Correlating Miocene sequences in onshore New Jersey boreholes (ODP Leg 150X) with global $\delta^{18}O$ and Maryland outcrops

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ABSTRACT

Recent onshore New Jersey drilling (Ocean Drilling Program Leg 150X) provided excellent recovery of lower to middle Miocene sequences that we dated with Sr isotopic stratigraphy. Sequence boundaries correlate with deep-sea $\delta^{18}O$ increases (inferred glacioeustatic lowerings), indicating a primary control by global sea-level change. Maryland Miocene outcrops appear to correlate with New Jersey sequences and the $\delta^{18}O$ record, although diagenesis and intense bioturbation limit Sr isotopic age resolution in Maryland. The early Miocene is not well represented in Maryland due to regional tectonics; in contrast, early Miocene accommodation in New Jersey was provided by flexural effects due to sediment loading.

INTRODUCTION

The Oligocene-Holocene is an interval suitable for evaluating the relation between glacioeustasy inferred from $\delta^{18}O$ studies (e.g., Miller et al., 1991; Wright and Miller, 1992) and the deposition of sequences on passive margins. The U.S. Middle Atlantic Coastal Plain (Fig. 1) provides an excellent record of shallow-marine sequences, particularly in Miocene outcrops in Maryland and Virginia and the New Jersey subsurface. However, previous studies of the Miocene outcrops were limited by poor age correlations due to the absence of index fossils. Initial efforts to date Miocene sequences in New Jersey with Sr isotopes suggested a possible correlation between sequences and $\delta^{18}O$ changes (Sugarman et al., 1993), although the study was limited by discontinuous sampling of boreholes. As part of the New Jersey Sea Level Transect, Leg 150X (a collaboration of Continental Scientific Drilling and the Ocean Drilling Program) drilled three continuously cored boreholes at Island Beach, Atlantic City, and Cape May, New Jersey (Miller et al., 1994, 1995; Fig. 1). We provide detailed Sr isotopic age estimates for the Miocene sequences at the Atlantic City and Cape May boreholes and compare them to Maryland outcrops (Fig. 1).

The Miocene strata of Maryland and Virginia (Calvert and Choptank Formations) have provided an informal standard for shallow-water sequences because of the extensive studies of outcrops along Chesapeake Bay (the Calvert Cliffs, Fig. 1; e.g., Shattuck, 1904; Gibson, 1971; Andrews, 1988; Kidwell, 1984; Ward, 1992). The age correlations of the outcrops are not known with certainty because they lack good plankton biostratigraphic control. The primary means of dating the outcrops has been through provincial mollusk (Ward, 1992) and diatom zonations (Andrews, 1988) that are poorly correlated to the time scale.

Sr isotopic stratigraphy allows the calibration of Miocene shallow-marine sections to the time scale with age resolution of ±0.4 m.y. for the early Miocene and ±0.9 m.y. for the middle Miocene (e.g., Oslick et al., 1994). We synthesized published (Sugarman et al., 1993; Miller et al., 1994, 1995) and new Sr isotopic results from the New Jersey boreholes (Fig. 1) with new Sr isotopic results from Maryland outcrops (Table 1). Sr isotopic data were generated on shells using standard techniques (Sugarman et al., 1993; Oslick et al., 1994) and are reported using the Berggren et al. (1985) and Cande and Kent (1992) time scales (Table 1).

NEW JERSEY MIOCENE KIRKWOOD FORMATION

Ages of the lower-middle Miocene Kirkwood Formation are determined primarily from subsurface data because outcrop samples are virtually barren of calcareous material. Sugarman et al. (1993) used Sr isotopic stratigraphy and Andrew's (1988) diatom biostratigraphy to define four Kirkwood sequences in the subsurface: Kw1 (22.6–19.2 Ma), Kw2a (17.4–17.0 Ma), Kw2b (16.0–15.5 Ma), and Kw3 (13.6–12.2 Ma). Although Sugarman et al.'s (1993) study provided the first precise ages for the Kirkwood sequences, they relied primarily on updip boreholes where the sections are thinner and less complete. Continuous coring downdip at Atlantic City and Cape May provided longer, more continuous lower to middle Miocene sections than were previously available, and contained numerous shells suitable for Sr isotopic age estimates.

