CENOZOIC GLOBAL SEA LEVEL, SEQUENCES, AND THE NEW JERSEY TRANSECT: RESULTS FROM COASTAL PLAIN AND CONTINENTAL SLOPE DRILLING

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Abstract. The New Jersey Sea Level Transect was designed to evaluate the relationships among global sea level (eustatic) change, unconformity-bounded sequences, and variations in subsidence, sediment supply, and climate on a passive continental margin. By sampling and dating Cenozoic strata from coastal plain and continental slope locations, we show that sequence boundaries correlate (within ±0.5 myr) regionally (onshore-offshore) and interregionally (New Jersey–Alabama–Bahamas), implicating a global cause. Sequence boundaries correlate with $\delta^{18}O$ increases for at least the past 42 myr, consistent with an ice volume (glacioeustatic) control, although a causal relationship is not required because of uncertainties in ages and correlations. Evidence for a causal connection is provided by preliminary Miocene data from slope Site 904 that directly link $\delta^{18}O$ increases with sequence boundaries. We conclude that variation in the size of ice sheets has been a primary control on the formation of sequence boundaries since ~42 Ma. We speculate that prior to this, the growth and decay of small ice sheets caused small-amplitude sea level changes (<20 m) in this supposedly ice-free world because Eocene sequence boundaries also appear to correlate with minor $\delta^{18}O$ increases. Subsidence estimates (backstripping) indicate amplitudes of short-term (million-year scale) lowerings that are consistent with estimates derived from $\delta^{18}O$ studies (25–50 m in the Oligocene–middle Miocene and 10–20 m in the Eocene) and a long-term lowering of 150–200 m over the past 65 myr, consistent with estimates derived from volume changes on mid-ocean ridges. Although our results are consistent with the general number and timing of Paleocene to middle Miocene sequences published by workers at Exxon Production Research Company, our estimates of sea level amplitudes are substantially lower than theirs. Lithofacies patterns within sequences follow repetitive, predictable patterns: (1) coastal plain sequences consist of basal transgressive sands overlain by regressive highstand silts and quartz sands; and (2) although slope lithofacies variations are subdued, reworked sediments constitute lowstand deposits, causing the strongest, most extensive seismic reflections. Despite a primary eustatic control on sequence boundaries, New Jersey sequences were also influenced by changes in tectonics, sediment supply, and climate. During the early to middle Eocene, low siliciclastic and high pelagic input associated with warm climates resulted in widespread carbonate deposition and thin sequences. Late middle Eocene and earliest Oligocene cooling events curtailed carbonate deposition in the coastal plain and slope, respectively, resulting in a switch to siliciclastic sedimentation. In onshore areas, Oligocene sequences are thin owing to low siliciclastic and pelagic input, and their distribution is patchy, reflecting migration or progradation of depocenters; in contrast, Miocene onshore sequences are thicker, reflecting increased sediment supply, and they are more complete downdip owing to simple tectonics. We conclude that the New Jersey margin provides a natural laboratory for unraveling complex interactions of eustasy, tectonics, changes in sediment supply, and climate change.

1. INTRODUCTION AND BACKGROUND

Global sea level change (eustasy) has the potential to capture the imagination not only of geologists and geophysicists, but also of the public at large. Sea level can change globally by hundreds of meters (see summaries by *Donovan and Jones* [1979] and *Pitman and Golovchenko* [1983]) and rates of sea level change can be remarkably high (e.g., tens of meters per 100 years [*Fairbanks*, 1989]). Who cannot be awed by visions of the *coastal plains* of the world being inundated by rising sea level resulting from the melting of vast ice sheets? (Italics indicate terms defined in the glossary following the main text.) However, geologists and geophysicists have been frustrated in their attempts to quantify the timing, rates, amplitudes, controls, and effects of global sea level change (*eustatic change*) because eustatic effects on the stratigraphic record are complexly intertwined with other processes such as basin subsidence and changes in sediment supply. For example, estimates of the long-term fall in sea level over the past 80 myr range from

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Reviews of Geophysics, 36, 4 / *November 1998*
pages 569–601

8755-1209/98/98RG-01624*$15.00*

Paper number 98RG01624

350 m [*Pitman*, 1978; *Pitman and Golovchenko*, 1983] to 250 m [*Sahagian and Watts*, 1991] to 180 ± 100 m [*Kominz*, 1984], while a (in)famous rapid mid-Oligocene fall has been estimated as 400 m [*Vail et al*., 1977], 130 m [*Haq et al*., 1987], and 30–50 m [*Miller et al*., 1985].

Studies at *Exxon Production Research Company* (EPR) [*Vail et al*., 1977; *Haq et al*., 1987] broke new ground in recognizing unconformity-bounded units (*sequences*) and relating them to global sea level change. *Unconformities* are surfaces of erosion and/or nondeposition and can be used to divide the stratigraphic record into stratigraphic cycles [e.g., *Sloss*, 1963]. Such stratigraphic cycles have been attributed either to sea level change [*Suess*, 1885] or to *tectonic controls* [*Stille*, 1924; *Grabau*, 1936; *Sloss*, 1963] (see *Fairbridge* [1961] for a review). Even today, the role of tectonic versus eustatic control on cyclicity remains hotly debated.

The term "sequence" itself has been controversial since its definition as an "unconformity-bounded unit" [*Sloss*, 1963]. EPR defined a depositional sequence as a "stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities" [*Mitchum et al*., 1977, p. 53], with the genetic implication referring to the global sea level control. This definition has generated many opposing views, especially among those who view tectonic, not sea level, changes as the genetic control. *Christie-Blick* [1991] and *Christie-Blick and Driscoll* [1995] clarified the genetic connotation, recognizing *sequence boundaries* as unconformities associated at least locally with the lowering of *base level*, encompassing not only eustatic but also tectonic controls. Recent debates have centered on whether a genetic connotation for sequences and sequence boundaries is warranted or if a purely generic definition (e.g., "unconformity-bounded unit") is preferable (A. Salvador and the Working Group on Sequence Stratigraphy of the International Subcommission on Stratigraphic Classification, written communication, 1998). In either case, it is clear that unconformities provide a fundamental means for objectively subdividing the stratigraphic record and that many unconformities may be attributable to sea level changes (and hence be sequence boundaries in the EPR sense). Such terminological complexities have plagued the study of strata on continental margins and we provide a glossary to aid the reader.

Vail et al. [1977] first used seismic reflection profiles to identify sequences and to estimate the magnitude and ages of past sea level changes. Identification of sequences on seismic profiles was a revolution in itself, as by the following discussion between the late D. H. Matthews and P. R. Vail indicates [*Vail et al*., 1980, p. 155]: Matthews wrote,

> Can I have heard Dr Vail right? He said that seismic reflexions, correlated across a record, correspond to chronostratigraphic boundaries (bedding planes) and may be traced through changes of facies? I have been responsible for teaching several generations of undergraduate geologists that reflexions are solely due to changes in accoustic impedance, the product of velocity and density, and can *not* simply be interpreted as a geological section.

To this Vail replied,

> I would agree with Dr Matthews that seismic reflexions are generated by impedance contrasts. Our research in seismic stratigraphy, however, indicates that these impedance contrasts are produced at stratal (bedding) surfaces or unconformities. Since stratal surfaces are depositional surfaces, they are essentially time-synchronous.

Haq et al. [1987] extended EPR's seismic stratigraphic studies to outcrops and well logs, providing a more detailed Triassic–Recent chronology of sequences and eustatic changes. For example, they recognized 121 Triassic–Recent eustatic lowerings, versus ~38 reported by *Vail et al*. [1977]. The EPR "eustatic curve" has remained controversial [e.g., *Christie-Blick et al*., 1990; *Miall*, 1991] owing to questions about the methodology used and to its reliance on data that are largely unpublished.

Since the publication of the EPR eustatic curve [*Vail et al*., 1977; *Haq et al*., 1987], the scientific community outside of industry has pursued independent evidence to document the history of eustatic changes. Studies of reef terraces and atolls [e.g., *Fairbanks and Matthews*, 1978; *Fairbanks*, 1989] provide the best proxy for sea level over the past few hundred thousand years, although these records have provided only limited resolution for the older record [e.g., *Quinn*, 1991]. The $\delta^{18}O$ record of deep-sea sediments provides a proxy for glacially driven eustatic changes (*glacioeustasy*) over at least the past 42 myr (i.e., since the formation of the Antarctic ice sheet prior to the late Eocene; see discussion below and *Browning et al*. [1996]). Although $\delta^{18}O$ records provide good evidence for the timing of Cenozoic glacioeustatic changes, amplitudes of change can be only coarsely estimated [*Miller et al*., 1987, 1991a].

Passive margin stratigraphy potentially provides the longest record of sea level history (over 1 billion years), including critical information on eustatic amplitudes and related sedimentation responses. However, extracting the sea level signal from passive margin records is complicated because the effects of subsidence (including thermal subsidence, active tectonics, and isostasy/flexure) and sediment supply are difficult to distinguish from eustatic changes.

There are two primary ways to separate regional tectonic and local sedimentation changes from the global sea level signal recorded on passive margins. Both require dating sequence boundaries on a given margin, which in turn provides a chronology of base level lowerings for that margin [*Christie-Blick et al*., 1990]. The first method derives sea level directly from continental margin records. Similar timing of sequence boundaries on different margins indicates that they may have been controlled by a global process such as eustasy. Inverse models (e.g., the one-dimensional *backstripping* of *Watts*

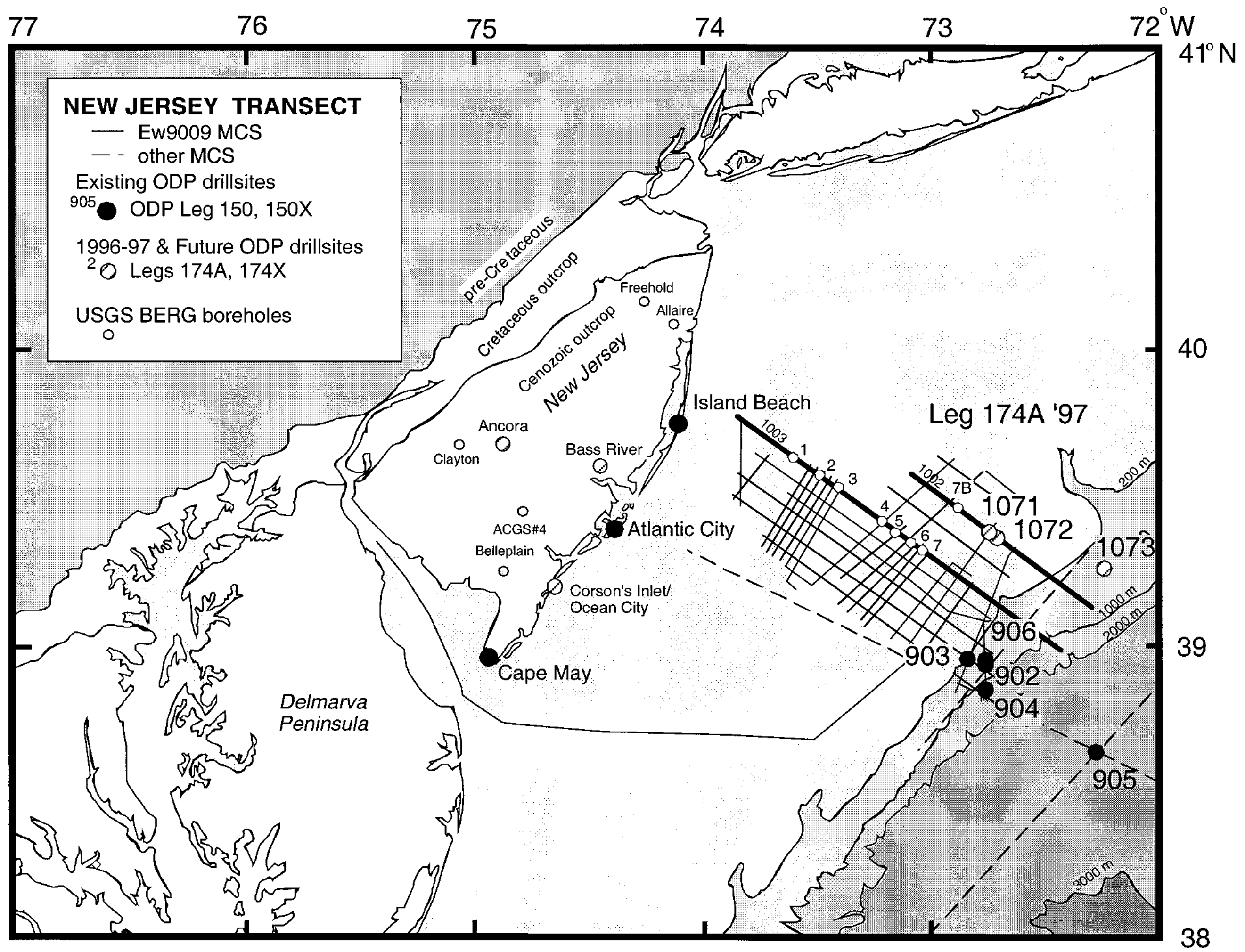

Figure 1. Bathymetric location map of the New Jersey Sea Level Transect showing the Ew9009 multichannel seismic grid. Heavy lines indicate Lines 1003 (Figure 2) and 1002 (Figure 3).

and Steckler [1979] or the two-dimensional geometric techniques of *Greenlee et al.* [1988] can be used to estimate the amplitudes of sea level change on a given margin; the eustatic component needs to be verified by comparing sea level records with other margins, particularly those in other tectonic settings. In the second method, global sea level is estimated using independent techniques (e.g., oxygen isotopic or atoll records [*Imbrie et al.*, 1988]); this record is then compared with ages of sequence boundaries, facies variations, and the *relative sea level* record of a given margin to evaluate the response of sedimentation to a known forcing mechanism. We apply both methods to the Cenozoic section of the *passive continental margin* of New Jersey.

The New Jersey margin is an ideal location to investigate the Late Cretaceous to Cenozoic history of sea level change for several reasons: rapid sedimentation, tectonic stability, good chronostratigraphic control, and abundant seismic, well log, and borehole data [*Miller and Mountain*, 1994]. To evaluate sequences and sea level changes, K. G. Miller, G. S. Mountain, and N. Christie-Blick designed the "New Jersey Sea Level Transect" as a series of boreholes from the onshore New Jersey coastal plain across the shelf to the slope and rise (Figures 1–3; see *Miller and Mountain* [1994] for discussion and history of the transect). We selected the locations of boreholes using seismic profiles that image Oligocene–Recent sequences (Figures 2 and 3) [*Greenlee et al.*, 1992; *Mountain and Miller*, 1994]. We focused on Oligocene–Recent sequences because this is a time of large glacioeustatic changes [*Miller et al.*, 1987, 1991] and because sequences of this age beneath the New Jersey shelf display clear *prograding* geometry on seismic profiles (Figures 2 and 3).

The transect was designed to sample Oligocene-Recent prograding sequences in three locations: (1) a distal setting (i.e., the slope), where the sequence boundaries can be best dated; (2) at the toe of each sequence-bounding *clinoform*, where overlying strata are most complete; and (3) at the top of each sequence boundary clinoform, immediately landward of the *clinoform roll-over*, where underlying strata are most complete and accumulated in shallow marine to nearshore environments. The latter two settings straddle a clinoform roll-over where the facies and paleodepths potentially pro-

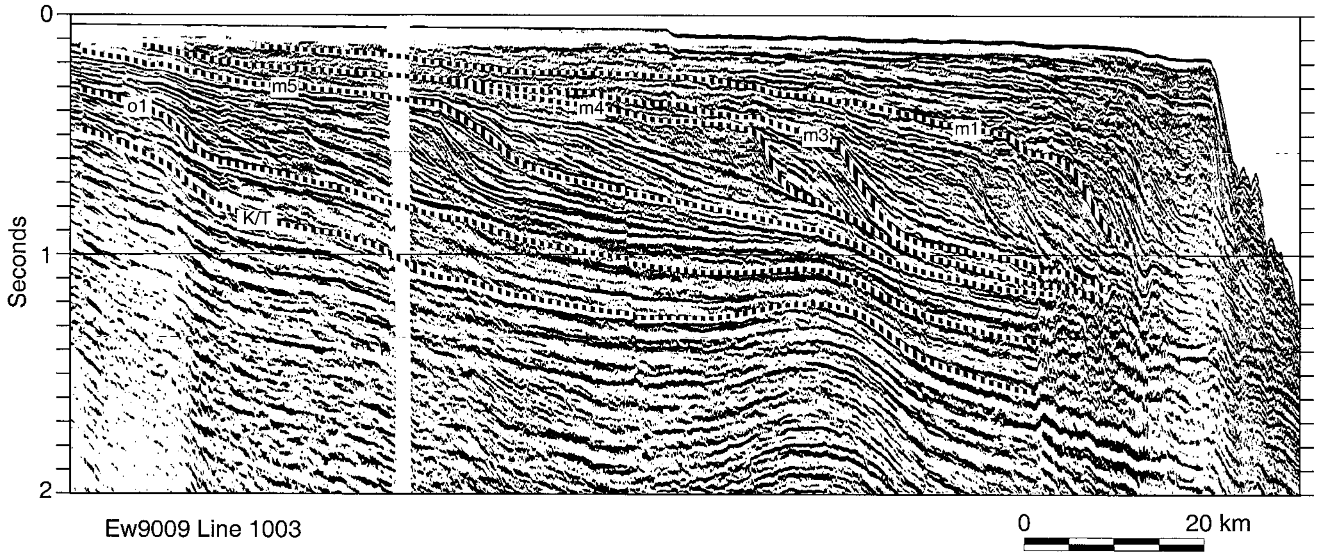

Figure 2. Ew9009 line 1003 showing reflections whose geometries define them as sequence boundaries. These have been traced to Leg 150 slope and 150X onshore drill sites as well as possible with available data, and correlated to the rock scale and timescale as discussed in the text. Vertical scale is seconds, two-way travel time.

vide a record of water depth changes across each sequence boundary that is needed to estimate the amplitude of sea level change. Leg 174A drilling at paired Sites 1071 and 1072 sampled on either side of clinoform rollovers but was affected by low core recovery in these sand-prone units [*Austin et al.*, 1998]. While the section at clinoform toes may be the most stratigraphically complete of the three settings, age control is best in the

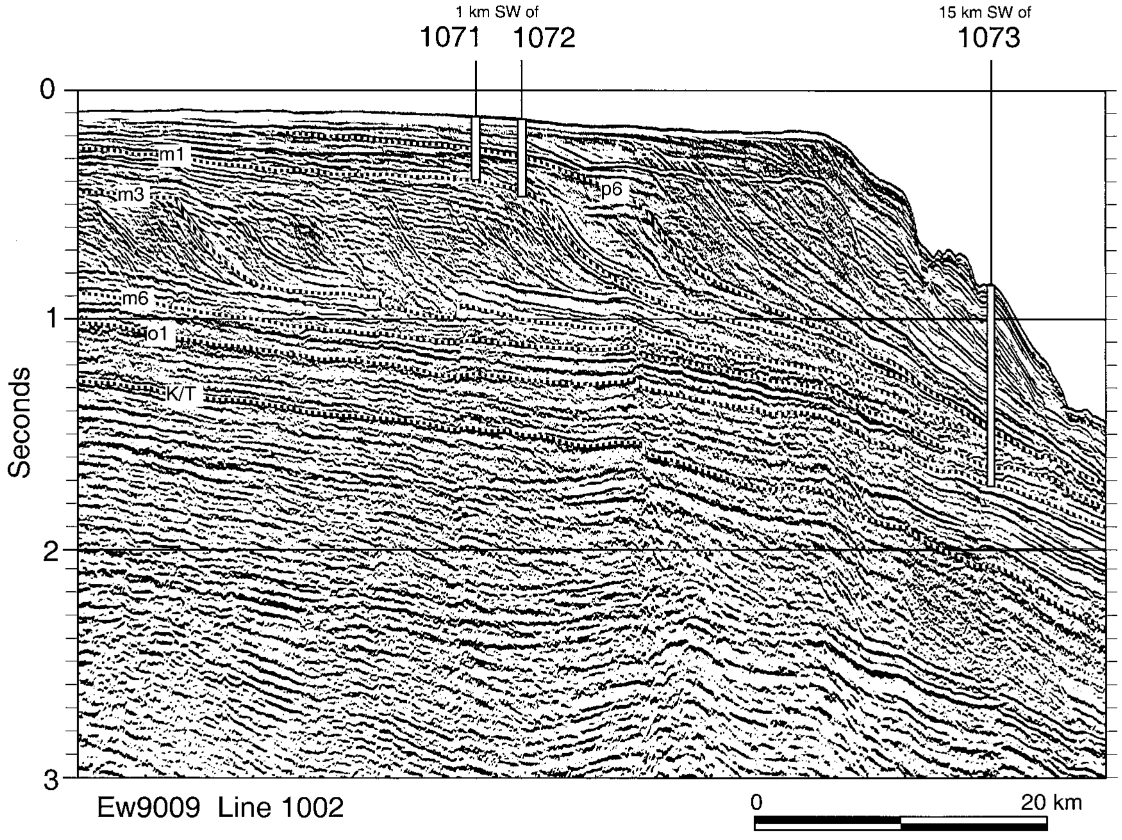

Figure 3. Ew9009 line 1002 showing reflections p6, m1, m3, m6, o1, and the Cretaceous-Tertiary (K-T) boundary. Sites 1071, 1072, and 1073, drilled in summer 1997 during Ocean Drilling Program (ODP) Leg 174A [*Austin et al.*, 1998] are projected onto the profile as noted. Vertical scale is seconds, two-way travel time.

basinward locations (e.g., the slope) owing to the greatest influence of *pelagic sediments*. Drilling on the *continental slope* (Leg 150) has proven to be very successful in this regard; quite surprisingly, onshore drilling (Leg 150X) in extreme *updip* settings has been remarkably successful as well owing to technological advances in dating (e.g., *Sr-isotopic stratigraphy*).

