicate that the sequences take the form of progradational wedges (Fig. 7). Each sequence attains its greatest thickness (several tens of meters) immediately seaward of the rollover in the underlying sequence boundary. (The rollover is the point in any profile at which the

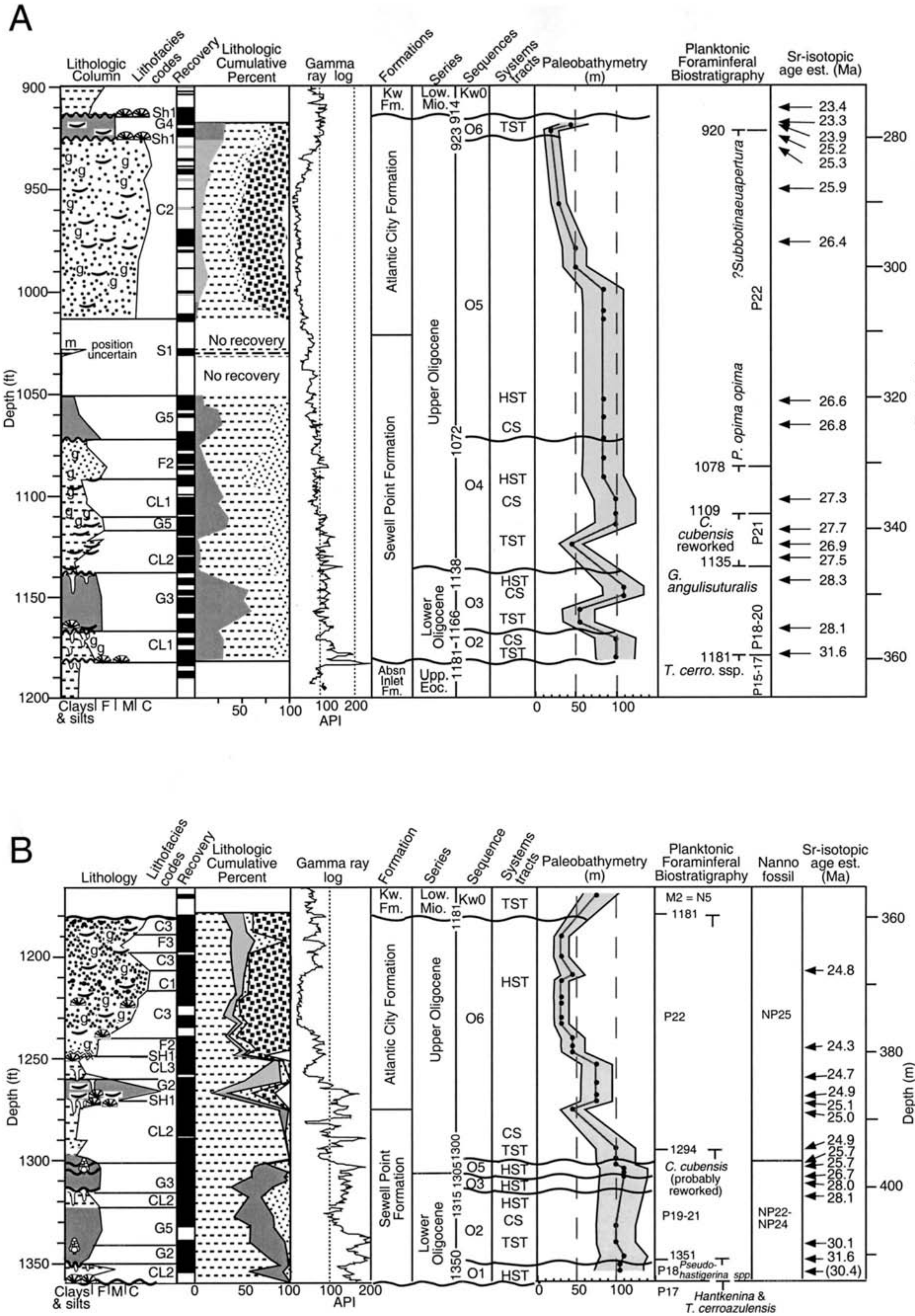
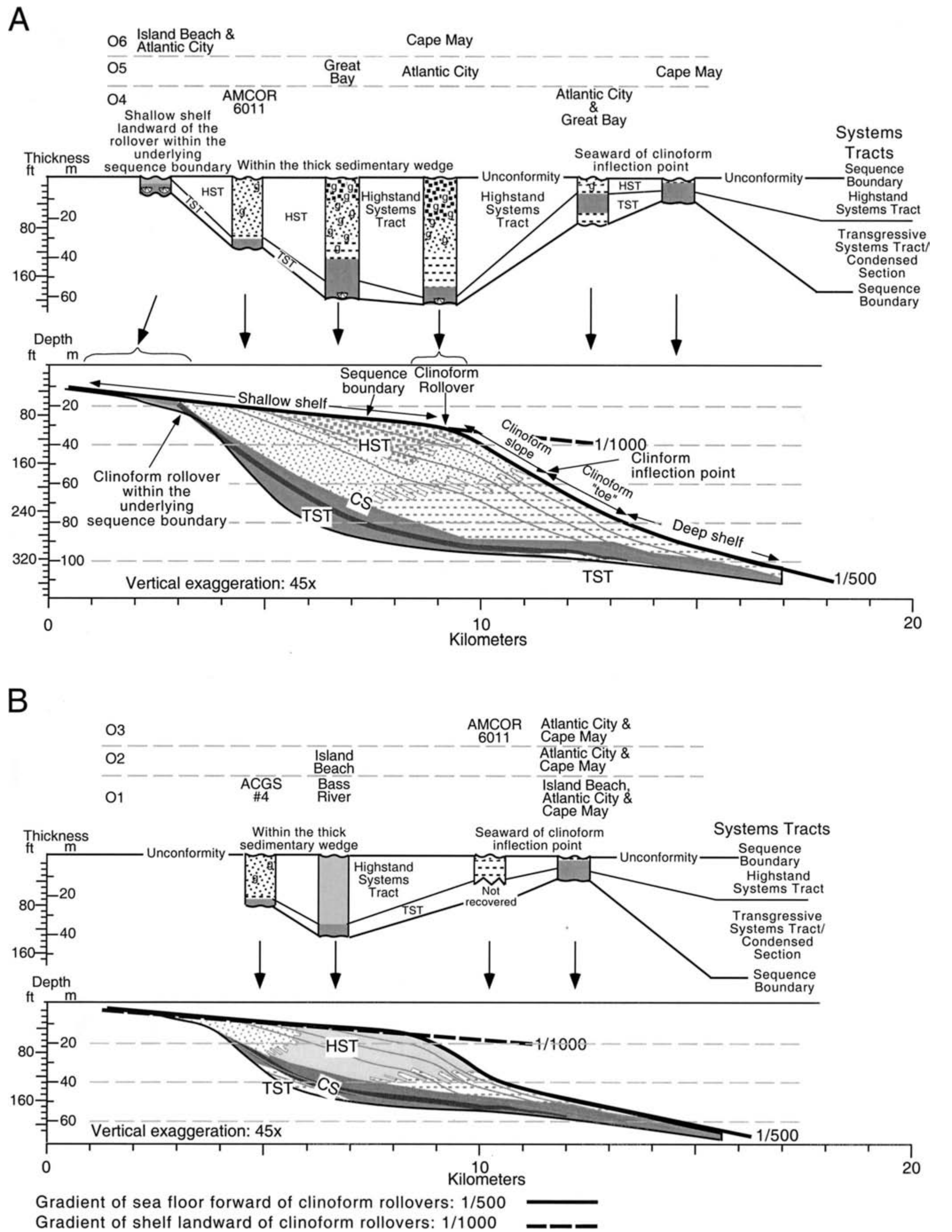


FIG. 6.—Summary diagrams for boreholes at **A)** Atlantic City and **B)** Cape May. See captions to Figures 3 and 4 for additional explanation.


A
O6 Island Beach & Atlantic City
Cape May
O5
Great Bay
Atlantic City
Cape May
O4
AMCOR 6011
Atlantic City & Great Bay
Shallow shelf landward of the rollover within the underlying sequence boundary
Within the thick sedimentary wedge
Seaward of clinoform inflection point
Thickness ft m
Unconformity
HST
TST
Highstand Systems Tract
Systems Tracts
Sequence Boundary
Highstand Systems Tract
Transgressive Systems Tract/ Condensed Section
Sequence Boundary
Depth ft m
Sequence boundary
Clinoform Rollover
Shallow shelf
Clinoform slope
1/1000
Clinform inflection point
Clinoform "toe"
Deep shelf
Clinoform rollover within the underlying sequence boundary
CS
1/500
Vertical exaggeration: 45x
Kilometers
B
O3
O2
O1
AMCOR 6011
Atlantic City & Cape May
Atlantic City & Cape May
Island Beach
ACGS #4
Bass River
Island Beach, Atlantic City & Cape May
Within the thick sedimentary wedge
Seaward of clinoform inflection point
Unconformity
Highstand Systems Tract
Not recovered
TST
Systems Tracts
Sequence Boundary
Highstand Systems Tract
Transgressive Systems Tract/ Condensed Section
Sequence Boundary
HST
CS
1/1000
1/500
Vertical exaggeration: 45x
Kilometers
Gradient of sea floor forward of clinoform rollovers: 1/500
Gradient of shelf landward of clinoform rollovers: 1/1000

gently inclined shallow shelf portion of any surface steepens into a clinoform.) Landward of this position, sequences tend to be thin and discontinuous. They also thin seaward of the rollover in the overlying sequence boundary, where that surface passes laterally into a clinoform. Individual clinoforms within each sequence are characterized by oblique sigmoidal geometry, flattening both updip and downdip from a clinoform inflection point. Seaward of the inflection point (clinoform toe), stratal surfaces become increasingly parallel to each other and to the underlying sequence boundary, and they pass gradually into the comparatively thin sediments of the deep shelf.

