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Reconstructing the stratal geometry of latest Eocene to Oligocene sequences in New Jersey: resolving a patchwork distribution into a clear pattern of progradation

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Abstract

Nine latest Eocene to Oligocene (34.2–23.9 Ma) sequences were identified and dated from eight sites situated on the onshore New Jersey Coastal Plain and nearshore region. These sequences show a patchy distribution, with more complete lower Oligocene sections updip and more complete upper Oligocene sections downdip. We projected these sequences onto a dip profile and reconstructed their original thicknesses and distributions by 2-D flexural backstripping. This demonstrated that depocenters migrated offshore during the Oligocene, indicating that the patchy distribution can be best explained by progradation of generally thin and spacially limited clinoforms over an Eocene carbonate ramp. During the late Eocene to Oligocene, the New Jersey passive margin underwent a major morphologic change. Reconstructions indicate that the margin was a relatively steeply dipping carbonate ramp (1:500 paleoslope gradient) during the Eocene and was transformed into a siliciclastic margin characterized by a gentler gradient of 1:1000 and prograding clinoforms by the Miocene. Clinoform progradation probably began during the latest Eocene. Increased sediment supply during the Oligocene resulted in the further progradation of sediments across the antecedent carbonate ramp. The heights of the clinoforms ranged from ~20 m during the latest Eocene and earliest Oligocene to nearly 50 m during the late Oligocene. Most sediment accumulated within clinoform wedges, with little or no sediment being preserved behind the clinoform inflection point.

Keywords: Miocene; seismic profile; systems tracts

1. Introduction

Oligocene and Neogene strata are characterized globally by similar stratal geometry observed on both passive and tectonically active siliciclastic margins (Bartek et al., 1991) as well as carbonate-dominated shelves (Eberli et al., 1997). On passive margins of the Atlantic, Eocene carbonate ramps were followed by starved early Oligocene shelves that shifted to prograding siliciclastic margins by the Miocene (Greenlee et al., 1992; Steckler et al., 1995; Miller et al., 1997a; Poulsen et al., 1998). In New Jersey, this transition from ramp to siliciclastic progradation resulted in widespread Eocene deposition and Miocene sequences that thicken downdip (Miller et al., 1997a), but yielded a patchy, apparently incoherent pattern for Oligocene strata (Pekar et al., 1997).

Understanding Oligocene deposition onshore in New Jersey has proven to be a challenge due to the absence of outcrops and poor subsurface sampling. Continuous coring at Mays Landing (ACGS#4; Fig.

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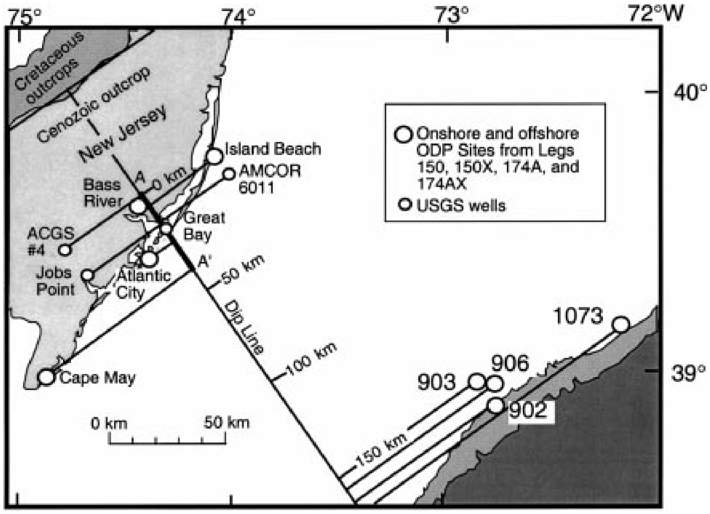


Fig. 1. Location map. The southern portion of New Jersey is shown with the location of the sites used in this study: Leg 150 (Sites 902, 903 and 906); Leg 150X (Island Beach, Atlantic City, and Cape May boreholes); Leg 174A (Site 1073); and Leg 174AX (Bass River borehole). Also shown are the USGS onshore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

1; Owens et al., 1988) and by Ocean Drilling Program Leg 150X (Island Beach, Atlantic City, and Cape May; Fig. 1; Miller et al., 1994, 1996a) provided material for the first systematic study of Oligocene sequences in New Jersey. Pekar et al. (1997) identified six Oligocene sequences in these boreholes by integrating benthic foraminiferal biofacies analysis, lithofacies and grain size analyses, Sr-isotopic chemostratigraphy, planktonic foraminiferal and nannofossil biostratigraphy, and magnetostratigraphy. Five of six Oligocene sequences occurred at more than one site in New Jersey and could be firmly established as resulting from regional, if not global discontinuities. They concluded that Oligocene sequence boundaries on the New Jersey margin were linked to glacioeustatic lowerings evinced by global $\delta^{18}O$ increases. However, the areal and temporal distribution of the sequences had a patchy or irregular distribution and did not seem to fit a predictable pattern (Pekar, 1999).

The distribution of Oligocene sequences in New Jersey consists of updip sections recording thicker lower Oligocene sections and downdip sections recording thicker upper Oligocene sections (Pekar, 1999; this study). This contrasts with Miocene sections that are stratigraphically thicker and more complete downdip, reflecting a hinged margin with increased subsidence downdip (Miller et al., 1997a).

Two possible explanations for the differential preservation of sequences in the Atlantic Coastal Plain have been proposed previously. The first invokes active basin tectonics that resulted in differential warping/uplift of crustal blocks (e.g. the rolling basins concept of Owens et al., 1997; see also Benson, 1994). The second suggests migration of sediment supply and depocenters along strike (i.e. lobe switching) resulting in differential accommodation and preservation of sequences (Miller et al., 1997a). Here, we propose a third explanation: that progradation of sequences from onshore to offshore in regions of generally low tectonic subsidence, compounded by a generally starved margin, resulted in the progressive migration offshore of preserved sequences. This paper presents borehole data and 2-D reconstructions to support our interpretation that this pattern resulted from clinoform geometry associated with the initiation of siliciclastic progradation in the latest Eocene to Oligocene.

2. Objectives

The primary goal of this paper is to present a new

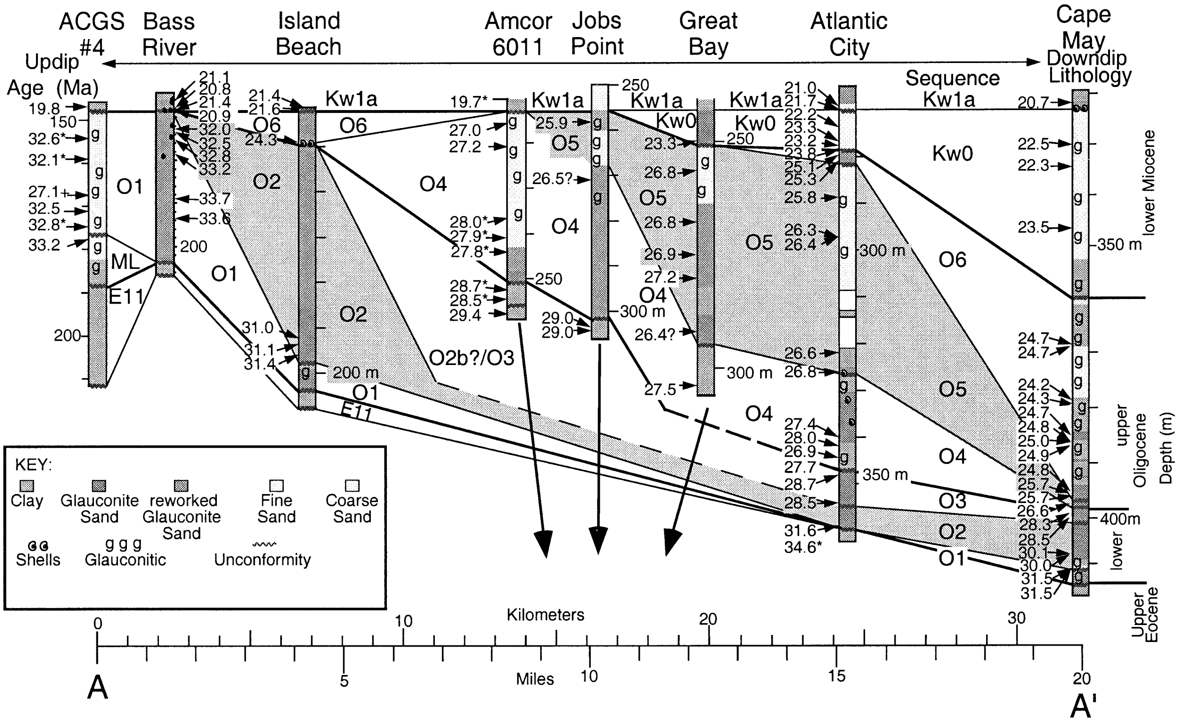


Fig. 2. Distribution of New Jersey Oligocene sequences projected onto the dip profile from line A to A′. Ages are from Strontium age estimates. Dates with an * indicate that the age is stratigraphically inconsistent. The thickest sequences at updip sites were deposited during the earliest Oligocene, younger depocenters are located progressively downdip. Wells locations on dip line are determined by projecting along strike (see Fig. 1). Datum line is the bottom of sequence Kw1a. The arrows on the bottom of AMCOR 6011, Jobs Point, and Great Bay wells indicates the location they fall on the dip profile.