Lowermost Miocene Sequences Kw0 and Kw1a

The lower Miocene sections at Atlantic City and Cape May contain at least four sequences, Kw0, Kw1a, Kw1b, and Kw2a: the latter three are typical New Jersey sequences that have shoaling-upward lithofacies (Sugarman et al., 1993).

The basal Miocene sequence (Kw0) is dominated by shelf glauconite (similar to Oligocene sequences in New Jersey), is best represented at Cape May, and is dated as ~22.7–22.6 Ma (Fig. 1). At Atlantic City, repetition of three thick (>0.5 m) shell beds and glauconite sands (286–282 m) spanning the Oligocene-Miocene boundary (Sr ages of 26–21.9 Ma; Fig. 1) may represent three thin, truncated sequences (Miller et al., 1994), including one (23.8–21.9 Ma) that correlates to Kw0 at Cape May (Fig. 1).

The earliest Miocene transition from Kw0 to Kw1 marks a fundamental change in depositional regime from shelf to deltaic and nearshore, although offshore seismic stratigraphic studies indicate that local deltaic deposition may have begun in the Oligocene (Greenlee et al., 1988). Kw1a is the most pervasive sequence in the New Jersey subsurface (Sugarman et al., 1993, Fig. 3B). Shell beds (~1 m thick) and glauconitic sands mark the base of Kw1a at both boreholes. At Atlantic City, the Kw1a sequence (56 m thick) shallows upward; shelf and prodelta silty clays are in the base and delta front sands are at the top. At Cape May, the Kw1a sequence (49 m) represents shelf environments that grade upward from middle to inner neritic. Kw1a was deposited between 20.9 and 20.4 Ma (Fig. 1).

Lower Miocene Sequence Kw1b

At Atlantic City, the Kw1b sequence is 23 m thick, and 20.4–20.2 Ma; at Cape May, the coeval (20.1 Ma) sequence is ~27 m thick (Fig. 1). Sr isotopes cannot be used to resolve a hiatus between Kw1a and Kw1b at either borehole, although a major disconformity is indicated by gamma logs, facies shifts, and an irregular surface at the contact

