TWO-DIMENSIONAL PALEOSLOPE MODELING: A NEW METHOD FOR ESTIMATING WATER DEPTHS OF BENTHIC FORAMINIFERAL BIOFACIES AND PALEOSHELF MARGINS

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ABSTRACT: **A new method developed for estimating water depths of benthic foraminifers was implemented for Oligocene foraminiferal biofacies from the New Jersey Coastal Plain. We combined benthic foraminiferal biofacies and two-dimensional flexural backstripping to construct a two-dimensional paleoslope model. The original depositional geometry of New Jersey Oligocene strata was reconstructed by calculating the effects of sediment accumulation and flexural loading. Paleodepth estimates for benthic foraminiferal biofacies were calibrated to inner neritic facies along the resulting nonlinear profile (e.g., with clinoforms). Paleodepth estimates for ten foraminiferal biofacies ranged from 20 ± 10 m to 115 ± 30 m and were consistent with more qualitative estimates based on other methods (e.g., foraminiferal abundances and species diversity).**

Applying this method to the New Jersey coastal plain for the Oligocene showed clear distributional patterns of benthic foraminiferal biofacies. This enabled paleobathymetry to be determined for the reconstructed New Jersey margin as well as significant stratal surfaces within sequences (i.e., systems tracts and condensed sections). Paleodepth estimates ranged from nearshore (20 ± 10 m) up to 85 ± 25 m for deposits landward of the clinoform rollover of the underlying sequence boundary and from middle neritic to outer neritic (50 ± 20 m to over 100 ± 30 m) on the slopes of the clinoforms.

During earliest transgressive systems tracts, paleodepths immediately seaward of the clinoform slope ranged from inner neritic (< 40 m) at updip sites to outer neritic (> 100 m) at downdip sites. During early highstands, paleobathymetry ranged from 45 ± 10 to 85 ± 25 m landward of the clinoform rollover to 85 ± 25 m to over 100 ± 30 m on the slope (seaward of the developing prograding sedimentary wedge), while during late HSTs, paleodepths shoaled to as shallow as 25 ± 10 m near the clinoform rollover.

This method can be applied to other continental passive margins to reconstruct the stratal geometry of and estimate water depths on the shelf. Furthermore, by extending this process, relative sea level and eustatic timings and amplitudes could be evaluated.

INTRODUCTION

Although the distribution of benthic foraminifera is constrained by the environmental conditions in which they live and not by water depth, these environmental conditions (e.g., substrate, salinity, temperature, wave energy, oxygenation, nutrients, etc.) are often depth-dependent (e.g., Walton 1964). This has enabled workers to use foraminiferal assemblages as paleobathymetric indicators. However, studies comparing benthic biofacies assemblages on shelves in different basins (e.g., Bandy 1964; Walton 1964; Sen Gupta and Kilborne 1976) indicate that although the relative positions of benthic biofacies assemblages from near shore to the shelf break remain fairly constant, the actual water depths for specific foraminiferal assemblages can vary greatly. This is because particular locales possess unique environmental conditions, including physiographic parameters such as shelf-margin geometry and water depths at the shelf edge. Therefore, water depths for benthic foraminiferal biofacies are distinctive to a particular margin. As a result, benthic foraminiferal paleobathymetric estimates that use data from other margins can be spurious, particularly for nearshore environments (Walton 1964).

Trends in foraminiferal abundance, diversity, and other parameters that change with distance from the shoreline and with increasing water depth (Bandy and Arnal 1957, 1960) can provide relative paleodepths; however, estimates of paleobathymetry are often of low resolution. Abundances of planktonic foraminifers increase with distance from the shore, suggesting that comparison of planktonic and benthic foraminifers (P/B ratios) can be a useful estimator of water depth (Stehli and Creath 1964). However, precision in calibrating water depth to P/B ratios has been difficult because of variations in sedimentation rates, planktonic productivity, and dissolution (Lipps et al. 1979).

Paleobathymetries for benthic foraminiferal assemblages also have been determined using fossil and modern benthic foraminiferal habitat studies (Bandy 1961; Walton 1964; Murray 1973). This has been most successful for strata of Neogene age and younger. However, many recent benthic foraminiferal species evolved since the late Eocene (Hayward et al. 1999). Thus, care is needed when comparing Paleogene or older records to modern-day analogs.

One-dimensional paleoslope modeling using benthic foraminifers has provided paleodepth estimates for biofacies on margins for various time periods (e.g., Cretaceous, Nyong and Olsson 1984; Miocene, Miller et al. 1997). This method is most useful for margins that contain a geometry similar to the present-day shelf. Therefore, it is limited in terms of scope because paleoslope gradients can vary from 1:300 to 1:500 (as in the case of a carbonate ramp; e.g., Steckler et al. 1999) to $< 1{:}1000$ on a typical siliciclastic shelf margin (e.g., present-day New Jersey margin; Bowman 1977). This method also does not take into account nonlinear geometry (e.g., clinoforms) due to variable sediment input and subsidence. Although the methods mentioned above have generated useful estimates of paleobathymetry on a given margin, the large uncertainties suggest that an improved method of estimating water depths of benthic foraminifers is needed.

The main goal of this paper is to develop and implement a new method for estimating paleodepths for benthic foraminiferal biofacies in New Jersey Oligocene strata. Estimating paleodepth ranges will be accomplished by: first, identifying benthic foraminiferal biofacies using factor analysis; and second, combining a high-resolution age model with the reconstructed stratal geometry derived from two-dimensional flexural backstripping. The resulting paleodepth model will be used to evaluate the relative position of benthic foraminiferal biofacies across the paleoshelf (with respect to the clinoform rollover), and the benthic foraminiferal biofacies within a sequence stratigraphic model (within systems tracts).

BACKGROUND

The New Jersey Oligocene Sequences

Study of the extent and distribution of Oligocene strata from New Jersey and the contained benthic foraminiferal assemblages has had a tumultuous history. As recently as 20 years ago, no Oligocene deposits were thought to have been preserved on the New Jersey Coastal Plain (Brown et al. 1972). Middle to upper Oligocene (Zones P20–P22) strata and benthic foraminiferal biofacies were first recognized in the subsurface of New Jersey by Olsson et al. (1980). The first continuously cored borehole to recover Oligocene strata was drilled at Mays Landing in 1986, with poor recovery of foraminifers (ACGS#4 borehole; 121 ft, 36.9 m Oligocene section; Poore

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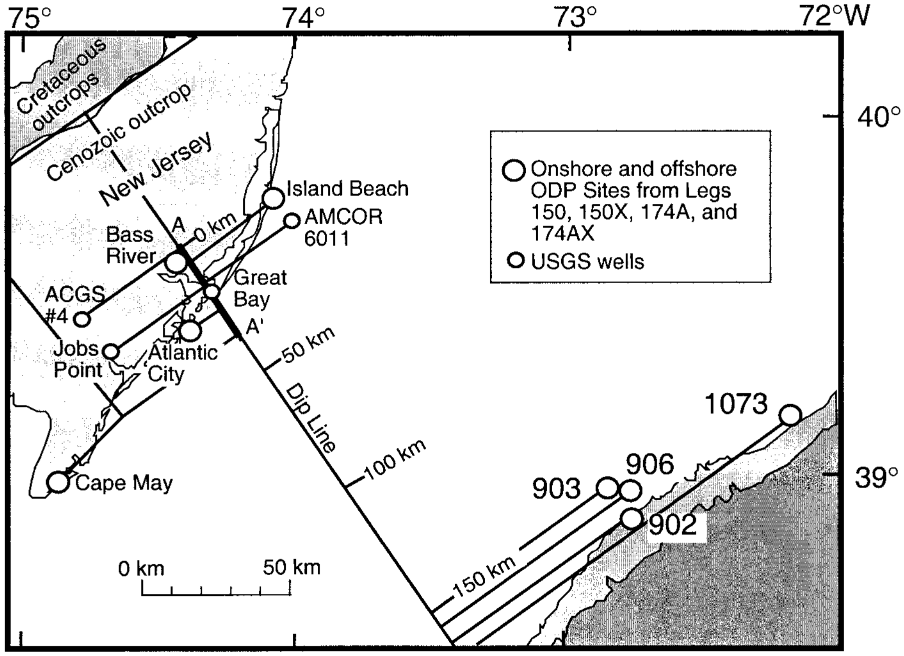


FIG. 1.—Location map. The southern part of New Jersey (eastern United States) is shown with the locations of the sites used in this study: Island Beach, Atlantic City, Cape May (Leg 150X boreholes); Bass River (Leg 174AX borehole), AMCOR 6011, ACGS#4, Great Bay, and Jobs Point (USGS onshore and offshore wells). Also shown are sites used for two-dimensional flexural backstripping: Sites 902, 903, 906 (Leg 150), and 1073 (Leg 174A). Dip lines are perpendicular to Cretaceous outcrops and strike lines are projected from the wells onto dip line A–A′ profile. The line of section A–A′ on the dip line 1 extends from the along-strike projections of Sites ACGS#4 (0 km) to Cape May (32 km).

and Bybell 1988). Since then, four onshore continuously cored boreholes (Bass River, Island Beach, Atlantic City, and Cape May) from ODP Legs 150X and 174AX (Miller et al. 1994), as well as three additional discontinuously drilled wells, have sampled Oligocene strata (Fig. 1). This allowed a detailed core study of Oligocene strata and benthic foraminiferal assemblages from the New Jersey Coastal Plain (Pekar et al. 1997; Pekar 1999; Pekar et al. 2000), from which eight sequences and ten benthic foraminiferal biofacies were identified (Figs. 2, 3).

The New Jersey Coastal Plain passive margin is well suited for paleoslope modeling because it is structurally uncomplicated (little or no faulting). This allows local tectonics to be estimated using backstripping, and it allows the chronostratigraphic units to be traced across the entire margin using wells and seismic profiles (Olsson and Nyong 1984).

