Drilling and Dating New Jersey
Oligocene-Miocene Sequences: Ice Volume, Global Sea Level, and Exxon Records

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Oligocene to middle Miocene sequence boundaries on the New Jersey coastal plain (Ocean Drilling Project Leg 150X) and continental slope (Ocean Drilling Project Leg 150) were dated by integrating strontium isotopic stratigraphy, magnetostratigraphy, and biostratigraphy (planktonic foraminifera, nannofossils, dinocysts, and diatoms). The ages of coastal plain unconformities and slope seismic reflectors (unconformities or stratal breaks with no discernible hiatuses) match the ages of global δ18O increases (inferred glacioeustatic lowering) measured in deep-sea sites. These correlations confirm a causal link between coastal plain and slope sequence boundaries: both formed during global sea-level lowerings. The ages of New Jersey sequence boundaries and global δ18O increases also correlate well with the Exxon Production Research sea-level records of Haq et al. and Vail et al., validating and refining their compilations.

Eustatic (global sea level) changes exert one of the primary controls on the stratigraphic record (1, 2), although controversy surrounds the age, magnitude, and mechanism of these changes (3). Vail et al. (4) and Haq et al. (5) reconstructed eustatic history by applying sequence stratigraphy to a global array of proprietary Exxon Production Research (EPR) data comprising seismic profiles, wells, and outcrops. Previously released EPR seismic data demonstrated that Oligocene to Recent sequences were well defined beneath the New Jersey shelf, although the age control on these sequences was poor (±1 million years or worse) (6). To improve understanding of sea-level change, we collected additional multichannel seismic data (cruise Ew9009) and traced seismic sequences from the New Jersey shelf to the slope (7). These sequences were dated at four slope sites drilled during Ocean Drilling Project (ODP) Leg 150 (8) (Fig. 1).

Drilling onshore at Island Beach, Atlantic City, and Cape May, New Jersey (ODP Leg 150X; Fig. 1), provided additional ages and facies of these same sequences in much shallower paleodepths (9). This report synthesizes Leg 150 and Leg 150X chronologic studies of Oligocene to middle Miocene sequences that are preserved onshore and have the clearly visible seismic reflection terminations offshore. We compare the stratigraphic record of the New Jersey sequence as published δ18O records (Figs. 1 and 2) and with the inferred eustatic record of Haq et al. (5).

Deep-sea δ18O records provide a proxy for ice volume and sea-level (glacioeustatic) changes during the Oligocene to Recent “Icehouse World” (10, 11). Glaciomarine sediments near Antarctica and deep-sea oxygen isotopic records (10, 11) indicate that large ice sheets have existed in Antarctica since the earliest Oligocene 135 million years ago (Ma) (12). Because ice preferentially sequesters light oxygen isotopes, fluctuations in ice volume cause changes in global seawater δ18O (δw). These global δw changes are recorded by benthic and planktonic foraminifera along with variations in seawater temperature and local isotopic composition. Comparisons of benthic and low-latitude (nonupwelling) planktonic foraminiferal δ18O records can be used to isolate ice volume effects from local isotopic and temperature changes (13). Using this strategy, Miller et al. (10) and Wright and Miller (14) identified 12 Oligocene to Miocene benthic foraminiferal δ18O increases (all >0.5 per mil); these increases culminated in δ18O maxima that were used to define zones O1 to O12 and Mi1 to Mi7 (Figs. 1 and 2 and Table 1). Six of the δ18O increases are also recorded by tropical or subtropical planktonic foraminifera; the other six lack suitable low-latitude isotopic records. Miller et al. (10) interpreted coeval increases in benthic and planktonic δ18O records as the consequence of glacioeustatic lowerings of ~30 to 80 m. On the basis of the ODP Site 747 δ18O record (Fig. 1), we suggest that the Mi3 increase (13.4 to 14 Ma; Table 1) can be split into two increases (Mi3a and Mi3b). We assume that all 13 Oligocene to early-to-late Miocene δ18O increases (Figs. 1 and 2) reflect million-year scale increases in ice volume (15).
volume, although additional low-latitude planktonic foraminiferal $\delta^{18}O$ data are needed to confirm this (15).

Oligocene to Recent seismic reflections beneath the New Jersey shelf exhibit eustatic truncation, onlap, downlap, and toplap and are thus objectively identified as sequence boundaries (4, 6, 8). We traced these sequence boundaries from the shelf to the slope, using both EPR and Ew9009 multichannel seismic data including Red, Tuscar, Yellow-2, Pink-2, and Green (6) plus Ochre, Sand, True Blue, Pink-3, and Green-2 (8). To simplify the nomenclature and incorporate reflections restricted to the slope, we use a unified alpha-numeric scheme (o1, m6; Figs. 1 and 2 and Table 1) based on the results of ODP Leg 150 (8).