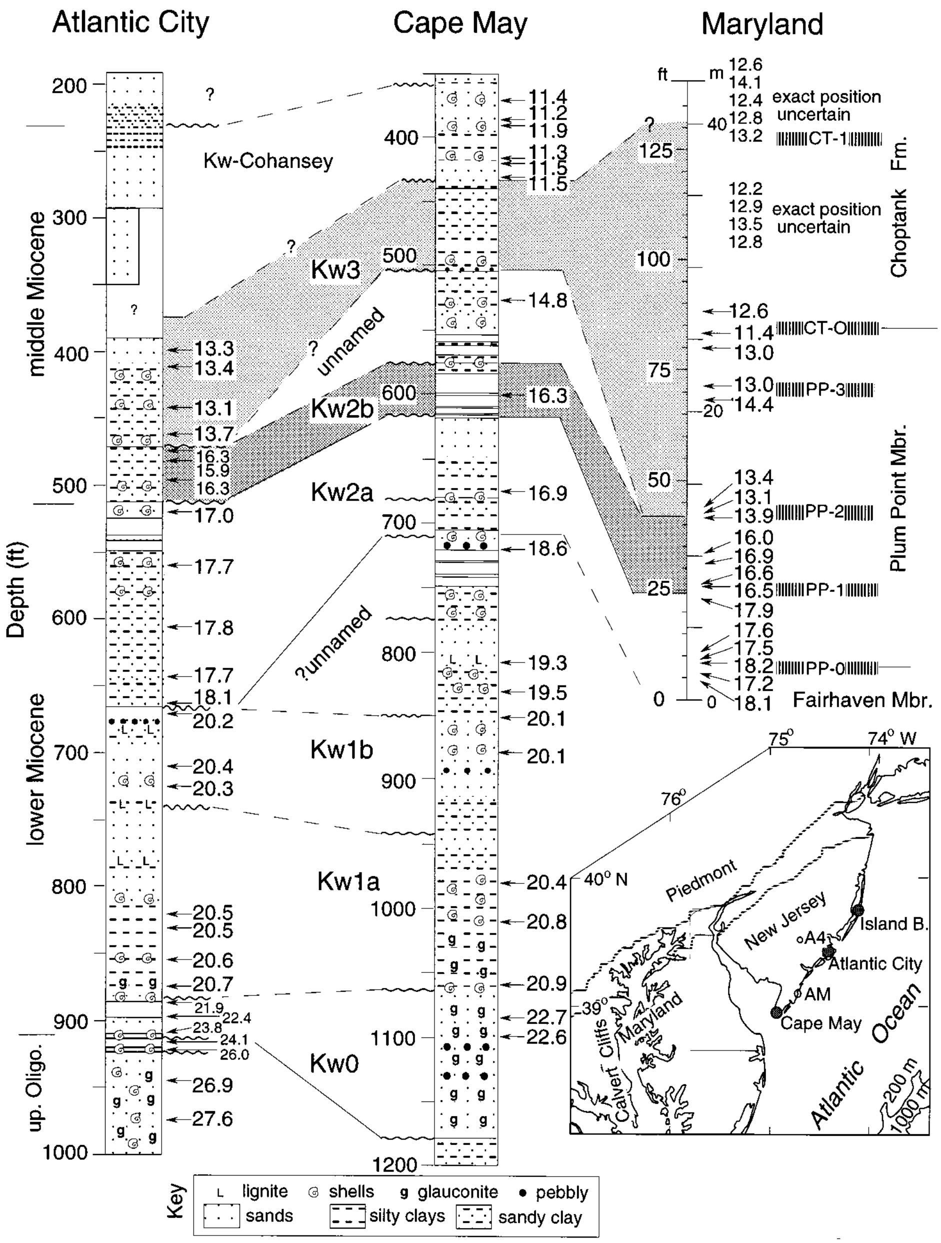

Figure 1. Miocene sections and Sr isotopic ages (Ma), Atlantic City and Cape May boreholes and Maryland outcrop (thickness in metres). Kw0–Kw3 are Kirkwood sequences. Wavy lines are unconformities; vertical-line bars are surfaces in Maryland outcrops (PP-0 to CT-1; Kidwell, 1984) (±1 m to reflect zone of mixing; Table 1). Thicknesses of Miocene units are from sections where Sr isotopic samples were collected (Table 1, keyed to Kidwell, 1984) and do not represent true composite thickness. Inset: Location map. A4 = ACGS#4; AM = Avalon Manor.

(Owens et al., 1988, ACGS#4 borehole; Fig. 1). The Kw1b sequence contains two coarsening-upward sections at Atlantic City. At Cape May, the Kw1b sequence coarsens upward from 287 to 259 m. The section from 259 to 216 m at Cape May appears to be younger (19.5–18.6 Ma) than the Kw1b sequence at Atlantic City; it may represent a previously unsampled sequence (Fig. 1) or an expanded upper Kw1b.

Upper-Lower (Kw2a) and Lower-Middle (Kw2b) Miocene Sequences

There is a major unconformity (0.5–2 m.y. hiatus) at the base of Kw2 (Fig. 1). At Atlantic City and Cape May, the uppermost lower Miocene Kw2a is a coarsening-upward sequence: (1) basal shelly, sandy silts and clays (shelf environments); (2) micaceous, carbonaceous, laminated clay-silts and fine sands (prodelta environments); and (3) interbedded sands and carbonaceous silts (delta-front environments). The Kw2a sequence is 18.2–17.0 Ma at Atlantic City and 16.9 Ma (single date) at Cape May. It correlates with the beginning of sedimentation (~18 Ma) in the Maryland outcrops (Table 1).