Spatial Variations of Sedimentation within Sequences

Landward of Rollover of Underlying Sequence Boundary.—Sediments are preserved landward of the rollover of the immediately underlying sequence boundary only within sequence O6. This interval is represented at Island Beach and Atlantic City (Figs. 3, 4C, 6A, 7A) by a basal shell bed (transgressive lag) and by several meters of *in situ* glauconite (glauconite sand with minor amounts of quartz sand). Upward deepening from inner to inner middle neritic is indicated by a quantitative assessment of benthic foraminiferal biofacies (Pekar and Kominz 2001). Sequence O6 is unconformably overlain by another transgressive lag, at the base of lower Miocene sequence Kw0 at Atlantic City and at the base of sequence Kw1a at Island Beach (Fig. 3).

Immediately Seaward of Rollover of Underlying Sequence Boundary.—Two-dimensional reconstruction of stratal geometry indicates that the thickness of sediment deposited immediately seaward of the rollover of the underlying sequence boundary is greatly expanded, to between 20 and 50 m (Fig. 7), with some notable variations in detail.

Lower Oligocene sequences consist almost entirely of highstand sediments 20–40 m thick, with transgressive sediments represented by no more than 1–3 m at the base (Fig. 7B). In sequence O1 at ACGS#4, an updip borehole, the highstand systems tract is composed mainly of medium to coarse quartz sand, whereas at Bass River, coeval sediments consist predominantly of detrital glauconite sand (Figs. 4A, 4B, 7B). We infer that quartz-rich highstand sediments are in general more proximal than glauconite-rich sediments. Glauconitic sand is similarly present in sequence O2 at Island Beach (Figs. 4C, 7B).

Upper Oligocene sequences also vary according to proximity to the rollover of the underlying sequence boundary. At AMCOR 6011, sequence O4 consists of a thin transgressive interval ($\sim$ 4 m) overlain by $\sim$ 36 m of quartz-rich highstand sediments (Figs. 5A, 7A), an arrangement that is similar to sequence O1 at ACGS#4. Sequence O5 at Great Bay contains a relatively thick transgressive unit ($\sim$ 10 m) compared to the same sequence O5 at the more downdip Atlantic City site, in which the condensed section directly overlies the sequence boundary with no transgressive sediments preserved (Figs. 5B, 6A, 7A). Transgressive units are similarly thin in sequence O6 at Cape May (Figs. 6B, 7A). Age models from Pekar et al. (2000) indicate that in sequence O5 at Atlantic City and sequence O6 at Cape May, sedimentation continued almost to the time represented by the correlative conformity of the overlying sequence boundary (i.e., sea-level low stand). This suggests that the sediments were deposited close to or seaward of the rollover of that surface (Fig. 7A), an interpretation that is corroborated by along-strike projection of those boreholes to *Oceanus 270* seismic profile 529 (Fig. 1; Pekar 1999).

Sediments Seaward of the Thick Sedimentary Wedges.—Strata deposited at clinoform ''toes'' and in deep shelf settings are typically thin ($<$ 10 m). They consist of clayey glauconite sand and glauconitic clay, silt and, less commonly, fine quartzose sand with thin-shelled bivalve fragments (Figs. 2, 3, 7; Pekar 1999). These units were deposited for the most part during early transgression (e.g., sequence O2 at Atlantic City), although in one case during late regression (e.g., sequence O2 at Cape May; Figs. 6B, 7A; Pekar 1999). Although lowstand systems tracts are not preserved in our cores, it is possible that thin, lenticular lowstand units are present outside the area studied. This could be the case especially for the basal sequence boundaries of lower Oligocene sequences ML and O1, for which significant sea-level falls appear to have resulted in subaerial exposure of the rollover. The expanded thickness of sequence O4 at Atlantic City ($\sim$ 20 m; Fig. 6A), with well developed transgressive and highstand intervals separated by a thin condensed section, suggests a location intermediate between the shallow shelf and deep shelf environments.

Substantial thicknesses of Oligocene sediment ($\sim$ 30–75 m) are found well offshore, near the present shelf break, and 100 to 150 km from the coastal-plain boreholes (Mountain et al. 1996). However, in the absence of sufficiently precise dating and constraints on changes in paleo-water depth, it is not possible to assign these deposits with confidence to a particular systems tract.

Three-Dimensional Variations in Sequence Development.—The reconstructed clinoformal architecture interpreted in this paper is well supported by both dating and facies analysis, and is corroborated by *Cape Hatteras 0698* seismic reflection data from the inner shelf (Monteverde et al. 2000). However, as might be expected, evidence exists for three-dimensional variability in sequence development. This is suggested by two-dimensional flexural backstripping estimates of depositional slopes that deviate from expected values (see above). For example, during the early Oligocene, the apparent gradient in the dip direction between ACGS#4 and Bass River was greater than the characteristic value of 1:1,000 (Fig. 2; Pekar et al. 2000). Similar variability is noted in the apparent gradient of the entire shallow shelf at $\sim$ 24 Ma (Pekar et al. 2000). Also, sequence O4 contains a relatively thick ''toe'' seaward of the Great Bay borehole. These departures from two-dimensionality are best explained in terms of laterally variable rates of sediment input and localized loading of the margin, and consequently, they draw attention to an issue that needs to be addressed in future research.

Amalgamated Sequence Boundaries

Most of the sequence boundaries in the Oligocene of New Jersey become amalgamated up dip (Fig. 8). The best example is the unconformity that in many places separates Oligocene from Miocene strata, and which has been correlated with the informally named surface m6 in offshore seismic reflection profiles (Fig. 8A; Miller et al. 1998b). At up-dip sites such as ACGS#4 and Bass River, this surface is associated with a hiatus in excess of 11 Myr (Pekar et al. 2000). The hiatus decreases in a seaward direction, to 7.4 Myr at AMCOR 6011, 3.1 Myr at Great Bay, 1.4 Myr at Atlantic City, and only 0.1 Myr at Cape May. The Eocene–Oligocene boundary is also a composite surface, but in this case the duration of the associated hiatus tends to increase in a seaward direction owing to a combination of sediment starvation and marine erosion on the deep shelf (Fig. 8B). At ACGS#4 (an up-dip site), the hiatus is only 0.3 Myr. The hiatus is 1.2 Myr at Bass River, 1.6 Myr at Island Beach, 2.9 Myr at Atlantic City, and 1.8 Myr at Cape May.

←

FIG. 7.—Generalized sequence stratigraphic architecture in New Jersey, showing lithology and systems-tract distribution within sequences: **A)** upper Oligocene; **B)** lower Oligocene. Also depicted in part A is the physiographic terminology used in this paper. Arrows indicate approximate location of generalized borehole stratigraphy within sequence framework. Paleo-water depths shown are for eustatic low stands. In contrast, paleo-water depths near the rollover during eustatic high stands are estimated to be 85 $\pm$ 25 m (Pekar and Kominz 2001). See Figure 3 for lithologic key.

