New Jersey Oligocene "Icehouse" sequences (ODP Leg 150X) correlated with global $\delta^{18}O$ and Exxon eustatic records

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ABSTRACT

Six Oligocene sequences and one earliest Miocene sequence were identified at Island Beach, Atlantic City, and Cape May, New Jersey, and correlated to the $\delta^{18}O$ proxy of glacioeustasy and the eustatic record of Haq et al. by integrating lithostratigraphy, biostratigraphy, Sr isotopic stratigraphy, and magnetostratigraphy. Seven global $\delta^{18}O$ increases are recognized by correlating $\delta^{18}O$ records among deep-sea sites; four of these increases (Oi1, Oi2, Oi2b, and Mi1; 33.5, 30.3, 27.1, and 23.8, respectively) were recognized previously, and three (Oi1a, Oi1b, and Oi2a; 32.8, 31.7, 28.3 Ma, respectively) are new. These $\delta^{18}O$ increases correlate well with Oligocene unconformities, indicating a glacioeustatic control on sequence boundaries. Except for an unconformity and glacioeustatic lowering at ~28.3 Ma, the New Jersey Oligocene sequences correlate well with the Haq et al. record, although we question the amplitudes of their eustatic record.

INTRODUCTION: $\delta^{18}O$ AND CONTINENTAL MARGINS

Controversy has surrounded the timing, amplitude, and cause of Oligocene global sea-level (eustatic) changes. Vail and Mitchum (1977) and Haq et al. (1987) suggested a dramatic (>140 m) mid-Oligocene lowering while paleoceanographers maintained that the first Antarctic ice sheet formed in the middle Miocene (e.g., Shackleton and Kennett, 1975). This posed an enigma, because glacioeustatic change is the only known mechanism for large, rapid sea-level change (e.g., Donovan and Jones, 1979). Studies in the 1980s extended glacioeustasy to the beginning of the Oligocene; evidence for large Cenozoic ice sheets (i.e., an "icehouse world") is recorded by Oligocene glaciomarine sediments and high deep-sea $\delta^{18}O$ values (summarized by Miller et al., 1991; Zachos et al., 1994). Although glacioeustasy provides a potential mechanism for large, rapid, sea-level change, independent verification of the Haq et al. (1987) record for the Oligocene has been hampered not only by poor continental margin records, but also by undersampled deep-sea $\delta^{18}O$ records.

Deep-sea benthic foraminiferal $\delta^{18}O$ can be used to correlate and to evaluate temperature and ice-volume changes. Miller et al. (1991) noted four intervals of high Oligocene–earliest Miocene benthic foraminiferal $\delta^{18}O$ values and used the $\delta^{18}O$ values to define global zones (Oi1, Oi2, Oi2b, and Mi1 at 33.5 Ma, 30.3 Ma, 27.1 Ma, and 23.7 Ma, respectively; Fig. 1). Although high benthic foraminiferal $\delta^{18}O$ values indicate the presence of ice sheets (e.g., >1.8‰ in *Cibicidoides*; Miller et al., 1991), they do not necessarily indicate the timing of ice growth, because benthic $\delta^{18}O$ variations reflect both bottom-water temperature and ice-volume changes. Different strategies have been developed to extract ice-volume history from $\delta^{18}O$ records (Shackleton and Opdyke, 1973; Fairbanks, 1989). Synchronous increases in benthic and low-latitude planktonic foraminiferal $\delta^{18}O$ records provide the best evidence for ice growth both in the Pleistocene (Shackleton and Opdyke, 1973) and in the Tertiary (Miller et al., 1991). Covariance between benthic and subtropical planktonic $\delta^{18}O$ records is associated with Oi1, Oi2, and Mi1 events, indicating that these are glacioeustatic lowerings; the increase associated with the Oi2b event lacks suitable planktonic data for similar confirmation (Miller et al., 1991).