Previous paleobathymetric estimates of benthic foraminiferal biofacies from New Jersey Oligocene strata have used one of two methods: (1) comparison of fossil taxa to modern fossil and modern biofacies distributions (Pekar 1995); and (2) vertical facies succession (relative depth ranking; Pekar et al. 1997). The succession of lithofacies and benthic foraminiferal biofacies were used to infer relative paleodepths. For example, clear upward-shoaling successions indicated by lithofacies and gamma-ray well logs correspond to shifts toward more shallow-water benthic foraminiferal assemblages (Pekar et al. 1997).

Oligocene Sequence Stratigraphic Architecture in New Jersey

Reconstructed geometry of New Jersey Oligocene strata shows that the stratigraphic architecture varies greatly in both sequence thickness and in lithofacies patterns (Pekar et al. 2000). These variations are due to the closeness of the locus of deposition and the position of the prograding sedimentary wedge and the clinoform rollover of the underlying sequence boundary (Fig. 4). There are three observed relationships:

(1) Deposits seaward of prograding sedimentary wedges (on the ‘‘toes’’ of the clinoforms or on the deep shelf) are typically thin ($<$ 10 m) and consist of clayey *in situ* glauconite sand and glauconitic clay, silt, and locally fine quartzose sand (Pekar 1999). Systems tracts within these sequences usually contain varying amounts of highstand systems tracts (HSTs) and possible early transgressive systems tracts (Pekar 1999).

(2) Deposits within the prograding sedimentary wedge make up expanded, relatively thick sections (50–70 m). Basal units consist either of glauconite sand with occasional shells or shell hash (transgressive lag; Pekar 1999) or a thin basal glauconitic quartz sand (early transgressive systems tracts) overlain by an upward-fining succession to a clayey glauconite sand (late transgressive systems tracts and condensed section). These units are overlain by thick (tens of meters) upward-shoaling successions consisting of glauconitic (reworked) silt and fine to coarse quartzose sand (HST; Pekar 1999).

(3) Oligocene strata deposited on the part of the shallow shelf landward of the rollover of the underlying sequence boundary (Fig. 4) are thin ($<$ 10 m). They often contain a shell bed at the base (transgressive lag), which is overlain by an *in situ* glauconitic unit (TST) (Pekar 1999).

ANALYSIS OF BENTHIC FORAMINIFERA

Methods

Samples from seven wells (AMCOR 6011, Atlantic City, Bass River, Cape May, Great Bay, Island Beach, and Jobs Point) were prepared using standard foraminiferal sampling and processing techniques (Pekar 1995). Benthic foraminifers were not preserved at the eighth well (ACGS#4) containing Oligocene strata in New Jersey. Approximately 300 benthic foraminiferal specimens from the $>$ 63 mm size fraction of each sample were sorted and identified for quantitative analysis. Samples with abundant foraminifers were split using a micro-splitter obtaining totals close to 300 specimens.

We evaluated the biofacies by using standard factor analysis on the combined data sets from Atlantic City and Cape May (Pekar et al. 1997) and new data from AMCOR 6011, Bass River, Great Bay, Island Beach, and Jobs Point (Table 1). Samples with greater than 50 specimens were grouped in a data set of 94 samples and 107 species and normalized to percentages showing relative abundances of each species (Pekar 1999). The data set was analyzed for variation among samples using Q-mode factor analysis. Ten principal components were extracted (eigenvalues $>$ 1) and were rotated to maximize the variance explained by the data set (varimax factor rotation) (Lipps 1979) (Table 1). By rotating the principal components, 73.4% of the faunal variation was explained. (See Acknowledgments section for location of archived data and factor analysis.) These biofacies were

TABLE 1.—*Factor scores for dominant species for each factor and corresponding biofacies.*

Factor	Biofacies	First Dominant Species	Factor Scores	Second Dominant Species	Factor Scores	Third Dominant Species	Factor Scores
1	D	*Bulimina gracilis*	9.75				
2	B	*Cibicides ornatus*	5.40	*Rectobulimina* spp.	5.52	*Textularia mayori*	2.91
3	G	*Trifarina bradyi*	9.56	*Globocassidulina californica*	1.19		
4	C	*Nonionellina pizarrensis*	9.63	*Cibcides lobatulus*	1.17		
5	J	*Trifarina angulosa*	8.88	*Globocassidulina subglobosa*	1.99	*Buliminella curta*	1.87
6	H	*Uvigerina juncea & subperegrina*	9.50	*Globobulimina auriculata*	2.24		
7	F	*Epistominella pontoni*	7.22	*Bolivina paula*	4.54	*Buliminella curta*	2.91
8	A	*Cibicides primulus*	6.55	*Hanzawaia prona*	4.41		
9	I	*Globocassidulina subglobosa*	5.95	*Globobulimina auriculata*	5.72	*Uvigerina elongata*	1.57
10	E	*Buliminella elegantissima*	5.85	*Globobulimina auriculata*	3.10		

labeled A through J, with biofacies A interpreted as the most shallow-water biofacies and biofacies J being the deepest. Population abundances (number of specimens per gram of sample) and species diversity (number of species per sample) were calculated for each biofacies.

An age model for the New Jersey Oligocene strata was developed by integrating Sr-isotope chemostratigraphy, planktonic foraminiferal biostratigraphy, nannofossil biostratigraphy, and limited magnetostratigraphy (Pekar et al. 2000). We used the Berggren et al. (1995) time scale for age correlations. While individual age estimates yield absolute uncertainties on the order of ± 0.3 to ± 0.7 m.y., the combined data set and sequence stratigraphic framework result in age estimates with a relative precision of about ± 0.1 m.y. This high precision was accomplished by correlating the maximum flooding surfaces (generally isochronous condensed intervals) among the seven sites. Relative sedimentation rates above and the below the MFS were inferred from sedimentation rates estimated by correlating five parasequences identified from the Cape May borehole to five 400 Ky cycles from isotopic records from ODP Site 929 (Pekar 1999). Thus, while the observed variations may shift in time by as much as ± 0.7 m.y. within any given sequence, the correlated relative ages are considerably more precise.

Results of Benthic Foraminiferal Analysis

Ten Oligocene benthic foraminiferal biofacies were defined using factor analysis from Oligocene strata in New Jersey. Each biofacies represents an assemblage of benthic foraminiferal species in which typically one to three species dominate within a given biofacies. They are described below from inner neritic to outer neritic.

Biofacies A (*Cibicides primulus* and *Hanzawaia prona* Biofacies).—This biofacies is dominated by *C. primulus* and *H. cf. prona* (Table 1) and

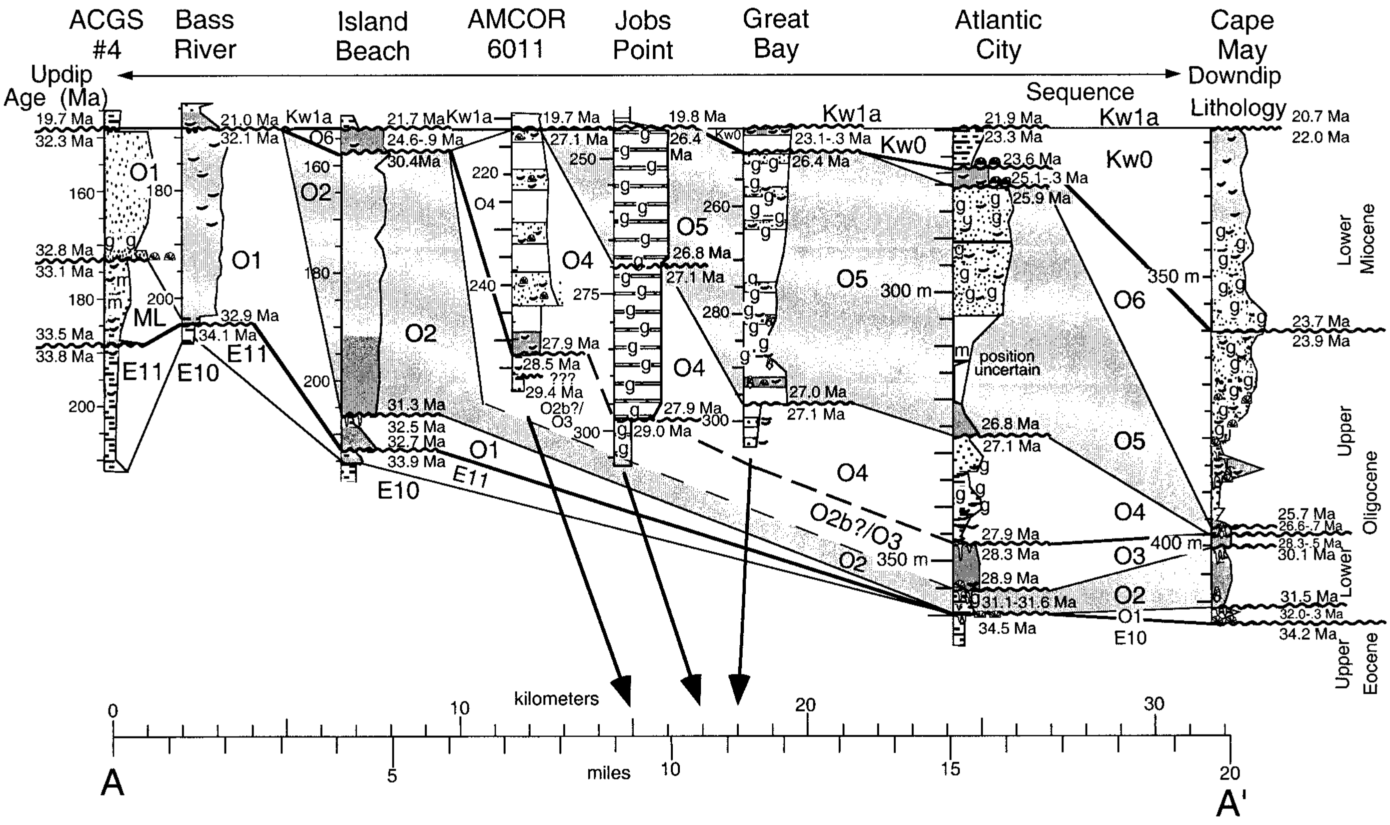


FIG. 2.—Distribution of New Jersey latest Eocene (E10–E11; Browning et al. 1997), Oligocene (ML, O1–O6; Pekar et al. 1997), and earliest Miocene (Kw0 and Kw1a; Miller et al. 1997) sequences and well locations projected along strike onto the dip profile from line A to A′ (see Figure 1). The sections are hung from the base of sequence Kw1a′, which represents the datum line. The thickest sequences at updip sites were deposited during the latest Eocene and earliest Oligocene; younger depocenters are located progressively downdip. Also shown are the lithofacies (Pekar 1999) as well as ages (based on age models in Pekar et al. 2000) of the strata immediately below and above the sequence boundaries. The O2 and O5 sequences are shaded gray to emphasize intersite correlations. Sections are measured in meters.