The lowermost middle Miocene Kw2b sequence is predominantly a burrowed clay-silt (prodelta environment) similar to Kw2a. Kw2b is 16.3 to 15.9 Ma at Atlantic City and 16.3 Ma at Cape May.

Middle-Middle Miocene Sequences

At Cape May, there appears to be a middle-middle Miocene unnamed sequence that is not present at Atlantic City (Fig. 1). The sequence is a shelf quartz sand with a single Sr isotopic age of 14.8 Ma. At Avalon Manor (Fig. 1), a Sr isotopic age estimate of 14.6 Ma (Sugarman et al., 1993) indicates that this sequence may be present only in the Cape May peninsula.

A major unconformity separates the unnamed and Kw3 sequences. The Kw3 sequence is 13.6–13.3 Ma (Fig. 1) at Atlantic City, although Sugarman et al. (1993) reported younger (up to 12.2 Ma) ages for this sequence in other boreholes (slashes in Fig. 2). Paleoenvironments in Kw3 are dominantly inner neritic and nearshore.

Another middle Miocene sequence is present at Cape May and is dated as 11.9–11.2 Ma. A possible correlative section at Atlantic City (Fig. 1) lacks shells for Sr isotopic analyses. At Cape May, the sequence is dominated by shelly quartz sands (inner neritic) and lesser amounts of laminated micaceous clay-silt and fine sand. We are uncertain whether this unit correlates with the middle Miocene Kirkwood Formation or the poorly dated Cohansey Formation (Owens et al., 1988), and we call it the Kirkwood-Cohansey sequence.

Maryland Miocene Outcrops

Macrofossils for Sr analyses were collected from beds 3 to 19 (Shattuck, 1904) of the Calvert and lower Choptank Formations and placed into the stratigraphic framework of Kidwell (1984; Fig. 2). Kidwell mapped four major surfaces (PP0, PP1, PP2, and PP3) in the Calvert Formation and two within the Choptank Formation (CT0, CT1). Unlike analyses from New Jersey sections, where Sr isotopic ages generally decrease monotonically upsection (Fig. 1), Sr isotopic analyses of the Maryland outcrops are complicated by diagenetic overprints and intense bioturbation. Shells were reworked up or piped down by >1 m at some stratigraphic contacts, often yielding ages immediately below surfaces that are equivalent to those of the sequences above (Table 1). Paired analyses of aragonitic and calcitic shells (e.g., 10A and 10CS; for others, see Sugarman, 1994) yielded values that are significantly different (0.000060) than sample reproducibility (±0.000020), suggesting diagenetic alteration. Because of these problems, we grouped ages between recognizable surfaces (e.g., the PP0–PP3, CT0,