In this study, $\delta^{18}O$ events (increases) and zones (maxima) are identified by comparing benthic foraminifera $\delta^{18}O$ records from Ocean Drilling Program Sites 522 (Miller et al., 1991) and 529 (Miller et al., 1991) with new benthic records that have higher resolution (Site 803, Barrera et al., 1993, 140 k.y. resolution; Site 522, Zachos et al., 1996, 9 k.y. resolution; Site 689, Thomas et al., 1995, 50 k.y. resolution). Three new $\delta^{18}O$ zones, Oi1a, Oi1b, and Oi2a, are defined on the maximum $\delta^{18}O$ values attained at 32.8, 31.7, and 28.3 Ma, respectively (Table 1; Fig. 1), and compare favorably with other studies (Abreu et al., 1995). These events and zones are characterized by large $\delta^{18}O$ increases (>0.5‰) with high maximum $\delta^{18}O$ values (>2.0‰), indicating the presence of ice sheets after the increases (Table 1). These increases are correlated among the different sites with biostratigraphy and Sr isotopic stratigraphy and calibrated to the time scale using magnetostratigraphy at Sites 529 and 522, establishing their global utility.

There are no suitable tropical, nonupwelling planktonic foraminiferal $\delta^{18}O$ records available for the Oligocene. A sparsely sampled middle to upper Oligocene planktonic $\delta^{18}O$ record at equatorial upwelling Site 77 (lat 00° 28.9′N, long 133° 13.7′W; Keigwin and Keller, 1984) shows low-amplitude (0.3‰–0.5‰) increases associated with the Oi2 and Oi2a events (Fig. 1). Additional planktonic $\delta^{18}O$ data are needed to evaluate the contribution of ice volume versus temperature change associated with these $\delta^{18}O$ increases. In any case, Zachos et al. (1996) showed that the early Oligocene $\delta^{18}O$ record (from Oi1 through Oi1b) fluctuates with high-frequency 41 k.y. oscillations that are indicative of high-latitude forcing (i.e., ice growth and decay), consistent with our interpretation that they are, in part, ice-volume events. These increases, as well as the four $\delta^{18}O$ increases previously reported, are correlated to the New Jersey sequence record (Fig. 1) to determine their relationships with this inferred glacioeustatic record.

Eustatic lowerings are expressed as unconformities on passive margins (Christie-Blick et al., 1990). The New Jersey coastal plain is characterized by a passive margin tectonic regime dominated by simple thermal subsidence and flexural loading (Steckler and Watts, 1978), making it an ideal location to evaluate eustatic controls on sedimentation. However, since the first identification of New Jersey Oligocene strata (Olsson et al., 1980), correlations of Oligocene sequences have been hampered by poor recovery.

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, 1996; Fig. 2). The Oligocene sections recovered (58.5 m, 81.4 m, and 54.9 m, respectively) provide material for the first comprehensive study of New Jersey Oligocene sequences.

We identify sequences and their bounding unconformities at the three sites by integrating lithostratigraphy, biostratigraphy, Sr isotopic stratigraphy, and magnetostratigraphy (Fig. 2; Miller et al., 1994, 1996; Pekar, 1995). We developed a composite sequence stratigraphic record of the New Jersey Oligocene coastal plain by comparing and correlating the Oligocene sequences from the three Leg