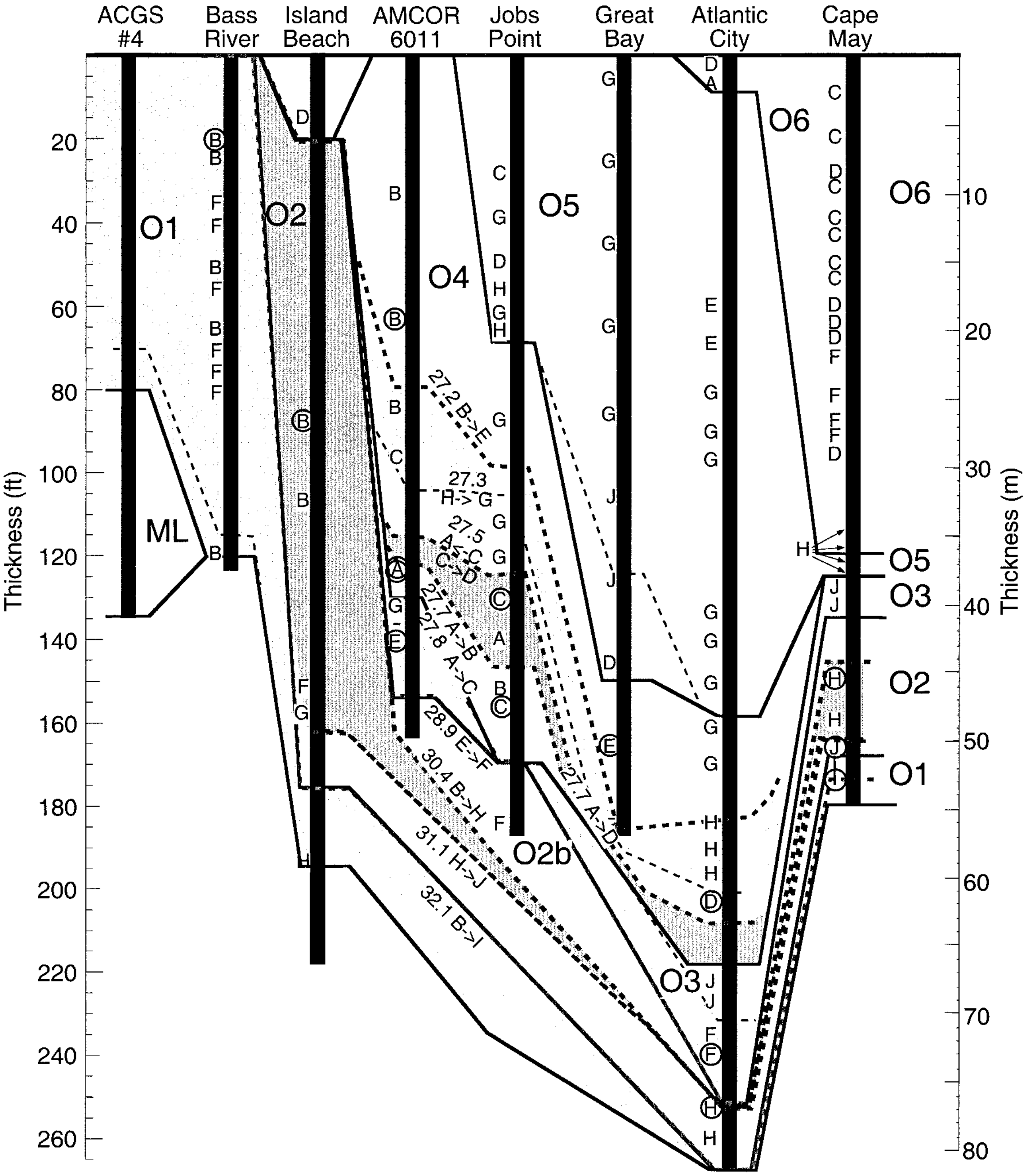


FIG. 3.—Distribution of New Jersey Oligocene sequences (sequences ML and O1–O6) are hung from the top of the Oligocene. Also shown are benthic foraminiferal biofacies for each site (biofacies A–J). The horizontal locations of the boreholes sites are not to scale on this diagram (scaled locations are shown in Fig. 2). Time horizons shown are used to calibrate the biofacies (circled). Ages of these horizons and the calibration schemes are indicated (e.g., 27.3 B > E means that the horizon is given an age of 27.3 Ma and biofacies E was calibrated by correlation with biofacies B).

is present in the top part of the Atlantic City well (923–920 ft; 281.3–280.4 m), in AMCOR 6011 (820 ft, 249.9 m), and Jobs Point (960 ft, 292.6 m) (Table 1; Figs. 3, 5). Murray (1991) and Walton (1964) observed *Hanzawaia* spp. as being dominant primarily on the inner shelf. *C. primulus* is estimated to have lived in shallow-water environments in North Carolina during the Miocene (Schnitker 1970). Benthic foraminiferal biofacies A is associated with a quartzose medium- to coarse-grained sandy shell bed and is interpreted to have been deposited in a nearshore environment. This lithofacies is similar to Miocene units described by Kidwell (1989) and is interpreted as the transgressive lag deposited during sedimentary bypass of the area (Pekar et al. 1997). Biofacies A contains low average diversity (16 species/sample) and low foraminiferal abundances (2 specimens/gram) (Fig. 6). All of the above suggest an inner neritic environment.

Biofacies B (*Rectobulimina* spp. and *Cibicides ornatus* Biofacies).—The dominant species in Biofacies B include *Rectobulimina* spp., *C. ornatus*, *Epistominella pontoni*, *Textularia mayori*, and *Hanzawaia* spp. (Table 1). The biofacies is observed at Bass River (590–565 ft, 179.8.3–172.2 m) and AMCOR 6011 sites (794–758 ft, 242.0–231.0 m) (Figs. 3, 5). Biofacies B contains low diversity (13 species/sample) and low average abundances (2.5 specimens/gram) (Fig. 6). It is associated with reworked glauconitic medium- to coarse-grained quartz sand. Schnitker (1970) has estimated a shallow-water environment for *C. ornatus* in Miocene strata in