In addition to recovering and dating Oligocene and younger sequences, onshore drilling at the ACGS#4 [*Owens et al*., 1988] (Figure 1), Island Beach, Atlantic City, and Cape May boreholes [*Miller et al*., 1994, 1996a], recovered an excellent record of Eocene sequences. This older interval is particularly critical for evaluating mechanisms of eustatic change and the validity of sequence stratigraphy for global correlation. Glacioeustasy is the only known mechanism for producing large, rapid sea level change [*Pitman and Golovchenko*, 1983]. Although it has been believed in general that there were no significant ice sheets prior to the middle Eocene, *Haq et al*. [1987] delineated numerous Cretaceous–early Eocene sequence boundaries and associated large (>50 m), rapid (<1 myr) sea level lowerings. There are four solutions to this apparent paradox [*Browning et al*., 1996]: (1) the Cretaceous to early Eocene sequences summarized by *Haq et al*. [1987] were restricted to local basin(s) and do not reflect eustasy (this is unlikely considering that many have been widely recognized [e.g., *Aubry*, 1985; *Olsson*, 1991; *Mancini and Tew*, 1991, 1995]; (2) the sequences were controlled by low-amplitude sea level changes (e.g., 10 m of lowering in 1 myr can be explained by numerous mechanisms [*Donovan and Jones*, 1979]); (3) mechanisms of sea level change are not fully understood; and (4) there were ice sheets throughout much of the Cretaceous to early Eocene [e.g., *Stoll and Schrag*, 1996].

The New Jersey Transect drilling to date (Figure 1) includes continuous coring on the New Jersey continental slope (Ocean Drilling Program (ODP) Leg 150; Sites 902–904, 906) [*Mountain et al*., 1994] and onshore in the coastal plain (ODP Leg 150X; Island Beach, Atlantic City, and Cape May boreholes [*Miller et al*., 1994, 1996a]). Drilling on the shelf began in 1997 (ODP Leg 174A, Sites 1071 and 1072) [*Austin* 1998], and additional shelf drilling has been proposed (Sites MAT1-7; Figure 1). Drilling onshore is continuing with a borehole at Bass River (November 1996 [*Miller et al*., 1998]) and boreholes at Ancora and Corson's Inlet/Ocean City (1998) (Figure 1).

In this contribution, we synthesize the major results of New Jersey Transect drilling to date on the coastal plain (ODP Leg 150X) and slope (ODP Leg 150). We have six goals in this paper: (1) to date Cenozoic sequences on this margin; (2) to establish the global correlations of the New Jersey sequences by comparing them with other margins and the EPR record; (3) to demonstrate a link between sequence boundaries and global sea level lowerings inferred from oxygen isotopic studies; (4) to delineate facies changes, demonstrating predictable facies successions within individual sequences in the coastal plain and slope; (5) to estimate amplitudes of Cenozoic sea level changes from the onshore record; and (6) to outline the evolution of the New Jersey margin over the past 65 myr.

2. DEFINING SEQUENCES ON THE NEW JERSEY MARGIN

The New Jersey margin (coastal plain, *continental shelf*, and continental slope; see Figure 1) is a classic passive continental margin that formed following Late Triassic–Early Jurassic rifting [*Grow and Sheridan*, 1988]. Postrift tectonics have been dominated by simple thermal subsidence and sediment loading (both *Airy* and *flexural isostasy* [*Watts and Steckler*, 1979; *Reynolds et al*., 1991]). Onshore, *Owens and Sohl* [1969] first recognized unconformity-bounded *transgression-regression* cycles in New Jersey coastal plain outcrops and attributed them to tectonic changes (e.g., variable subsidence/uplift histories in subbasins/crustal blocks in this region). R. K. Olsson and colleagues [e.g., *Olsson and Wise*, 1987; *Olsson et al*., 1987; *Olsson*, 1991] mapped and dated transgressive-regressive cycles in subsurface New Jersey sections, *correlated* them with the sequences of *Haq et al*. [1987], and attributed them to eustatic changes. Offshore, seismic profiles image thick (typically >100 m) Oligocene–Recent prograding sequences [*Schlee*, 1981; *Poag*, 1985; *Greenlee et al*., 1988; *Greenlee and Moore*, 1988] that have been used to estimate eustatic changes [e.g., *Greenlee and Moore*, 1988].

Previous onshore studies have been hampered by insufficient material for study: outcrops are deeply weathered, and virtually all previous rotary wells and boreholes were discontinuously sampled (the ACGS#4 borehole is a notable exception [*Owens et al*., 1988]). Continuous coring at Island Beach, Atlantic City, and Cape May addressed this problem by providing 4175 feet (1273 m) of core that allows identification and dating of Cenozoic sequences [*Miller et al*., 1994, 1996a]. Unconformities (surfaces of erosion and nondeposition) in the boreholes were identified on the basis of physical evidence (including irregular contacts, reworking, bioturbation, and major facies changes) and well log characteristics (e.g., gamma ray peak associated with sequence boundaries). Unconformities are generally associated with *hiatuses* detected with biostratigraphic and/or Sr isotopic breaks. Paleoenvironmental studies (benthic *foraminiferal biofacies* and *lithofacies* analyses) document that these unconformities are associated with shifts in base level (see papers in the *Miller and Snyder* [1997] volume) and thus are sequence boundaries in the sense of *Mitchum et al*. [1977] and *Christie-Blick and Driscoll* [1995].

Onshore sequences are named alphanumerically from older to younger (Figure 4), with Pa1 to Pa3 representing three Paleocene sequences, E1 to E11 rep-

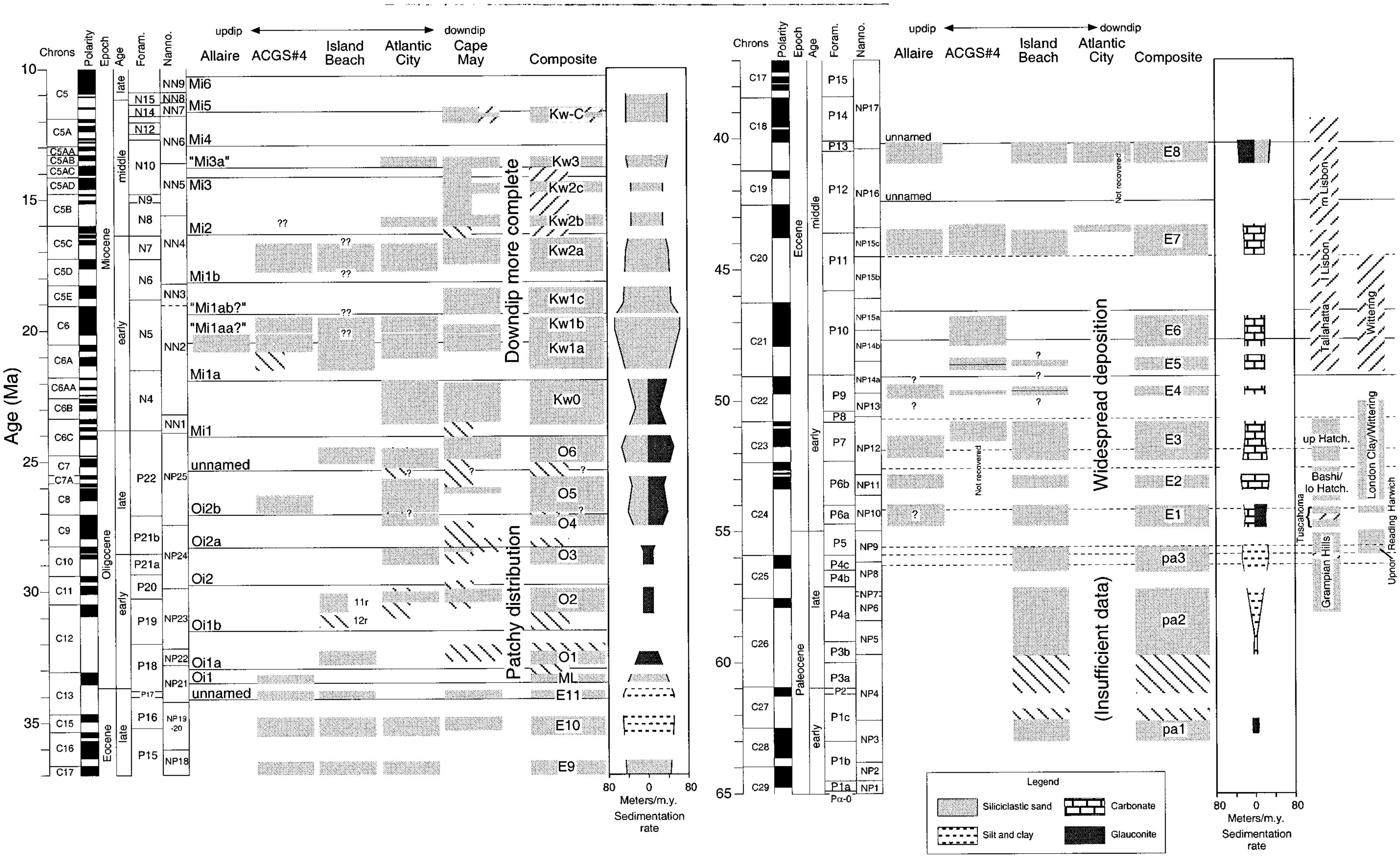

Figure 4. Comparison of the ages of Cenozoic sequences recovered onshore by Leg 150X. Stippled pattern indicates time represented by sediments. The hatched pattern indicates uncertainties in age. The timescale of *Berggren et al.* [1995] is used. Sedimentation rate is indicated with a "bulge" diagram, and the dominant lithologic components are indicated (see legend for component type). Horizontal lines indicate the timing of inflections in the $\delta^{18}O$ record (Table 1). Shown for comparison are Paleogene sequences in Alabama and northwest Europe (see text). Modified after *Miller et al.* [1997a].

resenting 11 Eocene sequences, O1 to O6 representing six Oligocene sequences, and Kw0 to Kw-Cohansey representing nine lower to middle Miocene sequences (Figure 4). Upper Miocene strata are difficult to date because they are marginal marine to estuarine, although *dinocysts* provide identification and correlation of four upper Miocene sequences (Ch3 to Ch6 *de Verteuil* [1997]) within the estuarine to nearshore deposits at Cape May. No Pliocene strata were identified in the boreholes (strata tentatively recognized ?Pliocene at Cape May [*Miller et al*., 1996a] are uppermost middle and upper Miocene on the basis of dinocysts [*de Verteuil*, 1997]). Pleistocene–Recent sections in these boreholes are also difficult to date, with only four radiocarbon ages [*Miller et al*., 1994, 1996a) and one interval of amino acid ages available [*Wehmiller*, 1997]. Because of problems in dating these upper Neogene sediments, we restrict our onshore comparisons to Paleocene–middle Miocene strata.

On the New Jersey shelf and slope we used seismic reflection profiles to recognize seismic unconformities (Figures 1–3). We used EPR *multichannel seismic* (MCS) data [*Greenlee et al*., 1992] to plan a detailed grid of 2400 km of MCS and single-channel seismic data that were collected on R/V *Maurice Ewing* cruise 9009 (EW9009) in 1990 (Figure 1 [*Miller and Mountain*, 1994]). These profiles (Figures 2 and 3) represent a clear improvement over older seismic data (e.g., EPR data of *Greenlee et al*. [1988, 1992]), in part through our use of a tuned air gun array (six guns totaling 1350 cubic inches (2.21×10^4 cm^3)), shallow towing depths (6 m), short streamer group lengths (12.5 m), F–K filtering to minimize water column reverberations, and efforts to preserve seismic images of shallow, fine-scale stratal geometry during all stages of acquisition and processing. Vertical resolution is approximately 15–20 m down to nearly 1 km below seafloor, and we were able to detect seismic discontinuities at a finer scale than those detected on the EPR data.

Using the Ew9009 MCS data, we mapped Oligocene–Recent seismic unconformities beneath the New Jersey shelf that exhibit top discordant (*offlap*, including erosional truncation and/or *toplap*) and/or base discordant (*onlap* and/or *downlap*) geometries [*Mountain et al*., 1994]; these criteria allow objective recognition of sequence boundaries [e.g., *Mitchum et al*., 1977]. We related the sequence boundaries on the Ew9009 profiles to the Oligocene–Miocene surfaces of *Greenlee et al*. [1992]. We traced these seismic reflections from the shelf to the slope where they were dated at Sites 903 and 904 (Figures 1, 5, and 6 [*Mountain et al*., 1994]). However, uncertainties remain in some correlations of the slope (Figures 2 and 3) to the shelf reflections owing to problems with downlapping, erosion, and concatenation of reflections. Therefore *Mountain et al*. [1994] established a slope alphanumeric scheme (reflections m1 to m6, o1, etc.; see Figures 5–7a) that was tentatively correlated with the sequence boundaries traced beneath the shelf. This alphanumeric scheme is used here, with the recognition that the correlations are subject to minor changes as additional high-resolution seismic data become available. For example, *Miller et al*. [1996c] correlated reflection m2 on the slope to Yellow-2 of *Greenlee et al*. [1992]; subsequent studies indicate that m2 is, in fact, slightly younger than Yellow-2, which was also not interpreted at a consistent level within the outer shelf area.

3. DATING SEQUENCES ON THE NEW JERSEY TRANSECT: TIMING OF RELATIVE SEA LEVEL FALLS

3.1. Methods of Dating

Dating onshore and offshore sequences relies on integrating strontium isotopic, biostratigraphic (planktonic foraminiferal, *nannofossil*, dinocyst, and diatom), and magnetostratigraphic data. Sr isotopic dating is especially useful in dating Oligocene–middle Miocene sequences. Eocene sequences are dated using integrated magnetobiostratigraphy, whereas Paleocene sequences are dated using only *biostratigraphy* (i.e., Sr isotopic stratigraphy is not readily applicable to Paleocene–Eocene strata).

Sr isotopic data from onshore and offshore sites are derived from analyses of foraminifera and molluscan shells [*Miller et al*., 1996b, 1997b; *Sugarman et al*., 1997] using standard techniques on a VG Sector mass spectrometer at Rutgers University [*Miller et al*., 1988]. At Rutgers, NBS987 is routinely measured as 0.710255 ^{87}Sr/^{86}Sr ($1\sigma = \pm 0.000008$, normalized to $^{86}\mathrm{Sr}/^{88}\mathrm{Sr} = 0.1194$ [*Oslick et al*., 1994]). Internal precision (intra-run variability) is ±0.000010 (mean value) for the analyses used in Leg 150 and 150X studies. Our external precision (inter-run variability) is approximately ±0.000020 or better [*Miller et al*., 1998, 1991b; *Oslick et al*., 1994]. Sr isotopic ages are derived using the late Eocene to Miocene age-Sr regressions of *Oslick et al*. [1994]. These regressions are based on Sr isotopic data from open ocean reference sites with excellent magnetostratigraphic records: Site 522 (late Eocene–Oligocene [*Miller et al*., 1988]) and Site 747 (latest Oligocene–early late Miocene [*Oslick et al*., 1994]). Error analysis [e.g., *Miller et al*., 1991b, equation (6)] of the late Eocene–Oligocene regressions demonstrates that a single analysis has an age uncertainty of about ±1 to ±0.6 myr (at the 95% confidence interval). The Miocene regression from 22.8 to 15.6 Ma has age uncertainties of ±0.6 myr (for one analysis at the 95% confidence interval) to ±0.4 myr (for three analyses at the 95% confidence interval), whereas the Miocene regression from 15.2 to ~10 Ma has age uncertainties of ±1.2 myr (for one analysis at the 95% confidence interval) to ±0.8 myr (for three analyses at the 95% confidence interval). We assume that the theoretical maximum resolution is equivalent to our estimate of external precision (±0.000020) divided by the slopes of the regressions; this corresponds to age uncer-