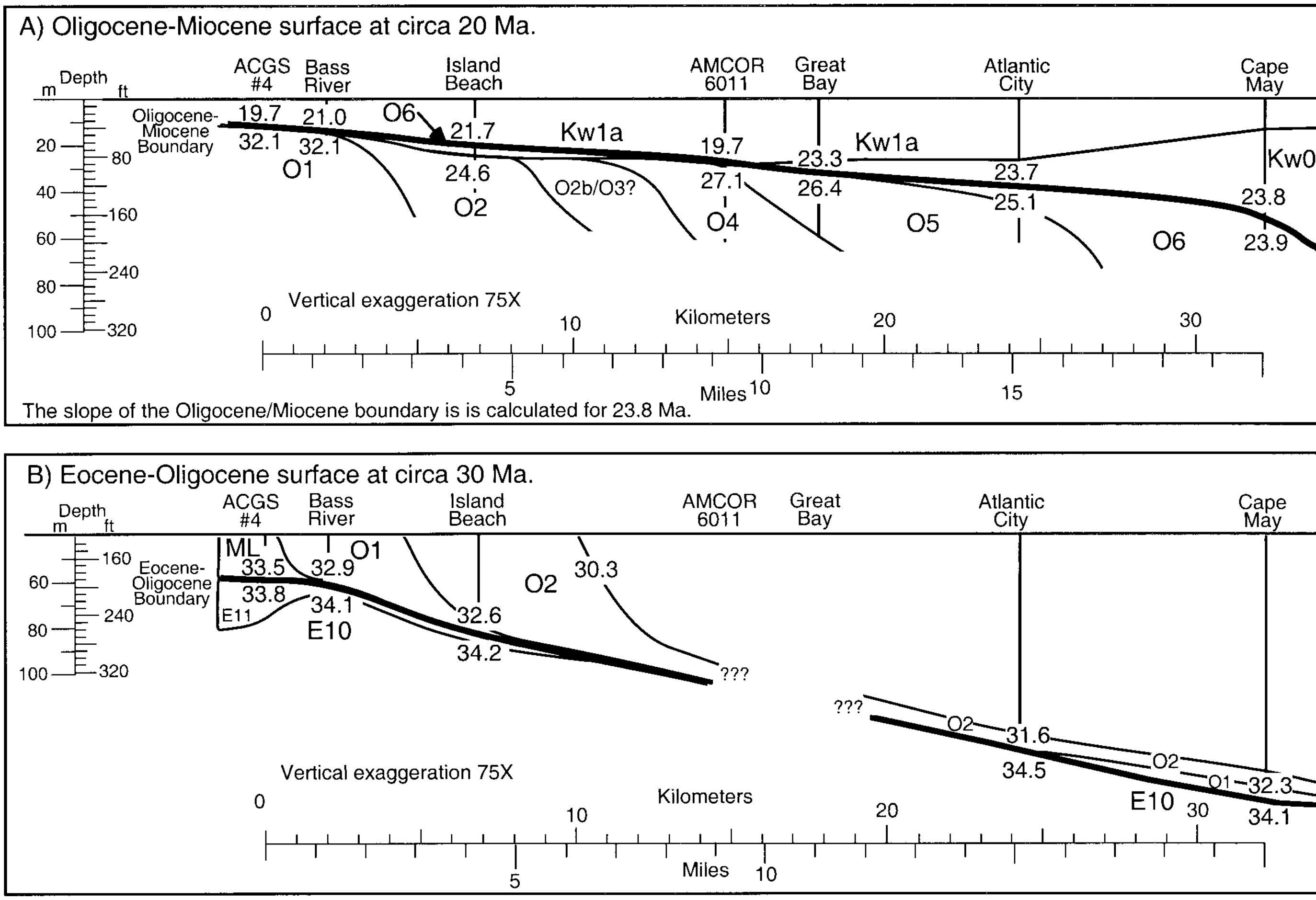


FIG. 8.—Ages of sediments immediately above and below **A)** Oligocene–Miocene boundary (seismic surface m6 of Mountain et al. 1996); and **B)** Eocene–Oligocene boundary (seismic surface o1 of Mountain et al. 1996). Potential erosion is greater in the updip part of the profile than in the downdip part. In part A, hiatus decreases in seaward direction from > 11 Myr at ACGS#4 to 0.1 Myr at Cape May. In part B, hiatus increases in seaward direction from 0.3 Myr at ACGS#4 to 2.9–1.8 Myr at Atlantic City and Cape May.

Evolution of Sequence Boundaries

An important result of our study is to show that sequence boundaries developed during progradation over a finite interval of geological time (see also Christie-Blick 1991; Helland-Hansen and Gjelberg 1994; Christie-Blick and Driscoll 1995; Plint and Nummedal 2000; Pekar et al. 2001). They did not form instantaneously in the manner suggested by Haq et al. (1987), Vail (1987), Posamentier et al. (1988), Van Wagoner et al. (1990), and Van Wagoner (1995), or according to the rationale of Posamentier and Allen (1999) and Posamentier and Morris (2000). In the case of the latter, sequence boundaries are inferred to correspond in time with the onset of ''relative'' sea-level fall, even though surfaces so interpreted tend to diverge from the most obvious stratal discordance. Offlap at sequence boundaries in the New Jersey Oligocene does not appear to be due to erosional truncation of originally sigmoid clinoforms. With the possible exception of lower Oligocene sequences ML and O1, lowstand deposition (a conceptual consequence of enhanced subaerial erosion) did not take place, and transgressive sediments are compositionally and texturally different from those associated with progradation. Offlap therefore must have arisen primarily (but not entirely) as a result of sediment bypassing and seaward propagation of each sequence boundary. In the case of the surface marking the top of sequence O6, we estimate that sedimentation ceased at least 1 Myr earlier at inboard sites such as Atlantic City and Island Beach than near the rollover of that surface at Cape May (Fig. 3). The composite sequence boundary that in many places divides Oligocene from Miocene sediments similarly evolved over a span of at least 7.7 Myr encompassing the deposition of sequences O2 to O6 (Fig. 8). We draw a careful distinction between the interval over which a particular unconformity may have evolved before it was buried and the time represented by the geometrically specified correlative conformity of that surface. The latter is well constrained, particularly in the case of upper Oligocene sequences, close to the time of eustatic low stand (Pekar et al. 2001).

Relation with Lithostratigraphy

Conventional lithostratigraphic units within the New Jersey Oligocene are markedly diachronous (Fig. 3). Two formations are recognized: the Atlantic City Formation is composed mainly of glauconitic quartz sand with subordinate silt and clay; the underlying Sewell Point Formation consists of glauconitic clay and silt with minor clayey glauconitic quartz sand. The unconformable top of the Atlantic City Formation becomes younger in a seaward direction, from 32.3 Ma (top of sequence O1) at ACGS#4 to 23.9 Ma (top of sequence O6) at Cape May (Fig. 3). The base of the same formation intersects as many as seven sequence boundaries from the unconformable base of sequence ML at ACGS#4 (33.5 Ma) to a level within sequence O6 at Cape May (< 25.7 Ma). The base of the Atlantic City Formation at Cape May is therefore at least 6.6 Myr younger than the top of the same formation at ACGS#4. While unsurprising in strongly progra-

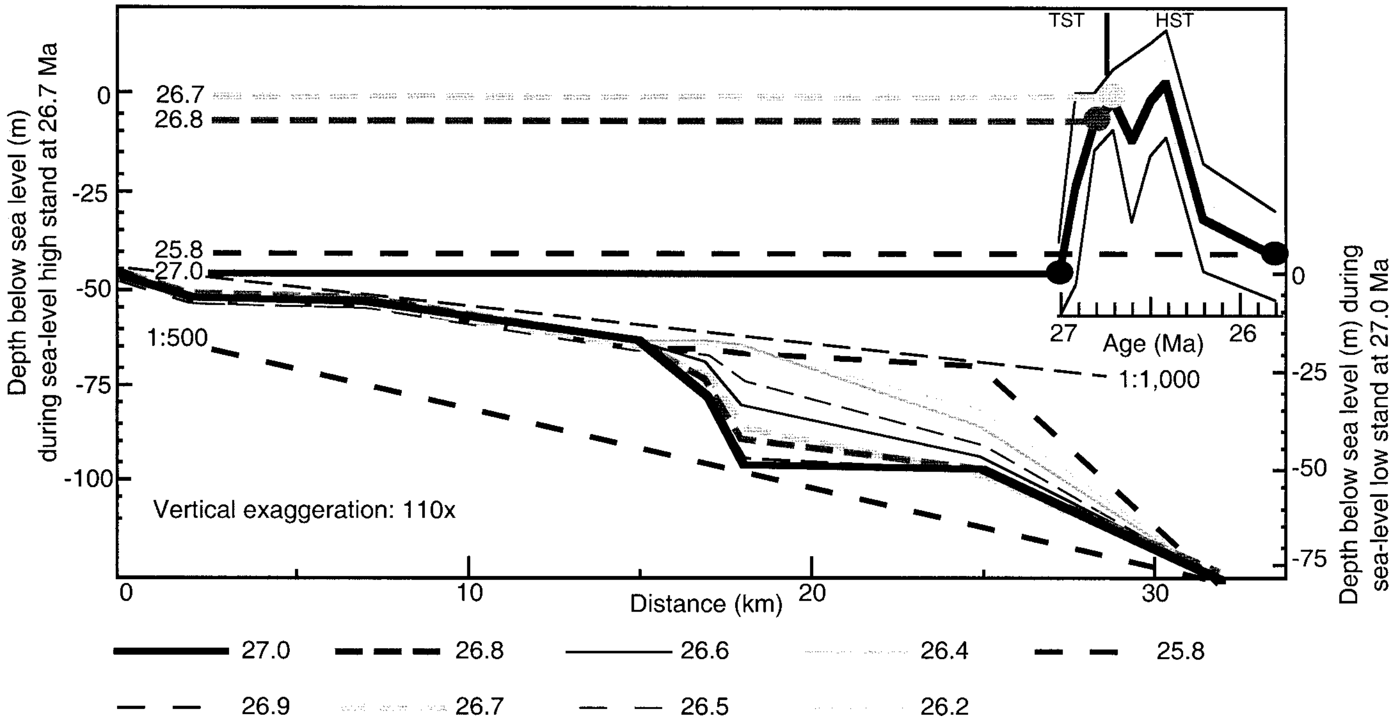


FIG. 9.—Dip profile for sequence O5 with time surfaces reconstructed by flexural backstripping, and an estimate of corresponding sea-level changes between 27.0 Ma and 25.8 Ma (from Kominz and Pekar 2001). Time surfaces show evolution of physiographic profile as sediments were deposited, by accounting for compaction of underlying sediments, flexural loading, and thermal subsidence. Gradient is ~ 1:1,000 for shallow shelf, and ~ 1:500 for deep shelf. Apparent sea-level changes were obtained by multiplying eustatic estimates by 1.48 to account for water loading, with spatial resolution indicated by shading. Time surfaces: 27.0 Ma is lower sequence boundary; 26.8 Ma divides lower transgressive interval from the mid- to late transgressive interval; 26.7 Ma represents the condensed section; 25.8 Ma is upper sequence boundary.

dational deposits, documentation of such extreme diachrony reinforces the point that lithostratigraphic subdivision tends to obscure rather than illuminate the manner in which the sediments accumulated.