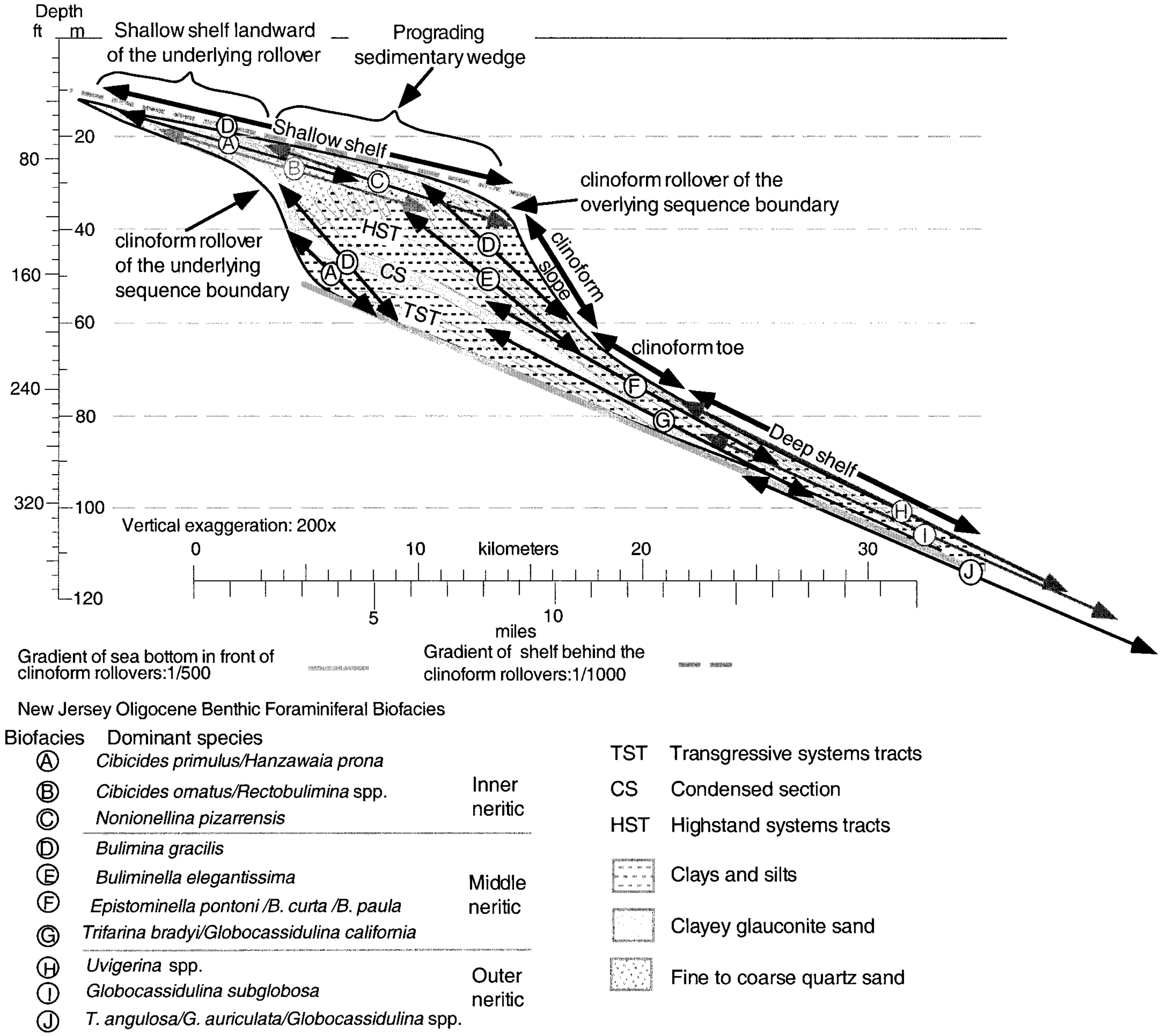


FIG. 4.—Estimated placement within an idealized New Jersey Oligocene sequence for benthic foraminiferal biofacies. Note that paleodepths are shown during the late highstand. Thus, paleodepths required by biofacies within early transgressive systems tracts are generally shallower and within the condensed section are generally deeper. Stratal geometry terminology used in this paper are also indicated. Light gray lines represent time lines; generalized lithology is also included.

North Carolina. All qualitative evidence suggest that this biofacies was deposited in an inner neritic environment.

Biofacies C (*Nonionellina pizarrensis* Biofacies).—This biofacies is dominated by *N. pizarrensis* and *Cibicides* spp. (Table 1) and is observed in Cape May (1200 ft; 365.8 m and 1212–1233 ft; 369.4–375.8 m), in AMCOR 6011 (794–758 ft; 242.0–231.0 m), and in Jobs Point (846–806 ft; 257.9–245.7 m) (Figs. 3, 5). *N. pizarrensis* is most common in reworked, glauconitic fine- to coarse-grained quartz sand. Benthic foraminiferal biofacies C contains low species diversity (13 species/sample) and low abundances (2.3 specimens/gram) (Fig. 6), suggesting a shallow-water habitat. The taxonomically similar *Nonionellina atlanticus* has a modern depth range of 20 to 50 m on the North Carolina shelf, with the highest abundance at 20 m (Schnitker 1970) and a depth range of ~ 20–40 m in the Gulf of Mexico (Walton 1964).

Biofacies D (*Bulimina gracilis* Biofacies).—The *Bulimina gracilis* biofacies is associated with middle neritic settings. It contains a much higher faunal abundance (51 specimens/gram) and diversity (18 species/sample) compared to the shallower biofacies (biofacies A–C) (Fig. 6). Biofacies D occurs at Atlantic City (1124 ft, 342.6 m), at Cape May (at 1276 ft, 388.9 m; 1247–1240 ft, 368.5–377.9 m; and 1209–1190 ft, 380.1–377.9 m), and at Island Beach (517 ft, 157.6 m) (Figs. 3 and 5). This biofacies is associated with glauconitic clayey silt and fine sand deposited in the HST and with glauconite with minor amounts of quartz sand deposited within the TST, landward of the rollover of the underlying sequence boundary. Miller et al. (1997), estimated this biofacies to be middle neritic on the basis of one-dimensional paleoslope modeling of New Jersey Miocene strata.

Biofacies E (*Buliminella elegantissima* Biofacies).—This biofacies is dominated by species *B. elegantissima* (Table 1). It is observed in the

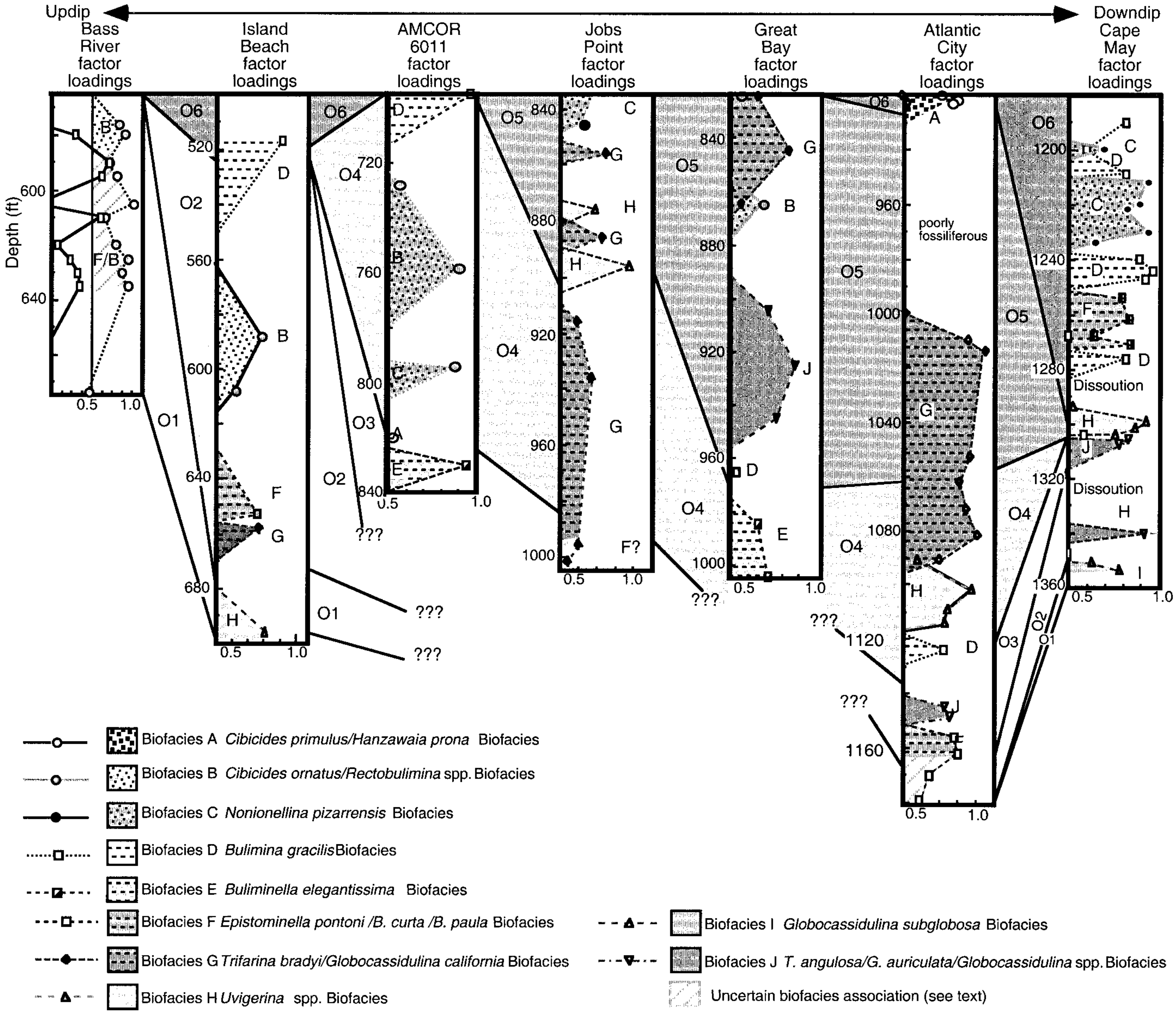


FIG. 5.—Factor loadings (> 0.50) for benthic foraminiferal biofacies for the seven sites. The datum line is the top of the Oligocene. Sequences are shown as shaded areas and are correlated between the sites.