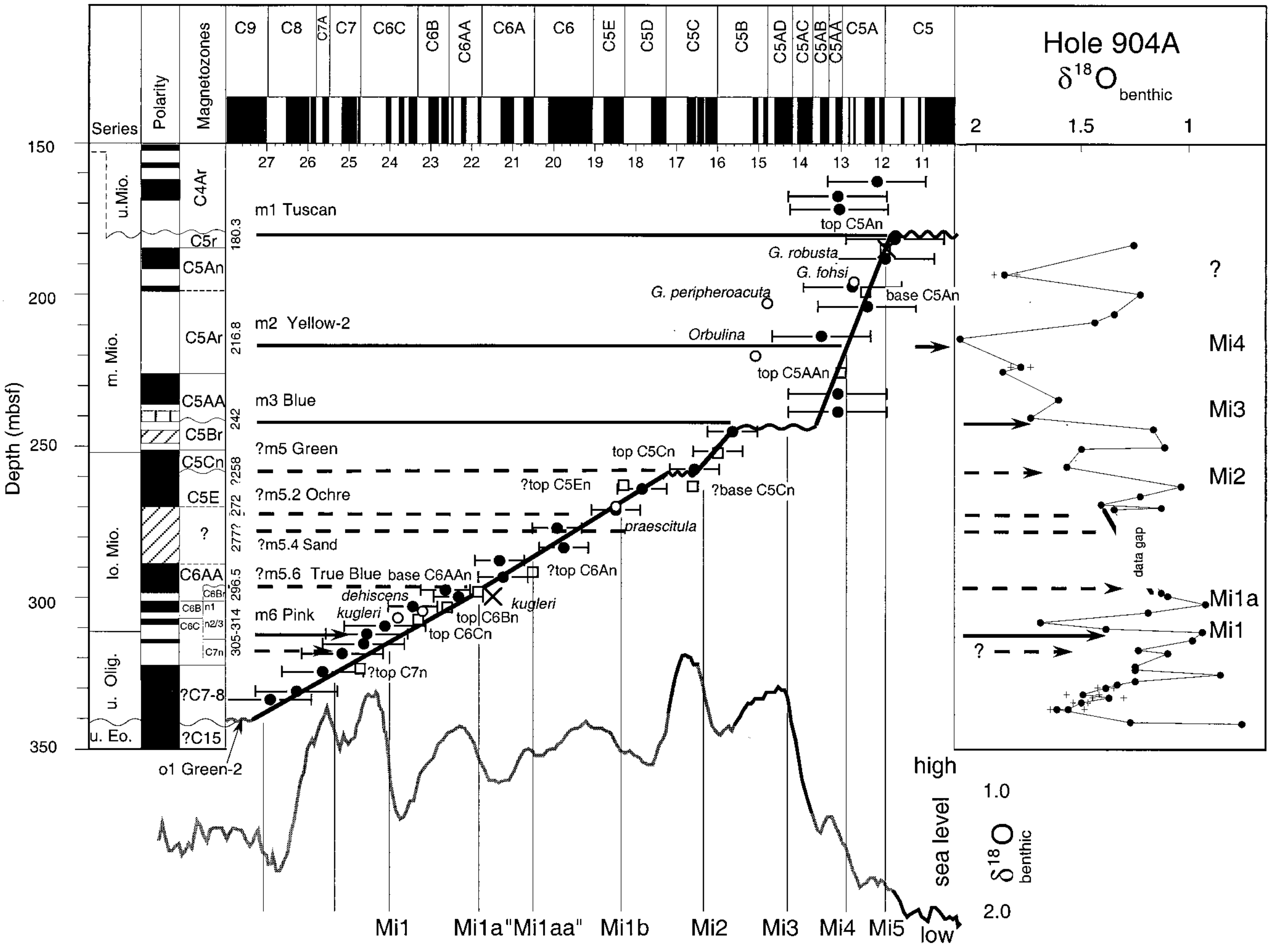

Figure 5. Age-depth diagram, Site 904, showing Sr isotopic ages (solid circles with error bars), planktonic foraminifera (open circles for lowest occurrences, crosses for highest occurrences) and magnetostratigraphic (squares) age estimates, and the timescale of *Berggren et al.* [1995]. Depth is in meters below seafloor (mbsf). Solid lines labeled *m*1, *m*2, etc., indicate reflections identified by *Mountain et al.* [1994]; dashed lines for *m*5, *m*5.2 indicate unconformities inferred from core studies (Table 1). Wavy lines indicate unconformities. A stacked, smoothed benthic foraminiferal oxygen isotopic record is shown at bottom plotted versus time; portions of the curve represented by sediments at Site 904 are indicated with thick (black) line. Vertical lines are drawn at the inflections of the global curve that predict the location of sequence boundaries. On right, new δ^{18}O from *Cibicidoides* spp. at Site 904 are shown plotted versus depth in the borehole. Mi1, Mi1a, etc. are δ^{18}O zones (Table 1). Modified after *Miller et al.* [1996a].

tainties of ±0.6, ±0.3, and ±0.8 myr for the intervals 35–22.8, 22.8–15.6, and 15.6–10 Ma, respectively.

Stable isotopic data provide a relative correlation tool and allow evaluation of the relationship of sequence boundaries and global δ^{18}O variations. Oxygen isotopic data are derived from analyses of the benthic foraminifera *Cibicidoides* spp. from slope Site 904, a taxon that secretes its tests constantly offset from δ^{18}O equilibrium [*Shackleton and Opdyke*, 1973]. Samples examined for benthic foraminiferal isotope analyses were washed with sodium metaphosphate (5.5 g L^{-1}) in tap water through a 63-μm sieve and dried in an oven (<50°C). Benthic foraminifera were roasted at 370°C in a vacuum. Stable isotope measurements were made using an Autocarb attached to a VG Prism II mass spectrometer at the University of Maine. Samples were lightly crushed and reacted in phosphoric acid at 90°C. The isotopic values are reported relative to the Peedee belemnite (PDB) scale via NBS-19 and NBS-20 standards. Values for each of these standards are reported by *Coplen et al.* [1983]. The precision (1σ) of the NBS (National Bureau of Standards, now National Institute of Standards and Technology (NIST)) standards analyzed along with the samples was 0.06‰ for δ^{18}O and 0.05‰ for δ^{13}C.

3.2. Onshore Sequences

While not all sequences are represented in any one borehole, we have assembled a composite of 30 Paleocene–middle Miocene onshore sequences (Figure 4) by sampling at numerous locations. Studies conducted as

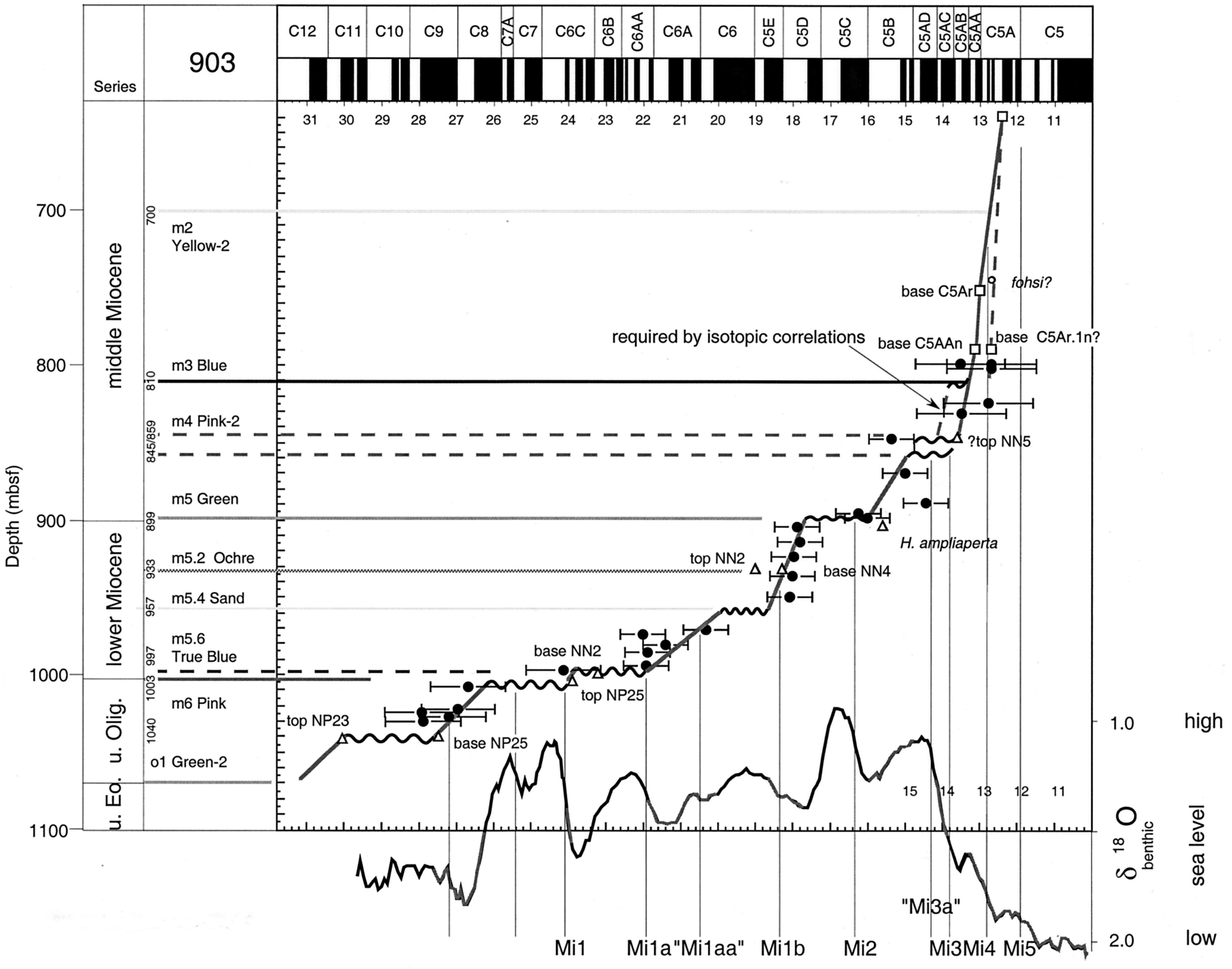

Figure 6. Integrated uppermost Eocene–middle Miocene section and age-depth diagram, Site 903. See Figure 5 caption for explanation. A dashed line indicates an alternative or uncertain age model. The timescale is from *Berggren et al.* [1995]. Time intervals represented by sedimentation on the slope and onshore are shaded. Slope reflections o1 and m1 to m6 (sequence boundaries) are indicated with heavy lines. Approximate age error bar of ±0.5 is shown for onshore and slope sequences. Oxygen isotopic data are the synthesis of *Miller et al.* [1987] recalibrated to the geomagnetic polarity timescale (GPTS) of *Berggren et al.* [1995]. *Haq et al.* [1987] sequences are recalibrated to the *Berggren et al.* [1995] scale; for the Oligocene we interpolated between three points: (1) *Miller et al.* [1993] revised the correlation of the TB1.1 sequence boundary to latest chron C11r (~30.0 Ma on the *Berggren et al.* [1995] timescale), (2) the age of the Oligocene-Miocene boundary should be revised from 25.5 Ma [*Haq et al.*, 1987] to 23.8 Ma [*Berggren et al.*, 1995], and (3) the Eocene-Oligocene boundary is 33.7 Ma. Modified after *Miller et al.* [1996a].

part of ODP Leg 150X have provided firm dates for most of these sequences (see papers in the *Miller and Snyder* [1997] volume). The chronology of onshore sequences was derived from age-depth diagrams for the Paleocene [*Liu et al.*, 1997], early–middle Eocene [*Browning et al.*, 1997a], late Eocene [*Browning et al.*, 1997b], Oligocene [*Pekar et al.*, 1997], and Miocene [*Miller et al.*, 1997b]. In general, sedimentation rates were linearly interpolated between age estimates (biostratigraphic or magnetostratigraphic datum levels or Sr isotopic age estimates) to provide the age interpretations of sequences (Figure 4).

Paleocene ages derived from the age-depth diagrams are constrained by biostratigraphy [*Liu et al.*, 1997] and have approximately ±1-myr resolution; the ages of Paleocene sequences are the least well constrained because they were sampled only at Island Beach. Early–middle Eocene sequences (E1 to E9) have excellent age control that is provided by integrating detailed magnetostratigraphic and biostratigraphic correlations; resolution ranges from as fine as ±0.1 myr to as coarse as ±0.5 myr [*Browning et al.*, 1997a]. The ages of the upper Eocene sequences E10 and E11 (Figure 4) are only moderately well constrained (±0.5 myr), whereas the duration of sequence E9 cannot be firmly estimated owing to stratigraphic mixing [*Browning et al.*, 1997b].

Oligocene sequences are dated by integrating Sr isotopic stratigraphy with biostratigraphy and limited magnetostratigraphy [*Pekar et al.*, 1997], yielding resolution that ranges from approximately ±0.5 to ±1.0 myr. This is a clear improvement over previous studies and is a significant achievement for Oligocene sediments that are notoriously difficult to date. Although Oligocene sequences recovered by Leg 150X are relatively well dated, there are still uncertainties in their identifications and ages. For example, O4, O5, and O6 appear to be distinct sequences separated by unconformities associated with shifts in base level (Figure 4); however, the hiatuses associated with these sequence boundaries are not discernible within the ±0.5 to 1.0-myr resolution afforded by Sr isotopic stratigraphy and biostratigraphy. Therefore it is possible to interpret O4 to O6 as one thick sequence [*Pekar et al.*, 1997]. One lowermost Oligocene sequence (ML) has been reported only from the ACGS#4 borehole (Figure 1) [*Owens et al.*, 1988; *Poore and Bybell*, 1988], and sequence O4 has been reported from only one site (Cape May); their regional and interregional significance requires verification.

Prior to the advent of Sr isotopic stratigraphy, dating onshore Miocene sequences was difficult because of the rare planktonic marker taxa. *Sugarman et al.* [1993] used Sr isotopic stratigraphy and recognized, dated, and mapped three lower to middle Miocene sequences (Kw1, Kw2, and Kw3, named after the local Kirkwood Formation) at the updip ACGS#4 and Belleplain boreholes and discontinuously sampled sections. Subsequent studies conducted on Leg 150X boreholes (Figure 4). (1) identified a lowermost Miocene Kw0 sequence that is thin at Atlantic City and thick at Cape May, (2) confirmed that the Kw1 sequence consists of two distinct sequences (Kw1a and Kw1b), (3) recognized an additional Kw1c sequence at Cape May, (4) subdivided the Kw2 sequence into Kw2a and Kw2b and identified the Kw3 sequence at Cape May, and (4) documented a Kw-Cohansey (Ch) sequence at Cape May [*Miller et al.*, 1997b]. The dates on Miocene sequences rely primarily on Sr isotopic ages [*Miller et al.*, 1997b; *Sugarman et al.*, 1997].

De Verteuil [1997] split Kw2a into possible sequences Kw2a′ and Kw2a″ and split Kw3 into Kw3a and Kw3b on the basis of short hiatuses (~0.2 myr) inferred from dinocyst zonations. It is not clear that these are definitely distinct sequences separated by sequence boundaries because there is limited or no evidence for erosion and base level lowering with these biostratigraphically determined gaps. In addition to the Kw sequences discussed here (Figure 4), he recognized one additional uppermost middle Miocene sequence (Ch2) and four upper Miocene sequences (Ch3 to Ch6) that are younger than the Kw sequences (his Ch1 is equivalent to our Kw-Ch sequence). These upper middle to upper Miocene Ch sequences have been identified only at the Cape May borehole and understanding their regional significance will require additional documentation.

Most of the Paleocene to middle Miocene sequences identified here (21 of 30) are found in more than one borehole (Figure 4). Comparison among the boreholes (Figure 4) shows that Eocene to middle Miocene hiatuses associated with sequence boundaries correlate from site to site. Sequence boundaries are generally associated with hiatuses that occur throughout the coastal plain (Figure 4). The only exceptions are sequence boundaries at the bases of O5, O6, Kw1b, and Kw1c. There is no discernible hiatus associated with the base of Kw1b. The hiatuses associated with O5, O6, and Kw1c are short (<0.5 myr) and are thus within our age errors. Nevertheless, physical stratigraphy indicates evidence for erosion and base level shifts at these sequence boundaries, with some time gap implied. Although the hiatuses correlate from site to site, the updip sections are generally less complete than the downdip sections, particularly in the Miocene (Figure 4).

3.3. Offshore

Twenty-two seismic reflections were correlated to core samples and dated at slope Sites 903 (444-m water depth) and 904 (1123-m water depth) [*Mountain et al.*, 1994]. Two-way travel time–depth (t-d) relationships for correlation of seismic profiles to the boreholes were derived from three sources: the velocity log from the Continental/Offshore Stratigraphy Test (COST) B-3 slope well (2 km north of Site 902), semblance velocities from analysis of Ew9009 CDP stacks on the adjacent shelf, and sonobuoy data from the continental rise [*Mountain et al.*, 1994]. Synthetic seismograms were computed using log [*Mountain et al.*, 1994] and core physical properties data [*Lorenzo and Hesslebo*, 1996]. In general, shipboard predictions of borehole-seismic correlations proved to be accurate within ~3% (typically ~10 m), and subsequent iterations improved these correlations [*Mountain et al.*, 1994]. The thicker section at Site 903 (Figure 6) had longer hiatuses than at Site 904 (Figure 5), while the latter site had more *carbonates*, better biostratigraphic control, and a clear magnetostratigraphic record (Figure 5). However, as a result of stratal thinning to below seismic resolution on the Ew9009 MCS profiles, many of the critical lower Miocene surfaces (m5.6 to m5) could not be traced to the better dated section at Site 904 (Figure 5).

The geometric relations that define sequences in seismic reflection profiles [*Mitchum et al.*, 1977] are not expressed on the New Jersey slope, although these seismic criteria are revealed beneath the modern shelf and can be traced to their lateral equivalents on the slope [*Greenlee et al.*, 1992; *Miller and Mountain*, 1994]. In general, the lithologic expression of sequence boundaries on the slope is not as pronounced as it is onshore or beneath the shelf. Furthermore, their expression on the slope is variable: several sequence boundaries traced seismically to the slope display no evidence of erosion,

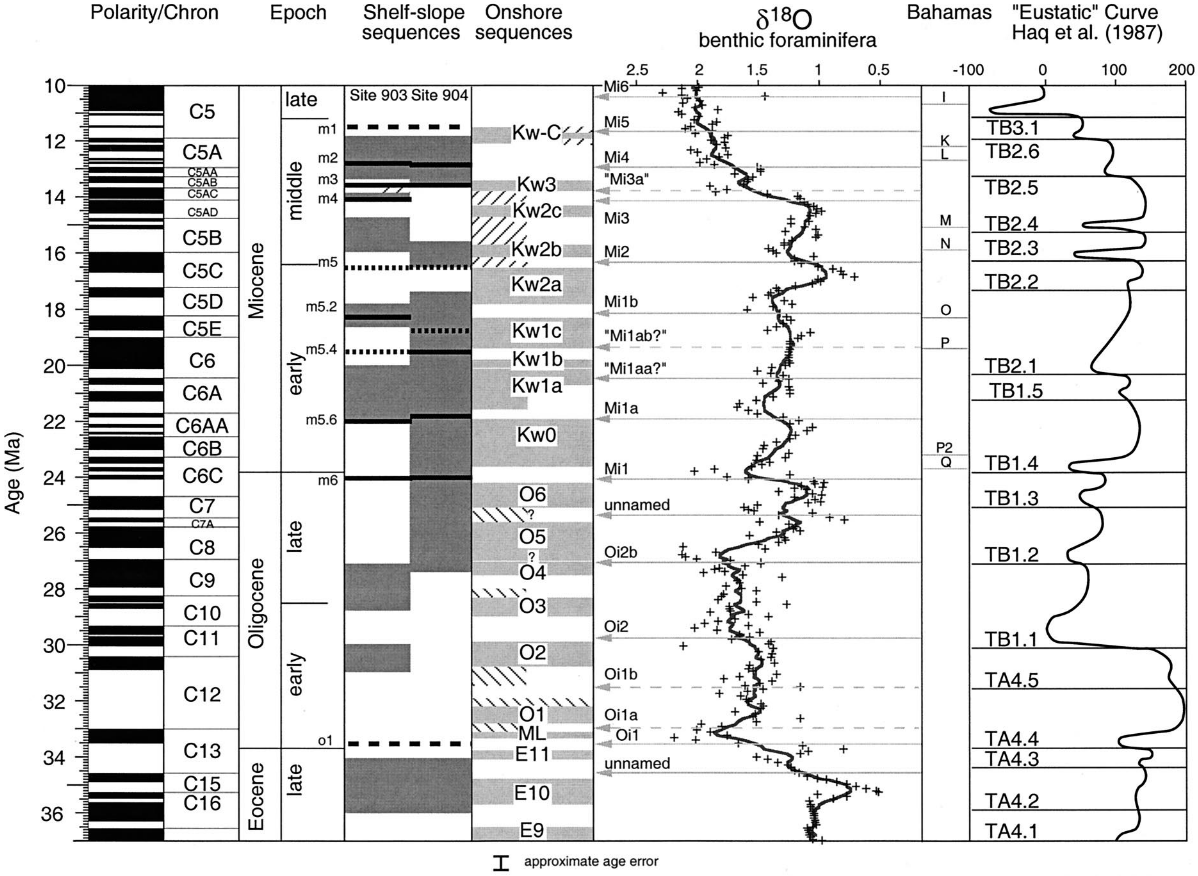

Figure 7a. Revised comparison of Oligocene-Miocene slope sequences, onshore sequences, oxygen isotopes, Bahamian reflections [*Eberli et al.*, 1997], and the inferred eustatic record of *Haq et al.* [1987]. Modified from *Miller et al.* [1996b].

whereas others show clear evidence of erosion similar to onshore boundaries. Evidence of erosion does not require that a surface on the slope be viewed as a sequence boundary because erosional processes other than base level lowering are important in slope environments. Nevertheless, seismic correlations to many of the surfaces observed in slope cores can be traced to sequence boundaries defined by reflector geometry beneath the shelf. Many of these slope sequence boundaries are associated with increased sand content and/or indurated zones immediately above the boundary [*Mountain et al.*, 1994]. Studies of the cores for sandy (glauconitic) silt beds and indurated zones were thus used to provide estimates of the equivalent placement of reflections m5.2 to m5 at Site 904 (dashed lines in Figure 5).

