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12. STRONTIUM-ISOTOPIC CORRELATION OF OLIGOCENE TO MIOCENE SEQUENCES, NEW JERSEY AND FLORIDA[1]

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ABSTRACT

We use Sr-isotopic age estimates to date siliciclastic, carbonate, and mixed siliciclastic-carbonate Oligocene and Miocene sequences for the New Jersey Coastal Plain and Florida Peninsula and to correlate sequence boundaries with the deep-sea δ^{18}O record and the inferred eustatic record of Exxon. The New Jersey onshore Oligocene to 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. The age of Oligocene to Miocene sequence boundaries determined in continuous boreholes from New Jersey, Alabama, and Florida show excellent correlation with deep-sea δ^{18}O increases, which are inferred glacioeustatic lowerings. This is strong confirmation that global sea-level change is a primary control on the timing of Oligocene to Miocene sequence boundaries for the coastal plain sections studied here.

Whereas global sea level has a significant influence on coastal plain sequences, there are major differences in the preservation of sequences within the same depositional basin (e.g., Salisbury Embayment) and between basins (e.g., Florida basins vs. Salisbury Embayment). These intra- and interbasinal differences must be ascribed to noneustatic processes such as tectonics or differential erosion. Tectonic mechanisms include faulting of crustal blocks, mobile basins with evolving arches and depocenters, local flexural subsidence, or differential subsidence caused by sediment loading.

INTRODUCTION

A major goal of the New Jersey Coastal Plain Drilling Project, Ocean Drilling Program (ODP) Leg 150X, is the study of global sea-level change during the Oligocene to Holocene "Icehouse World," an interval when ice-volume variations exerted significant control on changes in global sea-level (see Miller, Chapter 1, this volume). Oxygen isotopic records provide a precise means for calibrating sea-level changes to the geologic time scale for the last 35 m.y. (e.g., Miller et al., 1996b). However, the oxygen-isotope method can be affected by temperature and local salinity changes, and more importantly, provides no information on the influence or magnitude of tectonically induced sea-level changes (Miller and Mountain, 1994).

Comparing the stratigraphy of shallow-water siliciclastic and carbonate sequences on different passive continental margins provides another means for evaluating timing of sea-level events. Similar timing of interregional unconformities indicates a global cause. If these interregional unconformities correlate with δ^{18}O increases, then a glacioeustatic control is indicated. However, shallow-water (<100 m) chronologic control is often limited because of problems with facies controls on magnetobiostratigraphy (Miller and Kent, 1987). Sr-isotope stratigraphy circumvents these problems and can provide a chronology for critical Oligocene to Holocene "Icehouse" sequences (Sugarman et al., 1993).

The New Jersey Coastal Plain provides a record of numerous Oligocene to middle Miocene sequences. Biostratigraphic correlations of Miocene sequences in New Jersey primarily rely on diatoms (Abbott, 1978; Andrews, 1988) that are not yet precisely calibrated to the time scale. Sugarman et al. (1993) applied Sr-isotopic studies to the first continuously cored boreholes in New Jersey, ACGS#4 and Belleplain (Fig. 1), to decipher the sequence stratigraphy of the Miocene Kirkwood Formation and calibrate it to the time scale. Drilling of the Island Beach, Atlantic City, and Cape May boreholes by Leg 150X provided additional material to map and date Oligocene to Miocene sequences (Miller, et al., 1994, 1996a; Miller and Sugarman, 1995; Pekar and Miller, 1996). Correlation of these sequence boundaries with the deep-sea δ^{18}O glacioeustatic proxy indicates a primary control by global sea level (Miller and Sugarman, 1995; Miller et al., 1996b; Miller et al., Chapter 1, this volume; Pekar and Miller, 1996).