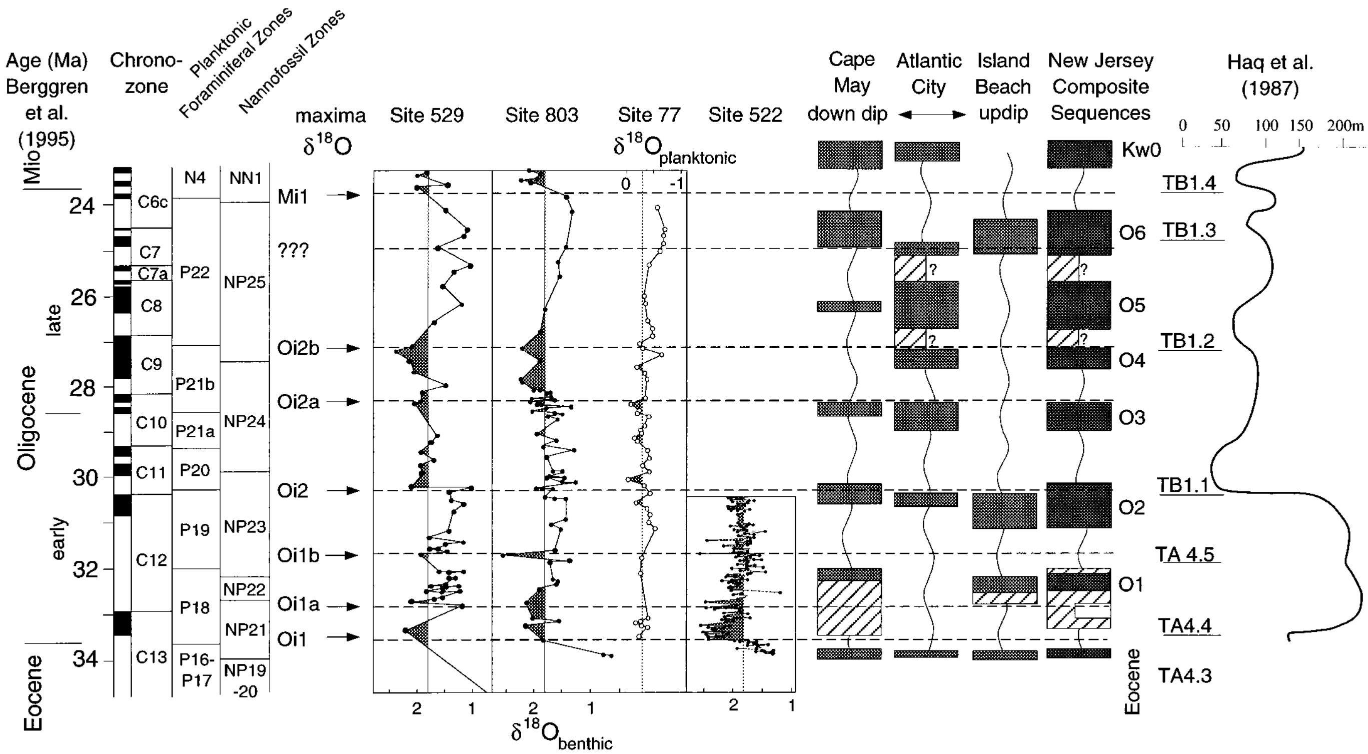

Figure 1. Ages of New Jersey Oligocene sequences compared to benthic $\delta^{18}O$ record at Sites 803 (Barrera et al., 1993) and 529 (Miller et al., 1991) and planktonic $\delta^{18}O$ record at Site 77 (Keigwin and Keller, 1984; open symbols). Oi1 through Mi1 are bases of oxygen isotopic zones. Boxes indicate time represented, white areas indicate hiatuses. Haq et al. (1987) sequence and eustatic records are shown using Berggren et al. (1995) time scale (see text for explanation). Dashed lines indicate times of maximum $\delta^{18}O$ values.

150X boreholes (Fig. 2). To test whether these changes in relative sea level were primarily controlled by eustasy, we compared the New Jersey sequences to the $\delta^{18}O$ proxy of glacioeustasy and the Haq et al. (1987) inferred eustatic record (Fig. 1).

METHODS

Lithologic descriptions of the Leg 150X boreholes were provided by Miller et al. (1994, 1996), and the Oligocene sections were described in further detail by Pekar (1995). Planktonic foraminiferal and nannofossil zones are from Miller et al. (1994, 1996). Van Fossen et al. (1994) provided magnetostratigraphy. Sr isotopic analyses are from Miller et al. (1994, 1996) and Pekar (1995), using the calibration of Oslick et al. (1994). Together, these provide the primary age control on the boreholes. The time scale of Berggren et al. (1995) is used throughout. Benthic foraminifera analyses and paleobathymetric studies were used to delineate water depth changes (Pekar, 1995).

Stratigraphic resolution is better than 0.5 m.y. in most cases, especially in the early Oligocene (Figs. 1 and 2). Intervals with poor biostratigraphic control (e.g., the later Oligocene between ~28 and 24 Ma; Fig. 2) rely primarily on Sr isotopes for ages; resolution for these intervals is as poor as ±0.8 m.y. (Oslick et al., 1994).