The ages of Oligocene–middle Miocene slope reflections are derived from age-depth diagrams at Sites 904 (Figure 5) and 903 (Figure 6). These diagrams use data published by *Miller et al.* [1996b] but differ in some details: (1) they have been updated to the *Berggren et al.* [1995] timescale, (2) hiatuses are interpreted with reflections (sequence-bounding unconformities) at 1040, 997, 899, and 849/859 m below seafloor (mbsf) at Site 903 and 258 m at Site 904, and (3) the equivalents of m5.2, m5.4, and m5.6 are estimated on the basis of sand beds on indurated zones at Site 904 within an apparently continuous section (Figure 5).

The ages of the reflections agree remarkably well between Sites 903 and 904 (Figure 7a), except that reflection m5.2 appears to be slightly older at Site 904 (18.8 Ma) than at Site 903 (18.3 Ma). We attribute this to uncertainties in the correlation of m5.2 at Site 904. There remain two major dating uncertainties. First, the section between reflections m4 and m3 is poorly dated at Site 903, and the sequence between reflection m4 and m3 is missing at Site 904; we assume that the age of this sequence is equivalent to that predicted by oxygen isotopic stratigraphy (14.3 Ma, the age of Mi3a (Table 1)), close to the age of ~14.5 Ma obtained by *Greenlee et al.* [1992]; our age estimate is slightly older than the age of ~13.8 Ma obtained by assuming linear sedimentation rates at Site 903 (Figure 6). While assuming that m4 correlates with isotopic increase Mi3a (Figure 7a) is admittedly circular, this difference is within the age error bars. Second, reflection m5.4 is not resolved at Site 904, and its age at Site 903 is constrained by only one Sr isotopic age below the reflector.

TABLE 1. Comparison of the Ages of Onshore Hiatuses, Slope Reflections, δ^{18}O Maxima, δ^{18}O Increases, and the *Haq et al.* [1997] sequences

Onshore		*Slope*								
Sequence	*SB/Hiatus Age, Ma*	*Reflector*	*Age, Ma*	*Age Error, Ma*	*Oxygen Isotope Maximum*	*Magnetochron (of Isotope Maximum)*	*Age of Maximum, Ma*	*Age of Inflection, Ma*	*Haq et al. [1987] Sequence*	*Haq Age Corrected to BKSA95, Ma*
NR		NR			Mi7	base C4n (C4A?)	8.7	~8.8	3.2	9.0
NR		NR			Mi6	lower C5n	10.3	~10.4	NR	
NR		m1	11.5	11.0–11.9	Mi5	base C5r	11.7	11.9	3.1	11.0
Kw-Ch	12.1–13.4	m2	12.8	12.6–12.8	Mi4	base C5Ar	12.9	13.1	2.6	11.9
Kw3	13.8–14.3	m3	13.6	13.4–13.8	Mi3	C5ABr	13.7	13.8	2.5	13.9
NR		m4	?14.1	13.6–15.0	"Mi3a"	base C5ACr	14.2	14.3	2.4	15.1
Kw2c	14.7–15.6	?Red	?15.2	13.6–15.3	Mi2a	base C5ADr	14.8	14.9	NR	
Kw2b	16.1–16.5	m5	16.6	16.6–17.2	Mi2	C5Br	16.1	16.3	2.3	16.6
Kw2a	17.8–18.4	m5.2	18.3	18.2–18.8	Mi1b	C6Dr	17.9	18.15	2.2	17.9
Kw1c	19.4–19.5	NR			"Mi1ab?"	C5En	18.5	18.6	NR	
Kw1b	20.1	m5.4	19.5	18.7–19.9	"Mi1aa?"	base C6n	20.1	20.5	2.1	20.3
Kw1a	21.1–21.9	m5.6	22.0	21.8–22.0	Mi1a	C6Ar	21.5	21.7	1.5	21.7
Kw0	23.6–24.2	m6	24.0	23.8–24.1	Mi1	C6Cn	23.8	23.9	1.4	23.8
O6	25.1–25.6	NR			unnamed	(C7n)	25.0	25.2	1.3?	24.8
O5	27.0	NR			Oi2b	(top C9n)	27.1	27.3	1.2	27.1
O4	27.5–28.3	NR			Oi2a	(C10n1)	28.3	28.5	NR	
O3	29.0–29.9	NR			Oi2	(base C11n)	30.1	30.2	1.1	30.2
O2	30.8–32.3	NR			Oi1b	(C12r)	31.7	31.8	4.5	32.0
O1	32.8–33.2	NR			Oi1a	(lowest C12r)	32.8	32.9	NR	
ML	33.5–33.8	o1	33.5	33.0–34.0 (31.0–34.0)	Oi1	C13n	33.5	33.6	4.4	33.5
E11	34.1–34.8	NR			unnamed	(C13r)	34.1	34.15	4.3	34.7
E10	35.7–36.0	NR			NR				4.2	35.7
E9	36.5–40.5	NR			unnamed	(C18n)	39.9	40.2	3.6?	39.0
E8	41.2–43.2	NR			unnamed	(C19r)	41.9	42.4	3.5?	41.5
E7	44.5–47.0	NR			unnamed	(C20r)	44.4	44.5	3.4?	43.4
NR		NR			unnamed	(C21n)	46.4	46.6	3.3?	46.2
E6	47.7–48.3	NR			unnamed	(C21n)	47.5	47.7	3.2?	48.3
E5	48.6–49.6	NR			unnamed	(C21r)	48.1	49.1	3.1?	49.7
E4	49.9–50.9	NR			unnamed	(C22r)	50.6	50.7?	2.8	50.7
NR		NR			unnamed	(C23r)	51.8	51.9?	2.7	52.2
E3	52.3–52.9	NR			unnamed	(base C23r)	52.4	52.6?	2.6?	52.8
E2	53.4–54.0	NR			unnamed	(C24r)	54	54.2?	2.5?	53.5
E1	54.7–55.7	NR			unnamed	(C24r)	55.6	55.6?	2.3	55.7
NR		NR			unnamed	(base C24r)	55.8	55.9?	2.2	55.9
NR		NR			unnamed	(C25n)	56.2	56.3?	2.1	59.2
pa3	56.5–57.3	NR			NR					
pa2	59.7–62.2	NR			NR					
pa1	63–?	NR			NR					

Abbreviations: NR, not resolved; SB, sequence boundary; BKSA95, *Berggren et al*. [1995]. *Haq et al*. [1987] sequences refer to the TA2.1–4.5 and TB1.2–TB3.2 sequence boundaries. Preferred error of 33.0–3.40 Ma for o1 is based on slope outcrops [*Miller et al*., 1996b].

4. COMPARISONS WITH OTHER PASSIVE MARGINS AND THE EPR RECORD

Few passive margin stratigraphic records have attained age resolution comparable to the New Jersey coastal plain and continental slope. Four regions have recently provided improved ages of Eocene–Miocene sequences that allow preliminary comparisons with the New Jersey records: the Bahamas, Florida, Alabama, and northwest Europe. These comparisons indicate that Oligocene–Miocene sequences fulfill our first expectation of a global process such as eustasy: they correlate within the requisite resolution (±0.5 myr) both regionally (e.g., onshore-offshore of New Jersey) and interregionally (New Jersey–Alabama–Bahamas). Although New Jersey Eocene sequences correlate regionally within our ±0.5-myr (or better) resolution (Figure 4), interregional comparisons are still limited by uncertainties in ages in northwest Europe and Alabama.

4.1. Bahamas

Recent drilling in the Bahamas [*Eberli et al*., 1997] has dated seismic sequences that were recognized on MCS profiles. The Q/P2, P, O, N, M, K/L reflections apparently correlate with the bases of the following New Jersey Miocene onshore sequences Kw0, Kw1c, Kw2a, Kw2b, Kw2c, and Kw-Coh, respectively (Figure 7a). Ages for the Bahamian reflections are derived from planktonic foraminiferal and nannofossil biostratigraphy. Integration of nannofossil and planktonic foraminifera biostratigraphy can provide a theoretical resolution of 0.2–0.5 myr for this interval [*Eberli et al*., 1997]. However, the sampling interval and discrepancies between planktonic and nannofossil zonations in the Bahamas boreholes [*Eberli et al*., 1997] indicate that age uncertainties are probably closer to ±0.5 myr.

4.2. Florida

Recent studies of Florida [*Mallinson et al*., 1988; *Jones et al*., 1993; *Scott et al*., 1994; *Wingard et al*., 1994; *Mallinson and Compton*, 1995; *McCartan et al*., 1995] have yielded Sr isotopic ages for Oligocene–middle Miocene sequences that are similar to those in New Jersey [*Sugarman et al*., 1997]. The New Jersey onshore Oligocene–lower Miocene sequences correlate reasonably well with the Florida Miocene sequences; however, the majority of middle Miocene sequences mapped in New Jersey are missing from central Florida [*Sugarman et al*., 1997]. Additional studies are needed to overcome several problems in interpreting the Florida sequences: (1) they are not as complete as the New Jersey onshore sequences, (2) lithofacies assemblages vary little from one sequence to another and, unlike their counterparts in New Jersey, cannot be used to distinguish one sequence from another, (3) carbonate diagenesis is potentially a problem for Sr isotopic correlations, and (4) Oligocene–Miocene sections contain few planktonic index fossils and thus have poor biostratigraphic control [*Sugarman et al*., 1997].

4.3. Alabama

Uppermost Eocene–lower Oligocene sequences in Alabama have been well dated by integrated magnetobiostratigraphy [*Miller et al*., 1993]; these sequences correlate to better than ±0.5-myr resolution with the onshore New Jersey sequences [*Sugarman et al*., 1997]. Upper Oligocene sequences in Alabama are poorly dated. Alabama offshore Miocene sequences also appear to correlate with those in New Jersey [*Greenlee and Moore*, 1988], although these sequences are only coarsely dated (±1 myr or worse) by biostratigraphic studies of industry well cuttings.

Lower–middle Eocene sequences in Alabama are dated with planktonic foraminiferal biostratigraphy [e.g., *Mancini and Tew*, 1995]. On the basis of the published biostratigraphy, New Jersey sequences E1, E2, E3, E5/6, E7, and E8 (Figure 4) appear to correlate with the Tuscahoma, Bashi Marl–lower Hatchetigbee, upper Hatchetigbee, Tallahatta, lower Lisbon, and middle Lisbon sequences, respectively (Figure 7b) [*Baum and Vail*, 1988; *Mancini and Tew*, 1995]; the equivalent break between E5/6 has not been discerned, and the equivalent of E4 is represented by a hiatus in Alabama as it is in northwest Europe (see section 4.4). Uncertainties still exist in placing of the unconformities in Alabama (e.g., *Baum and Vail* [1988] and *Mancini and Tew* [1995] differ in details), and age control relies primarily on foraminiferal biostratigraphy with a resolution of ±0.5–1.0 myr in the lower Eocene and worse in the middle Eocene (as much as ±1.25 myr). These moderately large age error estimates are based on the durations of the planktonic foraminiferal zones that have been identified in the sequences. Future integration of nannofossil, isotopic [e.g., *Baum et al*., 1994], and magnetostratigraphic control should yield improved age resolution on these lower–middle Eocene Alabama sequences and determine if the major breaks correlate with those in New Jersey.

4.4. Northwest Europe

Northwest Europe has nannofossil [*Aubry*, 1985] and limited magnetostratigraphic age control [*Ali and Hailwood*, 1995] on Eocene sequences. The equivalent breaks between Pa3/E1, E1/E2, and E3/E4–5 have been recognized in northwest Europe (corresponding to the Reading/Harwich, Harwich/London Clay, and intra-Wittering breaks) [*Ali and Hailwood*, 1995] (Figures 4 and 7b). However, the equivalent breaks between E2/E3 and E5/6 have not been discerned (the equivalent of E4 is represented by a hiatus). We attribute this to the lack of adequate age resolution in the northwest European sections.

4.5. Comparisons With the EPR Record

Our results agree with the general number and timing of Eocene–middle Miocene sequences published by EPR (Figures 7a and 7b; *Haq et al*. [1987]). Comparison of Paleocene onshore sequences and the *Haq et al*. [1987] record are limited by coarse age control at Island Beach [*Liu et al*., 1997]. Comparisons of Eocene to middle Miocene sequences with the EPR record show similar timing of their sequence boundaries and ours (Figures 7a and 7b), especially considering the greater than ±1 myr age resolution inherent in the *Haq et al*. [1987] synthesis. The *Haq et al*. [1987] Eocene–Miocene sequence boundaries also are similar in number and ages to global δ^{18}O variations (Figures 7a and 7b). This implies that the sequence boundaries reported by *Haq et al*. [1987] were caused by glacioeustatic lowerings (see also *Abreu and Haddad* [1998], although it is not possible to demonstrate this unequivocally because of their large age errors (>±1 myr) and unpublished data. In contrast to the *Haq et al*. [1987] record, New Jersey Eocene–middle Miocene sequences are well correlated to the geomagnetic polarity timescale (GPTS) of the *Berggren et al*. [1995] timescale and thus provide a testable chronology of eustatic falls. The New Jersey record (Figures 7a and 7b) cannot be used as a "global standard" until it is verified fully by studies on other margins; nonetheless, it provides an excellent chronology of unconformities for the Eocene to middle Miocene.

Although the EPR synthesis has been widely accepted and applied in industry, various studies have criticized the EPR record for unsubstantiated assumptions, largely unpublished documentation, and coarse chronological

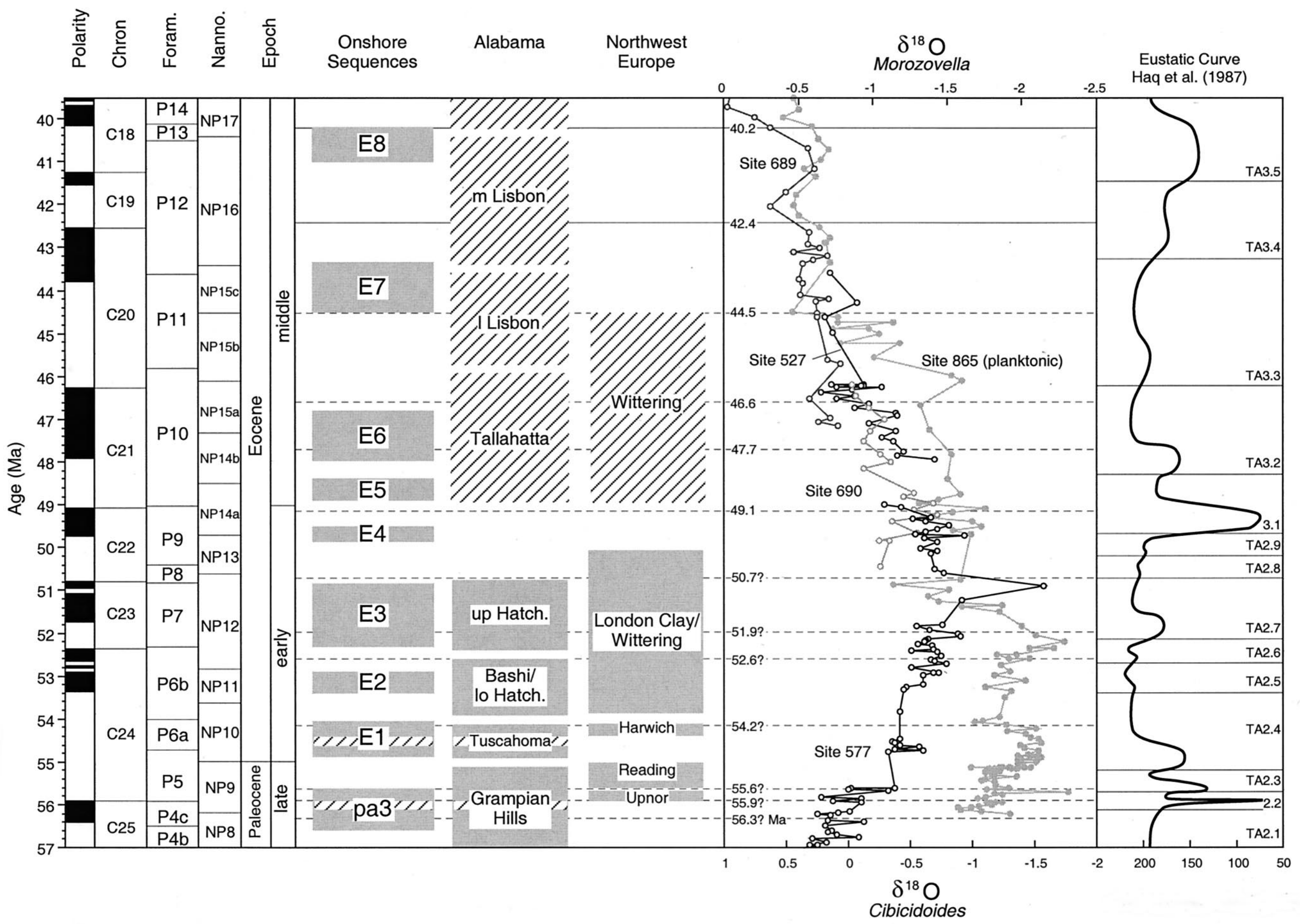

Figure 7b. Comparison of Eocene onshore sequences, Alabama [*Mancini and Tew*, 1995] and northwest European sequences [*Ali and Hailwood*, 1995], oxygen isotopes, and the inferred eustatic record of *Haq et al.* [1987]. Modified after *Browning et al.* [1996].

control [e.g., *Miall*, 1991]. In particular, *Christie-Blick et al.* [1990] questioned the global sea level records of *Vail et al.* [1977] and *Haq et al.* [1987] because (1) all sequence boundaries were assumed to be eustatic in origin, (2) identification and calibration of these boundaries to the timescale was not documented and thus not testable by others, and (3) the amplitudes were largely conjectural. Although the New Jersey record of eustatic falls is similar to that of *Haq et al.* [1987], two lines of evidence indicate that the amplitudes of their eustatic falls are generally too high. First, our backstripping results (see section 7) support lower amplitude changes than were reported by *Haq et al.* [1987]. Second, although oxygen isotopic records provide limited constraints on the amplitudes of late middle Eocene–Miocene glacioeustatic changes (see section 5.1), oxygen isotopes studies indicate that the *Haq et al.* [1987] estimates may be too high by a factor of 2 or more. As *Christie-Blick et al.* [1990, p. 135] previously concluded: "Apart from indicating the timing of global unconformities . . . the significance of [the *Haq et al.* [1987] curve] is unclear."