Our experience in the Oligocene suggests that comparable patterns may be present in older deposits of the New Jersey coastal plain. The Cretaceous, for example, is composed of at least four gross stratigraphic intervals, each representing a span of 2 to 7 Myr (cf. 9.6 Myr for the Sewell Point and Atlantic City formations of the Oligocene), and characterized by a basal glauconitic sand, a medial unit of silt and clay, and an upper unit of quartz sand (Olsson 1991). Owing to the limited constraints currently provided by only two continuously cored boreholes and with higher-order sequence development yet to be recognized, it is not possible to evaluate the degree to which facies within these intervals are diachronous.

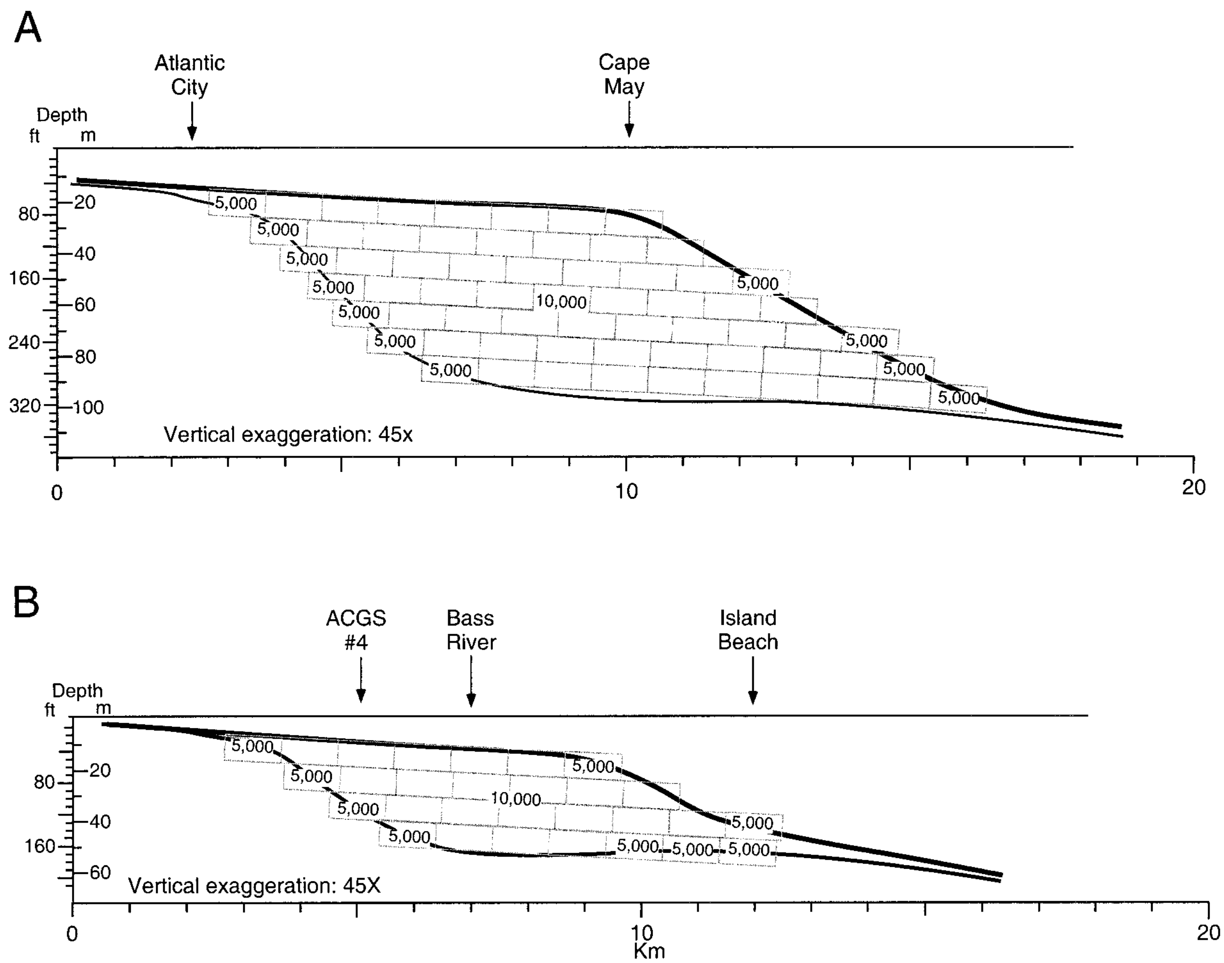
FACTORS CONTROLLING PATTERNS OF SEDIMENTATION

Factors controlling patterns of sedimentation in the Oligocene of the New Jersey margin include physiography, generally low siliciclastic sediment flux, a location landward of the hinge zone of the passive margin, slow subsidence, low to moderate amplitudes and rates of eustatic change (10–50 m over spans of ~ 1–2 Myr), and an active wave climate, especially on the shallow shelf. Many of these factors are interrelated, with feedbacks. For example, an increase in sediment supply tends to result in a decrease in water depth, and in more energetic wave action at the sea floor.

Physiography

Two-dimensional flexural backstripping of the New Jersey margin shows that uppermost Eocene and Oligocene sediments prograded onto an existing starved carbonate-dominated shelf with a gradient of 1:500 (0.11°; Fig. 2; Steckler et al. 1999; Pekar et al. 2000). This led to the development of a terraced physiography, in which the deep shelf was separated from a lower-gradient coastal plain and shallow shelf (1:1,000; 0.06°) by an intermediate slope (< 1:100; 1.0°) with < 50 m of bathymetric relief (here termed the intra-shelf slope). This relief was smallest for the earliest-deposited Oligocene sediments (~ 20 m for sequence ML), and increased with time (Steckler et al. 1999; Kominz and Pekar 2001).

The paleo-water depth at the rollover, as it existed at any moment within a sea-level cycle, typically varied from a minimum of 20 ± 10 m to a maximum of 85 ± 25 m (Pekar and Kominz 2001). The minimum estimate is constrained by benthic foraminifers recovered from immediately below the tops of sequences O1, O2, O4, O5, and O6; by an estimated paleo-water depth of ~ 20 m in the lower part of sequence O6 at Atlantic City, located immediately landward of the underlying sequence boundary rollover; and by two-dimensional reconstructions (Fig. 9) that indicate paleo-water depths in the range of 20–30 m at the rollover near eustatic low stands. At Cape May, close to the rollover at the top of sequence O6, sedimentation ceased at a water depth of 30 ± 10 m and resumed at a depth of 45 ± 15 m. The sequence boundary is associated with a hiatus of < 0.2 Myr, suggesting that there was minimal erosion at this site. No fluvial, deltaic, estuarine, shoreface, or other nearshore sediments (< 15 m paleodepth) have been identified either immediately below or immediately above any of the sequence boundaries. Although such sediments could have been preserved locally but not intersected in existing boreholes, their absence at multiple levels at each location sampled is consistent with the other constraints. Only in the case of the boundaries at the tops of sequences E11 (basal Oligocene) and ML was the shallow shelf exposed in the vicinity of the rollover. This is indicated by foraminiferal evidence for paleo-water depths as shallow as 25 ± 10 m at clinoform toes at the base of sequence ML at ACGS #4 and sequence O1 at Bass River (Pekar and



Sequence	Area of thick sedimentary wedge (m^2)	Duration (Myr)	Flux (m^2/Myr)
O1	245,000	1.2	204,000
O6	585,000	1.8	325,000

FIG. 10.—Estimates of cross-sectional area and sediment flux (m^2/Myr) for **A)** upper Oligocene sequence O6 and **B)** lower Oligocene sequence O1. The reconstructions are based upon decompacted thicknesses at boreholes indicated (from Kominz and Pekar 2001) and assume gradients for shallow shelf, slope and deep shelf of 1:1,000, 1:100, and 1:500, respectively (Pekar 1999; Steckler et al. 1999). The horizontal distance between rollovers in boundaries of sequence O6 was measured on seismic profile Oceanus *270* line 529 (see Fig. 1). The distance between rollovers in the boundaries of sequence O1 assumes that rollover in lower surface is no more than 4.5 km landward of ACGS#4, and that rollover in upper surface is $\sim$ 2.5 km landward of Island Beach. This is based upon estimates of slope relief ($\sim$ 25 m) and slope gradient (1:100). Each complete rectangle represents 10,000 m^2. Partially filled rectangles are taken to represent 5,000 m^2. No account is taken of coeval sediments deposited on deep shelf.

Kominz 2001), a stratigraphic level at which the bathymetric relief of the shelf slope was only 20 m.

Sediment Flux

Estimates of decompacted sediment thickness coupled with high-resolution age control indicate that the siliciclastic sediment flux was generally low in the Oligocene, increasing from an average of 0.20 km^2/Myr during deposition of sequence O1 to $\sim$ 0.33 km^2/Myr for sequence O6 (Fig. 10). This increased flux continued into the early Miocene, increasing in the middle Miocene to as much as forty times that of the Oligocene (Steckler et al. 1999). The low Oligocene estimates are consistent with the abundance of authigenic glauconite (a qualitative indicator of low sedimentation rates), particularly in lower Oligocene sequences, and with an increase in the siliciclastic component with time. Sedimentation rate also varied substantially as a function of location, and during the deposition of any particular sequence. Highest average rates of accumulation are estimated immediately seaward of the rollover in an underlying sequence boundary (40 to 70 m/Myr; Pekar et al. 2000), and lowest rates ($<$ 15 m/Myr), in the vicinity of the clinoform toe and deep shelf portions of each sequence. Comparable differences in accumulation rate characterize highstand versus transgressive units, with glauconitic sediments being most abundant in the latter.