NEW JERSEY OLIGOCENE SEQUENCES

New Jersey onshore Oligocene strata consist of trangressive-regressive successions that are bracketed by unconformities, similar to New Jersey Cretaceous and Miocene

TABLE 1. COMPARISON BETWEEN THE TIMING OF SEQUENCE BOUNDARIES FROM THE NEW JERSEY OLIGOCENE COMPOSITE AND OXYGEN ISOTOPE ZONES

Sequence boundaries			Oxygen isotopic zonal boundaries						
Sequence boundary	Age* (Ma)	Foraminiferal zone	Isotope zone	Age† (Ma)	Magnetochron	Foraminiferal zone	Type location	$\delta^{18}O$ increases	Maximum $\delta^{18}O$
Kw0	24.1-23.3	P22/N4a boundary	Mi1	23.7	C6Cn	N4a	522	1.0‰	2.2.‰
O6	25.7-25.2	P22		~25.0?	C7n	P22	529	0.6‰	1.6‰
O5	27.1-26.8	P21b/P22 boundary	Oi2b	27.1	latest C9n	top P21b	689	0.6‰	2.4‰
O4	28.3-27.6 Ma	lower P21b	Oi2a	28.3	C9r/C10n	P21b	689	0.6‰	2.6‰
O3	30.1-29.0	lower P20	Oi2	30.3	C11r	P19/P20	529	1.1‰	2.1‰
O2	32.0-31.1 Ma	lower P19	Oi1b	31.7	late C12r	lower P19	522	0.9‰	2.6‰
O1	33.8-32.7 Ma	lower P18	Oi1a	32.8	early C12r	upper P18	522	0.6‰	2.5‰
			Oi1	33.5	C13n	lower P18	522	1.0‰	2.4‰

* Age of hiatus.

†Age of maximum $\delta^{18}O$ values.