view of the distribution of latest Eocene through Oligocene sequences derived from recently published and new borehole data. To attain this objective, we:

1. identify and date latest Eocene to Oligocene sequences in onshore (Cape May, Atlantic City, Great Bay, Jobs Point, Bass River, and ACGS#4) and offshore (AMCOR 6011) New Jersey boreholes by integrating Sr-isotopic, bio-, and limited magneto-stratigraphy;
2. evaluate the distribution of latest Eocene to Oligocene sequences in these boreholes by projecting into a dip profile; and
3. reconstruct original thicknesses and distributions of the sequences by applying 2-D flexural backstripping to the dip profile.

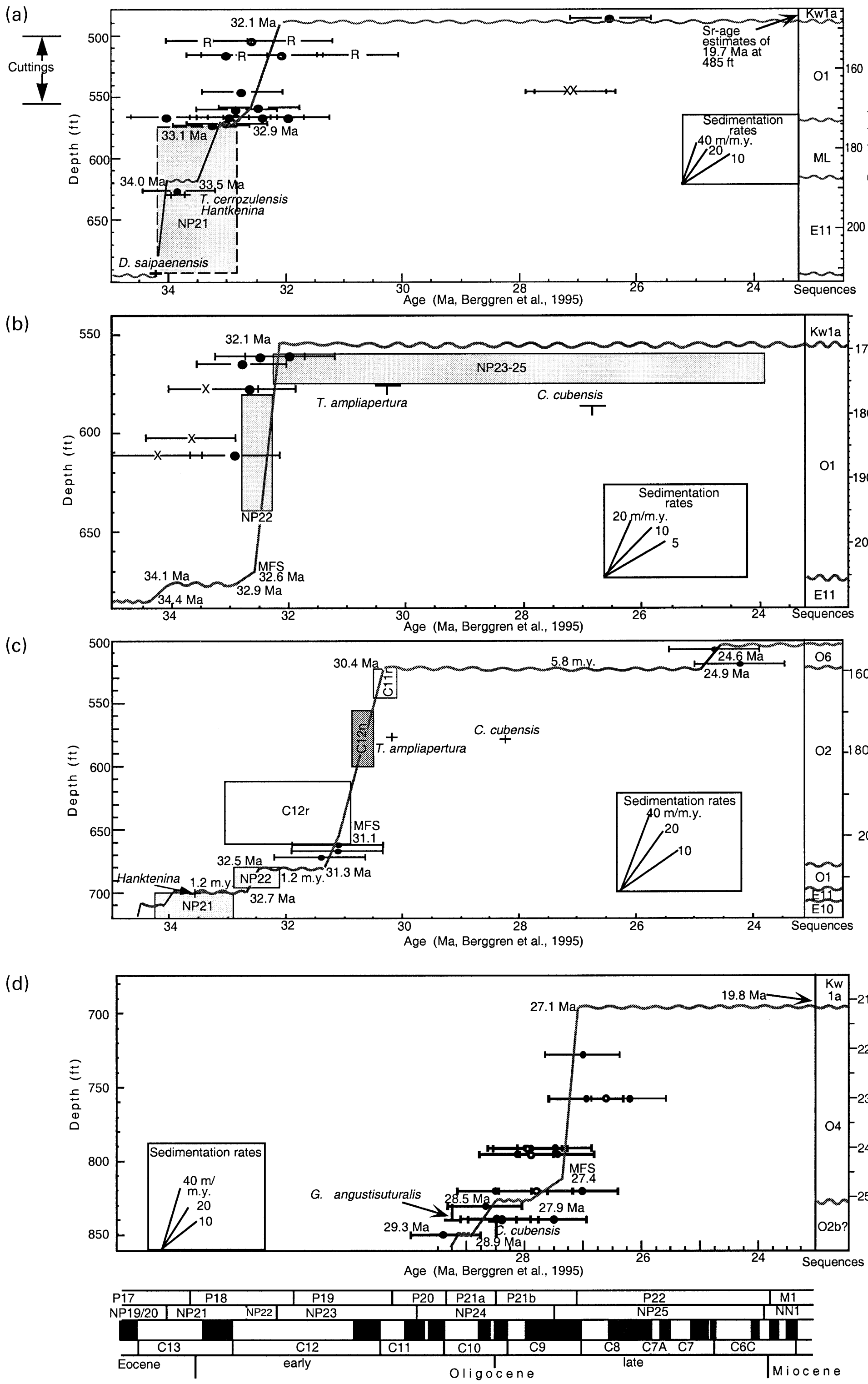
We explain the previously recognized patchy distribution of New Jersey latest Eocene to Oligocene sequences as a result of progradation of sediments within a clinoform geometry.

3. Methods and chronology

3.1. Integrated sequence stratigraphy

We build on the sequence stratigraphic framework developed for the latest Eocene to Oligocene of New Jersey (Pekar and Miller, 1996; Browning et al., 1997; Pekar et al., 1997) by (re)evaluating sequence-bounded unconformities in previously published and newly obtained boreholes. Unconformities in continuously cored boreholes are recognized by lithologic criteria,[1]

[1] These include irregular surfaces, hard grounds (indurated surfaces), major lithofacies changes, and intense bioturbation. In many cases, the interval above the unconformity consists of coarse sand or a gravel lag and ripup clasts of the underlying lithology.



(a)
(b)
(c)
(d)
Cuttings
Depth (ft)
Depth (m)
Age (Ma, Berggren et al., 1995)
Sequences
32.1 Ma
33.1 Ma
32.9 Ma
34.0 Ma
33.5 Ma
T. cerroazulensis
Hantkenina
NP21
D. saipaenensis
Sr-age estimates of 19.7 Ma at 485 ft
Sedimentation rates
40 m/m.y.
20
10
Kw1a
O1
ML
E11
NP23-25
T. ampliapertura
C. cubensis
NP22
MFS
32.6 Ma
34.1 Ma
34.4 Ma
32.9 Ma
5
30.4 Ma
5.8 m.y.
24.6 Ma
24.9 Ma
C11r
C12n
C12r
MFS 31.1
32.5 Ma
31.3 Ma
32.7 Ma
Hanktenina
1.2 m.y.
O6
O2
E10
19.8 Ma
27.1 Ma
Kw 1a
O4
O2b?
MFS 27.4
G. angustisuturalis
28.5 Ma
27.9 Ma
29.3 Ma
28.9 Ma
40 m/ m.y.
P17
P18
P19
P20
P21a
P21b
P22
M1
NP19/20
NP24
NP25
NN1
C13
C12
C11
C10
C9
C8
C7A
C7
C6C
Eocene
early
Oligocene
late
Miocene

sharp gamma ray log increases, benthic foraminiferal biofacies changes, and hiatuses (Pekar et al., 1997). In discontinuously cored sites, unconformities typically are not recovered, but are bracketed by samples that contain changes in lithofacies, benthic foraminiferal biofacies and significant hiatuses (Pekar, 1999). The precise locations of unconformities in discontinuously sampled sites (AMCOR 6011, Great Bay, and Jobs Point) are estimated by abrupt changes in gamma ray values measured with wireline logging tools.