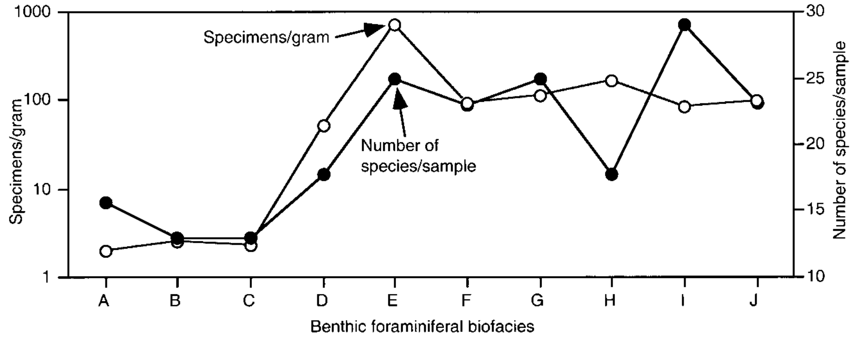
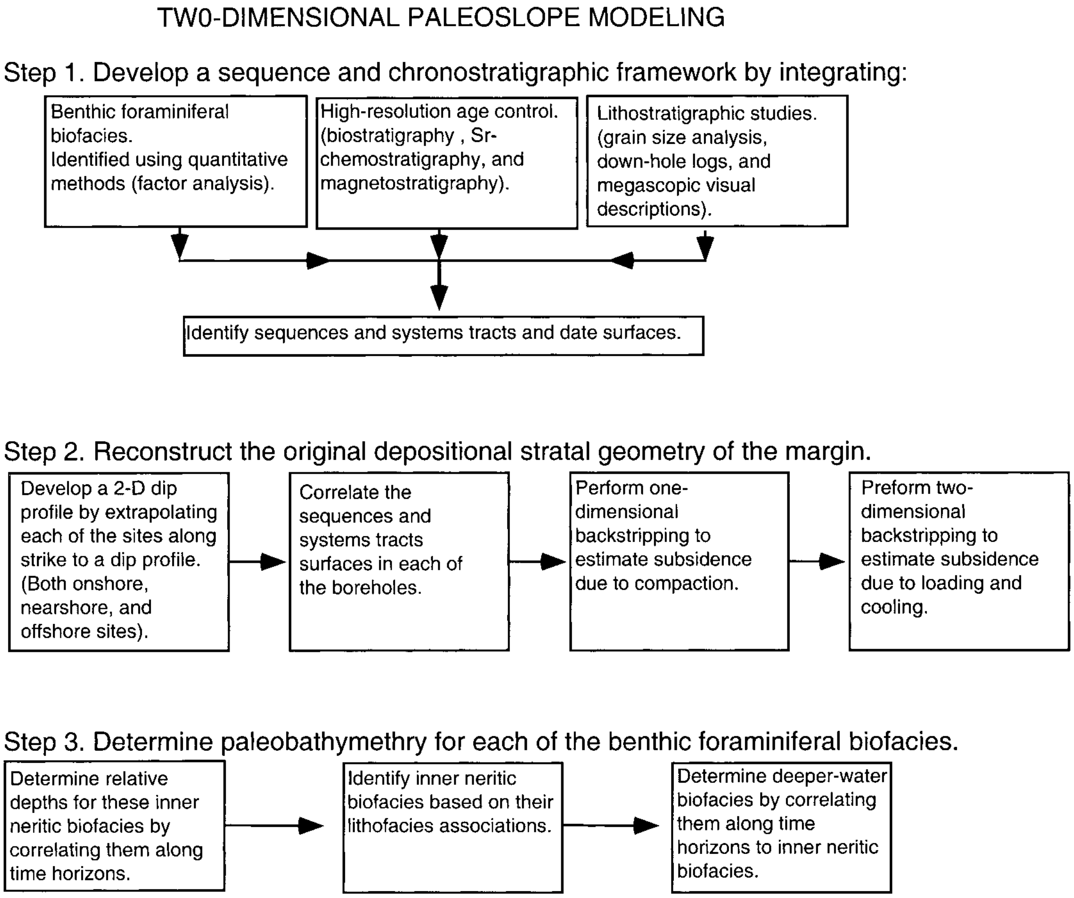


FIG. 6.—Graph showing foraminiferal abundances/gram and species diversity for the ten biofacies. Note that biofacies E contains the highest abundance/gram but is not the biofacies with the deepest paleodepth estimates.


TW0-DIMENSIONAL PALEOSLOPE MODELING

Step 1. Develop a sequence and chronostratigraphic framework by integrating:

Benthic foraminiferal biofacies. Identified using quantitative methods (factor analysis).

High-resolution age control. (biostratigraphy , Sr-chemostratigraphy, and magnetostratigraphy).

Lithostratigraphic studies. (grain size analysis, down-hole logs, and megascopic visual descriptions).

Identify sequences and systems tracts and date surfaces.

Step 2. Reconstruct the original depositional stratal geometry of the margin.

Develop a 2-D dip profile by extrapolating each of the sites along strike to a dip profile. (Both onshore, nearshore, and offshore sites).

Correlate the sequences and systems tracts surfaces in each of the boreholes.

Perform one-dimensional backstripping to estimate subsidence due to compaction.

Preform two-dimensional backstripping to estimate subsidence due to loading and cooling.

Step 3. Determine paleobathymethry for each of the benthic foraminiferal biofacies.

Determine relative depths for these inner neritic biofacies by correlating them along time horizons.

Identify inner neritic biofacies based on their lithofacies associations.

Determine deeper-water biofacies by correlating them along time horizons to inner neritic biofacies.

FIG. 7.—Flow chart showing method for determining paleobathymetric estimates for benthic foraminiferal biofacies in New Jersey. Some implications from this modeling include:

1) determining water depths for the margin and systems tracts (this study);
2) extending this technique to estimate relative sea-level changes and eustasy (Kominz and Pekar 2001); and
3) applying this method to older and younger sequences and other equally-well constrained data sets from other passive margins.

AMCOR 6011 core (840 ft, 256.0 m) and the Great Bay core (1005–985 ft; 306.3–300.2 m) (Figs. 3, 5) and is associated with micaceous glauconitic silty clay. This biofacies contains the highest average abundances (718 specimens/gram) and relatively high diversity (25 species/sample) (Fig. 6). *B. elegantissima* is typically associated with shallow-water habitats (Walton 1964; Schnitker 1970).

Biofacies F (*Epistominella pontoni, Buliminella curta,* and *Bolivina paula* Biofacies).—This biofacies contains an assemblage dominated by *Epistominella pontoni, B. paula,* and *B. curta* (Pekar 1999 and Table 1). Both average abundance and diversity are relatively high (94 specimens/gram and 23 species/sample, respectively). It is found at Cape May (1271–1253 ft, 387.4–381.9 m), Island Beach (658–653 ft, 200.6–199.0 m), and Bass River (635–605 ft, 193.5–185.9 m) (Figs. 3, 5). At Cape May, it has been observed near the base of an expanded sequence and is overlain by glauconitic silt and fine-grained quartz sand (*B. gracilis* biofacies) to medium/coarse-grained quartz sands (*N. pizarrensis* biofacies), providing an indication of the relative bathymetric position of the associated biofacies (Pekar 1999). In the Gulf of Mexico, similar biofacies patterns occur with an *Epistominella–Bolivina* spp. assemblage dominant in 60 to 80 m paleodepth and a *Nonionella* spp. assemblage shoreward (Walton 1964).

Biofacies G (*Trifarina bradyi* and *Globocassidulina california* Biofacies).—This biofacies is represented by *T. bradyi* and *G. california* (Table 1). It has been identified at Atlantic City (1091–1010 ft, 332.5–307.8 m) and Jobs Point (930, 916, 886, and 850 ft; 283.4, 279.2, 270.1, 259.1 m) (Figs. 3, 5). This biofacies contains a relatively high average abundance (113 specimens/gram) and diversity (25 species/sample; Fig. 6). It has been observed in fine-grained clayey glauconite sand, occasionally with a low percentage of silt and very fine-grained quartz sand, and is indicative of middle to outer neritic environments (Pekar 1999). The modern depth range of *T. bradyi* has been estimated by Phleger and Parker (1951) as outer middle neritic and deeper.

Biofacies H (*Uvigerina* spp. Biofacies).—The *Uvigerina* spp. biofacies is associated with sediment-starved environments, which include condensed sections (Pekar 1999). This biofacies is represented by the morphologically similar species *U. subperegrina* and *U. juncea* as well as *Globobulimina auriculata.* It has been observed at Atlantic City (1114–1102 ft, 339.5–335.9 m), Cape May (1302–1294 ft, 396.8–394.4 m and 1340–1332 ft, 408.4–406.0 m), and at Jobs Point (897–878 ft, 273.4–267.6 m; Figs. 3, 5). At Atlantic City, a *Uvigerina* spp. assemblage is dominant between 1179 and 1162 ft (359.4 and 354.2 m) and is placed within this biofacies. This biofacies has the second highest abundances in this study (168 specimens/gram) although it has a moderate diversity for an outer neritic biofacies (18 species/sample) (Fig. 6). This is consistent with Uvigerina ''floods'' associated with the condensed section (Miller et al. 1997; Pekar et al. 1997; Pekar 1999). *U. juncea* is a striated variety of *Uvigerina.* Striate *Uvigerina* spp. have been associated with low-oxygen environments. Low oxygen may be related to water depth (such as oxygen minimum zone) or may be due to environmental criteria that vary independently of water depth (e.g., high input of organic carbon resulting in a reducing environment at the sediment–water interface (Miller and Lohmann 1982). Using one-di-