5. COMPARISONS WITH THE GLOBAL δ^{18}O RECORDS

5.1. Oxygen Isotopes as a Glacioeustatic Proxy

Deep-sea δ^{18}O records provide a proxy for ice volume and glacioeustatic changes during intervals with continental-scale ice sheets. Glaciomarine sediments near Antarctica and deep-sea oxygen isotopic records indicate that large ice sheets have existed in Antarctica since at least the late middle Eocene (~42 Ma; see summary by *Browning et al.* [1996]). Because ice preferentially sequesters light oxygen isotopes, fluctuations in ice volume cause changes in global seawater δ^{18}O (δ_W). These global δ_W changes are recorded by benthic and planktonic foraminifera along with variations in seawater temperature and local isotopic composition. *Miller et al.* [1991a] and *Wright and Miller* [1992] identified 12 Oligocene–Miocene global benthic foraminiferal δ^{18}O increases (all >0.5‰); these increases culminated in δ^{18}O maxima that were used to define zones Oi1 to Oi2b and Mi1 to Mi7 (Figures 4–8; Table 1). Subsequent studies have split the Mi3 increase (13.4–14 Ma; see Table 1)

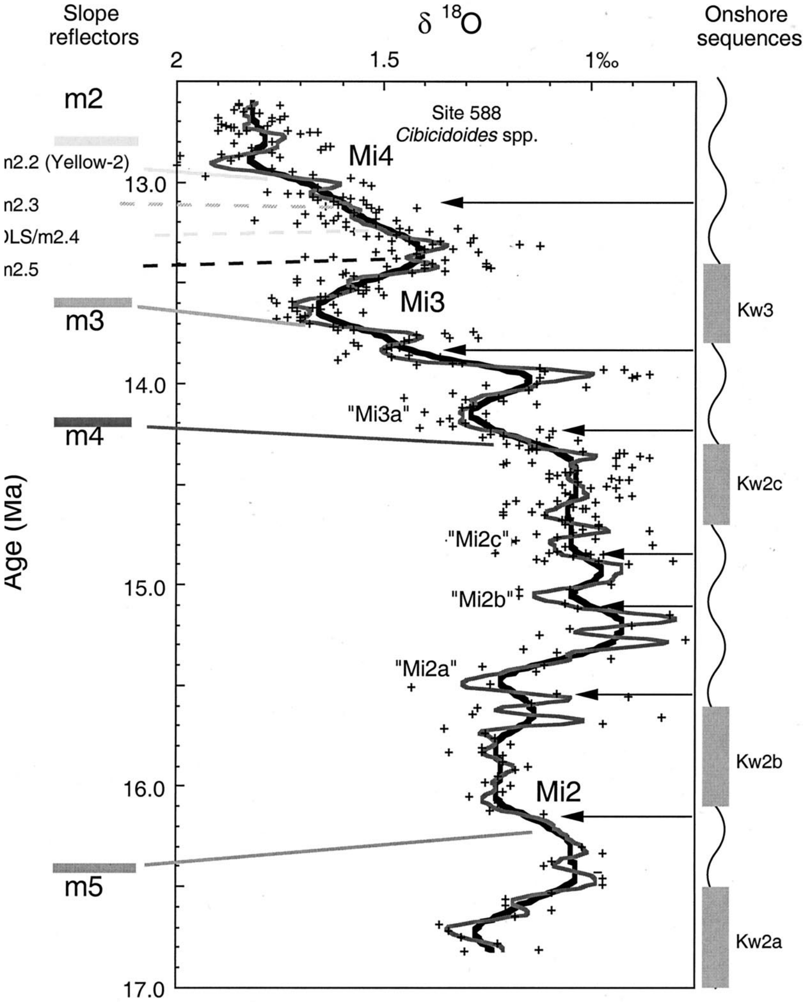

Figure 8. Comparison of a high-resolution stable isotopic record for the late early to early middle Miocene with slope reflections and onshore sequences. Isotopic data from Site 588 in the western Pacific were generated on the benthic foraminiferal genus *Cibiciodoides* with a an average sampling interval of 9.7 kyr (data after *Flower and Kennett* [1995]). Data were interpolated to a constant 12-kyr time step and smoothed using 11-point and 41-point Gaussian convolution filters which remove frequencies higher than 1/66 and 1/246 kyr, respectively. The age model was derived using the following parameters: highest occurrence of *Discoaster kugleri*; 250.4 m, 12.2 Ma; Mi4 isotopic maximum, 268.1 m, 12.9 Ma; Mi3 isotopic maximum, 280.11, 13.7 Ma; Mi2 isotopic maximum, 308.32 m, 16.06 Ma; and highest occurrence of *Catapsydrax dissimilis*, 320.0, 17.3 Ma. Isotopic levels were derived from correlation to the magnetostratigraphically dated Site 748 [*Wright and Miller*, 1992]. Note that three scales of isotopic (inferred eustatic) variability are represented in the data (pluses): (1) the 1 to 2-myr-scale events (Mi2, Mi3, Mi4) first recognized in the isotopic record by *Miller et al.* [1991a] and *Wright and Miller* [1992]; (2) a quasi-400-kyr period (black line) that allows recognition of additional isotopic events ("Mi2a" to "Mi3a"); (3) a quasi-100-kyr periodicity (gray line). DLS stands for downlap surface; it is unclear if m2.4 is a sequence boundary or DLS.

into two increases (Mi3a and Mi3b [*Miller et al.*, 1996c]) and recognized several smaller Miocene (Mi1aa? and Mi1ab? [*Miller et al.*, 1997b]) and Oligocene increases (Oi1a, Oi1b, unnamed [*Pekar and Miller* [1996] (Figure 4)). These increases provide a well-dated (resolution $<\pm 0.25$ myr) history of million-year-scale δ^{18}O increases during the Oligocene–Miocene (Table 1).

Although the timing of Oligocene–Miocene deep-sea δ^{18}O variations is well constrained by magnetostratigraphy, amplitudes of ice volume and glacioeustatic change reflected in δ^{18}O records are poorly known. The large (>0.5‰), rapid ($\ll 0.5$ myr) δ^{18}O variations used to define the major oxygen isotope zones of *Miller et al.* [1991a] must reflect some ice growth and decay, but the relative role of ice versus temperature is not known. Comparisons of benthic and low-latitude (nonupwelling) planktonic foraminiferal δ^{18}O records can be used to isolate ice volume effects from local isotopic and temperature changes [*Shackleton and Opdyke*, 1973], although evidence for tropical cooling during glacial periods complicates this interpretation [e.g., *Guilderson et al.*, 1994]. Although tropical and subtropical sea surface temperature undoubtedly varied during the interval examined here, we regard synchronous increases in both deep-sea benthic foraminifera and low-latitude, surface-dwelling planktonic foraminifera as the best indicator of global changes in δ_W due to ice volume variations. Six of the Oligocene–Miocene benthic foraminiferal δ^{18}O increases are also recorded by tropical or subtropical planktonic foraminifera; others lack suitable low-latitude isotopic records [*Miller et al.*, 1991a]. Using the Pleistocene δ^{18}O–sea level calibration (0.11‰/10 m [*Fairbanks and Matthews*, 1978]), these coeval increases in benthic and planktonic δ^{18}O records of 0.3–0.9‰ were interpreted as the consequence of ~30 to 80-m glacioeustatic lowerings [*Miller et al.*, 1991a]. We assume that all of the Oligocene–Miocene δ^{18}O increases (Figures 7a and 8) reflect million-year-scale increases in ice volume, although additional low-latitude planktonic foraminiferal δ^{18}O data are needed to confirm this.

Eocene δ^{18}O increases are not as well documented as the younger record, and the importance of ice sheets in this interval remains debatable. *Browning et al.* [1996] identified synchronous increases in low-latitude, surface-dwelling planktonic and benthic δ^{18}O records at 40.2 and 42.4 Ma (Figure 7b, Table 1) and interpreted these increases as reflecting global δ_W changes due to ice growth and attendant glacioeustatic lowerings of 20–30

m. Examination of the Eocene benthic and planktonic foraminiferal $\delta^{18}O$ record (Figure 7b) synthesized by *Browning et al*. [1996] indicates other increases at ca. 34.2, 44.5, 46.6, 47.7, 49.1, 50.7?, 51.9?, 52.6?, 54.2?, 55.6?, 55.9?, and 56.3? Ma (Figures 7a and 7b; Table 1). The 46.6, 47.7, and 49.1 Ma increases (Figure 7b) are part of a general (several million years) benthic foraminiferal $\delta^{18}O$ increase in the early middle Eocene that has been known for some time from sites throughout the deep ocean [*Shackleton et al*., 1984; *Kennett and Stott*, 1991; *Miller*, 1992]. The significance of the other $\delta^{18}O$ events is not known (Figure 7b). The 44.5 Ma increase is recognized only in the low-latitude planktonic $\delta^{18}O$ record from Site 865 (generated on surface dwelling *Morozovella* spp. [*Bralower et al*., 1995]); benthic $\delta^{18}O$ records from this interval are sparsely sampled. The 50.7 Ma increase is recognized only in the Site 577 Pacific benthic record [*Pak and Miller*, 1992]. The 51.9 Ma increase appears as a low-amplitude (~0.3‰) event in both the Site 577 and Site 865 $\delta^{18}O$ records and is interpreted as resulting from a minor glaciation. The 52.6, 55.6, 55.9, and 56.3 Ma events are very minor $\delta^{18}O$ increases in the Site 577 record. These uncertainties underscore that we are not certain that early–early middle Eocene $\delta^{18}O$ increases were due to global δ_w changes, nor are we convinced that there were large continental ice sheets prior to 42 Ma. Still, it is interesting to compare our margin records with $\delta^{18}O$ variations for this warm, though possibly not ice-free, world.

5.2. Comparisons of Oxygen Isotopes and New Jersey Sequence Boundaries

Inflections in the benthic foraminiferal $\delta^{18}O$ records (= inferred glacioeustatic lowerings) are associated with Oligocene to middle Miocene hiatuses and coastal plain sequence boundaries (Figure 7a). Hiatuses and sequence boundaries at the bases of 15 onshore sequences correlate with 15 $\delta^{18}O$ increases. All 17 latest Eocene–middle Miocene onshore sequence boundaries have corresponding $\delta^{18}O$ increases except for O4 and Kw2c, and every $\delta^{18}O$ increase is associated with a hiatus (Figure 7a; Table 1). We are uncertain about the significance of the Kw2c sequence boundary because this surface has been recovered at only one borehole (Cape May). The age of the Kw-Cohansey sequence may overlap with the $\delta^{18}O$ increase associated with Mi5. However, the age of this sequence is poorly constrained by Sr isotopic stratigraphy, and dinocysts indicate that this sequence is older than Mi5 [*de Verteuil*, 1997].

Miocene slope reflections also correlate with $\delta^{18}O$ increases, with seven reflections (o1 through m1) corresponding to seven increases (Oi1 through Mi5) within our resolution (approximately ±0.5 myr (Figure 7a; Table 1)). Of the Miocene $\delta^{18}O$ increases, only Mi1aa?, a minor and poorly defined increase, fails to have an equivalent reflection. (Oligocene seismic resolution is limited by the thin section and concatenated reflections on the slope.) This suggests a causal link between sequence boundaries traced from the shelf and glacioeustatic changes.

Comparing onshore and offshore sequences with $\delta^{18}O$ records (Figure 7a) fulfills our second expectation of unconformities formed by glacioeustatic lowerings: the hiatuses/sequence boundaries correlate with $\delta^{18}O$ increases. Nevertheless, because there are uncertainties in the ages of the hiatuses/sequence boundaries, our age comparisons (Figure 7a) do not require a causal relationship, although the similar number and ages of events onshore, offshore, and in the $\delta^{18}O$ records argue strongly for a link.

We provide preliminary direct evidence for a causal link between $\delta^{18}O$ increases (inferred glacioeustatic falls) and sequence boundaries (reflections on the slope traced to sequence boundaries on the shelf) by measuring benthic foraminiferal (*Cibicidoides*) $\delta^{18}O$ data from slope Site 904 (Figure 5). Most previous studies of passive margin (versus typical deep-sea) locations have been ambiguous owing to diagenesis, hiatuses, and local temperature and salinity effects in the shelf environment. We focused $\delta^{18}O$ studies on Site 904 for several reasons: (1) it has a shallow burial depth (<350 m) with no evidence of diagenesis, (2) the lower–middle Miocene section is reasonably complete, and (3) although it is on the slope, it is currently in a deep-water oceanic setting with minimal variations in bottom water salinity and temperature (Figure 5). Our studies are preliminary because sampling at Site 904 is not sufficient to resolve unequivocally the Mi (Miocene isotope) events.

Comparison between the measured $\delta^{18}O$ record (Figure 5, right panel) and sequence boundaries/reflections (horizontal lines in Figure 5) at Site 904 demonstrates that the m2, m3, ?m5, ?m5.6, and m6 reflections apparently coincide with the Mi4, Mi3, Mi2, Mi1a, and Mi1 $\delta^{18}O$ increases, respectively, measured at this site. These correlations between reflectors and $\delta^{18}O$ increases are independent of age control and age uncertainties. This establishes a first-order link between sequence boundaries and $\delta^{18}O$ increases (= glacioeustatic lowerings); it potentially provides prima facie evidence for a causal link between $\delta^{18}O$ increases (inferred glacioeustatic falls) and sequence boundaries (reflections and core disconformities on the slope). However, additional $\delta^{18}O$ data from Site 904 are needed to improve the resolution of the Mi events (Figure 3) in order to substantiate this causal link.

Eocene comparisons of onshore hiatuses/sequence boundaries and $\delta^{18}O$ (Figure 7b) are surprising because they hint at a glacioeustatic record that extends back through the supposedly ice-free "greenhouse" early Eocene. Late middle to late Eocene comparisons show that $\delta^{18}O$ increases are associated with the hiatuses at the base of E8, E9, and E11, consistent with a glacioeustatic cause as suggested by *Browning et al*. [1996]. There is no $\delta^{18}O$ increase associated with E10, although isotopic records for this earliest late Eocene interval are poorly sampled. However, our comparisons show that hiatuses

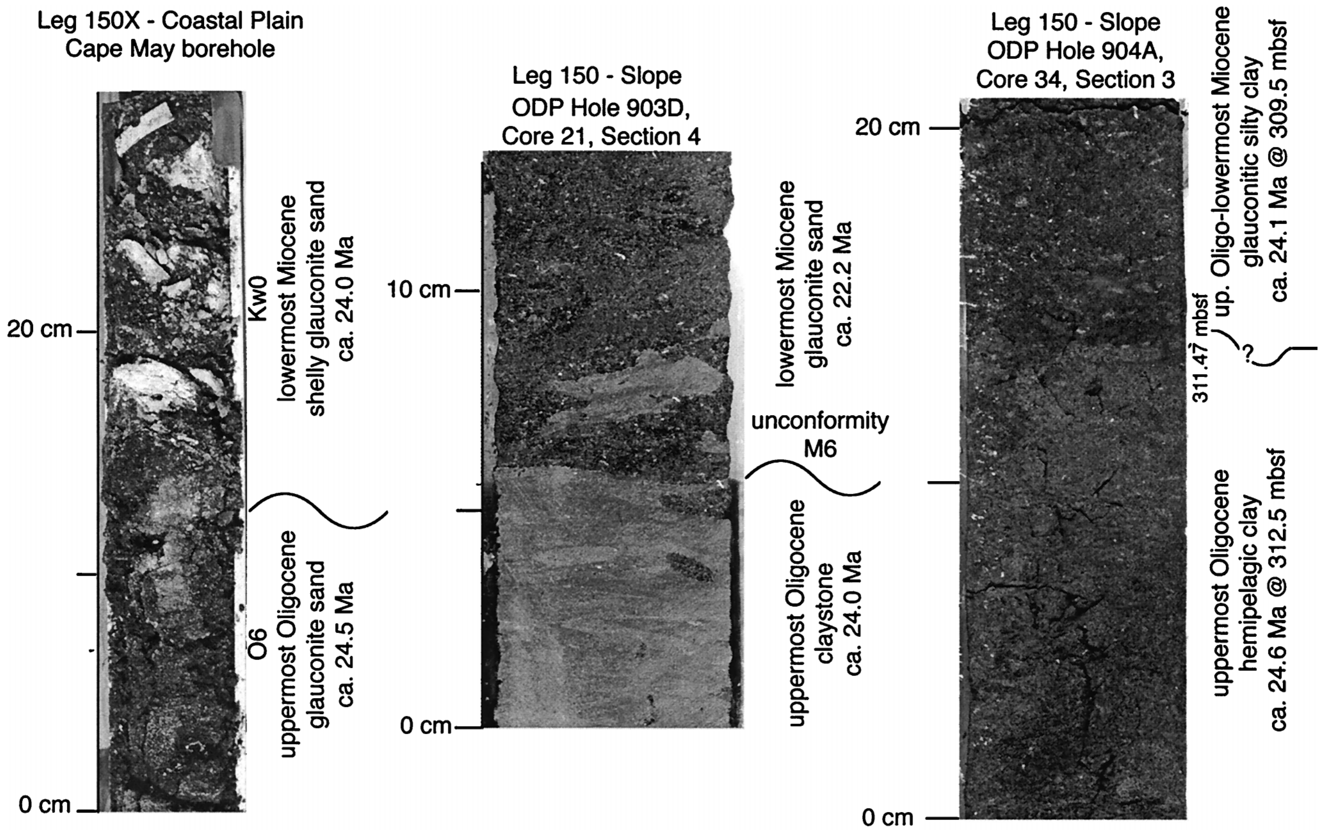

Figure 9. Comparison of correlative sequence boundaries onshore (base Kw1a) and offshore (m6 equivalent).

and sequence boundaries at the bases of E7 through E1 are correlated with possible δ^{18}O increases (Figure 7b). Only the hiatus/sequence boundary at the base of E6 is slightly mismatched with the δ^{18}O, and one possible δ^{18}O increase (?51.9 Ma) appears to be associated with continuous deposition (Figure 7b). We caution that we have not demonstrated that early–early middle Eocene δ^{18}O increases are global, as they must be if caused in part by glacioeustasy. In addition, the amplitude of the increases is generally small (0.2–0.3‰). Using the Pleistocene δ^{18}O–sea level calibration (0.11‰/10 m, [*Fairbanks and Matthews*, 1978]), these increases correspond to 18–27 m sea level equivalent if ascribed entirely to ice volume and 12–18 m if partitioned into ice and temperature as in the late Pleistocene (i.e., 67% due to ice [*Fairbanks*, 1989]). We conclude that there is limited evidence for growth and decay of small ice sheets during a time previously thought to be ice-free and that these ice volume changes caused small (<20 m) glacioeustatic variations.

We have focused our comparisons of sequences and δ^{18}O on the million year scale, where the δ^{18}O variations average 1.2 myr between maxima but exhibit no clear periodicity. These 1- to 2-myr-scale events in the δ^{18}O record reflect composites of many *Milankovitch*-scale (10^4- to 10^5-year scale), astronomically modulated climate cycles that yield long-term increases [*Zachos et al.*, 1994]. This is illustrated by a moderately high resolution (~10 kyr sampling [*Flower and Kennett*, 1995]) δ^{18}O record (Figure 8) that shows that the major million-year-scale slope reflections (m2 through m5) correlate with major δ^{18}O increases, although there is higher-order variability contained in both records. Further study of New Jersey sections may continue to detect additional, smaller-scale sequences, such as some of those found onshore and offshore (see section 9).