Lithologic descriptions of the Cape May, Atlantic City, Island Beach, and Bass River boreholes were provided by Miller et al. (1994, 1996a, 1998) and Pekar (1999), Jobs Point site by Olsson et al. (1980), and AMCOR 6011, ACGS#4, and Great Bay sites by Pekar (1999). In addition, cumulative percentage data of the medium-coarse quartz sand, fine quartz sand, silt-clay, glauconite sand, and shell components were collected for each of the eight sites (Pekar, 1999). The percent silt-clay was determined quantitatively from samples washed through a 63 μm sieve for foraminiferal studies. In sections with glauconite, the abundances of other components were visually estimated from the greater than 63 μm size-fraction; in sections without glauconite and shell material, the percentages of fine versus medium-coarse sand were obtained by dry sieving and weighing.

Age estimates for Oligocene strata were developed by integrating Sr-isotopic chemostratigraphy, planktonic foraminiferal biostratigraphy, nannofossil biostratigraphy, and limited magnetostratigraphy and are illustrated here (Figs. 2 and 3). Planktonic biostratigraphy of Great Bay and AMCOR 6011 is provided by Pekar (1999). Planktonic foraminiferal and nannofossil biostratigraphy for Island Beach is from Miller et al. (1994) and Pekar (1999), and for Bass River is from Miller et al. (1998). Nannofossil biostratigraphy for ACGS#4 site is from Poore and Bybell (1988). Sr-isotopic analyses are provided by Miller et al. (1994, 1997b) are supplemented by Pekar et al. (1997, 1999). Magnetostratigraphy was successful in recognizing several Oligocene polarity zones at Island Beach (Van Fossen, 1997). Together, these provide the primary age control on the sites (Figs. 2 and 3). The Berggren et al. (1995) time scale is used throughout. Sr-isotopic ages were calibrated to the Berggren et al. (1995) time scale using the regression of Reilly et al. (1996). Sr-isotopic regressions for the late Oligocene have age uncertainties of approximately ± 0.7 m.y., whereas early Oligocene regressions have uncertainties of ± 0.6 m.y. (Reilly et al., 1996).

Systems tracts within sequences were interpreted using benthic foraminiferal biofacies, well log, and lithofacies data (Pekar, 1999). Maximum Flooding Surfaces (MFS) separate the Transgressive Systems Tracts (TST) from the Highstand Systems Tracts (HST). Maximum flooding surfaces were identified using the following criteria: (1) high concentrations of in situ glauconite sand, which is an indicator of low sedimentation rates and sediment starved depositional environments (McRae, 1972); (2) peak abundances of benthic foraminiferal species of *Uvigerinids* (Pekar et al., 1997); (3) greatest benthic foraminiferal abundances (Pekar et al., 1997); and (4) changes from deepening to shallowing upward successions as indicated by biofacies and lithofacies (Miller et al., 1997a). Typically, Oligocene sequences were dominated by expanded HSTs (30–70 m). TSTs are usually thin (<10 m). Lowstand Systems Tracts (LST) are occasionally preserved at more downdip sites and are also relatively thin (<10 m) (Pekar, 1999).

3.2. Chronology and sedimentation rates of latest Eocene to Oligocene sequences

Uppermost Eocene and Oligocene strata sampled from one offshore and seven onshore sites are divided

Fig. 3. Identification and ages of New Jersey Oligocene sequences for updip sites at (a) ACGS#4, (b) Bass River, (c) Island Beach, and (d) AMCOR 6011. Sr-isotopic ages with single analyses and with low rubidium concentrations are shown as solid points. Open circles or + on the Sr-isotopic ages represent averaged data for that interval. R-symbols represents age analyzes that contain high Rubidium concentrations. Sr-isotopic age estimates with X are stratigraphically inconsistent and are interpreted to be outliers. Time scales are from Berggren et al. (1995). Planktonic foraminiferal maker species highest and lowest occurrences are shown. Sequence E11 is uppermost Eocene (Browning et al., 1997), sequences ML and O1–O6 are Oligocene (Pekar et al., 1997), and sequences Kw0 and Kw1a are lower-most Miocene in age (Miller et al., 1997a,b). Maximum flooding surfaces and age are shown. Slope changes in lines of age correlation are based on estimates of specific lithologic accumulation rates based on Pekar (1999). Note that the vertical scales are not the same for all diagrams.

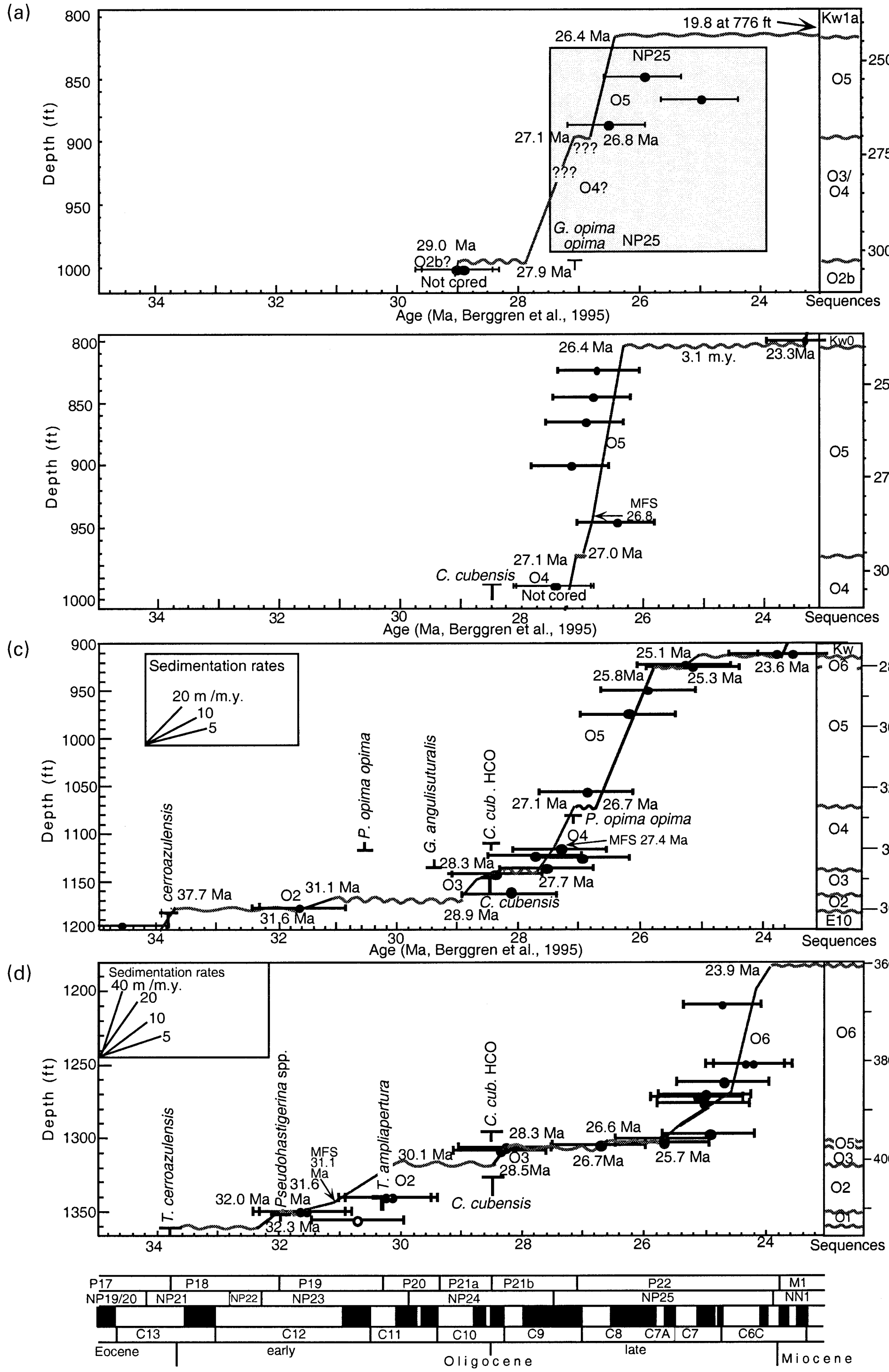


Fig. 4. 4a–d Identification and ages of New Jersey Oligocene sequences for downdip sites at Jobs Point, Great Bay, Atlantic City, and Cape May. See Fig. 3 caption for description.

into nine unconformity bounded sequences ranging in age from 34.2 to 23.9 Ma (Fig. 2). New Jersey Oligocene strata have been difficult to date using biostratigraphy or magnetostratigraphy because: (1) shallow-water paleoenvironments exclude pelagic biostratigraphic markers; and (2) magnetostratigraphy is difficult in coarse shallow-water sediments (Miller et al., 1990). Sr-isotopic age estimates provide the most reliable and consistent method for dating the New Jersey Oligocene sediments. Ages of sequences are also constrained using lowest and highest occurrence of planktonic foraminifers and sparse nannofossil zones. Correlations of three magnetochron boundaries at Island Beach are also used in developing the age models. These data were integrated and plotted as age–depth diagrams (Figs. 3 and 4) to determine ages of sequences and determine sediment accumulation rates. Because MFSs are time sensitive surfaces, they were used as correlation tools between sites. The following section discusses the ages of the sequences from the most landward to the most downdip location.