We derived time-depth relations for correlating seismic profiles to the boreholes from three sources: the velocity log from the Continental Offshore Stratigraphic Test (COST) B-3 well, semblance velocities from analysis of Ew9009 Common Depth Point (CDP) stacks on the adjacent shelf, and sonic data from the continental rise (8). Synthetic seismograms derived from log (8) and core physical properties data (16) were used to evaluate these correlations. The sedimentary expression of sequence boundaries on the slope is muted because of relatively uniform Oligocene to Miocene lithologies (siltysilts) (8), and several reflectors are associated with a corresponding $(\delta^{18}O)$ increase (17). Still, many sequence boundaries are associated with hiatuses or increased sand content immediately above the boundary, both of which yield impedance contrasts (8) and consequently seismic reflections.

We developed the Oligocene to middle Miocene chronostratigraphy on the slope by integrating Sr isotopic stratigraphy (17) and magnetostratigraphy (18) with planktonic foraminiferal (19), nannofossil (20), dinocyst (21), and diatom (22) biostratigraphy (Table 1). We do not discuss late Miocene to Recent history here because (i) the chronostratigraphy of the upper Miocene slope sections is still uncertain, (ii) Miocene strata are poorly represented in the slope boreholes, and (iii) the recovered Quaternary sections were restricted to the middle Pleistocene (stages 5 to 3.5) and Recent (23).

Onshore boreholes recovered fossiliferous Oligocene to middle Miocene strata; younger strata were mostly unfossiliferous and undatable (9, 24). We identified unconformities (sequence boundaries) in the onshore boreholes using physical stratigraphy, including erosional contacts, reworking, bioturbation, major facies changes, gamma-ray peaks, and paraconformities inferred from biostratigraphic and Sr isotopic age breaks. Onshore sequences consist of basal transgressive deposits (Transgressive Systems Tracts; glauconitic in the Oligocene; occasionally shelly in the Miocene) that progressively shallow upsection to medial silts and upper sands (High-Stand Systems Tracts); lowstand deposits are not found on the coastal plain but are restricted to beneath the shelf and slope (6). Miocene onshore sequences were named KwO to Kw-Cohansey (9, 25), whereas Oligocene sequences were termed O1 to O6 (26). Age control for the Miocene onshore sections relies primarily on Sr isotopic stratigraphy with an age resolution of ±0.4 million years for the early Miocene and ±0.9 million years for the middle Miocene (27). Diatom and planktonic foraminiferal biostratigraphy supplements Miocene onshore control (9, 25). We derived age control for Oligocene onshore sections by integrating magnetostratigraphy, biostratigraphy (planktonic foraminifera and nannofossils), and Sr isotopic stratigraphy, with a resulting stratigraphic resolution of better than ±0.3 million years in most cases.

There is excellent correlation between the timing of the major Oligocene to middle Miocene slope reflectors dated at the Leg 150 slope sites and glacioeustatic lowings inferred from the $\delta^{18}O$ record (Figs. 1 and 2 and Table 1). Reflectors o1, m6, m5.6, m5.2, m5, m4, m3, m2, and m1 correlate with the O1, M1, M1a, M1b, M2, M3a, M3b, M4, and M5 $\delta^{18}O$ increases, respectively (Figs. 1 and 2 and Table 1). This similarity confirms a link between sequence boundaries traced from the shelf and glacioeustatic changes. Of the reflectors, only m5.4 does not appear to have a corresponding $\delta^{18}O$ increase. Of the $\delta^{18}O$ increases, only O1b and O12 fail to have equivalent reflectors because Oligocene seismic resolution is limited by the thin section and concatenated reflections on the slope (Fig. 2).

Detailed comparison of the ages of slope reflectors and their corresponding error estimates with three of the middle Miocene planktonic foraminiferal $\delta^{18}O$ records used to define the Mi zones (Fig. 1) shows remarkably similar ages for the $\delta^{18}O$ inflections and reflectors. This comparison indicates that the sequence boundaries formed during intervals of rapid glacioeustatic fall, as predicted by various models (28).