6. INTRASEQUENCE FACIES CHANGES

EPR and others have provided lithofacies models that try to predict lithologic and environmental patterns within sequences. In particular, the EPR systems tracts (the so-called “slug” model of *Posamentier et al.* [1988]) have explained such within-sequence lithofacies changes in terms of those formed during eustatic lowerings (*lowstand systems tracts*, or LST), during the most rapid rises of sea level (*Transgressive Systems Tracts*, TST), and during late stages of rise and early falls (*Highstand Systems Tracts*, HST). Our studies address the edges of the slug model by sampling sequences updip in the coastal plain and downdip in the continental slope. Seismic profiles (Figures 2 and 3) allow us to trace sequence boundaries from the coastal plain to the slope (Figure 9), but provide no definitive lithofacies information for the intervening shelf. We find a strongly predictive and

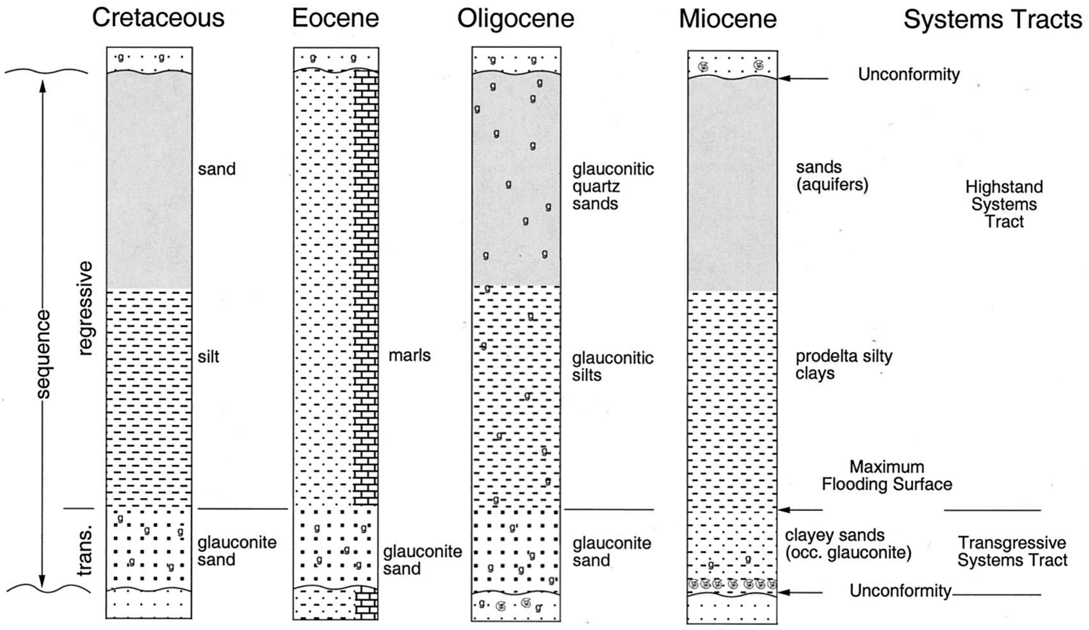

Figure 10. Anatomy of New Jersey onshore sequence. Generalized models of New Jersey sequences showing the upsection shallowing common to different facies successions of the Cretaceous, Eocene, Oligocene, and Miocene. The equivalent systems tracts of *Posamentier et al.* [1988] are shown on the right. Glauconite in the Oligocene HST is reworked. Abbreviations are trans., transgressive; occ., occasional. After *Miller et al.* [1997b].

repetitive lithofacies pattern in the coastal plain but subdued cyclicity on the slope.

6.1. Coastal Plain Lithofacies

Lithofacies changes within onshore sequences follow repetitive transgressive-regressive patterns that were recognized in the New Jersey coastal plain long before EPR published their syntheses [*Owens and Sohl*, 1969; *Owens and Gohn*, 1985]. An idealized onshore sequence consists of a basal transgressive *glauconite* sand (Figure 9) overlain by a coarsening upward succession of regressive medial silts and upper quartz sands (Figure 10) [*Owens and Sohl*, 1969]. The basal glauconite sand (the condensed section of *Loutit et al.* [1988]) is equivalent to the TST of *Posamentier et al.* [1988]. The overlying medial silt is equivalent to the lower HST, whereas the upper quartz sands represent the upper HST [*Sugarman et al.*, 1993]. Lowstand systems tracts (LSTs) have not been identified in the coastal plain, and the TSTs are generally thin.

Because the TSTs are thin, *maximum flooding surfaces* (MFS) are difficult to differentiate from unconformities. Both can be marked by shell beds. Gamma ray peaks also can be associated with sequence boundaries (Figure 11) and MFSs [e.g., *Loutit et al.*, 1988]. Flooding surfaces, particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up clasts at the latter, lithofacies successions, and benthic foraminiferal changes. For example, MFSs are commonly marked by high organic carbon and associated peak abundances of *Uvigerina* [e.g., *Loutit et al.*, 1988], benthic foraminiferal abundance maxima [e.g., *Pekar et al.*, 1997], and changes from deepening upward to shallowing upward biofacies successions. Onshore lithofacies successions vary somewhat from the Cretaceous to Miocene (Figure 10), reflecting differences in paleodepth, provenance, and preservation.

Miocene sequences generally consist of thin basal units of shelly, quartz sands deposited in neritic environments (glauconite is usually absent), medial silty clays deposited in prodelta environments, and upper quartz sands deposited in nearshore and delta front environments. Because the basal sands are thin or absent, the silty clays and thick sands commonly stack together as a series of coarsening and shallowing upward successions. Facies patterns within Miocene coastal plain sequences Kw1a and Kw1b illustrate updip-downdip and along-strike variations resulting from interfingering of marine, transitional marine, and deltaic environments (Figure 11). Sequences tend to thin updip, although they may thicken along strike. For example, the Kw1a sequence thins updip between Cape May and Atlantic City; however, this sequence thickens toward Island Beach, a site that projects updip of Cape May and Atlantic City, as a result of an along-strike change toward the deltaic source (Figure 11, top). Highstand deposits generally become progressively coarser and shallower updip (e.g., the Kw1b between Cape May and Atlantic City), although the Kw1b highstand is finer grained at Atlantic City than at Cape May because of the juxtaposition of prodelta–delta front versus neritic-nearshore environments (Figure 11). The strike section (Figure 11, bot-

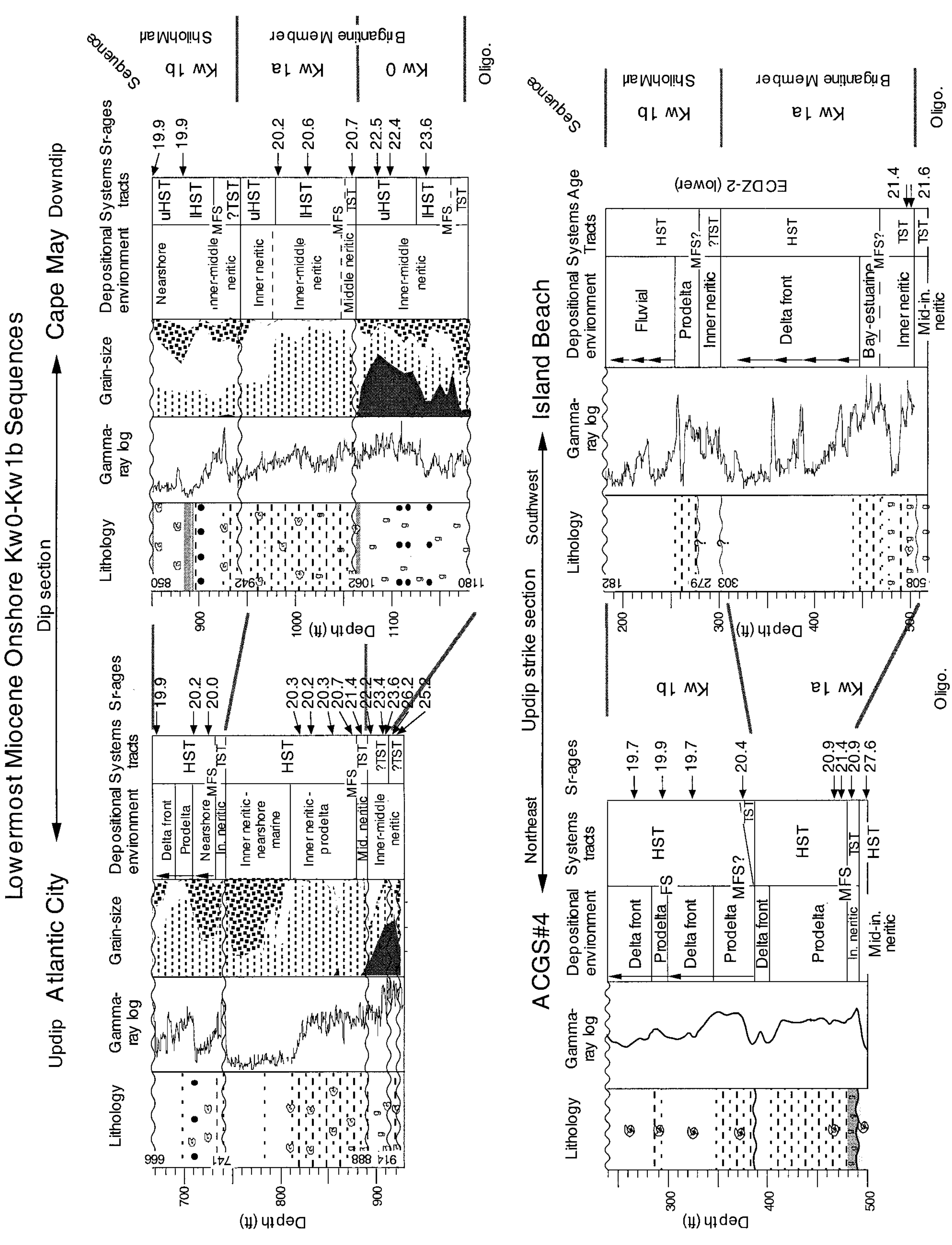

Figure 11. Example of Kw1a sequence at four coastal plain boreholes.

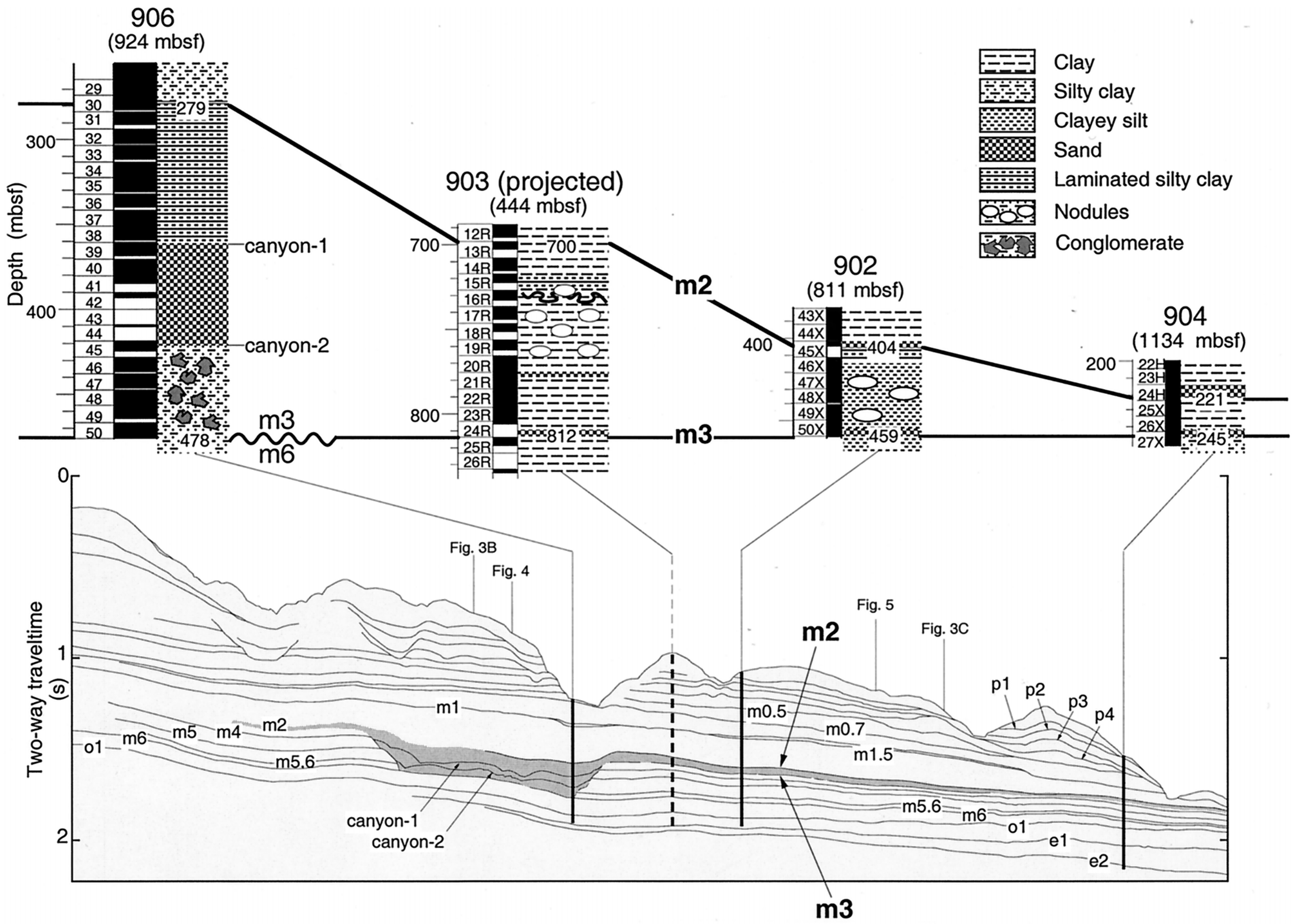

Figure 12. Anatomy of slope sequence m2 to m3 (12.5–13.5 Ma). After *Mountain et al.* [1996a].

tom) shows that the depocenter shifted from near Island Beach during Kw1a to near ACGS#4 during Kw1b. We observe small-scale *parasequences* (shoaling upward successions bounded by flooding surfaces [*Van Wagoner et al.*, 1988]) within several sequences (e.g., within the Kw1b sequence, at Atlantic City, Island Beach, and ACGS#4; within Kw1a at Island Beach (Figure 11)).

Oligocene lithofacies variations within sequences are similar to those of the Miocene (Figure 10) but differ because they represent deeper-water shelf (inner to outer neritic) environments. In situ authigenic glauconite typifies Oligocene transgressive deposits as it does in older sequences. However, recycled glauconite is abundant in Oligocene highstand deposits, unlike older or younger deposits. This juxtaposition of glauconite transgressive with glauconite (reworked) highstand deposits can mask Oligocene facies successions [*Pekar and Miller*, 1996; *Pekar et al.*, 1997].

The expression of Eocene onshore sequences (Figure 10) is muted, reflecting deposition in the deepest shelf paleodepths of Cenozoic onshore strata (middle to outer neritic) [*Olsson and Wise*, 1987; *Browning et al.*, 1997a, b]. Eocene sequences contain a thin basal glauconitic clay or clayey sand overlain by carbonate-rich foraminiferal/radiolarian clay. Benthic foraminifera indicate that maximum water depths (MFSs) were attained at the top of the glauconite sands, and the sections shallow upsection above MFSs in otherwise homogeneous carbonate clays.

Paleocene to Cretaceous sequences show distinct upsection successions from basal glauconite, medial silts, and upper sands [*Sugarman et al.*, 1995]. Leg 150X recovered little Paleocene–Upper Cretaceous sediment, although continuing onshore drilling at Bass River, Ancora, and Corson's Inlet/Ocean City (Figure 1) will provide detailed information on sequences of this age.

6.2. Slope Lithofacies

Lithofacies variations within slope sequences are subdued at the sites drilled by Leg 150 (Figure 1), in part because Sites 902–904 were intentionally located away from modern and ancient submarine canyons [*Mountain et al.*, 1994]. Oligocene and Miocene sediments at these sites consist primarily of silty clays and clayey silts that were deposited primarily by *hemipelagic* settling (Figure 12). The sand content is generally low (<10%, rarely exceeds 50%), and is largely glauconite at levels below reflection m3 (~13.6 Ma). Above reflection m3, quartz becomes the dominant sand-sized component, although glauconite is present [*Mountain et al.*, 1994]. In the intercanyon regions, sequences generally thin from the upper slope (Site 903) to the middle slope (Site 904 (Figure 12)), although sequences can thicken dramatically when traced into canyon *thalwegs* (e.g., Site 906 (Figure 12)). Lithofacies successions associated with sequence boundaries generally consist of basal sands or sandy silts (Figures 9 and 12); indurated zones (typically less than 1 m thick) and/or disturbed mass flow deposits commonly occur immediately above and/or below the sequence boundary, grading upward to massive mudstones. We suggest that the basal strata are lowstand deposits, representing the basinal equivalent of the LST. Strong, mappable reflections correlate to these basal sediments and appear with available seismic data to correlate to sequence boundaries on the adjacent shelf that are recognized on the basis of stratal geometry [*Greenlee and Moore*, 1988; *Greenlee et al*., 1992; *Mountain et al*., 1994]. Sediments at the base of slope sequences commonly contain transported shelf taxa (*Buliminella gracilis* and *Nonionella pizarrensis* [*Katz and Miller*, 1996]), suggesting that these surfaces formed during sea level lowstands.

Analysis of seismic and sedimentological data from the sequence resting on m3 (13.6 Ma) shows that a tripartite subdivision of this sequence can be traced across the upper to middle slope [*Mountain et al*., 1996a] (Figure 12). Site 906 was drilled in a Miocene canyon thalweg associated with reflection m3. It contains (Figure 12) (1) basal conglomeratic debris shed from the canyon walls, (2) medial turbidite sands that bypassed adjacent intercanyon regions, and (3) a cap of hemipelagic laminated silty clays deposited during the eventual burial of the canyon, presumably after the source of the turbidite sands had abated [*Mountain et al*., 1994, 1996a]. A threefold subdivision of the sequence overlying reflection m3 appears applicable outside of canyon area; at Site 902 and 903, basal sandy beds are overlain by medial nodule-rich silty clay and an upper laminated silty clay to clay (e.g., Figure 12). The nodules represent pelagic Miocene carbonate that has been mobilized into diagenetic precipitates and probably represent the greatest pelagic influence. The sequence thins and the diagenetic nodules largely disappear as they are traced to middle slope Site 904, where only a basal sandy bed and upper clay unit can be recognized. The generally homogeneous slope sediments cannot be readily subdivided further using lithologic or faunal criteria.

In summary, heterogeneity of reworked sediments constituting the lowstand deposits generally leads to the strongest, most regionally extensive reflections on the slope. Drilling on the New Jersey slope recovered mostly in situ material dominated by hemipelagic settling because it focused on intercanyon areas; incised slope canyons contain significant amounts of transported shallow-water sediment that are not found on the adjacent intercanyon regions. Clearly, a lithofacies model that completely describes the full range of slope sedimentation must acknowledge the full complexity of slope processes in both intercanyon and canyon regions.

7. BACKSTRIPPING: ESTIMATING EUSTATIC AMPLITUDES FROM COASTAL PLAIN BOREHOLES

Although we have established the timing of Eocene to Miocene sequences (Figs. 4–7b), we are only beginning to extract sea level amplitudes using one-dimensional inverse models termed *backstripping* [*Watts and Steckler*, 1979; *Bond and Kominz*, 1984; *Bond et al*., 1989]. Backstripping removes the effect of sediment loading from observed basin subsidence. By assuming thermal subsidence on a passive margin, the tectonic portion of subsidence is removed and a eustatic estimate is obtained. Kominz et al. [1998] estimated eustatic amplitudes by backstripping the Island Beach, Atlantic City, and Cape May boreholes. Although these onshore sites provide a relatively complete record of deposition (Figure 4), they provide only a partial sea level history because of regional downward shifts in onlap at sequence boundaries (i.e., the full amplitude of sea level lowering may not be recorded). Nevertheless, backstripping results are consistent for the Island Beach, Atlantic City, and Cape May boreholes (Figure 13), indicating (1) a long-term (10^8–10^7 years) eustatic fall of ~100–150 m since 55 Ma (early Eocene), which is consistent with best estimates from ridge-volume changes but is considerably lower than the long-term estimate used by EPR, and (2) short-term eustatic amplitudes that are about one half of EPR's estimates [*Haq et al*., 1987].