3.2.1. ACGS#4 borehole (Mays landing)

The ACGS#4 borehole is the most updip borehole with substantial uppermost Eocene and lowermost Oligocene strata preserved (Fig. 3a). One uppermost Eocene sequence (Eil;695–615 ft, 211.8–187.5 m) is dated between 34.4–34.1 Ma based on Sr-isotopic chemostratigraphy, planktonic foraminiferal and nannofossil biostratigraphy (Browning et al., 1997). The chronology of the Oligocene strata at the ACGS#4 borehole, originally developed by Miller et al. (1990) using Sr-isotopic age estimates, palynology, and nannofossil biostratigraphy, identified two distinct Oligocene sequences, a lowermost Oligocene sequence (615–565 ft, 187.5–172.2 m) and an upper Oligocene sequence (565–485 ft, 172–147.8 m). The lower sequence is dated here between 33.5 and 33.1 Ma, based on Sr-isotopic age estimates and biostratigraphy. Although, both the lower and upper sequence boundaries of this sequence represents relatively short hiatuses (~0.5 m.y.), they are identified by lithologic and benthic foraminiferal criteria (Pekar, 1999). The sedimentation rate for this sequence is ~40 m/m.y (Fig. 3a).

In Miller et al. (1990), the age of the upper sequence was uncertain due to a lack of biostratigraphy, inconsistent Sr-isotopic age estimates, and the reliance of cuttings, although it was estimated to be upper Oligocene age (~27 Ma). Additional Sr-isotopic age estimates from this study revealed that the upper sequence is actually lowermost Oligocene (32.9–32.1 Ma), but younger than the underlying sequence (Fig. 3a). A possible short hiatus may separate the two sequences (<0.5 m.y.). Two age models are shown (Fig. 3a), one showing continuous deposition and the other indicating a hiatus at 565 ft (172.3 m). The lowermost Oligocene sequence has been named the ML sequence (Mays Landing Sequence), based on the location of its first identification (Pekar et al., 1997) and the upper sequence is correlated to sequence O1 of Pekar et al. (1997).

3.2.2. Bass River (New Gretna, New Jersey)

Sr-isotopic and planktonic and nannofossil biostratigraphy indicate one uppermost Eocene (34.2–33.8 Ma) and a single lower Oligocene (32.9–32.1 Ma) sequence at Bass River (Fig. 3b). The uppermost Eocene sequence is thin (684.9–675.4 ft, 208.8–205.9 m) and is correlated to sequence E11 of Browning et al. (1997) based on planktonic foraminiferal and nannofossil biostratigraphy. Six Sr-isotopic age estimates indicate the entire the Oligocene section at Bass River correlates to sequence O1 of Pekar et al. (1997). Sr-isotopic age estimates indicate that the Oligocene/Miocene boundary at 555 ft (169.2 m) contains a hiatus of 11.1 m.y. Duplicate Sr-isotopic ratios obtained for three intervals (611.3, 602.0, and 577.4 ft; 183.5, and 176.0 m) were averaged together. Nannofossil data indicate that Zone NP22 extends from 640.04 to 575.3 ft (205.9–175.4 m) and Zone NP 23 extends from 575 to 555 ft (175.3–169.2 m). Planktonic foraminiferal biostratigraphy correlate the Oligocene at Bass river to undifferentiated Zones P18-P19. Based on the age data, sequence O1 has an average sedimentation rate of 46 m/m.y.

3.2.3. Island Beach

Uppermost Eocene and Oligocene strata at Island Beach extend from 710 to 503 ft (216.4–153.3 m) and are dated by Sr-isotopic age estimates, magnetostratigraphy, and planktonic foraminiferal and nannofossil biostratigraphy (Fig. 3c). The uppermost Eocene unit is thin (710–696 ft, 216.4–212.1 m) and is correlated to sequence E11 of Browning et al. (1997) based on planktonic foraminiferal and nannofossil data (Fig. 2).

The section between 696 and 678 ft (212.1 and 206.7 m) is dated as lower Oligocene based on nannofossil data (Zone NP22; 32.8–32.3 Ma), correlating this sequence to sequence O1 from Pekar et al. (1997). The age of the next sequence (678–524 ft, 206.7–159.7 m) is 31.3–30.4 Ma, based on: (1) Sr-isotopic age estimates; (2) the highest occurrence (HO) of *Turborotalia ampliapertura* (30.3 Ma at 577 ft, 175.9 m); and (3) the correlation of three polarity zones to magnetochrons Chron Cl2r (33.1–30.9 Ma), Cl2n (30.9–30.5 Ma), and C11r (30.5–30.1 Ma), based on integration of other chronological data (Fig. 3c). This unit correlates with sequence O2 of Pekar et al. (1997) and has a sedimentation rate of 53 m/m.y. A thin unit at the top of the Oligocene section (524–503 ft, 159.7–153.3 m) is an uppermost Oligocene sequence (25.0–24.8 Ma) based on two Sr-isotopic age estimates, correlating with sequence O6 of Pekar et al. (1997) (Fig. 3c).

3.2.4. AMCOR 6011 (offshore)

The AMCOR 6011 borehole did not penetrate deeper than upper lower Oligocene strata. The Oligocene strata at AMCOR 6011 are 153 ft thick (46.6 m) and are dated as uppermost lower Oligocene to upper Oligocene (29.2–27.0 Ma) by 17 Sr-isotopic age estimates and planktonic biostratigraphy (Fig. 3d). However, poor recovery (5–10%) in the upper section resulted in uncertainties in the identification of sequence boundaries. They were placed between samples that contained abrupt changes in benthic foraminiferal biofacies, lithofacies, and evidence of hiatuses. A gamma ray log was used to estimate the exact placement of sequence boundaries.

The first sequence preserved in the AMCOR 6011 borehole extends from a total depth (850 ft, 259.1 m) to ~840 ft (256.0 m) and is dated by a single Sr-isotopic age estimate of 29.4 Ma. This tentatively correlates this unit to sequence O2b. The section between 840 and 827 ft (256.0–252.1 m) is dated as an uppermost lower Oligocene sequence (28.9–28.5 Ma), by four Sr-isotopic age estimates, the FO of *Globigenna angustisuturalis* (29.4 Ma), and the HO of *Chiloguembelina cubensis* (28.5 Ma) at 839 ft (255.7 m), correlating it to sequence O3 of Pekar et al. (1997). The estimated sedimentation rate for sequence O3 is 10 m/m.y.

The third sequence (827–696 ft, 252.1–212.1 m) is dated as lower upper Oligocene (27.9–27.1 Ma), correlating it to sequence O4 of Pekar et al. (1997) (Fig. 3d). The age model for this sequence was constructed using 11 Sr-isotopic age estimates (Fig. 3d) ranging from 27.0 to 28.4 Ma, correlating this unit to the O4 sequence. Two Sr-isotopic age estimates of 26.2 and 26.9 Ma are inconsistent with the stratigraphy and are considered outliers. The estimated sedimentation rate for sequence O4 at AMCOR 6011 is 50 m/m.y.