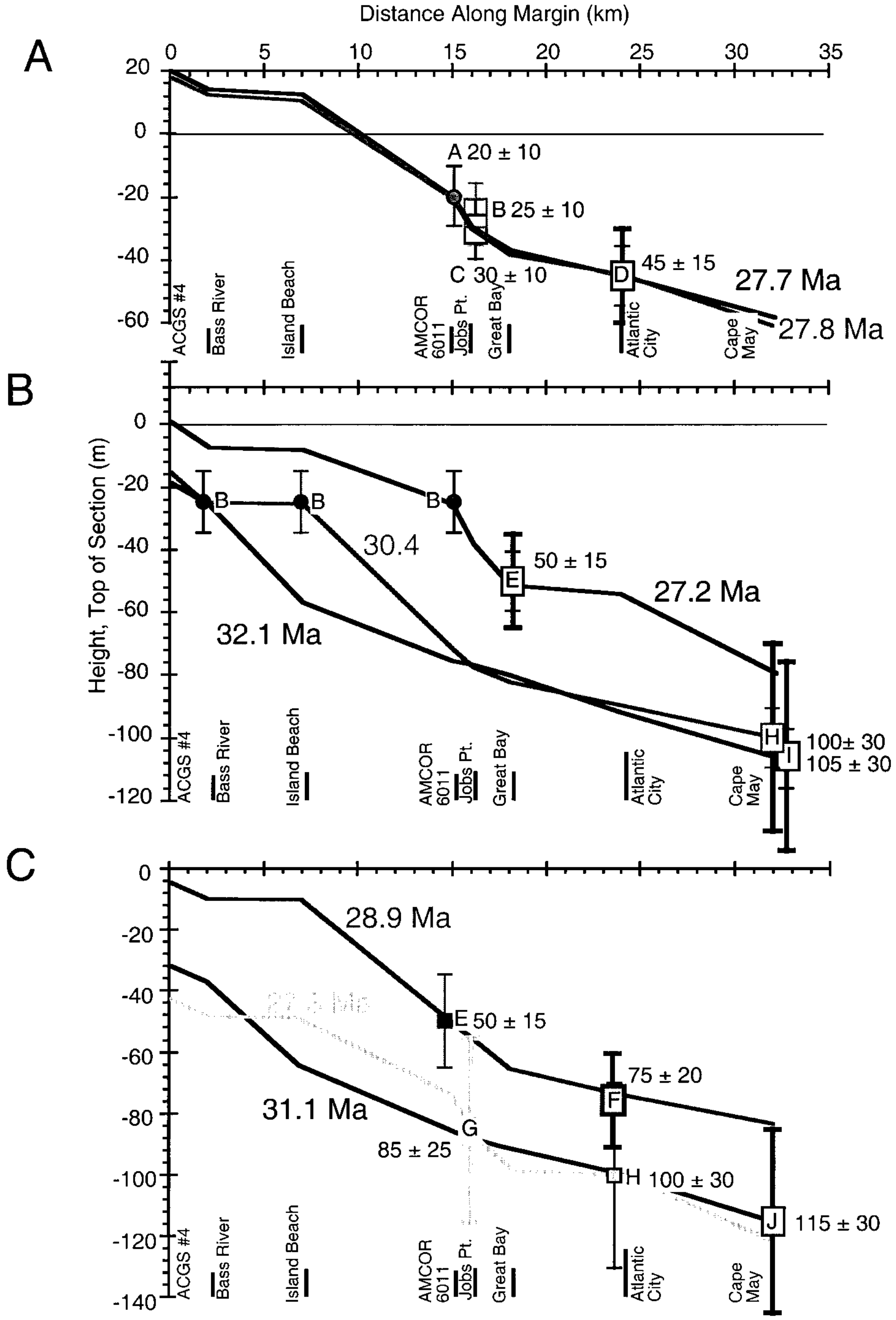


FIG. 8.—Sediment surface geometry obtained from two-dimensional backstripping of time horizons used to constrain benthic foraminiferal biofacies paleodepths. The solid line for each time horizon plotted was obtained by averaging low and high-end porosity vs. depth curves (Kominz and Pekar 2001). **A)** Comparison of the three inner neritic facies shows an internal consistency with the estimated water depths. Also shown is the constraint for inner middle neritic biofacies D. **B)** Three middle and outer neritic biofacies ranges (biofacies E, H, and I) were constrained by correlation to one of three inner neritic biofacies. **C)** Biofacies F, G and J were not found in correlative horizons with inner neritic facies and were tied to the paleodepth ranges of biofacies E and H.

mensional paleoslope modeling for New Jersey Miocene strata, Miller et al. (1997) estimated the paleodepth for *U. juncea* as 75 m and deeper. *U. isidroensis* is morphologically similar to *U. subperegrina* and is most typically observed in outer shelf depths (Boersma 1984). *G. auriculata* is observed in outer middle to outer neritic environments on the modern Northeast Atlantic margin shelf (Sen Gupta 1971).

Biofacies I (*Globocassidulina subglobosa* Biofacies).—This biofacies is dominated by *G. subglobosa,* followed by *G. auriculata, and Uvigerina elongata* (Table 1). It is found only at Cape May (1354–1351 ft, 412.7–411.8 m; Figs. 3, 5). Although this biofacies contains a moderately low abundance (18 specimens/gram), it represents the highest-diversity biofacies observed in this study (29 species/sample) (Fig. 6). The lithology from 1354 to 1351 ft (412.7 to 411.8 m) at Cape May consists mainly of clayey glauconite sand and glauconitic clay, consistent with a middle to outer neritic environment.

Biofacies J (*Trifarina angulosa, Globobulimina auriculata,* and *Globocassidulina* spp. Biofacies).—This biofacies is dominated by *G. auriculata, Trifarina angulosa,* and *G. subglobosa* (Table 1). Biofacies J contains moderately high abundances (98 specimens/gram) and diversity (23 species/sample) (Fig. 6). It is found at Atlantic City (1149–1135 ft, 350.2–345.9 m), Cape May (1307–1305 ft, 398.4–397.8 m, and at 1347 ft, 410.6 m), and Great Bay (945–925 ft, 288.0–281.9 m) (Figs. 3, 5). The lithology associated with this biofacies consists of clayey glauconite sand, which is consistent with deeper water. *T. angulosa* is observed in Recent outer ne-

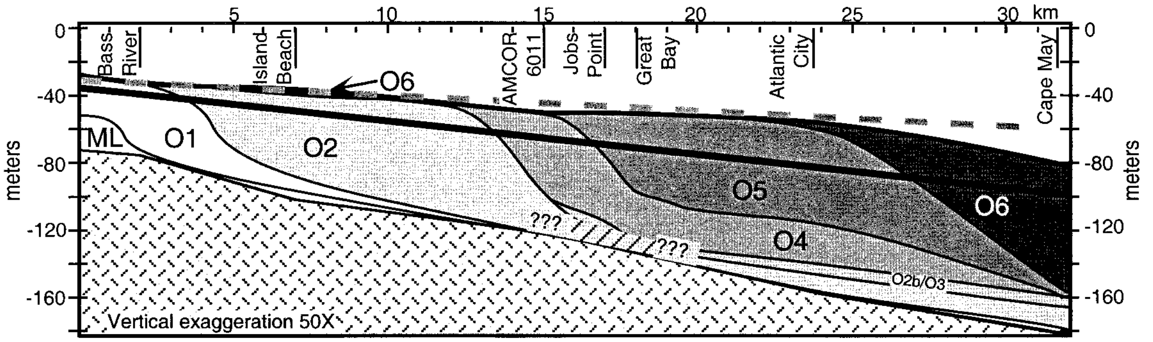


FIG. 9.—Geometry of New Jersey Oligocene sequences projected onto dip line A–A′ at the end of the Oligocene (circa 24 Ma). Clinoform rollover heights are based on two-dimensional flexural backstripping (Kominz and Pekar 2001). The original depth and gradient (1/500) of the surface separating the Eocene and Oligocene is the thick solid black line. The paleo-shelf gradient landward of the clinoform rollover is 1/1000 (dashed gray line).

ritic environments (Kafescioglu 1975) and along the modern North Carolina shelf edge (60 to 140 m) by Schnitker (1970).

PALEOSLOPE MODELING

Methods for Backstripping Analysis

Reconstructions of the geometry of New Jersey Oligocene strata were generated using: (1) one-dimensional backstripping results from each site to estimate sediment compaction; and (2) two-dimensional flexural backstripping results incorporating sites from across the shelf, which allow calculation of subsidence due to flexural loading (Fig. 7). For an in-depth description of the method used in reconstructing the stratal geometry using two-dimensional backstripping results see Kominz and Pekar (2001). A major difficulty in generating a paleoslope model for the New Jersey Oligocene strata is the presence of clinoforms. The nonlinear slope thus makes it impossible to estimate paleodepths using a one-dimensional model. We assumed a post-Eocene surface with a gradient of 1:500, based on backstripping of this margin by Pekar (1999) and Steckler et al. (1999). Kominz and Pekar (2001) calculated the geometry of the Oligocene sediment surface through time by adding Oligocene sediment in increments of 0.1 m.y. Lithology-dependent porosity vs. depth curves were used to estimate the thickness and density of sediment in the sedimentary sections of all eight coastal plain boreholes and four offshore, near-slope ODP sites (Sites 902, 903, 906, and 1073) (Fig. 1). Using empirical data from borehole and seismic data, these thicknesses and densities were progressively loaded onto a plate. We used a rigidity equivalent to an elastic plate thickness of 30 km landward of the hinge zone, decreasing to a 23 km thickness near the shelf-slope break (150 km on the composite dip section). Rigidities were simplified from Steckler et al. (1999) and were assumed to be constant during this short geologic interval (about 34 Ma to 23 Ma).

Two-Dimensional Paleoslope Modeling

Establishing the Pre-Oligocene Ramp.—The paleoslope model for the New Jersey Oligocene strata requires an estimate of the paleoslope gradient. However, the estimates of paleogradient of the pre-Oligocene shelf in New Jersey are controversial. Although previous estimates assumed paleoslope gradients similar to the present (1:1000) (Browning et al. 1997), recently completed studies using two-dimensional backstripping results indicate paleoslope gradients ranging from 1:500 (landward of the hinge line) to 1:300 (seaward of the hinge line) for the shelf during the Paleogene (Steckler et al. 1999; Pekar 1999). All of the onshore sites are landward of the hinge line; thus we used a 1:500 paleoslope gradient.

Estimating Paleodepths Associated with Benthic Foraminiferal Biofacies Using a Two-Dimensional Paleoslope Model.—This method reconstructed the stratal geometry of the New Jersey margin by two-dimensional flexural backstripping and placing the benthic foraminiferal biofacies within the reconstructed margin to estimate paleodepths (Fig. 7). The procedure is examined in detail below.