Tectonic Setting and Subsidence

Oligocene sediments beneath the present coastal plain accumulated entirely landward of the hinge zone, the transitional region between thinned

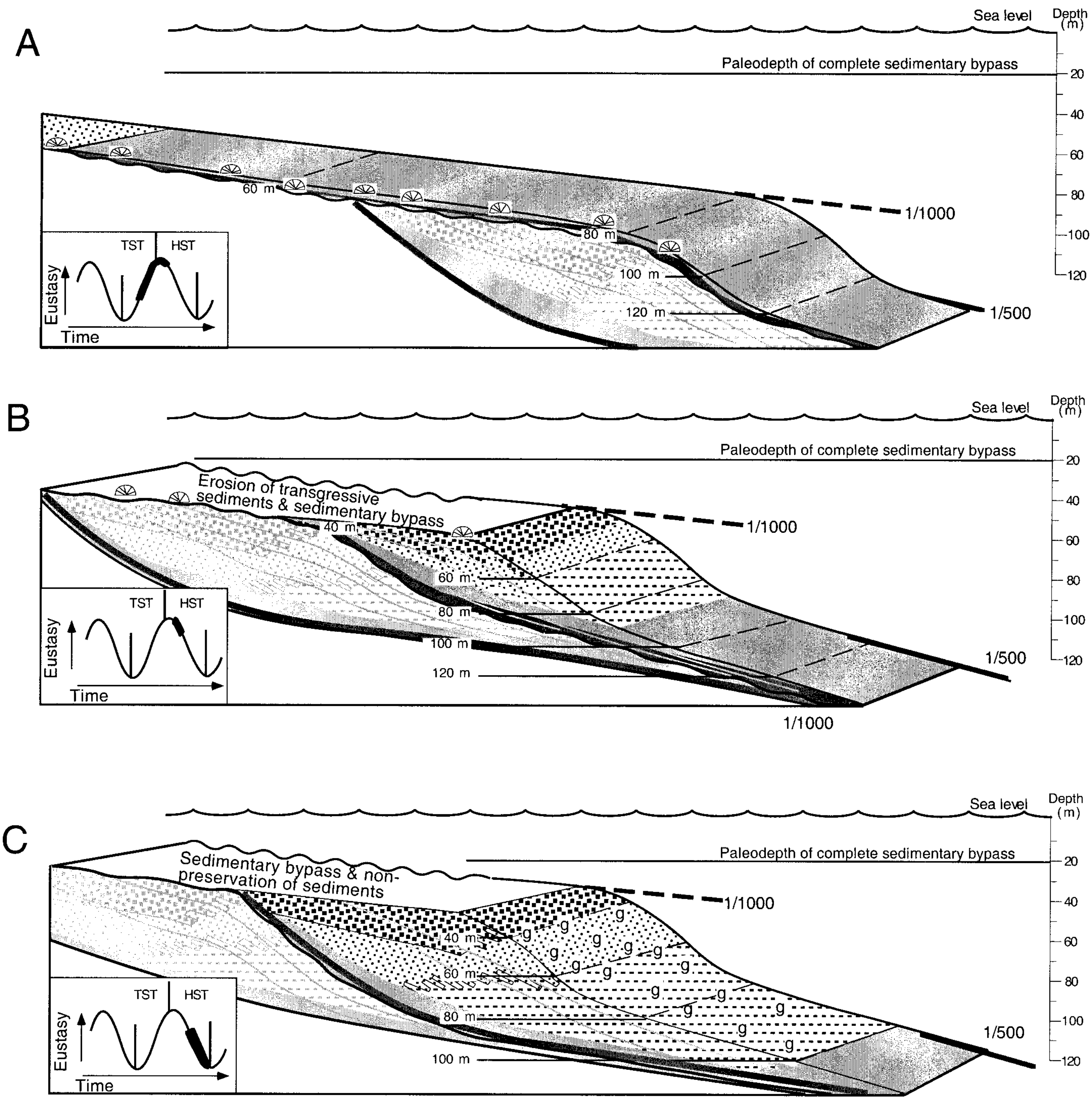


FIG. 11.—Three-dimensional block diagram showing lithologic distribution and physiography during deposition of sequences O2 to O6, with reference to interpretations of eustatic change (from Kominz and Pekar 2001): **A)** eustatic rise and eustatic high stand; **B)** early eustatic fall; **C)** late eustatic fall. Total sedimentary bypass is estimated to have begun at water depths at least as deep as ~ 20 ± 10 m. Previous sequence is shown in gray. See Figure 3 for lithologic key.

and comparatively unthinned crust (Reynolds et al. 1991; Steckler et al. 1993). Tectonic subsidence was extremely slow, first because the margin was already 130 Myr old at the beginning of the Oligocene (Reynolds et al. 1991; Steckler et al. 1993; Steckler et al. 1999), and second because the subsidence had to be transmitted flexurally from the stretched portion of the margin through a lithospheric plate with an effective elastic thickness of ~ 30 km (Kominz and Pekar 2001). The total subsidence was augmented by compaction and sediment loading, but the latter was limited by plate rigidity and by the fact that Oligocene sedimentation was for the most part restricted to an area little more than 35 km across.

Eustatic Change

Eustatic change influenced both the locus and character of Oligocene sedimentation at the New Jersey margin (Figs. 3, 7). Low to moderate amplitudes and corresponding rates of sea-level fall (10–50 m fluctuations

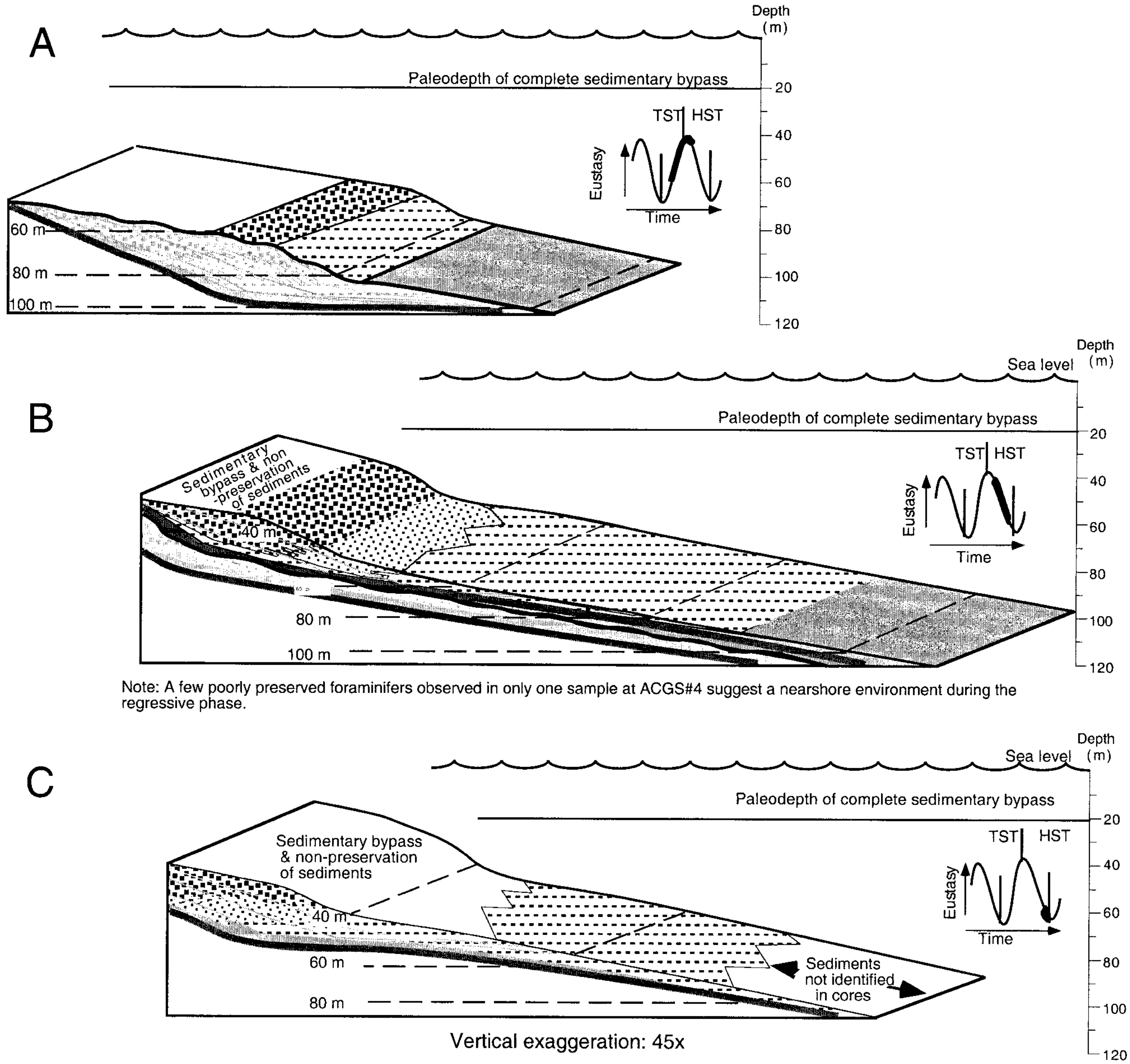


FIG. 12.—Three-dimensional block diagram showing lithologic distribution and physiography during deposition of sequences ML and O1, with reference to interpretations of eustatic change (from Kominz and Pekar 2001): **A)** eustatic rise and high stand; **B)** early eustatic fall; **C)** latest eustatic fall. Sediments deposited on the deep shelf are poorly represented in cores. Total sedimentary bypass is thought to have begun at paleo-water depths at least as deep as ~ 20 ± 10 m. Previous sequence is shown in gray. See Figure 3 for lithologic key.

over intervals of ~ 1–2 Myr) were sufficient to overcome the exceedingly slow subsidence and generate sequence boundaries. A long-term eustatic fall of ~ 30 m between 34 Ma and 23 Ma (Kominz and Pekar 2001) resulted in the overall pattern of offlap that is characteristic of Oligocene sequences at the New Jersey margin.