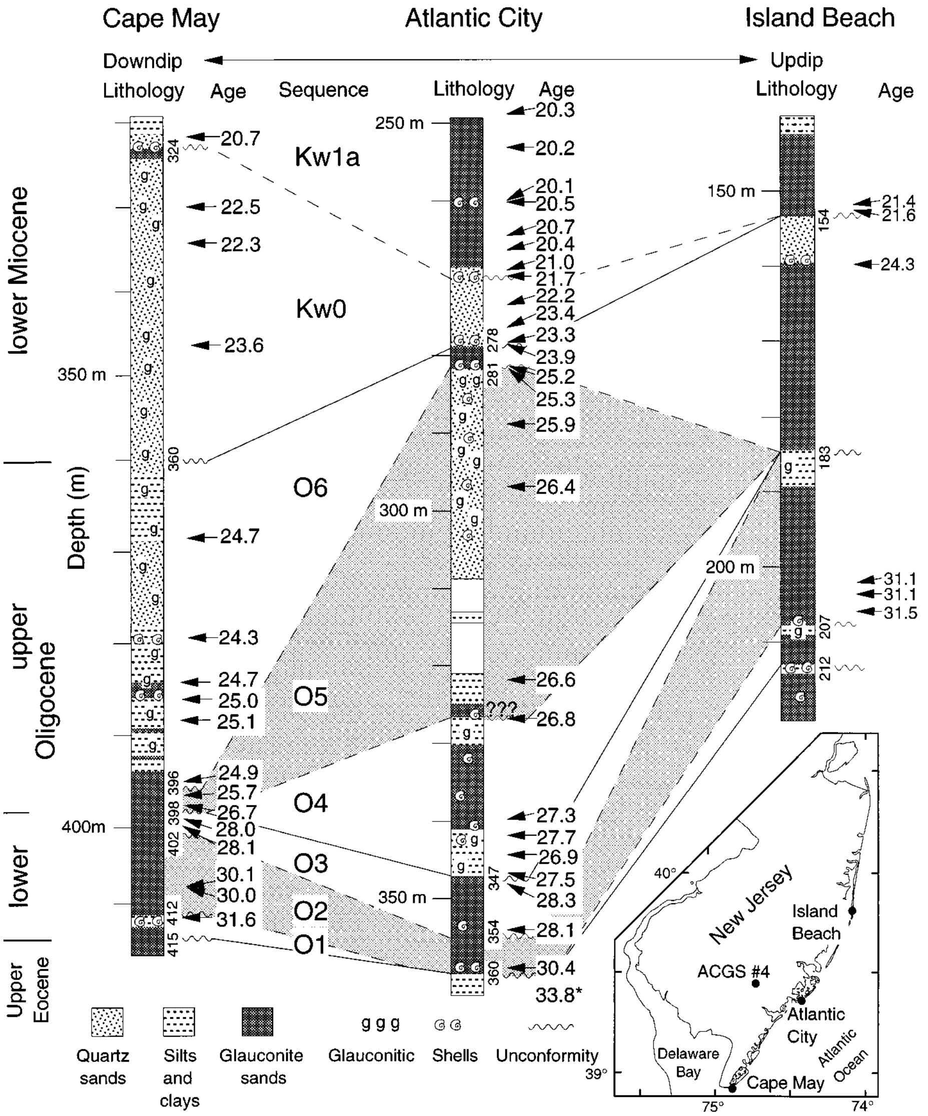

Figure 2. Oligocene and lower Miocene sections at Cape May, Atlantic City, and Island Beach. O1–O6, and Kw0 and Kw1a are sequences. Depths on stratigraphic columns are in metres. Ages (Ma) are strontium isotopic estimates. Sequence boundaries are indicated by wavy lines and depths are given in metres. White areas represent no recovery. Inset map shows location of three Leg 150X borehole sites and ACGS #4 borehole. O2 and O5 sequences are stippled to emphasize intersite correlations. Dashed lines between boreholes indicate sequence boundaries; solid lines between boreholes indicate age boundaries. Asterisk indicates strontium isotopic age estimate at 367 m.

sequences (Sugarman et al., 1993; Miller and Sugarman, 1995). Unconformities are identified by burrowed surfaces, rip-up clasts, and shells at the base of the sequence, gamma ray log kicks, abrupt changes in the facies, and hiatuses. A typical Oligocene sequence has glauconite sand, shells, and/or clays at the base (transgressive systems tract), medial glauconitic silts (lower highstand systems tract), and upper glauconitic quartz sands (upper highstand systems tract). The glauconite is in situ within the transgressive systems tract and interpreted as recycled in the highstand systems tract. Six Oligocene sequences are recognized in New Jersey, four of which are observed at two or more boreholes and are termed O1 through O6 (Table 1; Figs. 1 and 2).

DISCUSSION

The New Jersey Oligocene sequence boundaries correlate well with benthic foraminiferal $\delta^{18}O$ changes, indicating a glacioeustatic control on the unconformities (Fig. 1). The basal unconformity of sequence O1 (33.8–32.7 Ma) correlates with the Oi1 (33.5 Ma) and Oi1a (32.8 Ma) $\delta^{18}O$ increases. The O2 (32.0–31.1 Ma) and O3 (30.1–29.0 Ma) basal sequence boundaries correlate with the $\delta^{18}O$ increases Oi1b (31.7 Ma) and Oi2 (30.3 Ma), respectively. The late Oligocene to earliest Miocene sequence boundaries O4, O5, and Kw0 show good correlation with $\delta^{18}O$ increases Oi2a, Oi2b, and Mi1, respectively (Fig. 1). The lower sequence boundary of O6 correlates with a minor $\delta^{18}O$ increase of 0.6‰ at 25.1 Ma at Site 529 (Fig. 1); maximum values attained (1.6‰) are significantly lower than the major $\delta^{18}O$ events and ice is not required at this time, although the $\delta^{18}O$ increase is substantial enough that it probably reflects ice accumulation and a minor sea-level lowering. We conclude that during the Oligocene, as in the Miocene (Miller and Sugarman, 1995), ice-volume variations were the predominant influence on global sea-level changes.