Although the lower sequence boundary at 827 ft (252.1 m) represents only a short hiatus (0.6 m.y.), the surface is recognized as a sequence boundary by a sharp change in lithofacies and benthic foraminiferal biofacies above and below the boundary (Pekar, 1999). The upper bounding surface (697 ft, 212.4 m) represents a significant hiatus of 7.3 m.y., with the unit above dated as lower Miocene (19.8 Ma), equivalent to sequence Kw1a of Miller et al. (1997b).

3.2.5. Jobs Point

The Jobs Point site did not penetrate deeper than upper lower Oligocene strata. The Oligocene section was correlated using biostratigraphy (Olsson et al., 1980) and was revisited in this study with three Sr-isotopic age estimates (Fig. 4a). The Oligocene strata at Jobs Point extend from ~820 ft (249.9 m) to a total depth at 1002 ft (305.4 m) and are uppermost lower to upper Oligocene (29.0–26.4 Ma), based on Sr-isotopic chemostratigraphy and biostratigraphy (planktonic foraminiferal and nannofossils; Olsson et al., 1980). Lithofacies and benthic foraminiferal biofacies suggest three distinct sequences (820–885 ft; ~897–986 ft; 986–1002 ft; 249.9–269.7 m, 273.4–300.5 m, and 300.5–305.0 m: Fig. 4a). Age data for these sequences are limited and Sr-isotopes and biostratigraphy differentiate only two sequences: upper Oligocene (25.7–26.6 Ma; 820 to ~885 ft, 249.9–269.7 m) and lower Oligocene (~29.0 Ma; 990–1002 ft, 301.8–305.4 m). These units correlate with sequences O5 and O2b/O3, respectively. From the top of the sequence to near the base at 897 ft (273.4 m), Sr-isotope age estimates concur with planktonic foraminiferal biostratigraphy (upper Oligocene Zone P22, 23.8–27.1 Ma). The interval from 986 to 1002 ft (300.5–305.0 m) is assigned to Zone P21 (27.1–29.4 Ma), based on the highest occurrence of *Paragloborotalia opima opima*. Nannofossil data extends from the top of the Oligocene unit to 985 ft (300.2 m), placing this section within the upper Oligocene (Zones NP24–25, 23.9–29.9 Ma). A sequence (897–986-ft, 273.4–300.5 m) between these two is correlated to sequence O4 based on nannofossil data indicating an upper Oligocene age.

3.2.6. Great Bay (Tuckerton, New Jersey)

Only Oligocene and younger strata were penetrated at the discontinuously cored site at Great Bay (Fig. 3b). Oligocene strata extend from ~805 ft (245.4 m) to a total depth at 1005 ft (306.3 m). Planktonic foraminiferal biostratigraphy and Sr-isotopic age estimates indicate that this section is upper Oligocene (Fig. 4b). Sequence O4 is the oldest Oligocene sequence recognized at Great Bay. It extends from a total depth at 1005 ft (306.3 m) to between 985 and 967 ft (300.2 and 294.7 m). The basal unconformity of sequence O4 was not penetrated and the upper bounding surface is not clearly delineated by gamma ray logs. Two Sr-isotopic age estimates (27.6 and 27.5 Ma at 1005 ft) correlate this sequence with Biochron P21b partim. This conflicts with the presence of *C. cubensis* in this interval that suggest a correlation with Biochron P21a. However, in other cores recovered from onshore boreholes, the occurrence of *C. cubensis* often conflicts with other age estimates (e.g., nannofossils, Sr-isotope age estimates) due to reworking. Therefore, Sr-isotope age estimates at Great Bay Site are given priority over the HO of *C. cubensis*. The next sequence (~965–805 ft; 294.1–245.4 m) is dated by Sr isotopic stratigraphy from 27.0 to 26.4 Ma; the HO of *P. opima opima* is at 945 ft (288.0 m), correlating it to Biochrons P21b and P22 (28.5–23.8 Ma). Thus, Sr-isotopic and biostratigraphy correlate this interval with sequence O5 of Pekar et al. (1997). The average sedimentation rate for sequence O5 at Great Bay is ~80 m/m.y.

3.2.7. Atlantic city

Uppermost Eocene strata are not recognized at Atlantic City (Browning et al., 1997); however, an expanded thick Oligocene section was identified. The chronostratigraphy of Oligocene strata at Atlantic City was determined using Sr-isotopic and planktonic foraminiferal and nannofossil biostratigraphy (Fig. 4c). The oldest sequence (1181–1166 ft; 360–355.4 m) is dated by one Sr-isotopic age estimate (31.6 Ma) and is assigned to nannofossil Zone NP23 (32.2–29.9 Ma; Pekar et al., 1997), correlating it with sequence O2 of Pekar et al. (1997). The next sequence is also thin (1166–1138 ft, 355.4–346.9 m), has an age estimate of 28.9–28.3 Ma (Fig. 3c) based on two Sr-isotopic age estimates, and a sedimentation rate of 16 m/m.y. The highest occurrence of *C. cubensis* (Fig. 4c) is attributed to reworking. However, the highest common occurrence (Fig. 4c) of this taxon fits very well with the Sr-isotopic age estimates.

Sequence O4 is represented at Atlantic City between 1138 and 1072 ft (346.9–326.7 m; Fig. 4c) and is correlated to Biochron P21b. The basal disconformity is indicated by: (1) a sharp gamma ray increase; (2) an abrupt change in lithology from generally glauconite sand below to clays above; and (3) a shift across the boundary in the dominant benthic foraminiferal species (Pekar, 1999). Sequence O4 was dated by the HO of *P. opima opima* (27.1 Ma; at 1078 ft, 328.6 m) and Sr-isotopic age estimates. A best fit through the Sr-isotopic and biostratigraphic data indicates an age of 27.7–27.1 Ma, resulting in a sedimentation rate of 33 m/m.y. (Fig. 4c).

Sequence O5 is observed at Atlantic City (1072–923 ft, 326.7–281.3 m) and has an age of 26.7–25.8 Ma (Fig. 4c), correlating it with Biochron P22. Although the basal surface at 1072 ft (326.7 m) contains no discernible hiatus, it is recognized as a sequence boundary by an abrupt shift in lithology and biofacies (Pekar, 1999). The sequence is dated by four Sr-isotopic age estimates (one duplicate) ranging from 26.8 to 25.9 Ma (Fig. 4c). It contains a sedimentation rate of 50 m/m.y.

Sequence O6 is dated by two Sr-isotopic age estimates (25.3 and 25.1 Ma) and estimated to extend from 25.3 to 25.1 Ma. Although there is no discernible hiatus, the basal surface of sequence O6 is recognized by a thick shell lag and a shift in biofacies (Pekar, 1999). This shell lag at the base of this thin sequence (10 ft, 3.0 m) is similar Miocene sequences observed by Kidwell (1989).

3.2.8. Cape May

Cape May is the most downdip borehole in this study and contains five of the eight Oligocene sequences (Fig. 4d). Uppermost Eocene strata were not identified at Cape May (Browning et al., 1997). The oldest Oligocene sequence at Cape May is sequence O1 (Pekar et al., 1997). It is dated only by planktonic foraminiferal biostratigraphy and is correlated to Zone P18 (33.8–32.0 Ma). Sequence O2 is dated by four Sr-isotopic age estimates ranging in age from 31.5 (two at 1350 ft, 411.5 m) to 30.1 Ma (two at 1340 ft, 408.4 m). Sequence O3 is thin (1314–1304 ft, 400.5–397.5 m) and dated by two Sr-isotopic age estimates of 28.3 and 28.5 Ma (Fig. 4d). Sequence O5 is also very thin (1304–1300 ft, 397.5–396.2 m) and is dated by a single Sr-isotopic age estimate of 26.6 Ma. Sequence O6 is expanded at Cape May (1300–1180 ft, 396.2–359.7 m) and is dated by ten Sr-isotopic age estimates ranging in age from 25.7 to 24.3 Ma and dinocysts assigning this sequence as uppermost Oligocene (25.7–23.9 Ma). The average sedimentation rate for sequence O6 is 21.5 m/m.y.