Sedimentation associated with the eustatic rise and transgression of the shoreline was dominated by glauconitization under conditions of sediment starvation. The onset of eustatic fall led to shoaling of the shallow shelf, repeated cannibalization of terrigenous sediment, and a gradual increase in the terrigenous flux. Glauconization ceased on both the shallow shelf and slope, but detrital glauconite continued to be delivered to the slope as a result of the erosion of previously deposited transgressive sediment. Glauconization also continued on the deep shelf, where rates of sediment accumulation remained low. Progradation (''highstand'' sedimentation) continued until the eustatic minimum because the conditions generally required for the development of a lowstand systems tract did not arise (Pekar et al. 2001).

Wave Climate

The development of marked offlap during the Oligocene is ascribed to marine bypass and slow degradation of the shallow shelf while siliciclastic sediments continued to accumulate in adjacent slope and deep shelf settings (Figs. 7, 11, 12). Evidence described above suggests that with the possible exception of the two lowermost Oligocene sequence boundaries, the minimum paleo-water depth at the rollover was never less than 20 ± 10 m. We infer that the shallow shelf was characterized by a wave climate comparable to that of the modern shelf at the same water depths, with signif-

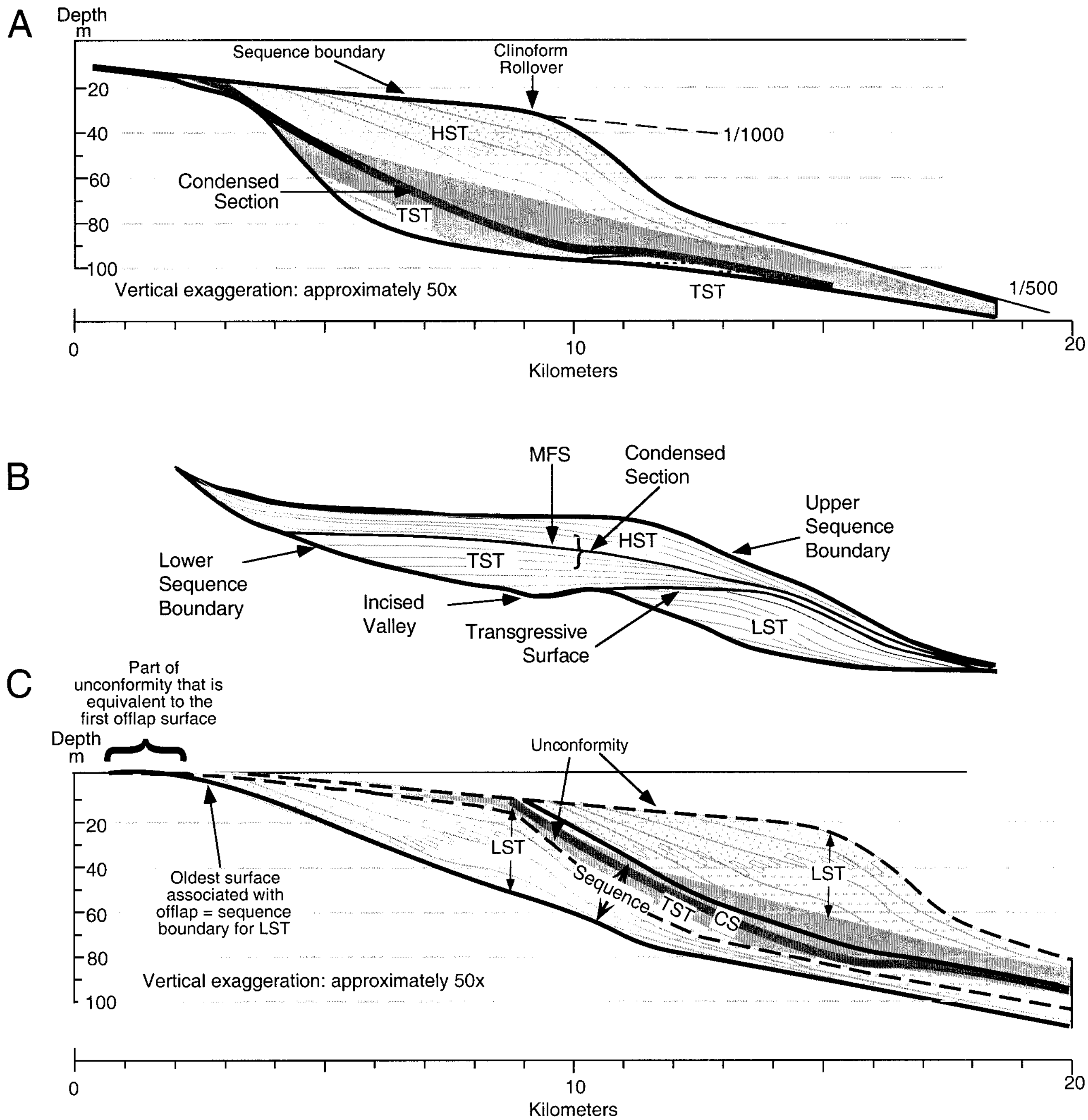


FIG. 13.—Comparison of conceptual models for sequence architecture: **A)** New Jersey Oligocene (this paper); **B)** Vail et al. (1987); and **C)** architecture from A, reinterpreted according to the forced-regression concept of Posamentier et al. (1992) and Posamentier and Allen (1999). In C, sequence boundaries are located immediately above condensed sections, where no hiatus can be recognized, and the most prominent offlap surfaces are within sequences. Dashed lines indicate location of sequence boundaries, as interpreted in part A. Abbreviations for systems tracts: HST, highstand; TST, transgressive; LST, lowstand. See Figure 3 for lithologic key for A and C.

icant along-shelf transport. Once the shallow shelf had shoaled to a depth of less than about 90 m, the depth at which the rollover begins on active modern shelves (D.J.P. Swift, personal communication, 2001), marine bypass would have started. Continued shoaling would eventually have led to a situation in which all of the available sediment was accumulating seaward of the rollover, and the shelf itself was subject to marine erosion. On the basis of paleo-water-depth variations and preserved sequence architecture, we estimate that ~ 65–80% of the shallow shelf flooded during each eustatic rise would have become subaerially exposed during the subsequent fall. However, the absence of major river systems prevented the shoreline from reaching the rollover in most of the sequences studied, in spite of rates of eustatic fall considerably greater than the local rate of tectonic subsidence.

Unlike the considerably steeper and deeper modern continental slope that merges with the continental rise, the Oligocene intra-shelf slope is inferred to have been wave-influenced to a depth of as much as several tens of meters below the rollover, with no evidence for mass wasting or sediment gravity flow. Sandy sediments are found preferentially in upper intra-shelf slope settings. With the exception of one sequence at Bass River, there is no evidence for the interstratification of transported shallow-water benthic foraminifers (such as abraded or broken tests) and *in situ* deeper-water benthic foraminifers (Pekar and Kominz 2001). The deep shelf was dominated by hemipelagic sedimentation below wave base. Only at eustatic low stands associated with the tops, sequences E11 (basal Oligocene) and ML, was the deep shelf wave-influenced at its updip limit (Fig. 12).

COMPARISON WITH PUBLISHED MODELS

Sequence architecture in the New Jersey Oligocene differs significantly from the standard ''Exxon model'' (Figs. 13A, B; e.g., Haq et al. 1987; Vail 1987; Posamentier et al. 1988; Van Wagoner et al. 1990). This is due in part to the unique combination of factors governing sedimentation in the example that we have studied and in part to assumptions by earlier workers that may prove to be invalid. Sequences in the New Jersey Oligocene are highstand-dominated because the bulk of the sediment accumulated during progradation across a formerly sediment-starved deep shelf, and point sources that might have led to the deposition of lowstand systems tracts did not develop. Highstand systems tracts do not extend significantly inboard of underlying sequence boundary rollovers owing to exceedingly slow tectonic subsidence augmented by flexurally transmitted sediment loading and a long-term eustatic fall through the Oligocene (Kominz and Pekar 2001). Transgressive systems tracts are thin to absent owing to sediment starvation and, on the shallow shelf, as a result of erosion during subsequent sea-level falls. This is an extreme case of the situation described by Kidwell (1997) from the Miocene of Maryland, in which any sediments deposited during regression of the shoreline were subsequently stripped off, leaving a series of transgressive units separated by sequence boundaries. Architecture illustrated in the Exxon model may be appropriate for settings characterized by greater differential subsidence and sediment supply.

Evidence discussed in this paper for the manner in which sequence boundaries evolve during progradation is of general significance. The expectation that eustatic falls at rates considerably more rapid than the rate of tectonic subsidence lead more or less inevitably to complete shelf exposure, valley incision, and lowstand deposition is not borne out by our data. The offlap geometry that characterizes Oligocene sequences in New Jersey is consistent with the geometry of the falling-stage systems tract of Plint and Nummedal (2000), and with their qualitative interpretation with respect to the timing of ''relative'' sea-level change. However, our data cast doubt on the universal applicability of the concept of forced regression in accounting for such offlap (cf. Hunt and Tucker 1992; Posamentier et al. 1992; Posamentier and Allen 1999; Posamentier and Morris 2000).