This link between offshore New Jersey sequences and $\delta^{18}O$ records is further strengthened if one compares the slope sequences with their correlative onshore counterparts (Fig. 2). Early to middle Miocene onshore sequence boundaries correlate...
well with major δ18O increases (24, 25) (Fig. 2 and Table 1), indicating that these unconformities were formed by global sea-level lowerings. Oligocene O1, O2, and O2b δ18O increases also correlate with onshore sequences O1, O3, and O5, respectively (26). Sequence boundaries O2, O4, and O6 may correlate with minor δ18O increases noted in recently published records (29).

The onshore and offshore sequences compare well with each other and with the δ18O record. The exceptions are as follows: (i) The Kw1c sequence boundary correlates with the m5.4 slope reflector but with no δ18O change within 1 million years. Either Kw1c or m5.4 sequences are the result of a local lowering of base level, or they may correlate with a minor δ18O increase at about 21 Ma (14). (ii) The Kw2c boundary has no definite offshore counterpart. We are uncertain of the significance of this sequence boundary onshore because it has been recovered at only one borehole (Cape May). (iii) The Oligocene onshore borehole records sequence resolutions on slopes seismic profiles because of on slope sediment starvation.

Although the record of Haq et al. (5) has come under criticism as a reliable indicator of eustatic change (3), there is excellent correlation between the record of Haq et al. and the New Jersey records in both the number and ages of Oligocene to Middle Miocene sequences (Fig. 2 and Table 1). Comparison of the ages of the two independent sets of sequences shows the following essentially identical ages: TB2.6 and m2 sequences (~12.6 Ma); TB2.5 and m3 (~13.6 Ma); TB2.3 and m5 (~16.5 to 16.9 Ma); and TB1.5 and m5.6 (22 Ma). The ages of the Oligocene TB1.4 and m6, TB1.3 and O6, TB1.2 and O5, TB1.2 and O3, TB4.3 and O2, and TB4.4 and O1 sequences are similar when they are corrected for differences in the time scale used in each study (30). The record of Haq et al. (5) also compares well with the δ18O increases (Table 1). However, on the basis of our correlation to the New Jersey sequences and δ18O records, there are differences compared to the ages of several other of the Miocene sequences of Haq et al. (Table 1). It appears that TB3.1 (10.5 Ma), TB2.4 (15.5 Ma), and TB2.2 (17.5 Ma) correlate with ~11-Ma, 14.8-Ma, and 18.5-Ma slope reflectors and with the ~11.4-Ma, 14.4-Ma, and 18.5-Ma δ18O increases, respectively (Table 1). The minor differences in age (Table 1) among the sequences of Haq et al., New Jersey slope reflectors, and the δ18O increases are generally within the errors in dating the margin sequences. For example, differences in age between the δ18O inflections and the New Jersey sequences are less than 0.6 million years in all cases but one (Table 1); differences with the record of Haq et al. are larger because the latter relied on well cuttings [particularly on the New Jersey margin (6)] and not on continuously cored boreholes.

We suggest that the ages of the δ18O increases (inflections on Table 1) provide the best estimates on the timing of Oligocene to Miocene eustatic falls and that unconformities (including seismic sequence boundaries) are formed during falls in sea level. Our records show that deposition resumed in the coastal plain by the time of the lowest low stand (maximum δ18O values; Fig. 2). Our margin chronologic resolution is insufficient to evaluate small leads and lags (~3/4 of a cycle or a resolution of better than 0.25 to 0.5 million years) between eustatic falls and the timing of unconformities or hiatuses on the New Jersey margin. Reynolds et al. (31) used forward models to predict that the unconformities begin to form on old, slowly subsiding margins such as New Jersey early in the fall of sea level (before the inflection and the maximum rate of fall). We cannot yet evaluate at what point in an eustatic fall the unconformities begin to form on this margin.

Although it is not possible to evaluate fully the age errors in the EPR records, ours can be specified. Stratigraphic resolution is coarse in some intervals (for example, slope reflectors m5 and m5.4 have age uncertainties of at least ±0.9 and ±1.1 million years, respectively; Table 1), whereas others are well dated by integrating Sr isotopic, magnetostratigraphic, and biostratigraphic data. For example, the small uncertainty in the age of reflector m6 (23.8 ± 0.2 Ma) allows a precise and unequivocal correlation with the Mi1 oxygen isotopic increase (infection at 23.8 Ma; Fig. 2).

Given that some reflectors and sequences have ages errors of greater than 0.5 million years, one could argue that the correlations shown on Figs. 1 and 2 are at best fortuitous and, at worst, are beyond the precision of the geochronology that we have used. Using this argument, Miall (3) claimed that stratigraphic resolution may not be sufficient to document precise correlation and causal links between sequences and the global synthesis of Haq et al. (5).