The first step in backstripping is to remove the effects of compaction, loading, and water depth from total subsidence; we assume an Airy isostatic response to loading. The resulting R1 subsidence (first reduction of *Bond et al*. [1989]) curves provide an estimate of *accommodation* that includes the effects of both tectonics and eustasy (see *Kominz et al*. [1998] for a display of the R1 curves for the onshore sites). The second step removes theoretical tectonic subsidence. The resulting R2 (second reduction of *Bond et al*. [1989]) curves provide eustatic estimates. Because subsidence recorded in the coastal plain is due primarily to a flexural effect linked to sediment loading and thermal subsidence offshore [*Watts*, 1981], the form of subsidence is that of a thermally subsiding basin. Best fit thermal subsidence curves for the onshore sites were calculated by first fitting an exponential curve with a decay constant of 36 myr and assuming breakup age of 150 Ma. R2 curves are reduced for water loading, under the assumption (not necessarily correct) that it is representative of eustatic change. The curves are plotted with modern sea level set at 0 m (Figure 13).

Backstripping documents that active tectonics (e.g., faulting, salt movement) played a minor role on the New Jersey margin in the Cenozoic and that subsidence was controlled primarily by simple lithospheric cooling, com-

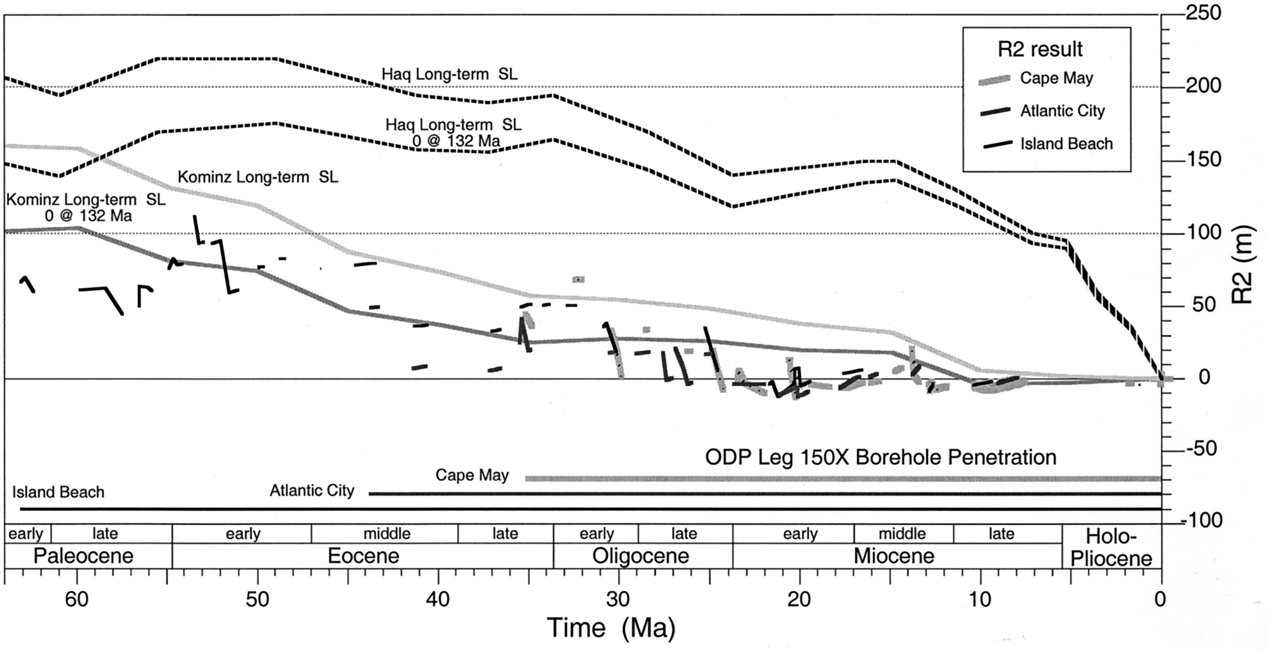

Figure 13. "Eustatic" record derived from onshore backstripping. Shown are the Cenozoic portion of R2 curves (second reduction) generated from coastal plain borehole data. R2 curves are constrained to zero at present (0 Ma). Also plotted are the long-term sea level curves of *Haq et al.* [1987] and *Kominz* [1984]. These curves are also plotted with an adjustment for the maximum long-term sea level change that can be observed at the boreholes. All data are plotted using the *Berggren et al.* [1995] timescale. After *Kominz et al.* [1998].

paction, and loading. The long- and short-term amplitudes of the R2 curves are similar for sequences that are represented in all three boreholes (Figure 13). This suggests that dating, paleoenvironment, and backstripping assumptions are consistent and that we have successfully isolated the preserved eustatic signal.

The long-term eustatic (R2) estimates from the coastal plain (Figure 13) are similar to *tectonoeustatic* estimates derived from changes in ridge volume [*Kominz*, 1984] but are substantially lower than the long-term sea level estimates used by *Haq et al.* [1987] (their first-order cycle). Because the R1 curves begin at about 130 Ma (i.e., the time of initial deposition in the coastal plain), the maximum long-term sea level change that can be obtained from this analysis must return to zero sea level change at about 130 Ma. Thus we reset both the *Kominz* [1984] and *Haq et al.* [1987] long-term eustatic curves to 0 m at 132 Ma for comparison with the backstripping results (Figure 13). The long-term eustatic pattern derived from the coastal plain is virtually identical to the adjusted record derived from changes in ridge volume but is clearly lower than the *Haq et al.*'s [1987] curve (Figure 13). We conclude that the New Jersey estimates support ridge-volume eustatic estimates that show a long-term lowering of 150–200 m since 65 Ma (Figure 13).

As was noted above, the short-term (0.5 to 3 myr scale) amplitudes of the R2 curves (third-order cycles of *Haq et al.* [1987]) cannot be fully constrained onshore because only the transgressive and highstand portions of sequences are generally preserved in the coastal plain. Maximum variation in R2 of the onshore sequences is as much as 40 m but is generally less than 20 m. Although the full short-term eustatic amplitudes are not recorded in the coastal plain, amplitudes are 20–30 m in the most complete Miocene sequences. Within individual sequences, R2 variations of 15–30 m are seen at about 20–22 Ma. In this interval, any hiatuses are within the detection limit of our dating methods. In this case, we suggest that the R2 amplitudes may approximate eustatic change; even assuming that the absent lowstand deposits represented 50% of the eustatic cycle, amplitudes would still be less than 60 m.

Our short-term amplitude changes are similar to estimates derived from $\delta^{18}O$ records but are significantly lower than those of *Haq et al.* [1987]. Estimates from $\delta^{18}O$ records range from <20 m for the early Eocene to 30–80 m for the late middle Eocene to middle Miocene [*Miller et al.*, 1991a; *Wright and Miller*, 1992; *Browning et al.*, 1996]. In cases where the onshore sequences are most complete (e.g., circa 20 Ma (Fig. 13), the R2 fall is 15–30 m, in contrast to ~60 m for the correlative falls of *Haq et al.* [1987]. We conclude that short-term amplitudes are still poorly known, although they generally appear to be ≪100 m based on backstripping (Figure 13) and stable isotopic estimates [*Miller et al.*, 1991a; *Wright and Miller*, 1992; *Browning et al.*, 1996] versus the generally greater than 50 to 100-m variations estimated by EPR [*Haq et al.*, 1987].

8. CENOZOIC EVOLUTION OF THE NEW JERSEY MARGIN: GLOBAL SEA LEVEL, TECTONICS, AND CHANGES IN SEDIMENT SUPPLY

Our results onshore and offshore document that the New Jersey margin is an ideal place to evaluate the timing of Cenozoic eustatic changes. Initial drilling both onshore and offshore (DSDP Leg 95 [*Poag et al*., 1987]) suggested that New Jersey sections represent more stratigraphic gap than record. By strategically locating continuously cored boreholes, we were able to obtain a more complete and detailed record and to assemble a mosaic of sequences for the entire Paleocene to middle Miocene (Figures 4 and 7). It is quite clear from the evidence presented here that eustasy was a primary control on the timing of sequence boundaries and the development of shallowing-upward successions. Although our backstripping shows no evidence of active tectonics (e.g., faulting, salt movement), it is also clear that minor tectonic events and major changes in sediment supply molded the margin, resulting in distinct sedimentation patterns.

Our results from the onshore boreholes yield interesting glimpses of the influence of basinal tectonics. Regional and local tectonics resulted in differential preservation of sequences in the Mid-Atlantic region (Figure 1). For example, lower Miocene marine sequences are well represented in the New Jersey coastal plain, but are less complete in the Maryland coastal plain, whereas the inverse is true for upper Miocene marine sequences [*Miller and Sugarman*, 1995]. *Owens et al*. [1997] termed such progressive shifts in basin depocenters the "rolling basin" concept, although the tectonic mechanism responsible for this differential subsidence pattern has not been established. *Brown et al*. [1972] suggested that faulting of crustal blocks controlled subsidence of the Mid-Atlantic coastal plain, whereas *Benson* [1994] ascribed a large (250 m) change water depth in the Oligocene section of Delaware to a combination of eustatic change and faulting. Our backstripping results are not consistent with major (100-m scale) active subsidence/uplift of crustal blocks as a means of explaining differential subsidence within this basin. We observe differential subsidence of the order of tens of meters; such differences may be related to migration of sediment supply [*Miller and Sugarman*, 1995] or minor variations in lithospheric stress [e.g., *Karner et al*., 1993].

Differences in the distribution of Oligocene versus Miocene strata in the New Jersey coastal plain provide clues about the mechanism causing differential subsidence and preservation. In general, Miocene downdip sections in the New Jersey coastal plain are stratigraphically more complete than updip sections, reflecting a simple hinged margin with increased subsidence downdip (Figure 4). In contrast, Oligocene sequences have a patchy distribution (Figure 4): lower Oligocene sequences are better preserved updip at Island Beach, whereas middle Oligocene sequences are better preserved at Atlantic City than they are downdip at Cape May. These differences result from differential subsidence and/or erosion of the order of tens of meters and probably reflect migration of sediment supply and/or depocenters.

The evolution of the New Jersey margin also records changes in global/regional climate and sediment supply (Figure 14). The early to middle Eocene on the New Jersey margin was strongly influenced by pelagic carbonate deposition, minimal *siliciclastic* input, warm paleoclimates, and a gentle ramp-shaped physiography. A switch from pelagic carbonate to siliciclastic sedimentation occurred in two steps: carbonate production shut down onshore in the late middle Eocene [*Browning et al*., 1996]; on the slope, carbonate production declined in the earliest Oligocene [*Miller et al*., 1996b] (Figure 14)]. Both of these events correlate with major global δ^{18}O increases (Figure 14). Regional climate also cooled dramatically in the late middle Eocene and earliest Oligocene in response to global climate changes that accompanied the growth of an Antarctic ice sheet. Cooler surface water temperatures may have inhibited carbonate production, particularly on the wide ramp of the continental shelf. The change from carbonate ramp to siliciclastic shelf occurred not only in New Jersey but also on margins throughout the Atlantic at about this time [*Steckler et al*., 1995], implicating a global process such as climate cooling.

The early to middle Oligocene was characterized by slow (<20 m myr^{-1}), glauconite-rich sedimentation in the onshore boreholes. The entire New Jersey margin was sediment starved not only of siliciclastic input but also of pelagic carbonate throughout this interval, contributing to the poor representation of strata of this age both onshore and on the slope (the "cryptic lower Oligocene" [*Miller et al*., 1996b]).

Sedimentation on the margin changed in the late Oligocene to early Miocene as sedimentation rates increased and thick prograding sequences developed. Sedimentation rates increased onshore to $\sim$40 m myr^{-1} during the late Oligocene ($\sim$27–25 Ma (Figure 14)), and medium-coarse quartz sand appeared as an important constituent in the onshore boreholes. This increase in siliciclastic input clearly marks the beginning of increased sediment input from the hinterland. By 21 Ma, deltaic sedimentation dominated at all three onshore sites, and sedimentation rates at these sites reached their Cenozoic maximum of over 40 m myr^{-1} (Figure 14). This early Miocene event marks a fundamental change in depositional regime, with a change from glauconite-dominated shelfal deposition to a quartz sand- and silt-dominated deltaic deposition. High sedimentation rates and widespread deposition in the early Miocene resulted in thick onshore sequences.

Offshore, the increased supply of sediments resulted in the development of thick (hundreds of meters) prograding sequences. These sequences prograded across what is now the New Jersey inner continental shelf

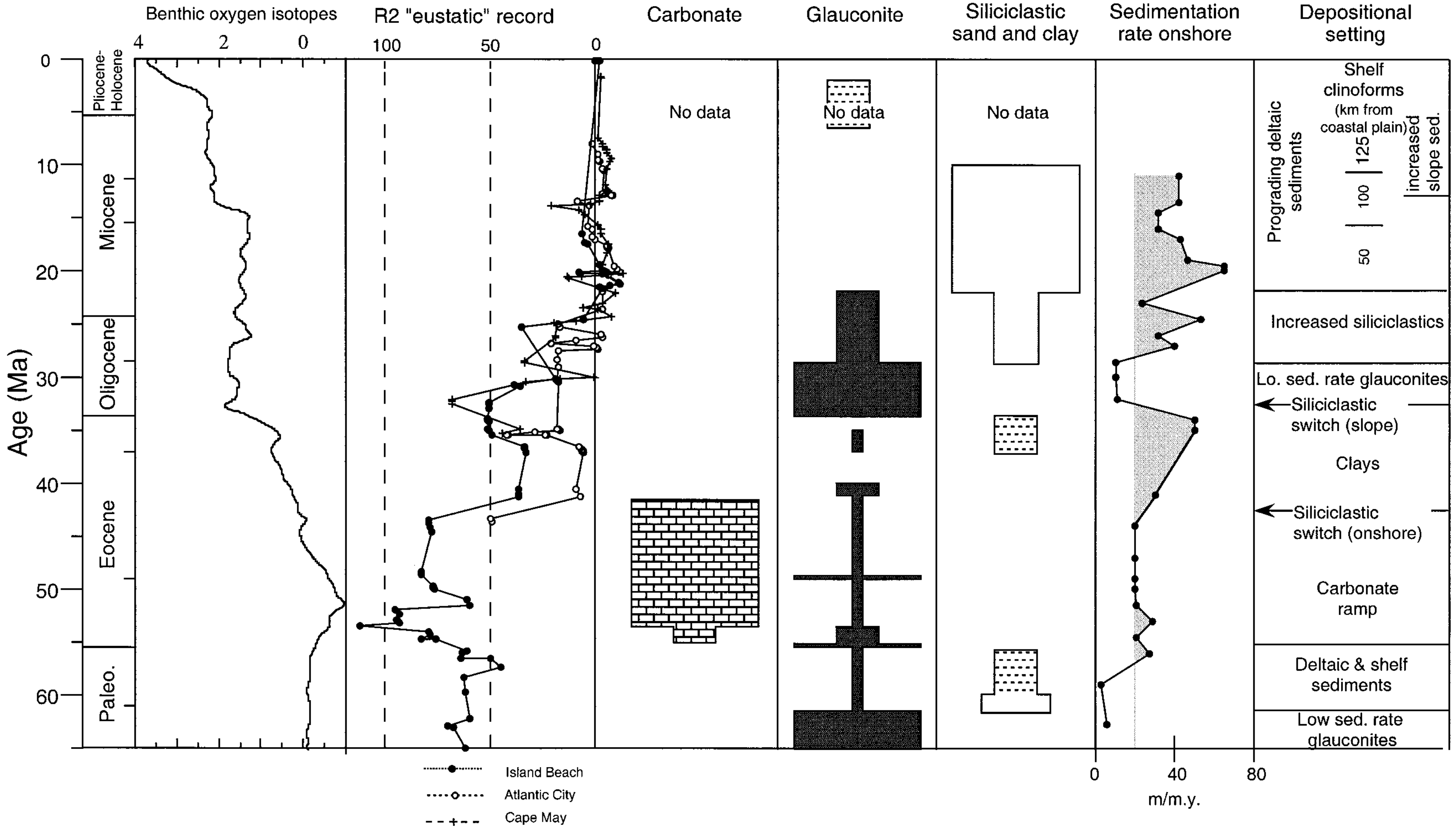

Figure 14. Cenozoic evolution of the New Jersey margin. Composite diagram shows changes in the Atlantic benthic foraminiferal $\delta^{18}O$ records, estimated eustatic changes (R2), major sediment components, sedimentation (sed.) rates, and general depositional setting of the New Jersey coastal plain. Changes in depositional setting include generalizations for the coastal plain, distance offshore of Neogene clinoforms, and changes in slope sedimentation. The timescale is from *Berggren et al.* [1995]. The $\delta^{18}O$ is modified to this timescale using the synthesis of *Miller et al.* [1987]. Modified after *Miller et al.* [1997c] using the R2 record of *Kominz et al.* [1998].

during the ?late Oligocene to early Miocene [e.g., *Schlee*, 1981]. Clinoforms associated with the progradation are clearly revealed in seismic profiles (Figures 2 and 3) and probably represent deposition in neritic water depths, although the precise environments of deposition are not known (Shelf drilling is designed to determine the depositional setting of these clinoforms). By the middle Miocene (~11–12 Ma), clinoforms were centered beneath the modern middle shelf (~100 km seaward of Island Beach (Figure 14 and *Miller and Mountain* [1994])). At about 13.6 Ma there was a dramatic increase in progradation and channel cutting on the shelf and sedimentation rates on the slope (to >30 m myr^{-1} [*Mountain et al.*, 1994]). By the late middle Miocene (approximately 10 Ma), clinoforms had built seaward to beneath the modern outer shelf (~125 km seaward of Island Beach (Figure 14)), canyon formation became widespread on the slope owing to increased sediment supply to this region, and slope sedimentation rates increased to ~300 m myr^{-1} [*Miller and Mountain*, 1994].

Although the switch to a siliciclastic margin appears to be related to cooling, the late Oligocene to mid-Miocene development of a high-sedimentation rate, prograding regime cannot be entirely ascribed to climate effects because global climate both warmed and cooled during this interval [e.g., *Miller et al.*, 1987]. *Poag and Sevon* [1989] and *Pazzaglia* [1993] ascribed progradation to changes in sediment supply linked to hinterland (central Appalachian) uplift. They noted the largest increase in shelf to rise sedimentation occurred in the middle Miocene. We agree that changes in hinterland tectonics are a reasonable cause for the increase in sediment supply. However, it is clear from the data synthesized here that sediment supply increased in the New Jersey region by the late Oligocene (Figure 14), implying that hinterland uplift began prior to the middle Miocene.

9. DISCUSSION

Although we have documented the nature and effect of glacioeustatic changes on the m.y. scale, it is well known that periodic, astronomical ("Milankovitch") cyclicity dominated climatic changes on shorter timescales (periods of 19/23 kyr, 41 kyr, ~100 kyr [*Hays et al.*, 1976; *Imbrie et al.*, 1984], and ~400 kyr [*Hilgen*, 1991; *Olsen and Kent*, 1996]. Four studies have provided sufficient sampling (better than 10 kyr) to evaluate 20 to 400-kyr scale δ^{18}O and associated glacioeustatic variations during the Oligocene–middle Miocene: (1) equatorial Pacific Site 574, middle Miocene [*Pisias et al.*, 1985]; (2) Pacific Site 588, late early–early middle Miocene [*Flower and Kennett*, 1995]; (3) equatorial Atlantic Site 926, latest Oligocene–earliest Miocene [*Zachos et al.*, 1997]; and (4) South Atlantic Site 522, earliest Oligocene [*Zachos et al.*, 1994]. Although these records are all shorter than 3 myr in duration, they clearly show that the million-year-scale events discussed here (e.g., the Oi1 thorough Mi7 δ^{18}O events (Figure 7a)) are not artifacts of signal aliasing but are composites of many Milankovitch-scale (10^4 to 10^5-year scale) climate cycles that yield long-term increases. They also show that the dominant periodicity contained in all four records is ~40 kyr, consistent with high-latitude forcing by ice sheets [*Pisias et al.*, 1985; *Zachos et al.*, 1994, 1997; *Flower and Kennett*, 1995].