We choose not to use the falling-stage terminology of Plint and Nummedal because in our data it amounts to little more than relabeling highstand deposits, and it suffers from most of the same conceptual limitations as the Vail scheme without improving that scheme. As a general proposition, we doubt whether highstand and falling-stage deposits can be objectively distinguished, or whether such distinctions are useful. Application of the interpretive rationale of Posamentier and Allen (1999) and Posamentier and Morris (2000), in which sequence boundaries are inferred to correspond in time with the onset of ''relative'' sea-level fall, in our data requires the tracing of ''sequence boundaries'' at condensed sections, leaving the most obvious unconformities within ''sequences'' (Fig. 13C). These authors are at liberty to propose a new classification scheme for sediments and sedimentary rocks, but we think that what they suggest is fundamentally at odds with the principles of sequence stratigraphy.

CONCLUSIONS

Factors controlling the development of stratigraphic architecture at passive continental margins were evaluated quantitatively using the Oligocene record at the New Jersey margin. We conclude that the following were important in the formation of the observed highstand-dominated sequences with well developed offlap: the existence of a terraced physiography; generally low siliciclastic sediment flux; a location landward of the hinge zone of the passive margin, with slow subsidence; modest amplitudes and rates of eustatic change; and an active wave climate that permitted efficient lateral transport and bypass of sediment across the shallow shelf.

Our data cast doubt on several widely held assumptions in sequence stratigraphy. Sequence boundaries in the New Jersey Oligocene formed gradually during progradation, and not as a result of short-lived subaerial exposure and incision of the shelf. This is in spite of rates of eustatic fall that at times greatly exceeded the local rate of tectonic subsidence. Offlap in New Jersey is not necessarily due to forced regression. The absence of lowstand sediments is consistent with the continuation of highstand sedimentation to eustatic minima (see Pekar et al. 2001). Although the example studied represents an end member in the spectrum of sedimentary systems, our data show that geometrically delineated sequence boundaries do not necessarily correspond with the onset of falling ''relative'' sea level.

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APPENDIX 1

Sequence ML.—The Mays Landing (ML) sequence is observed only at ACGS#4 (615–565 ft; 187.5–172.2 m; Fig. 4A) and is the oldest Oligocene sequence observed beneath the New Jersey coastal plain (33.5–33.2 Ma). The basal surface is associated with a possible hiatus of 0.7 Myr (34.2–33.5 Ma). A shelly glauconite sand just above the surface (lithofacies G1; 615–613.5 ft; 187.5–186.8 m) is interpreted as a transgressive lag. The rest of the sequence consists of clay and silt (lithofacies S1; 613.5–580 ft; 186.8–176.8 m), overlain by silty fine quartz sand (lithofacies F1; 580 ft to the top of the sequence at 565 ft; 176.8 to 172.2 m), and is interpreted as highstand systems tract. Benthic foraminifers are rare within Oligocene samples, probably as a result of dissolution. Rare specimens of *Elphidium* spp. near the top of the sequence suggest a possible nearshore environment ($<$ 20 m; Christensen 1995).

Sequence O1.—Sequence O1 is observed at ACGS#4 (Fig. 4A), Bass River (Fig. 4B), Island Beach (Fig. 4C), and Cape May (Fig. 6B), and is dated as early Oligocene (32.9–32.1 Ma). The sequence is thickest and coarsest-grained at ACGS#4 and Bass River, with calcareous microfossils best preserved at the latter. The basal surface at Bass River (Fig. 4B) is located at 676 ft (206.0 m), and is associated with a hiatus of 1.2 Myr (34.1–32.9 Ma). Above that level, a thin interval of clayey glauconite sand (lithofacies G2; 675–670 ft; 205.7–204.2 m) is interpreted as transgressive. This is overlain by sandy glauconite sand (reworked; lithofacies DG1; 670–555 ft; 204.2–169.2 m) and accounts for the rest of the sequence. Paleo-water depths shoal upwards from 75 $\pm$ 20 m to 25 $\pm$ 10 m (Pekar and Kominz 2001). The upper sequence boundary is located at 555 ft (169.2 m) and is associated with a hiatus of 10.9 Myr. It is characterized by sharp lithologic changes within a 0.5 m interval between shelly medium quartzose glauconite sand below and shelly dark grayish brown glauconitic silty clays above. Within this interval are reworked small shells. In contrast, large thick shells are found within overlying silty clays (analogous to shell lags of Kidwell 1997).

At ACGS#4 (Fig. 4A), the basal surface is overlain by indurated shelly clayey glauconitic quartzose sand (lithofacies SH1; 565.5–565.0 ft, 172.4–172.2 m), interpreted as transgressive; and is overlain in turn by shelly fine to medium to coarse quartzose sand (lithofacies F3 to C4; 565–490 ft; 172.2–149.4 m), interpreted as highstand systems tract. The upper sequence boundary is located at 490 ft (149.4 m) and is associated with a hiatus of 12.4 Myr. A sharp lithologic change is observed between shelly fine to coarse quartz sand below and sandy silty clays above.

At Island Beach and Cape May (Figs. 4C and 6B), sequence O1 is thin (< 10 m), consisting of clayey silty glauconite sand (lithofacies G5) and slightly sandy glauconitic clay (lithofacies CL2; Pekar et al. 1997a), with an outer neritic paleo-water depth estimate ($\sim 100 \pm 30$ m; Pekar and Kominz 2001). The basal unconformity of sequence O1 at Island Beach (697 ft, 212.4 m) is associated with a possible hiatus of 1.2 Myr. It is characterized by weathered shells extending upwards from the base and a sharp lithologic change from clays below to medium-grained glauconite sands above. The basal unconformity of sequence O1 at Cape May (1360 ft, 414.5 m) is associated with a hiatus of 1.5 Myr. It separates clays below from sandy glauconitic clays above. These sediments were deposited well seaward of clinoform rollovers, and they are thought to represent early transgressive or late highstand deposition.

Sequence O2.—Sequence O2 is present at Island Beach (Fig. 4C), Atlantic City (Fig. 6A) and Cape May (Fig. 6B), and is dated as early Oligocene (31.6–30.1 Ma; Pekar et al. 2000). The sequence is thickest at Island Beach (678–524 ft; 206.7–159.7 m).

At that borehole, the basal surface (678 ft, 206.7 m) is associated with a hiatus of 1.2 Myr (32.5–31.3 Ma). It separates clayey glauconitic fine quartz sand below from clayey glauconite sand above. Lowermost sediments are clayey *in situ* glauconite sand (lithofacies G5; 678 to $\sim$ 650 ft; 206.7 to $\sim$ 198.1 m), overlain by reworked glauconite sand (lithofacies DG2; $\sim$ 650–524 ft; 198.1–159.7 m). Benthic foraminiferal biofacies indicate that paleo-water depths shallowed from middle neritic (95 ± 25 m) between 678 and $\sim$ 650 ft (206.7 and 198.1 m) to inner neritic ($< 30 \pm 10$ m) between $\sim$ 630 and 523 ft (206.7 and 159.4 m; Pekar and Kominz 2001). The interval with *in situ* glauconite below 650 ft (198.1 m) is interpreted as transgressive, and the rest of the sequence is interpreted as highstand systems tract. At Atlantic City (Fig. 6A), sequence O2 is thin (< 5 m), consisting of a shelly basal layer, overlain by glauconitic clay, silt, and fine sand (lithofacies CL1). These sediments represent a span of 31.6–31.1 Ma, and are tentatively assigned to the transgressive systems tract on this basis. At Cape May (Fig. 6B), the lower surface is associated with a possible short hiatus of 0.4 Myr (1350 ft, 411.5 m) and separates silty clays below from clayey glauconite above. The sequence consists of clayey glauconite sand (lithofacies G2; 1350–1345 ft; 411.5–410.0 m), overlain by clayey sandy glauconite sand and glauconitic clay and silt (lithofacies G5 and CL2; 1345–1314 ft; 410.0–400.5 m). The lowermost part of the sequence (1350 to about 1341 ft; 411.5–408.7 m) is dated as 31.6 to 31.3 Ma, and must therefore have accumulated early in the transgression. The upper part of the sequence (1341–1314 ft; 408.7–400.5 m) is dated as 30.1 Ma, indicating late highstand deposition. Benthic foraminiferal biofacies indicate outer neritic paleo-water depths throughout sequence O2 at both Atlantic City and Cape May (Pekar and Kominz 2001).

A poorly constrained additional sequence (O2b) may be present at AMCOR 6011 (Fig. 5A; Pekar et al. 2000), where it is represented by a single sample of sandy micaceous slightly glauconitic clayey silt (lithofacies S2) at 849 ft (258.8 m). Owing to dissolution, it was not possible to identify benthic foraminiferal biofacies from this sample.