TABLE 1. SR ISOTOPE DATA FROM MARYLAND OUTCROPS

Sample	$^{87}Sr/^{86}Sr$ Error(±)	Age, Ma BVK85	CK92	Formation, Member	Comments	Bed	Diatom Zone
BGE	0.708853±5	12.6	12.8	Ch, BC	Baltimore Gas and Electric	19	7
M78-8	*0.708906±15	10.3	10.8	Ch, BC	Baltimore Gas and Electric	19	7
M78-11	*0.708891±70	10.9	11.4	Ch, BC	Baltimore Gas and Electric	19	7
V-13C	0.708821±6	14.1	14.0	Ch, BC	Nomini Cliffs, VA	19	7
DJB1232A	0.708859±16	12.4	12.6	Ch, BC	Drumcliff	19	7
Chopt. R.	0.708850±9	12.8	12.9	Ch, BC	Type section; 4 analyses	19	7
M-40	0.708839±40	13.2	13.4	Ch, BC	Tributary of Patuxent River	19	7
mean value above CT1		13.0					
				CT1 surface			
84-13	0.708856±41	12.5	12.7	Ch, DC?	Bioturbated zone across CT1	17?	6
84-13	0.708873±6	11.8	12.1	Ch, DC?	Bioturbated zone across CT1	17?	6
Top Drum.	0.708848±5	12.9	13.0	Ch, DC	Top of Drumcliff	17	6
M-46	0.708835±7	13.5	13.5	Ch, DC	Tributary of Patuxent River	17	6
M-74	0.708849±8	12.8	13.0	Ch, DC	Baltimore Gas and Electric	17	6
37-10	0.708851±6	12.7	12.9	Ch, DC	Bioturbated zone across CT0	17	6
37-10	0.708856±24	12.5	12.7	Ch, DC	Bioturbated zone across CT0	17	6
37-11	*0.709007±21	5.7	7.0	Ch, DC	Bioturbated zone across CT0	17	6
37-9	0.708880±11	11.4	11.8	Ch, DC?	Bioturbated zone across CT0	17	6
mean value between CT0-CT1		12.6					
				CT0 surface			
37-8	0.708846±24	13.0	13.1	Ca, PP	1.5 m below CT0	15	?
75-16	*0.708926±29	9.4	10.1	Ca, PP	0.3 m above PP3	14	5
75-15	0.708845±0	13.0	13.1	Ca, PP	0.2 m above PP3	14	5
mean value between PP3-CT0		13.1					
				PP3 surface			
75-14	0.708814±15	14.4	14.3	Ca, PP	0.7 m below PP3	13?	3-4
6-6	0.708837±7	13.4	13.4	Ca, PP	Bioturbated zone across PP2	12	3-4
32-17	0.708832±5	13.6	13.6	Ca, PP	Bioturbated zone across PP2	12	3-4
32-17	0.708856±8	12.5	12.7	Ca, PP	Bioturbated zone across PP2	12	3-4
6.-5	0.708824±11	13.9	13.9	Ca, PP	Bioturbated zone across PP2	12	3-4
mean value between PP2-PP3		13.7					
				PP2 surface			
6-7	0.708782±5	16.0	15.7	Ca, PP	~3 m below PP2	11	3-4
11A	0.708720±6	16.9	16.6	Ca, PP	Aragonite	11	3-4
10A	0.708779±6	16.1	15.8	Ca, PP	Aragonite	10	3-4
10CS	0.708712 ±6	17.0	16.7	Ca, PP	Calcite	10	3-4
14-4	0.708751±5	16.5	16.2	Ca, PP	0.25 m above PP1	10	3-4
mean value between PP1-PP2		16.5					
				PP1 surface			
14-3	0.708651±14	17.9	17.6	Ca, PP	0.6 m below PP1	4 to 9	2
22-23	0.708672±9	17.6	17.3	Ca, PP	1 m above PP0	4 to 9	2
22-22	0.708676±8	17.5	17.3	Ca, PP	0.5 m above PP0	4 to 9	2
15-2	0.708634±19	18.2	17.9	Ca, PP	Immediately above PP0	4 to 9	2
				PP0 surface			
15-1	0.708700±8	17.2	16.9	Ca, F	1.5 m below PP0	3b	2
HB-21	0.708638 ±8	18.1	17.8	Ca, F	Just below phosphate layer	3b?	2
mean value below PP1		17.8					

Note: Sr values are reported to NBS 987 standard of 0.710255 (Oslick et al., 1994). Ages were computed using the regressions of Oslick et al. (1994) and the time scales of Berggren et al. (1985; BVK85) and Cande and Kent (1992; CK92). Formations, Ch, Choptank, Ca, Calvert; Members: BC, Boston Cliffs, DC, Drumcliff, PP, Plum Point, F, Fairhaven. Beds refer to Shattuck (1904). Diatom Zones are the East Coast Diatom Zones of Andrews (1988). PP1-PP3, CT0, CT1 are the surfaces of Kidwell (1984). HB = Herring Bay; samples 15, 22, 14, 6, 75, and 37 are localities in Kidwell (1984).

*Values suspected to be altered by diagenesis.

and CT1 surfaces of Kidwell, 1984) for interregional comparison (Table 1).