3.3. Backstripping analysis

Developing an integrated chronostratigraphic framework of the Oligocene sequences enabled us to backstrip the New Jersey strata. Backstripping is a technique that progressively removes the effects of sediment loading (including the effects of compaction), eustasy, and paleoenvironment from basin subsidence to obtain tectonic subsidence (Watts and Steckler, 1979; Bond and Kominz, 1984; Bond et al., 1989). We have modified the method: by using one-dimensional backstripping results to estimate the subsidence due to compaction and two-dimensional flexural backstripping results to calculate the subsidence due to sediment loading[2], which enabled the geometry of the New Jersey Oligocene strata to be reconstructed. One-dimensional backstripping was performed on five boreholes: Cape May, Atlantic City, Island Beach, Bass River, and ACGS#4 (Kominz et al., 1998; Kominz and Pekar, submitted). The non-Oligocene Bass River borehole data are taken from Miller et al. (1998). Underlying sediments (Cenomanian and older, i.e. pre-Bass River Formation) were taken from the Island Beach rotary well but modified to the overall thickness estimated beneath the Bass River borehole (420 m of Potomac Formation). Porosity vs. depth curves for sandstone and shale are taken from estimates at the COST B2 well (offshore New Jersey; Rhodehamel, 1977). Porosity estimates for silt, and carbonates are from the generic curves of Bond and Kominz (1984). Kominz and Pekar (2000) backstripped using two end member porosity curves that bracket observed (COST B2) and composite porosity data.

Only Oligocene lithologies, ages, and paleobathymetries were available for the Jobs Point, AMCOR 6011, and Great Bay boreholes. Backstripping of these sites was accomplished by assuming that underlying and overlying sediment lithologies and environments were identical to the Island Beach borehole but thickness were increased in proportion to the distance between each site and the Island Beach borehole on the composite dip section (Kominz and Pekar, 2000). A similar procedure was used with the ACGS#4 borehole using data modified from the Bass River borehole. While these procedures are far from ideal, the relatively simple tectonic and depositional environment of the New Jersey Coastal Plain (Kominz et al., 1998) minimizes the impact of variations in the strata above and below the Oligocene. We assume a post-Eocene surface with a gradient of 1:500 based on backstripping of this margin by Steckler et al. (1999). Kominz and Pekar (2000) calculated the subsidence due to compaction by adding Oligocene sediments in increments of <0.5 m.y. The thickness of the Oligocene sediments through time is obtained as a direct result of one-dimensional backstripping.

A two-dimensional flexural model was developed by Kominz and Pekar (2000) to calculate the response of the basement of the Oligocene sediment load. In previous studies, backstripping methods used one-dimensional modeling that assumed an Airy isostatic response to loads (Kominz et al., 1998). This results in ϕ (the basement response function) being equal to one and an increase in the amount of subsidence due to loading by a factor of four. However, this is true only for sediments deposited on a thin crust in which subsidence is localized. The lithology-dependent porosity vs. depth curves were used to estimate the thickness and density of sediment grains in the Oligocene sedimentary sections of all eight coastal plain boreholes and in four ODP slope sites (Sites 902, 903, 906 and 1073; Kominz and Pekar, 2000). These thickness and densities were progressively loaded onto a plate with a rigidity equivalent to an elastic plate thickness of

[2] See Kominz and Pekar (2000) for an in depth description of the method used in reconstructing the stratal geometry using two-dimensional backstripping results.

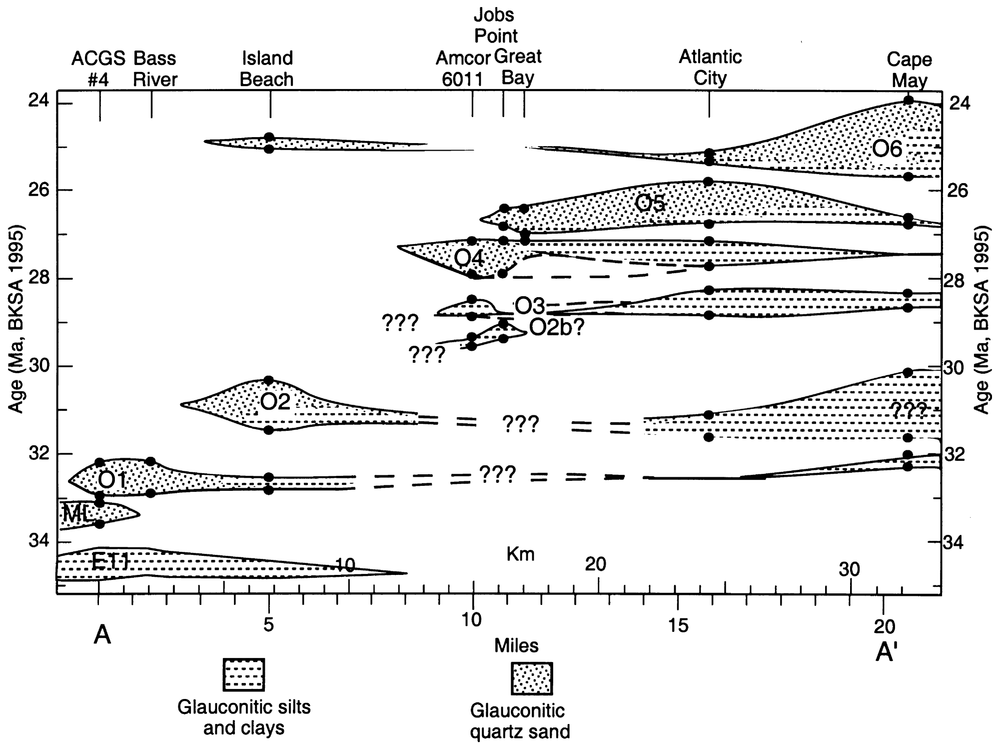


Fig. 5. Age-distance ("Wheeler") diagram of the New Jersey latest Eocene and Oligocene strata. Solid circles represent data points. Sediments preserved are represented by dashed lines (silts and clays) or dots (quartz sand). Time not represented by sediments are represented by the white areas. Time scale is from Berggren et al. (1995).

30 km landward of the hinge zone and decreasing to a 20 km elastic plate thickness near the shelf-slope break continent-ocean transition (150 km on the composite dip section). Rigidities are simplified from Steckler et al. (1999) and are assumed to be constant during this short geologic interval (about 34–23 Ma).

4. A model for New Jersey Oligocene sequences: clinoform progradation

We projected onshore and offshore latest Eocene through Oligocene sequences onto a dip section through Great Bay (Figs. 1, 2, 5 and 6). This section was selected because it required only modest (<5–35 km) projection along strike, except for the Cape May borehole that required a long-distance (60 km) projection. The strike component is generally well constrained and subparallels basement contours (Volkert et al., 1996) and the Cretaceous outcrop belt (Fig. 1). Two-dimensional flexural backstripping provides evidence of along strike variability, by estimating the sedimentary accumulations at each site. These results indicate that although there are indeed variations in sedimentation along strike, they are relatively minor and do not affect the clinoform model proposed here (Pekar, 1999).

Evidence for progradation of New Jersey Oligocene strata is inferred in the stratal geometry of the onshore sequences in the dip section (Figs. 2, 5 and 6). Integration of data from preexisting sites (ACGS#4, AMCOR 6011, Island Beach, Jobs Point; Pekar et al., 1997) and newly drilled sites (e.g., Bass River, Great Bay, this study), reveals a distinct distributional pattern of uppermost Eocene and Oligocene onshore and nearshore sequences (Fig. 2). Uppermost Eocene and lowermost Oligocene sequences (E11, ML, O1) were thickest at updip sites (ACGS#4, Bass River), while downdip they were either thin or absent (e.g.