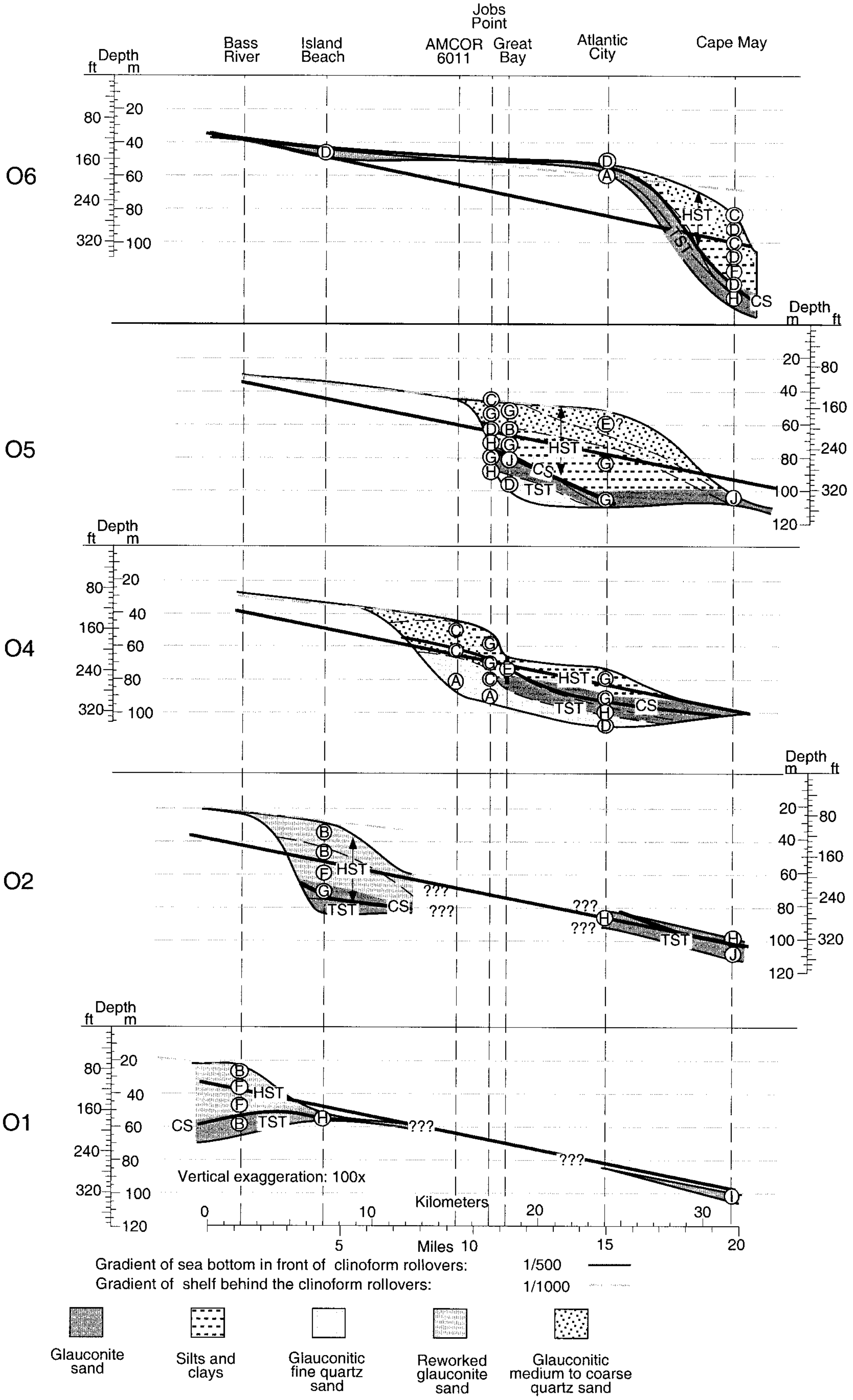
The nearshore positions were obtained from lithofacies data. The occurrence of coarse-grained, pebbly grained quartz sand (with benthic foraminifers) is indicative of nearshore and inner neritic (< 30 m) environments. Benthic foraminiferal biofacies associated with this lithofacies were assigned a paleodepth of < 40 m. Three benthic foraminiferal biofacies obtained by factor analysis were associated with coarse- to very coarse-grained lithofacies, and are assumed to have lived in paleodepths of less than 40 m (biofacies A, B, and C). The taxa in these biofacies are consistent with an inner neritic interpretation, as are the low species abundances and diversity of these biofacies.

Relative depths were obtained where two different inner neritic biofacies correlated along a single time horizon (Fig. 8A). During deposition of sequence O4 at about 27.7 Ma, biofacies A formed at AMCOR 6011 whereas biofacies C was deposited at Jobs Point (Fig. 8A). Biofacies A was deposited about 10 m shallower than biofacies C, and these biofacies were assigned paleodepths of 20 ± 10 m and 30 ± 10 m, respectively. Biofacies A correlated to biofacies B in the same two wells, respectively about 0.4 m.y. later. Here biofacies B was clearly deeper than biofacies A and well within our model paleodepth range of 25 ± 10 m. The lithofacies associated with biofacies foraminifers were also consistent with deepening environments from biofacies A through B to C.

Paleodepths for the seven remaining biofacies were calibrated by correlating them along a time horizon to biofacies with established paleodepth estimates (Fig. 8). Two steps were followed to calculate the paleodepth difference between any two points along a time horizon: (1) an inner neritic biofacies was used (wherever possible) to establish the depth of the profile at a specific location; and (2) the backstripped profile provided the paleodepth difference between the two sites.

→

FIG. 10.—Sequence stratigraphic reconstructions for each sequence from the two-dimensional flexural backstripping results of Kominz and Pekar (2001). The paleoslope gradient of the base of the Oligocene is the thick solid gray line. Generalized lithofacies are shown for each sequence (Pekar 1999). The biofacies are represented by circled letters for each well. Sequence boundaries are represented by thin solid black lines. Thick solid line represents the condensed section for each sequence, dividing the TSTs from the HSTs. Thin dashed lines within the sequences are time horizons indicating correlations among biofacies.


Bass River
Island Beach
AMCOR 6011
Jobs Point
Great Bay
Atlantic City
Cape May
Depth ft m
Depth m ft
O6
O5
O4
O2
O1
HST
TST
CS
???
Vertical exaggeration: 100x
Kilometers
0
10
20
30
Miles
5
10
15
20
Gradient of sea bottom in front of clinoform rollovers: 1/500
Gradient of shelf behind the clinoform rollovers: 1/1000
Glauconite sand
Silts and clays
Glauconitic fine quartz sand
Reworked glauconite sand
Glauconitic medium to coarse quartz sand

Using these methods, paleodepth estimates for four benthic foraminiferal biofacies were determined as follows (Figs. 8A, 8B):

(1) biofacies D was assigned a paleodepth of 45 ± 15 m, from its presence at Atlantic City and the presence of biofacies A at AMCOR 6011 at 27.7 Ma;

(2) biofacies E was assigned a paleodepth of 50 ± 15 m at Great Bay, from correlation of biofacies B (30 ± 10 m) at AMCOR 6011 at 27.2 Ma;

(3) biofacies H was estimated to have a 100 ± 30 m paleodepth at Cape May, from a paleodepth of 25 ± 10 m (Biofacies B) at Island Beach for the time slice 30.4 Ma; and

(4) biofacies I was assigned a paleodepth of 105 ± 30 m at Cape May from the time slice at 32.1 Ma and the paleodepth estimate of 25 ± 10 m (biofacies B) at Bass River.

Biofacies F, G, and J were not sampled at a time of coeval deposition of inner neritic biofacies. Biofacies F was estimated to have a paleodepth of 75 ± 20 m at Atlantic City, from its correlation with biofacies E at AMCOR 6011 at 28.9 Ma (Fig. 8C). Biofacies G was assigned a paleodepth of 85 ± 25 m at Jobs Point from its correlation to biofacies H at Atlantic City at 27.3 Ma. Biofacies J at Cape May was assigned a paleodepth of 115 ± 30 m from its correlation to biofacies H at Atlantic City at 31.1 Ma.

Paleodepth uncertainties for foraminiferal biofacies were assigned ranges of ± 10 m for the inner neritic (< 30 m); ± 15–25 m for the middle neritic (45–85 m); and ± 30 m for the innermost outer neritic (100–115 m). Because environmental factors become more stable with depth in neritic environments, any model must become less precise with depth. These 20–60 m ranges are comparable to the ranges observed in modern benthic foraminiferal studies that use foraminiferal assemblages (e.g., Bandy 1961, Walton 1964). Paleodepth uncertainties were generated in order to allow significant overlap in the estimates for successive biofacies and shoaling successions observed in wells (in the absence of a hiatus). Although the uncertainties for the biofacies showed that some of the paleodepths overlap (and may not necessarily occur in the strict order shown in this study), internal consistency within the data set suggests that these paleodepth estimates are robust (Kominz and Pekar 2001).

In this study, evidence of mixed assemblages or interbedded shallow and deep biofacies were interpreted as resulting from lateral transport. For example, at Bass River, between 625 and 595 ft (190.5 and 181.4 m), shallow-water taxa (e.g., *Cibicides ornatus*) were associated with deeper-water taxa *Epistominella pontoni*, which may have resulted from transport of the shallow-water taxa. Thus, this section was interpreted as being dominated by middle neritic biofacies F (75 ± 20 m) rather than by the inner neritic biofacies B, which was assumed to have been transported. With this exception, there was a general lack of transported tests in Oligocene strata from New Jersey. This may be due to the relatively low gradient of the slope of the clinoform (1:100) of the New Jersey Oligocene shelf compared to the modern New Jersey clinoform slope (1:30; Steckler et al. 1999).

Abraded and broken foraminiferal tests may also indicate transport of the foraminifers. Near the top of sequence O5 (990–924 ft, 301.8–281.6 m) at Atlantic City, and between 618 and 524 ft (188.4 and 159.7 m) at Island Beach, broken and poorly preserved foraminiferal tests were evident, suggesting that they may not be *in situ*. However, abraded and broken foraminifers may also indicate time spent in a high-energy environment (e.g., above wave base) and may be more characteristic of shallow-water coarse sediment substrates. Because these foraminifers were all interpreted as inner neritic taxa, and were associated with coarse-grained quartz sand, these samples were used in the paleoslope model.