Sr isotopic age estimates from the base of the Calvert Formation (beds 3–9; Shattuck, 1904) yielded an average of 17.8 ± 0.4 Ma (Table 1), and no discernible hiatus associated with the Fairhaven–Plum Point contact (PP0). The lower Calvert correlates with the Kw2a sequence (Fig. 2); the Kw1 and Kw0 sequences correlate with a hiatus in the Maryland outcrops (older than ~18 Ma; Fig. 2).

The middle Plum Point Member of the Calvert Formation (beds 10 and 11; between PP1 and PP2) has an average age of 16.5 ± 0.4 Ma (range 17.0–16.0 Ma). The PP1 surface at the base of this section is a disconformity with a ~0.5–1 m.y. hiatus (~17.5–17.0 Ma). Thus, it correlates with the Kw2b sequence (~16.3–15.9 Ma), although it may be slightly older (Fig. 2).

The upper Plum Point Member disconformably overlies the PP2 surface (hiatus of 2–3 m.y.; Table 1). Sr isotopic ages (14.4–12.5 Ma) indicate that this section (PP2–CT0) correlates with the Kw3 sequence. The upper Plum Point Member is divided into two sequences: beds 12 and 13 (between PP2 and PP3) and beds 14 and 15 (between PP3 and CT0 surfaces). Sr isotopes yielded a mean age of 13.7 ± 0.9 Ma for the lower sequence and 13.1 ± 0.9 Ma for the upper sequence. Sr isotopes and diatom biostratigraphy (Andrews, 1988) indicate a possible hiatus (<0.6 m.y.) at the PP3 disconformity.

The lower Choptank Formation (bed 17, Drumcliff Member) is upper-middle Miocene (mean age 12.6 ± 0.9 Ma). The upper Choptank (bed 19, Boston Cliffs Member) yielded a slightly older mean age (13.0 ± 0.9 Ma). Thus, using Sr isotopes alone, we can date the Choptank Formation only as ~14–11.5 Ma and cannot discern hiatuses associated with the CT0 surface (Calvert-Choptank contact) or CT1 surface. The Choptank Formation does not appear to have an equivalent in New Jersey, and it appears to correlate with a 13.3–11.9 Ma hiatus between Kw3 and the Kw-Cohansey sequence (Fig. 2). Alternatively, the Choptank could correlate with the Kw3 sequence (Sugarman, 1994).

DISCUSSION AND CONCLUSIONS

Although deposition was punctuated by hiatuses associated with at least four well dated sequence boundaries (the bases of Kw0, Kw1a, Kw1b, and Kw2a), the New Jersey subsurface provides a relatively complete early Miocene record of shallow-marine sequences (Fig. 2). The major sequence boundaries in New Jersey (Kw0, Kw1a, Kw2a, Kw2b, Kw3, and Kw-Cohansey) show an excellent correspondence to $\delta^{18}O$ increases associated with Mi1, M1a, M11b, Mi2, Mi3, and Mi5 oxygen isotope zones (Fig. 2). This correlation indicates a glacioeustatic influence on the New Jersey sequences because these $\delta^{18}O$ increases reflect global ice-volume increases (Miller et al., 1991). Hiatuses are associated with $\delta^{18}O$ increases. In addition, the bases of the New Jersey sequences generally correlate with the $\delta^{18}O$ maxima used to define the Mi zones (Fig. 2). This indicates that unconformities were cut during the most rapid eustatic falls, but that deposition resumed during the eustatic lowstands as subsidence outpaced the rate of sea-level fall. Kw1b is the only sequence without a corresponding $\delta^{18}O$ increase (Fig. 2); it could correlate with an ~20 Ma $\delta^{18}O$ increase that is poorly defined at present (indicated by ? in Fig. 2; Wright and Miller, 1992).