Comparison of a high-resolution (Milankovitch scale) stable isotopic record for 17–12.5 Ma with slope reflections and onshore sequences (Figure 8) suggests that there is 10^4 to 10^5-year scale variability embedded in the sequence stratigraphic record. As noted above, we matched reflections m5, m4, and m3 with Mi2, Mi3a, and Mi3, respectively. Our revised correlation of shelf reflection Yellow-2 of *Greenlee et al.* [1992] as older than slope reflection m2 is consistent with m2's correlation with Mi4. We filtered the Site 588 data (Figure 8) to emphasize both longer (>246 kyr; heavy line) and shorter (66–246 kyr; thin line) periods. In the interval between 12.9 and 13.7 Ma, we show ~100-kyr-scale δ^{18}O variability (peaks at 12.9, 13.05, 13.18, 13.38, 13.5, 13.6, 13.7 Ma (Figure 8)). Four sequences have been detected between reflections m2 and m3: m2.2, m2.3, DLS/m2.4, and 2.5. We cannot trace the sequence boundaries to the slope and date them because they downlap on reflection m3. However, simple pattern matching between the well-dated reflections m2 and m3 appear to correlate with these ~100-kyr cycles in the δ^{18}O record (Figure 8). This suggested correlation may be speculative (i.e., the ages of the new sequences are only known to be between circa 12.9 and 13.6 Ma), but it is clear that the many sequences deposited between m1 time and m3 time had durations on the scale of 100 kyr.

We conclude that studies of Legs 150 and 150X boreholes have dated the major, million-year-scale late middle Eocene–middle Miocene sequence boundaries and documented that they resulted from glacioeustatic changes. Higher-order (400, 100, 40, and 19/23 kyr) sea level events are probably recorded on this margin, but are revealed only in very high sedimentation-rate sections (e.g., the middle Miocene on the shelf) and/or in very high resolution seismic data (e.g., recently collected Oceanus 270 data on the shelf [*Austin et al.*, 1996; *Mountain et al.*, 1996b]).

10. CONCLUSIONS

In this contribution, we synthesize the major results of New Jersey Sea Level Transect drilling on the coastal plain (Leg 150X boreholes at Island Beach, Atlantic City, and Cape May) and continental slope (Leg 150 Sites 902–904 and 906). We attain six goals by dating sequences, correlating them regionally and interregionally, comparing them with a glacioeustatic proxy afforded by δ^{18}O records, evaluating facies models for changes within sequences, estimating eustatic amplitudes, and reconstructing the Cenozoic history of sedimentation on this passive margin.

1. Drilling onshore and offshore on the New Jersey Transect has provided firm dates on Eocene–middle Miocene sequences and preliminary ages on Paleocene sequences.
2. Correlation of sequence boundaries regionally (onshore-offshore), interregionally, and with those of EPR indicates a global control on their formation.
3. For at least the past 42 myr, sequence boundaries on the coastal plain and continental slope correlate (typically within ±0.5 myr) with glacioeustatic lowerings inferred from deep-sea $\delta^{18}O$ records obtained far from continental margins. These correlations appear to link margin erosion with glacioeustatic change on the million-year scale. However, uncertainties in the correlations between margin transects and deep-sea sites render it difficult to demonstrate unequivocally a causal relationship between sequence development and glacioeustatic change. We show that sequence boundaries at slope Site 904 are associated with $\delta^{18}O$ increases, providing evidence for a direct link independent of age control.
4. Facies models of variations within sequences show a repetitive pattern on the coastal plain that is consistent with models described by EPR, reflecting deposition in stacked transgressive-regressive cycles. Slope facies changes primarily reflect downslope transport during lowstands and subsequent hemipelagic settling.
5. Our initial estimates of sea level amplitudes (tens of meters) are much lower than those predicted by EPR (up to 140 m) but are consistent with amplitudes inferred from $\delta^{18}O$ changes.
6. Although global sea level changes controlled the formation of unconformities, the evolution of the New Jersey margin over the past 65 myr was influenced by tectonics, changes in sediment supply, and global and regional changes in climate.

The New Jersey Sea Level Transect is the first study to provide firm documentation linking ice volume changes and sequence boundaries. Such a link is not unexpected during intervals with large- or even moderate-sized ice sheets. Certainly large ice sheets (>50% of present East Antarctica, equivalent to >35 m of sea level change) have existed in East Antarctica since the Oligocene [*Miller et al.*, 1991a; *Zachos et al.*, 1994], while moderate-sized ice sheets (~20–35 m of sea level equivalent) existed in the late middle to late Eocene [*Browning et al.*, 1996]. One surprising conclusion is that small ice sheets (<20 m of sea level equivalent) may have controlled sea level changes in the early Eocene, an interval previously considered to be ice-free.

Additional drilling on the New Jersey margin is needed to provide better estimates of sea level amplitudes, to continue to evaluate the ages and phase relationships of glacioeustatic changes to margin response, to test shelf facies models, and to extend our sequence stratigraphic studies to the supposedly ice-free, "greenhouse" Cretaceous. Future drilling on other passive margins is needed to confirm the interregional validity of the observations made on the New Jersey passive margin. ODP Leg 174A [*Austin et al.*, 1998] has sampled the New Jersey shelf, and results should provide estimates for late Miocene–Recent sea level amplitudes. In addition, the coastal plain and slope drilling have not characterized the full ranges of facies variations associated with sea level change, particularly the region most sensitive to sea level change found beneath the modern shelf. Leg 174A was the first step toward evaluating facies models in a siliciclastic shelf setting and, together with proposed future drilling, should help to characterize the response of shelf sedimentation to large, rapid glacioeustatic changes.

GLOSSARY

Accommodation: The vertical space available for sediment accumulation.

Airy isostasy: The tendency for the elevation of the lithosphere to be controlled by its density distribution (e.g., less dense crust stands high and has roots into the mantle), under conditions of no lateral strength of the lithosphere.

Backstripping: 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. We have modified the method to obtain eustasy, after removing tectonic subsidence, sediment loading, and paleoenvironment.

Base level: A hypothetical surface, asymptotic to sea (or lake) level, above which significant sediment accumulation is not possible. Base level is affected by variations in the rates of subsidence and eustasy, as well as by variations in sediment supply and discharge that may be due in part to changes in climate. Relatively continuous sedimentation indicates either that space ("accommodation") is available for sediment to accumulate (e.g., in a marine environment) or that base level is being continuously raised as a result of subsidence, sea level rise, or regression of the shoreline.

Biofacies: Associated bodies of sediment or sedimentary rock distinguished on the basis of fossil assemblages. The term applies to both lateral and vertical (including sequential) associations of facies.

Biostratigraphy: A stratigraphic technique that makes use of fossils to correlate (establish equivalency).

Carbonates: Sediments composed primarily (>50%) of $CaCO_3$. Carbonates may be deposited under shallow-water conditions (e.g., reefs, carbonate platforms) or in the deep sea as oozes primarily composed of planktonic foraminifera and nannofossils.

Chronostratigraphy: The branch of stratigraphy dealing with time-rock units and the temporal relationships of strata. Chronostratigraphic control refers to how well the relative time relationships of events are known.

Clinoform: A depositional surface that is inclined to the horizontal as a result of progradation. Clinoforms may be recognized in seismic reflection and well log cross sections, and in some cases in outcrop if exposures are sufficiently large and clinoforms are sufficiently steep.

Clinoform rollover: A point on a cross section and a line on a three-dimensional clinoform where there is a sharp increase in downslope gradient.

Coastal plain: A generally flat (<1:1000 or <0.6° gradient) portion of the emergent continental margin. The coastal plain is the landward extension of the continental shelf and generally contains a record of past marine incursions.

Condensed section/interval: A thin marine stratigraphic interval characterized by very slow depositional rates, and typically associated with relatively deep-water sedimentation [*Loutit et al.*, 1988]. Sediment starvation may be associated with a downlap surface and with a time of maximum flooding in nearshore areas. Specific attributes include concentrations of pelagic organisms, abundant burrowing, development of carbonate hardgrounds, and abundant glauconite and/or phosphatic sediments.

Continental shelf: A generally flat (<1:1000 gradient; <0.06° slope) region of the submergent continental margin from 0 to typically 200-m water depth; it is the seaward extension of the emergent coastal plain. Shelf/slope breaks (shelf edges) average approximately 135 m today, although they may be as deep as 400+ m.

Continental slope: A region on a continental margin characterized by steep slopes (>1:40 gradients or >1.4° slopes) typically between 200- and 2000-m water depth.

Correlate: Establish equivalency in space (physical correlation) or time (temporal correlation). Geologists commonly imply time/temporal correlation when describing correlation of different records.

Dinocyst: Resting state of dinoflagellates, useful in biostratigraphy.

Downlap: Progressive downdip termination of strata against an underlying surface. Downlap surfaces exist within sequences, and also at sequence boundaries in downdip positions.

Exxon Production Research Company (EPR): Affiliate of Exxon Corporation at which scientists pioneered the concepts of seismic and sequence stratigraphy and their relationship to global changes in sea level [*Vail et al.*, 1977; *Haq et al.*, 1987; *Posamentier et al.*, 1988; *Van Wagoner et al.*, 1990].

Eustatic change: Global change in sea level with respect to an equipotential surface. *Posamentier et al.* [1988] defined eustatic change as variation with respect to the center of the Earth, although this does not account for for geodial effects.

Flexural isostasy: Tendency for the elevation of the lithosphere to be controlled by its density distribution, under conditions where the lithosphere has finite lateral strength. In contrast to Airy isostasy, loads on and within the crust are supported partially by the lithosphere in adjacent areas and not only by rocks immediately beneath the load alone.

Foraminifera: Protists that secrete tests ("shells") of calcium carbonate. Foraminifera either float (planktonic) or live at/in the bottom sediments (benthic); although they may carry symbiotic algae, they generally feed on other small microorganisms. Because of their rapid evolution and widespread distribution, planktonic forms are very useful in biostratigraphy. They are also very useful in stable isotopic studies, with planktonic forms recording surface, thermocline, and subthermocline information and deep-sea benthic foraminifera recording deep water and bottom water isotopic composition.

Glauconite: A green to black layered K-aluminosilicate mineral typically formed in low oxygen shelf environments associated with condensed intervals.

Glacioeustasy: Global sea level variations caused by changes in continental ice volume. Changes in the volume of buoyant ice have no influence on sea level.

Hemipelagic: Pelagic sediment dominated by siliciclastic muds typically found near continents.

Hiatus: Time gap, including those through nondeposition and/or erosion.

Highstand systems tract (HST): Uppermost systems tract of a depositional sequence, bounded below by a condensed interval, and above by a sequence boundary. The highstand unit is characterized by regression of the shoreline, by an aggradational to forestepping (migrating basinward) arrangement of higher-order units such as parasequences, and by sigmoid to oblique clinoforms. Some have interpreted the highstand systems tract as representing deposition during a relatively high stand of sea level [*Haq et al.*, 1987; *Posamentier et al.*, 1988], but the stratigraphic element can be identified independently of any assumptions or inferences about sea level.

Lithofacies: Associated bodies of sediment or sedimentary rock distinguished on the basis of lithic characteristics. The term applies to both lateral and vertical (including sequential) associations of facies.

Lowstand systems tract (LST): Lowermost systems tract of a depositional sequence, bounded below by a sequence boundary and above by a transgressive surface. The lowstand unit consists of an assemblage of seaward-building sediments and in deep water is associated with enhanced downslope transport. In shallow ramp settings it is characterized by regression of the shoreline and by a forestepping (migrating basinward) to aggradational arrangement of higher-order units such as parasequences. Some have interpreted the lowstand systems tract as representing deposition during a relatively low stand of sea level [*Haq et al*., 1987; *Posamentier et al*., 1988], but the stratigraphic element can be identified independently of any assumptions or inferences about sea level.

Milankovitch: Milutin Milankovitch (1879–1958), Serbian mathematician who quantified the prediction that minor variations in the Earth's orbit controlled incoming solar radiation (insolation), which in turn paced variations in glaciation. He predicted astronomically controlled periodicities of 19/23, 41, and ~100 kyr.

Multichannel seismic (MCS): Stacking together of many source-receiver pairs to enhance signal resolution.

Maximum flooding surface/interval (MFS): Surface or interval that corresponds with the time of maximum transgression. It is typically associated with sediment starvation in deep water and with the development of downlap. Some have interpreted this stratigraphic element as representing a time of rapid sea level rise [*Haq et al*., 1987; *Posamentier et al*., 1988], but this is not necessary for its identification. The MFS usually is not a distinct surface at all, but is an interval of sediment starvation, the condensed interval [*Loutit et al*., 1988].

Nannofossil: Fossil produced by yellow brown, chlorophyll-bearing algae, coccolithophoridae, that are useful in biostratigraphy; so named for the small size of the fossilizable carbonate plates made by the algae (typically 10 μm).

Onlap: Progressive lateral or up-dip termination of strata against an underlying surface. Basinward shifts in onlap are characteristic of sequence boundaries, but they may also develop in marine settings as a result of changes in the direction of progradation, with no base level change involved.

Offlap: Progressive up-dip termination of strata against an overlying surface [*Mitchum*, 1977; *Christie-Blick*, 1991]. Offlap may be due to sediment bypassing (toplap) or to erosional truncation of sediments. In practice, bypassing and erosion are very hard to partition as both take place in the development of virtually all sequence boundaries.

Parasequence: A relatively conformable succession of genetically related strata bounded by flooding surfaces and their correlative surfaces, and characterized internally by upward shoaling of sedimentary facies. Parasequences are often thought of as the building blocks of unconformity-bounded sequences. In reality, parasequences and sequences overlap in scale, and parasequence terminology is used when further subdivision of successions into higher-order sequences is not objectively possible [*Van Wagoner et al*., 1988]. The term has been used improperly as a synonym of "small sequence" (see *Posamentier and James* [1993] for discussion).

Passive continental margin: Diffuse boundary between continental and oceanic crust where there is no active plate boundary. Such continental margins are commonly characterized by little seismic or volcanic activity (hence the term passive), smooth relief, and thick successions of sediment that accumulated in space made available by thermally driven subsidence of the lithosphere and sediment loading.

Pelagic sediments: Sediments derived from settling through the water column, including carbonate oozes and marls (carbonate-rich muds) composed of planktonic foraminifera and nannoplankton.

Prograde/prograding: To build outward/the act of building outward toward the basin.

Regression: Seaward movement of the shoreline, as a result of variations in sediment supply, sea level and/or subsidence of the basin. Regressions may be caused by processes other than sea level change. For example, an increase in sediment supply can cause the strandline to move seaward even though sea level is rising.

Relative sea level: Sea level defined qualitatively as with respect to the crust or some datum within the sedimentary succession [*Posamentier et al*., 1988], and inferred on this basis to control the space available for sediment to accumulate (accommodation). As such, this term accounts for the effects of eustasy and subsidence. However, relative sea level change is also influenced by the amount of sediment that accumulates as a result of sediment loading, and the concept cannot be used to interpret the distribution of sediments quantitatively.

Sequence: A stratigraphic unit composed of a relatively conformable succession of genetically related strata, bounded at its top and base by unconformities and correlative surfaces that are associated at least locally with the lowering of base level (modified from *Mitchum et al*. [1977] to take into account modern usage of this term).

Sequence boundary: An unconformity associated at least locally with evidence for the lowering of base level. Sequence boundaries develop as a result of eustatic change and also as a result of tectonically driven uplift and tilting.

Siliciclastic: Terrigenous sands (generally composed of quartz) and muds derived from weathering of rocks and sediments.

Sr isotope stratigraphy: A relative dating tool (not a radiometric technique) that relies on the following: that the ratio of ^{87}Sr/^{86}Sr has varied in seawater through time, ^{87}Sr/^{86}Sr is well mixed in seawater, and the ratio is recorded in marine carbonates. Analysis of ^{87}Sr/^{86}Sr in unaltered marine carbonate potentially provides a means of correlations to a standard (known) record of ^{87}Sr/^{86}Sr through time.

Systems tract or facies tract: A predictable association of lithofacies deposited during a relative sea level cycle, defined as systems tract by *Posamentier et al*. [1988]. We prefer the more descriptive term facies tract.

Tectonoeustatic: Global sea level variations caused by changes in spreading rate or ridge length or other tectonic phenomena within the ocean basins.

Thalweg: Point of maximum depth of a channel (either fluvial or submarine canyon).

Toplap: Beds deposited behind the clinoform rollover that asymptotically thin; analogous to topset beds in a delta. See "offlap."

Transgressive systems tract (TST): Intermediate systems tract of a depositional sequence, bounded below by a transgressive surface and above by a condensed interval (maximum flooding surface). The transgressive unit is characterized by transgression of the shoreline and by a backstepping (migrating landward) arrangement of higher-order units such as parasequences. Some have interpreted the transgressive systems tract as representing deposition during a relatively rapid sea level rise [*Haq et al*., 1987; *Posamentier et al*., 1988], but the stratigraphic element can be identified independently of any assumptions or inferences about sea level. In many cases, the transgressive systems tract also contains nonmarine as well as marine sediments.

Transgression: Landward movement of the shoreline as a result of variations in sediment supply, sea level and/or subsidence of the basin.

Unconformity: A surface of erosion and/or nondeposition in the stratigraphic record.

Updip: The direction toward the basin margin in a sedimentary basin, as opposed to downdip (toward the deep basin.) Here "dip" refers to the angle between an inclined plane and the horizontal, measured in a vertical plane perpendicular to strike.

ACKNOWLEDGMENTS. We thank the members of the New Jersey Coastal Plain Drilling Project, Leg 150X and Leg 150, for making this study possible. The New Jersey Geological Survey supplied materials, personnel, and logging support for onshore drilling. The USGS BERG drillers did an outstanding job in obtaining the Leg 150X onshore cores. Rutgers University provided space for interim core storage and core analyses, field vehicles, and materials. R. K. Olsson (Rutgers) supplied unpublished data from other onshore wells and advice on planktonic foraminiferal studies. The National Science Foundation Continental Dynamic Program (L. Johnson, Program Director) and Ocean Drilling Program (B. Malfait, Program Director) cofunded the onshore boreholes (Leg 150X) and, along with Planning Committee (PCOM) and ODP, are to be commended for their flexibility and vision in authorizing Leg 150X as an ODP activity. We thank the ODP for their support. The offshore work was further enhanced by encouragement and promotion by Joint Oceanographic Institutions (particularly E. Kappel) and Marine Geology and Geophysics of the Office of Naval Research (J. Kravitz, Program Manager). We thank S. W. Snyder for co-editing the Leg 150X Scientific Results volume and D. Twitchell, C. W. Poag, and P. Blum for co-editing the Leg 150 Scientific Results volumes, which provided much of the data synthesized here. Reviews by R. Buffler, C. Nittrouer, C. W. Poag, and T. Torgersen are greatly appreciated. The work was supported by NSF grants EAR92-18210 (K. G. M., G. S. M.), EAR94-17108 (K. G. M.), EAR95-05957 (K. G. M.), HRD96-26177 (M. K.), and ONR grant N0014-95-1-0200 (G. S. M., K. G. M.). LDEO contribution 5857.

Thomas Torgersen was the editor responsible for this paper. He thanks R. Buffler, C. Nittrouer, and C. W. Poag for their reviews.

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