DISCUSSION

The new method presented in this paper generated a quantitative paleodepth model, in a complex (presence of clinoforms), ancient shelf environment using two-dimensional sequence stratigraphic backstripping to estimate the stratal geometry. Because the two-dimensional paleoslope model incorporated compaction and flexural loading, the paleodepth range of foraminiferal biofacies could be tested for degree of consistency. Furthermore, assigned paleodepths of the benthic foraminiferal biofacies allowed some differentiation within the traditional inner, middle, and outer neritic environments while maintaining uncertainties in keeping with the fact that these benthic species do inhabit a range of depths.

Relation of Biofacies to the Stratal Geometry in New Jersey

The Stratal Geometry.—The configuration of the New Jersey shelf during the late Paleogene was quite different from the current shelfal geometry. The present-day New Jersey margin consists of a broad low-gradient shelf with a sharp shelf break, approximately 150 km from the coastline in ~ 130 m of water. Beyond the shelf, the gradient increases from 1:1000 to 1:30 and continues down to the rise (Bowman 1977). During most of the Eocene, the margin consisted of a relatively steep carbonate ramp with gradients of 1:500 (landward of the hinge line) to 1:300 (seaward of the hinge line) with a shelf break in approximately 500 m of water far offshore (Steckler et al. 1999). The first clinoform geometry was initiated during the latest Eocene (Pekar et al. 2000). Deposits continued to prograde across the Eocene ramp during the Oligocene, thickening and growing in height (25–50 m) as they migrated into deeper waters (Fig. 9). This resulted in a margin with a widening low-gradient paleoshelf landward of the clinoform rollover (1:1000, similar to the present day), a shelf break, and a short, relatively gentle slope (~ 1° or 1:100; Steckler et al. 1999) merging into the old carbonate Eocene ramp (Figs. 9, 10).

Relation of Benthic Foraminiferal Biofacies to the Reconstructed Stratal Geometry.—The relationship between paleodepth estimates for the foraminiferal biofacies and the margin geometry was considered at multiple time horizons. Benthic foraminiferal biofacies locations on the margin were grouped into three depositional environments: the shallow shelf, on the clinoform slopes, and clinoform toe and deep shelf (seaward of the prograding sedimentary wedge) (Fig. 4).

Deposits on the shallow shelf contained five biofacies (biofacies A, B, C, D, and G) (Figs. 4, 10). Biofacies A was observed within a shell bed just above a sequence boundary at Atlantic City (sequence O6; Figs. 4, 10). This shell bed was interpreted as being part of the transgressive lag and is similar to Miocene sequences described by Kidwell (1989). Biofacies B and C were associated with medium- to coarse-grained glauconitic quartzose sand at Island Beach (sequence O4) and at Cape May (sequence O6), respectively. On the basis of two-dimensional reconstructions, biofacies D (paleodepth 45 ± 15 m) was deposited landward of the rollover of the underlying sequence boundary during the transgression, and is associated with a glauconite lithofacies that contains minor quartz sand (sequence O6; Figs. 4, 10). Biofacies G also occurred on the shallow shelf, immediately after the maximum transgression, and during the early highstand (e.g., at Great Bay in sequence O5; Fig. 10) (Pekar 1999). This suggests that on the shallow shelf (Fig. 4) sediment was deposited in paleodepths ranging from 20 ± 10 m to 85 ± 25 m near the paleoshelf break.

On the clinoform slopes, biofacies D, E, F, G, H, and J dominated (Figs. 4, 10). Species diversity and foraminiferal abundances of biofacies D and E showed an abrupt increase compared to the inner neritic biofacies (Figs. 4, 10). These patterns were typically observed on modern shelves near the shelf break (Walton 1964; Murray 1973), supporting our conclusions that biofacies D and E were deposited on the clinoform slope. On the clinoform slope, biofacies D was associated with silty glauconitic fine quartzose sand. Biofacies E and F were associated with micaceous silt and clay. Biofacies G, with an estimated paleodepth of 85 ± 25 m (outer middle neritic), was observed on the paleoslope during the highstand (e.g., at Great Bay and Atlantic City in sequence O5). Deeper-water biofacies H (100 ± 30 m) and J (115 ± 30 m) occurred at the base of the clinoform (e.g., base of sequence O5 at Great Bay and sequence O6 at Cape May). In summary, paleodepths on the paleoslope ranged from 50 ± 15 to at least 85 ± 25 m, whereas paleodepths at the base of the slope were generally at depths of 100 ± 30 m and greater.

The ''toes'' of the clinoforms contained biofacies F, H, I, and J. Biofacies F (paleodepth 75 ± 25 m) occurred immediately seaward of the paleoslope at updip sites (e.g., Island Beach in sequence O2; Fig. 10). Biofacies H was associated with the maximum flooding surface (MFS) of the sequence and was deposited seaward of the slope of the clinoform. Biofacies I and J generally occurred in strata deposited seaward of the slope of the clinoform at downdip sites (Atlantic City and Cape May) during sequences O1, O2, O3, O4, and O5 (Fig. 10). In one updip site (Bass River), inner to inner middle neritic paleodepths (25–40 m) were recorded in deposits at the base of the section. The strata were deposited just seaward of the previous clinoform (sequence ML) during an extreme sea-level low stand (Fig. 10). A clinoform height of ~ 20 m for sequence ML suggests that at least during the early Oligocene, the shoreline may have reached the paleoshelf break (clinoform rollover). Therefore, paleodepths immediately seaward of the clinoform slope ranged from as low as 30 ± 10 m to 45 ± 15 m at the most updip sites (Bass River and Island Beach) during sea-level low stands to 75 ± 25 to over 115 ± 30 m at the downdip sites (Atlantic City and Cape May).

Relation of Benthic Foraminiferal Biofacies to Reconstructed Systems Tract.—Foraminiferal biofacies were incorporated into a sequence stratigraphic model resulting in quantitative estimates of paleodepths for the systems tracts (transgressive systems tracts, condensed section, and highstand systems tracts). Inner-neritic-dwelling and middle-neritic-dwelling benthic foraminiferal biofacies generally occurred within specific systems tracts in New Jersey Oligocene strata, whereas outermost middle neritic and innermost outer neritic dwelling biofacies were inconsistent in their systems tracts affiliations.

Oligocene lowstand systems tracts were not identified in the New Jersey onshore sites. Transgressive systems tracts (TST's) were recognized immediately seaward of the clinoform and on the shallow shelf landward of the rollover of the underlying sequence boundary ($<$ 10 m; Figs. 4, 9). The latter were thin and consisted of a basal shell bed overlain by sandy glauconite sand (Pekar et al. 2000). At Atlantic City in sequence O6, biofacies A occurs within the shell lag, which is interpreted as the transgressive lag after Kidwell (1989) and biofacies D occurred within a glauconite sand. This suggests that during the TST, paleodepths landward of the rollover of the underlying sequence boundary were generally inner to inner middle neritic (20 ± 10 to 45 ± 15 m). Immediately seaward of the rollover of the underlying sequence boundary, transgressive systems tracts are typically thin ($<$ 10 m) and are best observed at downdip sites. Examples include sequence O4 at Atlantic City and sequence O5 at Great Bay (Fig. 10). TSTs are generally thin within the toes of clinoforms. Commonly, they appear to merge with the condensed section and are difficult to separate. The condensed sections and maximum flooding surfaces are recognized by deposits with low sedimentation rates, the dominance of *in situ* glauconite sand, and the presence of biofacies H and J (*Uvigerina* spp. and *Trifarina angulosa* biofacies).

Biofacies E, F, and G occur within the early HST, generally on the paleoslope. These gave paleodepth estimates for the early HST on the paleoslope ranging from 50 to 85 ± 15 m (Figs. 4, 10). Biofacies B and C (25–30 ± 10 m) formed during the latest part of the HST, on the actively prograding part of the shelf (Figs. 4, 10). This suggests that during the latest part of the HST, inner neritic paleodepths were reached near the rollover (paleoslope break). Biofacies I and J were the deepest paleodepth biofacies observed and occurred within the toes of the clinoforms, but their affinity to any specific system tract is uncertain.

CONCLUSIONS AND FUTURE RESEARCH

A new method developed to estimate paleodepths for benthic foraminiferal biofacies was implemented for New Jersey Oligocene strata. Ten benthic foraminiferal biofacies were recognized using standard factor analysis techniques. These were combined with reconstructed stratal geometry from two-dimensional flexural backstripping to construct a two-dimensional paleoslope model for estimating paleodepths for these biofacies. Paleodepth estimates of the biofacies ranged from 20 ± 10 m to 115 ± 30 m and are consistent with those from modern and ancient margins and with qualitative indicators (e.g., abundances, diversity) from this data set.

Combining the stratal reconstructions of the margins with the two-dimensional paleoslope modeling allowed consideration of the biofacies within the context of systems tracts and of the bathymetry of the margin. Paleodepth estimates of deposits on the shallow shelf ranged from nearshore (20 ± 10 m) to outer middle neritic (85 ± 25 m). Paleodepth estimates on the paleoslopes of the prograding sedimentary wedges ranged from 50 ± 15 m to over 100 ± 30 m. During earliest transgressive systems tracts, paleodepths immediately seaward of the paleoslope ranged from inner neritic at updip sites to outer neritic at the downdip sites. During sea-level high stands, paleodepths ranged from 25 ± 10 to 85 ± 25 m on the shallow shelf to 85 ± 25 m to over 100 ± 30 m on the slope and seaward.

This method allowed us to evaluate paleodepths associated with systems tracts and stratal surfaces. In another application, Kominz and Pekar (2001) constructed a eustatic curve for the Oligocene. These two applications in combination can be used to estimate the stratigraphic response to eustasy at the million-year scale. However, evaluation of the full sedimentological response at the time scale that glacioeustasy operated (Milankovitch periodicity, 10^4–10^5 yr.) will require construction of a higher-resolution data set. This method could also be applied to strata from other passive margins or time periods that contain equally well-constrained data sets.

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