Sequence boundaries recognized in the New Jersey Oligocene correlate well with the Haq et al. (1987) onlap record. To evaluate these correlations, the New Jersey and Haq et al. (1987) records must be displayed on a common time scale. Miller et al. (1993) accomplished this using a three-point calibration that included correlation of (1) basal Oligocene sequence TB4.4 to chron 13n (33.8 Ma using the new Berggren et al., 1995, time scale); (2) the unconformity at the base of the Chickasawhay Limestone (equal to the base of TB1.1) in Alabama to late chron C11r (30.3 Ma); and (3) calibration of the Oligocene-Miocene boundary to chron C6Cn.2n (23.7 Ma). The lower Oligocene sequence boundaries O1, O2, and O3 in New Jersey correlate well with third-order cycles TA4.4, TA4.5, and TB1.1. All of the upper Oligocene third-order cycles of Haq et al. (1987) are recognized in the New Jersey Oligocene. Sequence boundaries O5, O6, and Kw0 correlate with the third-order cycles TB1.2, TB1.3, and TB1.4, respectively (Fig. 1). However, the New Jersey Oligocene lower sequence boundary for O4 (28.3–27.6 Ma) does not correspond with any third-order cycle of Haq et al. (1987). Nevertheless, the O4 sequence boundary correlates well with $\delta^{18}O$ increase Oi2a (28.3 Ma). This indicates that eustasy was the primary control for the development of this sequence boundary.

Haq et al. (1987) presented high amplitudes of Oligocene eustatic change (up to 140 m fall in the mid-Oligocene). Such high amplitudes are not supported by either the $\delta^{18}O$ record or by the New Jersey record. The benthic foraminiferal $\delta^{18}O$ increases range from 0.6‰ to 1.1‰ (Table 1). Although we cannot determine the amount attributable to temperature vs. ice volume, Pleistocene calibrations provide a reasonable upper limit. Ascribing a maximum of 75% of the benthic foraminiferal increases to ice volume (Fairbanks, 1989), and using the Pleistocene ice-volume/sea-level calibration of 0.11‰/10 m (Fairbanks and Matthews, 1978), indicates that maximum amplitudes of eustatic fall were 40–75 m. This is consistent with benthic foraminiferal estimates of maximum water depth variations of 40–80 m (Pekar, 1995). Although these water depth changes are not corrected for isostatic effects, they still indicate substantially lower sea-level changes than indicated by Haq et al. (1987). The low-amplitude increases (0.3‰–0.4‰) in the Site 77 planktonic $\delta^{18}O$ record (Keigwin and Keller, 1984; Fig. 1) may indicate even lower amplitudes (~25–35 m), although this site is poorly sampled and lies in an upwelling zone. We conclude that although the amplitudes are poorly known, they were much less than those estimated by Haq et al. (1987).

CONCLUSIONS

We integrate biostratigraphy, Sr isotopic stratigraphy, and limited magnetostratigraphy to provide a chronology of seven New Jersey onshore Oligocene to earliest Miocene sequences. In addition, we evaluate global $\delta^{18}O$ records and suggest that there were at least seven glacioeustatic lowerings during the Oligocene to earliest Miocene, culminating in peak $\delta^{18}O$ values at 33.5, 32.8, 31.7, 30.3, 28.3, 27.1, and 23.7 Ma (Zones Oi1, Oi1a, Oi1b, Oi2, Oi2a, Oi2b, and Mi1, respectively). Similar unconformities noted among the three boreholes in the earlier and later Oligocene can be directly linked to the $\delta^{18}O$ proxies of glacioeustasy, indicating a causal link. The absence of mid-Oligocene strata at Island Beach and Cape May is ascribed to local tectonics; still, mid-Oligocene sequence boundaries at Atlantic City also correlate with global $\delta^{18}O$ records, again indicating a link of unconformities and glacioeustasy. Correcting for time-scale differences, all the Oligocene third-order sea-level events of Haq et al. (1987) can be identified in New Jersey. However, we suggest that there is one additional Oligocene sequence boundary (at 28.3 Ma) and suggest that the amplitudes of the eustatic record presented by Haq et al. (1987) are too high by a factor of two.

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