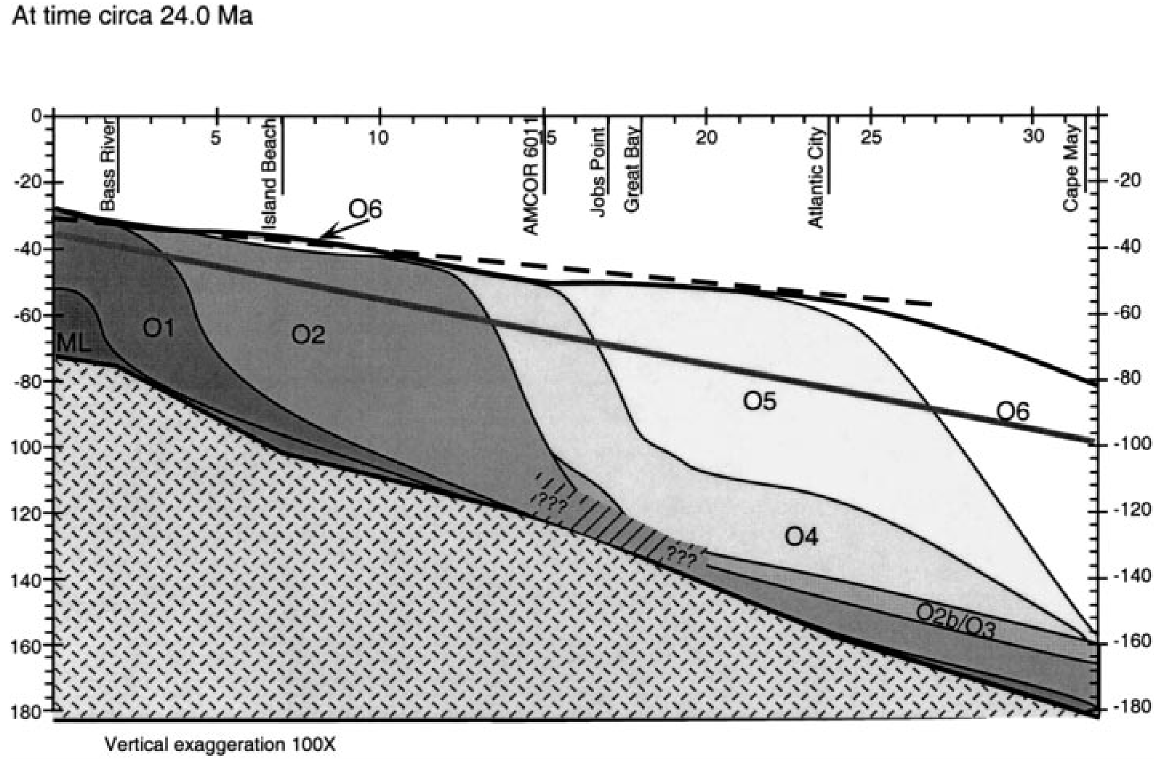


Fig. 6. Distribution of New Jersey Oligocene sequences projected onto a dip line. The tie points of the reconstructed sequence boundaries are the depths of sequence boundaries at each well site. The sigmoidal shape of the contours (sequence boundaries) is inferred, although the data do require some type of inclined surfaces between locations. The total thicknessess of the clinoform heights are based on 2-D flexural backstripping from Kominz and Pekar (submitted) and accounts for decompaction, flexural sediment loading. The original depth and gradient (1/500) of the Eocene/Oligocene surface is the solid straight line. The paleo-shelf gradient behind the clinoform inflection point is 1/1000 (thick dashed straight line). The maximum flooding surfaces are shown as thin dashed lines. The hatcher marks indicate uncertainties due non-penetration of the wells.

Atlantic City, Cape May, Fig. 2). The thickest Oligocene sequences became progressively younger in downdip sites (O2 at Island Beach, O4 at AMCOR 6011 and O5 at Great Bay and Atlantic City). At the most downdip site (Cape May), the thickest sequence is dated as uppermost Oligocene (sequence O6; 25.7–23.9 Ma, Fig. 2). Chronologically, the thickest Oligocene units appear to migrate across the shelf from the most updip sites (ACGS#4 and Bass River) to the most downdip sites (Atlantic City and Cape May, Fig. 5). This is consistent with an interpretation that clinoform packages prograded across the shelf.

Two-dimensional flexural backstripping results allowed reconstruction of the original geometry of the New Jersey strata (Fig. 6). In Fig. 6, the sediments have been decompacted, and subsidence due to cooling, compaction, and flexural loading has been estimated for time ca. 24 Ma (top of the Oligocene). The locations of sequence boundaries at each site were identified, and then correlated from site to site. The sigmoidal shape of the contours (Fig. 6) is inferred, although the data do require some type of inclined surfaces between locations.

A paleoslope gradient of 1:500 is used for the upper Eocene surface at the end of the Eocene (33.7 Ma; bold solid line in Fig. 6). This results in a gradient of ~1:1000 for the shallow shelf inboard of clinoform inflection point. This is similar to the present-day shelf gradient. The assumed gradient is supported by results from Steckler et al. (1999), indicating that:

1. progradation and aggradation of Oligocene to

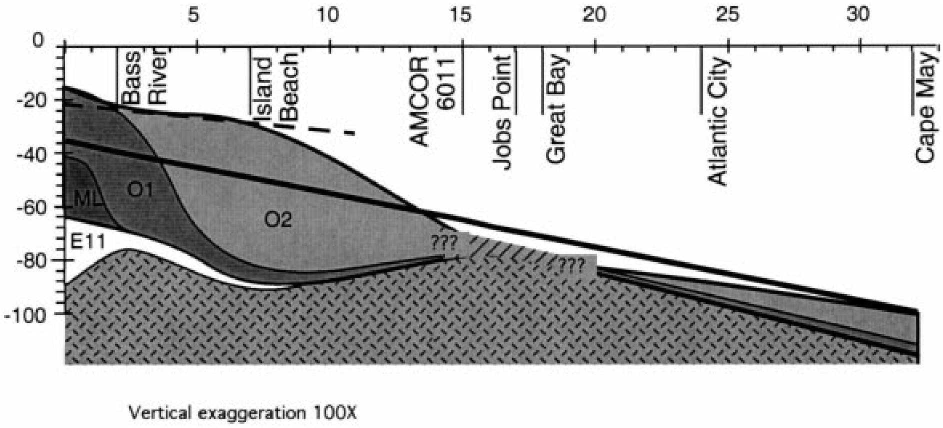


Fig. 7. Distribution of New Jersey latest Eocene and Oligocene sequences projected onto a dip line at 30.0 Ma. See Fig. 6 caption for further description.

Miocene sequence resulted in a physiographic gradient of 1:1000; and
2. the underlying Eocene carbonate ramp has a physiographic gradient of 1:300–1:500. This gradient is steeper than estimates of Eocene surfaces from previous studies (e.g. Browning et al., 1997) and is of particular importance when developing paleoslope models that are used to determine water depths and relative sea level.

5. Reconstructing New Jersey Oligocene stratal geometry

Three time slices were reconstructed from the earliest Oligocene to the latest Oligocene. The reconstructions extend from the most updip borehole that contains uppermost Eocene and Oligocene strata (e.g. ACGS#4) to the most downdip borehole (Cape May). These reconstructions show the progradation of Oligocene sequences over the Eocene/Oligocene surface.

The first reconstruction is a time slice at 30.0 Ma (Fig. 7). It shows an uppermost Eocene sequence (sequence E11 of Browning et al., 1997) and three lower Oligocene sequences (sequences ML, O1, and O2 of Pekar et al., 1997) prograding across the Eocene surface. Because there are no seismic data available for this reconstruction, the inferred shapes of the contours (Fig. 7) were constructed to conform to the data, because inclined surfaces are needed between locations. Sequence E11 of Browning et al. (1997) is the youngest Eocene sequence recognized in the New Jersey Coastal Plain and is thickest at ACGS#4 (slightly over 40 m, decompacted), consisting of micaceous silts and clays. At updip and downdip sites, it is either thin (<10 ft, 3 m) or absent (Browning et al., 1997). The lowermost Oligocene sequences (sequences ML and O1) are between 30 and 45 m thick (decompacted). The heights of Oligocene sediments are approximately 20 m above the original depth of Eocene/Oligocene surface at ACGS#4 and Bass River after taking into account subsidence due to compaction and flexural loading (Fig. 7). At Island Beach, the height of Oligocene sediments above the original depth of the Eocene/Oligocene boundary has increased to ~30 m with a total thickness of decompacted sediment of 65 m.

The next time slice is reconstructed at time 27.0 Ma (Fig. 8). Prograding sequences deposited during the late early Oligocene (29.5–28.3 Ma) are the least well defined and dated. Although, sequence O3 is well documented and dated at both Atlantic City and Cape May, identification of sequence O2b is speculative. Sequence O4 is represented in four sites (AMCOR 6011, Jobs Point, Great Bay, and Atlantic City) and contains a well-defined clinoform and extensive sediments in front of the clinoform.