Sequence O3.—Sequence O3 is identified at AMCOR 6011 (Fig. 5A), Atlantic City (Fig. 6A), and Cape May (Fig. 6B; Pekar et al. 2000) on the basis of apparent hiatuses at bounding surfaces. It is not well constrained owing to limited recovery at sites where the sequence is likely to be thickest, but it is thought to encompass at least the interval between 28.9 and 28.3 Ma on the basis of Sr-isotopic age estimates at Atlantic City. At AMCOR 6011 (Fig. 5A), the basal sequence boundary was not penetrated and the upper unconformable surface was not recovered. However, a lithologic change is present between 830 and 820 ft (253.0 and 249.9 m) from sandy silty clay to clayey glauconite sand. The sequence boundary is placed at 827 ft (252.1 m) on the basis of gamma ray logs, with a possible short hiatus of 0.6 Myr. The sequence consists of sandy clayey micaceous silt (lithofacies S2), extending from close to the bottom of the borehole at 840 ft (256.0 m) to 827 ft (252.1 m). Benthic foraminiferal biofacies indicate middle neritic paleo-water depths (55 ± 15 m; Pekar and Kominz 2001). With limited control, it is difficult to interpret systems tracts, but the sediments are tentatively interpreted as highstand deposits on the basis of their age (Pekar et al. 2000). At Atlantic City (Fig. 6A), the basal sequence boundary (1166 ft, 355.4 m) of sequence O3 is associated with a hiatus of 2.2 Myr and separates glauconitic clays below from clayey glauconite sand with minor fine quartz sand above (lithofacies G3; Pekar et al. 1997a). An increase in paleo-water depth in the lower part of the sequence (75 ± 25 m to 115 ± 30 m between 1166 and 1156 ft or 355.4–352.3 m; Pekar and Kominz 2001) indicates deposition during transgression. The rest of the sequence (1156–1138 ft; 352.3–346.9 m) is interpreted as late transgressive or early highstand systems tract. At Cape May (Fig. 6B), sequence O3 consists of glauconitic silt and clayey silty glauconite sand (lithofacies G3), and accumulated in an outer neritic setting (115 ± 30 m paleo-water depth; Pekar and Kominz 2001).

Sequence O4.—Sequence O4 is present at AMCOR 6011 (Fig. 5A), Great Bay (Fig. 5B) and Atlantic City (Fig. 6A), and is of early late Oligocene age (27.9–27.2 Ma). At Atlantic City, the sequence is relatively thick (1138–1072 ft; 346.9–326.7 m; Fig. 6A). The basal sequence boundary is associated with a 1.6 Myr hiatus and separates clayey glauconite sand below from sandy glauconitic clays above. A sandy clay unit observed in the lower part of the sequence (lithofacies CL2; 1135–1114 ft; 345.9–340.8 m; Pekar 1999) is interpreted as early transgressive. The interval from 1114 to 1009 ft (339.5–338.0 m) is characterized by an increase in glauconite up section, as well as by an increase in paleo-water depth from inner to outer neritic on the basis of benthic foraminiferal biofacies (lithofacies G5; Pekar and Kominz 2001). The highest concentration of glauconite sand is observed at 1109 ft (338.0 m), and this is taken to represent the top of the condensed section (Pekar et al. 1997a). The rest of the sequence consists of clayey glauconite sand (lithofacies CL1; 1109–1091 ft; 338.0–332.5 m), overlain by glauconitic clays and clayey fine quartz sand (lithofacies CL1 and F2; 1091–1072 ft; 332.5–326.7 m), and is interpreted as highstand systems tract. Paleo-water depths in this interval range from outer to outer middle neritic (Pekar and Kominz 2001). At Great Bay (Fig. 5B), only the upper part of the sequence was penetrated (1007 to about 975 ft; 307.0 to about 297.2 m). The lowermost sediments encountered (1007 to about 975 ft; 307.0 to about 297.2 m) consist predominantly of slightly glauconitic sandy clayey silt (lithofacies S2; Pekar 1999). Benthic foraminiferal biofacies indicate a middle neritic paleo-water depth (55 ± 15 m; Pekar and Kominz 2001). Incomplete preservation of the sequence makes it difficult to interpret systems tracts. A highstand systems tract is tentatively inferred on the basis of its age and sediment type. At AMCOR 6011 (Fig. 5A), dating is uncertain for this sequence owing to low recovery and stratigraphic mixing of sediments during coring. The basal unconformity at 827 ft (252.1 m) is associated with a possible hiatus of 0.6 Myr (Pekar et al. 2000). An increase in glauconite sand (40%) observed in the sample at 820 ft (249.9 m) is consistent with a gamma-ray well-log increase between 827 and 813 ft (252.1 and 247.8 m; lithofacies G4). A decrease in paleo-water depth between 820 and 794 ft (249.9 to 242.0 m) is indicated by (1) a decrease in the gamma-ray log; (2) a marked increase in medium to coarse quartz sand and a concomitant decrease in clay and glauconite; and (3) a change in the benthic foraminiferal assemblages (Pekar and Kominz 2001). Medium to coarse quartzose sand continues to the top of a sequence at 696 ft (212.1 m; lithofacies C4), indicating an inner neritic environment of deposition. Shallow-water benthic foraminiferal biofacies dominate from 794 to 728 ft (242.0 to 221.9 m), also indicating an inner neritic to inner middle neritic setting. The basal glauconitic interval (827–818 ft; 252.1–249.3 m) is interpreted as transgressive, and the rest of the sequence (818–696 ft; 249.3–212.1 m) is interpreted as highstand systems tract.

Sequence O5.—Sequence O5 is observed at Great Bay (Fig. 5B), Atlantic City (Fig. 6A), and Cape May (Fig. 6B), and is of late Oligocene age (27.0–25.9 Ma). An expanded section is present at Great Bay (980–805 ft; 298.7–245.4 m; Fig. 5B). A basal sequence boundary at $\sim$ 980 ft (298.7 m) is indicated by lithologic and benthic foraminiferal changes between samples at 985 and 965 ft (300.2 and 294.1 m). Clayey glauconite sand (lithofacies G2) represents an increase in paleo-water depth from inner middle to outer neritic between 965 and 945 ft (294.1 and 288.0 m), and is interpreted as transgressive systems tract. Between 945 and 805 ft (288.0 and 245.4 m), upward shoaling is suggested by an overall increase in quartz sand and grain size, and a decrease in clay, with a fine quartz sand facies (lithofacies F2) near the base, which is in turn overlain by medium quartz sand (lithofacies F3) and then coarse quartz sand (lithofacies C3). In the same interval, the paleo-water depth decreases from outer neritic (110 ± 30 m) to middle neritic (85 ± 25 m), and the sediments are interpreted as highstand systems tract. Detrital glauconite increases near the top of the sequence. Sequence O5 is also thick at Atlantic City (1072 to 923 ft; 326.7 to 281.3 m; Fig. 6A). The sequence boundary separates sandy clay below from glauconitic silt and clay above. A thin condensed section is present at the base (1072 to about 1060 ft; 326.7 to about 323.1 m) in the form of glauconitic silt and clay (lithofacies G5). The rest of the sequence shoals upwards (lithofacies S1 to C2). Benthic foraminiferal biofacies analysis indicates an outer middle neritic paleo-water depth (85 ± 25 m) for the lower part of the sequence. Preservation of benthic foraminifers decreases markedly up section; above 980 ft (298.7 m), rare foraminifer species and the coarse character of the lithofacies suggest an inner neritic environment. Sequence O5 is very thin at Cape May (1304.8–1302.0 ft, 397.8–396.8 m; Fig. 6B). The basal surface is associated with an estimated hiatus of 1.6 Myr.

Sequence O5 is dated at Cape May as 26.7 Ma (1303.8 ft; 397.5 m; Pekar et al. 2000), and contains a clayey glauconite sand (lithofacies G3) interpreted as being deposited in an outer neritic environment (Pekar and Kominz 2001).

Sequence O6.—Sequence O6 is of late Oligocene age (25.7–23.9 Ma), and is recognized at Island Beach (Fig. 4C), Atlantic City (Fig. 6A), and Cape May (Fig. 6B; Pekar et al. 2000). The sequence is thickest at Cape May (1300–1181 ft; 396.3–359.9 m). The basal sequence boundary separates sandy clay and silt below from clay above, with a short hiatus of 0.9 Myr. This sequence constitutes a classic shoaling-upward succession (lithofacies CL2 and CL3 overlain by lithofacies C3), with transgressive deposits limited to the basal 6 ft (1.9 m) from 1300 to 1294 ft (396.3–394.4 m). Smaller-scale shoaling-upward units (parasequences) are also observed (Pekar et al. 1997a; Pekar 1999). Three thin parasequences are identified between 1300 and 1270.9 ft (396.3 to 387.4 m) on the basis of lithofacies variations (Pekar et al. 1997a): 1300 to 1290.6 ft (396.3 to 393.2 m); 1290.6 to 1279.0 ft (393.2 to 389.8 m); and 1279.0 to 1270.9 ft (389.8 to 387.4 m). Two thicker parasequences are present between 1270.9 and 1210 ft (387.4 and 368.8 m) and from 1210 to 1181 ft (368.8 to 360.0 m). These five parasequences are also recognized in the gamma-ray log, with a sharp peak at each parasequence boundary. The upper sequence boundary is associated with a short hiatus of < 0.2 Myr, and separates clayey glauconitic medium to coarse quartz sand below from quartzose glauconite sand above. Sequence O6 is thin at Island Beach (Fig. 4C) and Atlantic City (Fig. 6A). In each borehole, abrupt deepening across the basal surface is indicated by shell lags (lithofacies SH1) overlain by glauconitic sand and clayey glauconite sand (lithofacies G4); and by benthic foraminiferal biofacies. Basal sequence boundaries are associated with hiatuses ranging from 5.5 Myr at Island Beach to 0.5 Myr at Atlantic City. The upper surface of the sequence is marked by a similar bed of shells and shell hash at the base of sequences Kw1 and Kw0 and is characterized by hiatuses of 2.6 and 1.5 Myr, respectively. At each borehole, sequence O6 was deposited landward of the rollover in the underlying sequence boundary, and it is represented entirely by transgressive deposits.