Table 1. Comparison of Sr isotope-based age estimates of Oligocene-middle Miocene seismic reflectors, New Jersey continental slope with onshore sequences (24, 26), oxygen isotopic increases (10, 14), and the sequences of Haq et al. (5). The column labeled Best uses the older (1985) time scale, whereas the column labeled BKSA95 provides the ages of sequences using the new (1996) time scale of Berggren et al. (12). We obtained corrected ages of Haq et al. (5) by linearly interpolating ages between TB1.4 corrected for time scale differences (24.2 versus 25.6 Ma), the revised age of the TB1.1 sequence of 32.2 Ma (30), and the revised age of TB4.4 of 35.9 Ma (30).

<table>
<thead>
<tr>
<th>Slope reflector</th>
<th>Age estimate (Ma)</th>
<th>Age/corrected age</th>
<th>δ18O</th>
<th>Haq et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1 (Tuscan)</td>
<td>~11 (10.5-11.3)</td>
<td>~11.5</td>
<td>M6</td>
<td>TB3.1</td>
</tr>
<tr>
<td>m2 (Yellow-2)</td>
<td>~12.5 (12.5-12.6)</td>
<td>12.7</td>
<td>M4</td>
<td>TB2.6</td>
</tr>
<tr>
<td>m3 (Blue)</td>
<td>13.6 (13.8-13.6)</td>
<td>13.6</td>
<td>M3a</td>
<td>TB2.5</td>
</tr>
<tr>
<td>m4 (Pink-2)</td>
<td>14.8 (13.8-15.0)</td>
<td>14.7</td>
<td>M3b</td>
<td>TB2.4</td>
</tr>
<tr>
<td>m5 (Green)</td>
<td>~16.0 (15.3-16.0)</td>
<td>~16.6</td>
<td>M2</td>
<td>TB2.3</td>
</tr>
<tr>
<td>m5.2 (Ochre)</td>
<td>16.2 (18.0-18.4)</td>
<td>17.7</td>
<td>M1b</td>
<td>TB2.2</td>
</tr>
<tr>
<td>m5.4 (Sand)</td>
<td>19-20 (18.4-20.6)</td>
<td>18.8-19.8</td>
<td>Kw1c</td>
<td>TB2.1</td>
</tr>
<tr>
<td>m6.6 (True Blue)</td>
<td>~22 (21.5-22.5)</td>
<td>21.8</td>
<td>Kw1a,b</td>
<td>TB1.5</td>
</tr>
<tr>
<td>m6 (Pink-2)</td>
<td>23.8 (23.6-24.0)</td>
<td>23.8</td>
<td>Kw1o</td>
<td>TB1.4</td>
</tr>
<tr>
<td>o1 (Green)</td>
<td>35.8-36.7 (32-36.7)</td>
<td></td>
<td></td>
<td>TB4.4</td>
</tr>
</tbody>
</table>

*Not a formal isotopic zone.
contrast, we propose that it is unnecessary to demonstrate that every event correlates with a resolution of better than 0.5 million years. We have anchored key stratigraphic levels (such as reflectors m1 to m4 and m6) to a precise chronology and report a similar number of events in both the margin and \(^{87}\text{Sr/}{\text{Sr}}\) records, indicating that unconformities (sequence boundaries) correlate with glacioeustatic lowerings. By firmly dating the sequences and providing error estimates for these ages, we provide a template of Oligocene to Miocene sequences that will be compared with records from other margins.

REFERENCES AND NOTES

12. W. A. Berggren, D. V. Kent, J. J. Flynn, J. A. van Couvering, Geol. Soc. Am. Bull. 69, 1407 (1988). We use this time scale throughout, except as noted on Table 1. Although the revised time scale of W. A. Berggren, D. V. Kent, C. C. Swisher, and M. P. Aubry [in Geochronology, Time Scales, and Global Stratigraphic Correlation (SEPM Special Publ. 54, Society for Sedimentary Geology, Tulsa, OK, in press) dramatically revise the Oligocene ages (with minor changes in this Miocene), we report the Leg 150 studies using the older scale to maintain consistency among all leg results.
15. There are higher frequency (10^5 to 10^6 years, "Mi- lanovitch cycles") \(^{87}\text{Sr/}{\text{Sr}}\) and sea-level variations embedded within the longer term (10^6 years) changes (Figs. 1 and 2) that we do not address.
20. L. de Verteuil, ibid., in press.
25. P. R. Vail, ibid., Rutgers University (1965);—— and K. G. Miller, unpublished manuscript.