Comparison of the New Jersey and Maryland Miocene records shows similarities and distinct differences (Fig. 2), although we are less certain of the precise ages assigned to the Maryland sections. For example, the PP1 sequence appears to be slightly older than Kw2b, and the Mi2 $\delta^{18}O$ maximum (~16.2 Ma) appears to fall in the middle of the sequence (Fig. 2). We attribute this apparent difference to the 1 m.y. scatter on ages in the Maryland sections. The PP1–PP3, CT0, and CT1 surfaces may correlate with $\delta^{18}O$ increases, but to demonstrate this, more precise age estimates must be obtained by drilling these sections downdip, where they are thicker and more complete.

Much of the lower Miocene of Maryland is missing in outcrop and the subsurface

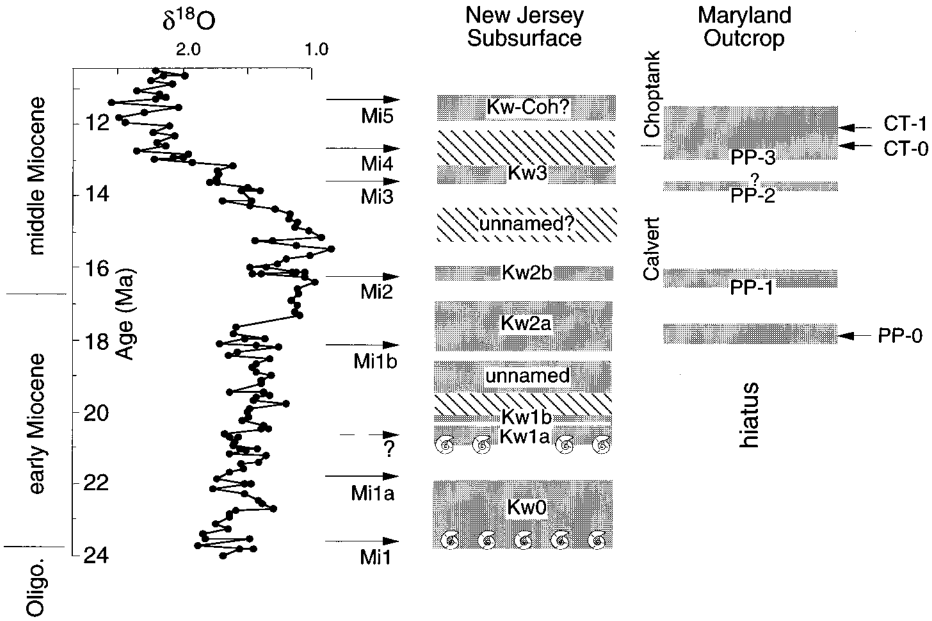

Figure 2. Comparison of deposition in New Jersey and Maryland (derived from Table 1) with benthic foraminiferal (*Cibicidoides*) $\delta^{18}O$ record from Site 747 (Miller et al., 1991; Wright and Miller, 1992). Arrows indicate times of maximum $\delta^{18}O$ values that form bases of $\delta^{18}O$ zones (e.g., Mi1, Mi1a) and are inferred maximum glacioeustatic lowstands. Shaded boxes indicate time represented by deposition. Diagonal-rule boxes indicate ages not known with certainty.

(Ward, 1992; Olsson et al., 1987). The long early Miocene hiatus in the Maryland versus the more complete record in New Jersey must reflect tectonic differences. The upper-middle to upper Miocene is better represented and more marine in Maryland than in New Jersey (Fig. 2; Owens et al., 1988). Whereas these differences can be explained by active tectonics (e.g., faulting of crustal blocks), we favor a more passive mechanism. Coastal plain accommodation is driven by flexural subsidence due to loading and thermal subsidence offshore (Watts, 1981). We suggest that increased sediment supply can also cause local flexural subsidence (e.g., Pazzaglia and Gardner, 1994). For example, early Miocene sedimentation rates increased in New Jersey as deltas prograded, and the depocenter was located just offshore of Atlantic City (Greenlee et al., 1988), causing increased subsidence in the coastal plain. By the middle Miocene, depocenters were located beneath the modern middle shelf and their loading and flexural effects were minimal on the New Jersey coastal plain.

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