The youngest time slice reconstructed is at 24.0 Ma and includes sequences O5 and O6 and their associated clinoforms (Fig. 6). The height of the sediment above the original depth of the Eocene/Oligocene

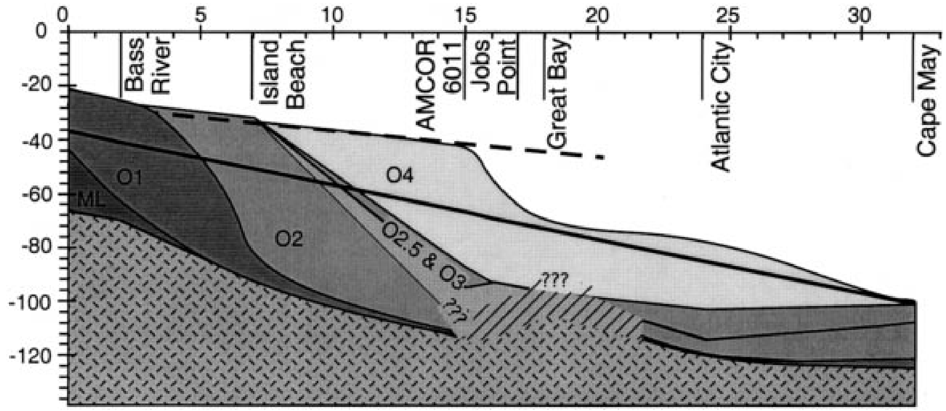


Fig. 8. Distribution of New Jersey Oligocene sequences projected onto a dip line 27.0 Ma. See Fig. 6 caption for further description.

surface increases to nearly 50 m at Cape May with a decompacted thickness of slightly over 100 m (Kominz and Pekar, 2000). The inferred stratal geometry illustrated (Fig. 6) for these upper Oligocene clinoforms is supported by data from seismic profile 529 from the *Oceanus 270* data and recently collected R/V Cape Hatteras 0698 data (Monteverde et al., this volume).

6. Discussion

Reconstructions indicate a change from a generally flat carbonate ramp[3] to the initiation of a prograding clinoformal shelf during the latest Eocene (Fig. 6). While Eocene sequences were widely distributed updip and downdip (Miller et al., 1997a,b), uppermost Eocene to lower Oligocene sequences were more localized, resulting in a wedge-shaped geometry. During the Oligocene, features resembling the present-day shelf geometry developed, such as a gentle gradient across the shelf and a clear clinoform inflection point. These changes resulted from increased siliciclastic sediment supply that resulted in clinoforms prograding across the shelf. As sediments prograded across the carbonate ramp, the available accommodation created during the Eocene was filled in (Steckler et al., 1999). Miller et al. (1997a,b) showed that medium-coarse quartz sand appeared as an important constituent during the late Oligocene (approximately 27–25 Ma) in association with an increase in sedimentation rates; here, we show that lower Oligocene sedimentation rates were also high, although the dominant sand-sized component is detrital glauconite.[4]

The clinoforms inferred on Fig. 6 represent the initiation of a new continental shelf on top of the older ramp. During the early and middle Eocene, terrigenous sedimentation to the margin was low (Browning et al., 1997; Steckler et al., 1999). Siliciclastic input increased during the late Eocene, due to increased weathering and may have been the result of climatic cooling observed globally (Miller et al., 1997a,b). As the climate cooled during the late Eocene, siliciclastic input increased as seen in the clay-rich sequence deposited during the latest Eocene (Sequence E11 of Browning et al., 1997). This sequence may represent the oldest Eocene siliciclastic sediments observed in New Jersey and may represent the initiation of siliciclastic progradation. Oligocene sequence ML overlays sequence E11 and consists of micaceous silts and quartz sand. It represents a transitional lithology from the silty clay below to the quartz-rich sand facies observed in younger Oligocene sequences. The increased siliciclastic input finally closed down the "carbonate factory" on the slope during the major cooling during the earliest Oligocene (Miller et al., 1997a,b). Although the age

[3] Offshore seismic profiles indicate that Eocene reflections were generally flat with little or no sigmoidal geometry and no evidence of clinoform progradation (Greenlee et al., 1992).

[4] Pekar et al. (1997) showed that much of the glauconite found in Oligocene sequences is recycled and detrital.

of the oldest siliciclastic clinoforms in New Jersey have not been determined[5], by the latest Eocene, we see evidence that there were indeed small siliciclastic wedges prograding basinward (e.g. E11 at ACGS#4; Fig. 7).

Clinoform heights changed in response to increased siliciclastic input during the Oligocene. As the clinoforms prograded across the shelf during the Oligocene, their heights increased from ~20 m at the most updip boreholes (ACGS#4 and Bass River) to nearly 50 m at the most downdip boreholes (Atlantic City and Cape May) (Kominz and Pekar, 2000). This was due to increased accommodation as the outbuilding of sediments crossed the Eocene ramp.

The majority of deposition in the New Jersey Coastal Plain for the latest Eocene to Oligocene occurred immediately in front of the previously deposited sedimentary wedges. Little or no deposition occurred behind the clinoform inflection point. The lack of aggradation was due to either the lack of new accommodation being created behind the clinoform inflection point or erosion removing the sediments from the shelf. Lack of accommodation[6] can be explained by the New Jersey margin experiencing little tectonic or flexural subsidence during the Oligocene (Kominz and Pekar, 2000). Thus, eustatic increases are the main mechanism for increasing accommodation for the onshore New Jersey sites during the latest Eocene to Oligocene. Marine erosion could also be invoked to explain the absence of sediments preserved behind the clinoform inflection point; sea-level during the Oligocene never regained its pre-Oligocene heights (Kominz and Pekar, 2000)[7] and the shelf behind the clinoform inflection point may have remained in water depths susceptible to marine erosion. This would have resulted in the erosion and transport of onshore sediments past the previous clinoform inflection point, adding to the developing clinoform wedge (Nummedal et al., 1993). This would explain the almost complete lack of sediments deposited behind the clinoform inflection point of the New Jersey Coastal Plain during this time.

Two-dimensional flexural backstripping can provide evidence for along strike variability by estimating the sedimentary accumulations at each site. During the early Oligocene, gradient on the dip profile between ACGS#4 and Bass River greater than 1:1000, which can be explained by along strike variation (Fig. 7). Along strike variability is also indicated by a varying gradient on the shelf behind the clinoform inflection point when projected into a dip profile at ~24 Ma (Fig. 6). This suggests the presence of localized subsidence (due to loading) and variable sedimentary input. This is most apparent in two cases: (1) preservation of a thin O6 sequence at Island Beach that suggests an increase in accommodation near Island Beach (localized subsidence); and (2) the presence of a slightly thicker Oligocene section at Atlantic City than predicted in our clinoform model, suggesting a depositional center near Atlantic City (e.g. an increase in sedimentation accumulation due to the proximity of fluvial systems). The along strike variability inferred in the 2-D backstripping model in no way contradicts the clinoform model presented here, indeed it demonstrates the viability of the model in delineating more subtle details of the stratal geometry impossible to resolve without seismic data.

7. Conclusions

Nine latest Eocene to Oligocene sequences are identified from eight sites situated on the New Jersey Coastal Plain. With the addition of five new sites, the "patchy" distribution of New Jersey Oligocene sequences observed in earlier studies (Pekar et al., 1997) is resolved into a clear pattern of progradation of generally thin and spacially limited latest Eocene to Oligocene clinoforms. These clinoforms probably began prograding across the carbonate Eocene ramp during the latest Eocene and early Oligocene. The heights of these rollovers ranged from ~20 m at the most updip sites (ACGS#4) to nearly 50 m at the most downdip sites (Cape May and Atlantic City). Sedimentation rates ranged from 40 to 80 m/m.y. for sections that were deposited within the clinoform wedges to less than 10 m/m.y. for sections that were deposited in front of the clinoform inflection point.

[5] For example, they may have begun anytime during the late middle Eocene to the late Eocene.

[6] Accomondation is a function of eustasy, sedimentary input, and local tectonics.

[7] During the transition from the Eocene to the Oligocene, a substantial eustatic fall occurred (~50 m, Kominz and Pekar, submitted).

Most sediment accumulated within the clinoform wedges, with little or no sediment being preserved behind the paleo shelf break. This is because very minor amounts of flexural subsidence due to sediment load combined with eustatic lowerings generated only minor new accommodation space.

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