Sr-isotope stratigraphy has also significantly improved the understanding of the middle Cenozoic history of Florida in the last two years (Jones et al., 1993; Mallinson et al., 1994; Scott et al., 1994; Wingard et al., 1994; Mallinson and Compton, 1995; McCartan et al., 1995c). For example, the lower half of the deposits assigned to the Hawthorn Group (Scott, 1988), previously thought to be Miocene, have yielded late Oligocene Sr-isotopic age estimates (Scott et al., 1994; Mallinson et al., 1994; McCartan et al., 1995c). Mallinson et al. (1994) investigated deposits in northeast Florida (where the Hawthorn Formation has not been divided), whereas Jones et al. (1993) studied northwest Florida. McCartan et al. (1995b, 1995c) and this study concentrate on strata in the central and southern Florida Peninsula.

This paper employs several approaches to focus on the timing of eustatic events recorded in the Atlantic Coastal Plain during the Oligocene–middle Miocene portion of the "Icehouse World." First, we present an Oligocene (from Pekar et al., Chapter 15, this volume) to Miocene (from this study and Miller et al., Chapter 14, this volume) sequence stratigraphic framework developed from Sr-isotopes, biostratigraphy, and geologic mapping of the three Leg 150X boreholes (Island Beach, Atlantic City, and Cape May) from the New Jersey Coastal Plain (Table 1). Emphasis is placed on determining the ages of sequence boundaries and duration of sequences. Second, we establish the age of Oligocene to Pliocene sequences and sequence boundaries in Florida using new (Table 2) and published Sr-isotope data

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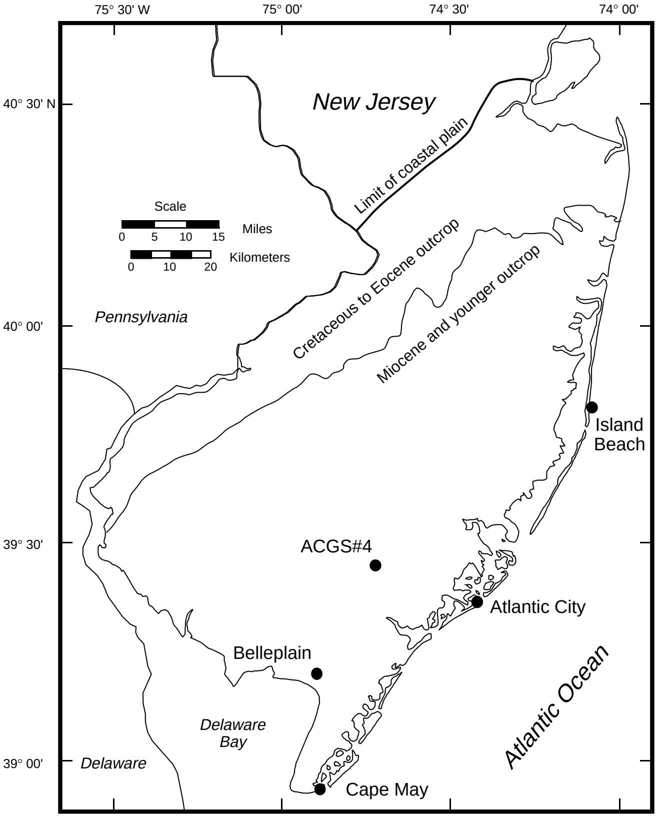

Figure 1. Location map of the New Jersey boreholes studied or referenced in this paper including the Leg 150X Island Beach, Atlantic City, and Cape May Sites.

from Florida (Jones et al., 1993; McCartan et al., 1995c) and records from Alabama (Miller et al., 1993). If coeval sequence boundaries exist along the length of the Atlantic and Gulf Coastal Plains, then timing of major eustatic events can be inferred. We also compare the combined New Jersey, Florida, and Alabama records with the deep-sea δ^{18}O and the Haq et al. (1987) inferred eustatic records. We conclude that similar events occur in all of these records, confirming eustasy as the primary control on depositional sequences. Nevertheless, basinal differences indicate that tectonics and differential erosion play an important role in determining the stratigraphic record.

METHODS

Samples were obtained from the Leg 150X Island Beach, Atlantic City, and Cape May boreholes (Fig. 1) at the Rutgers core facility in Piscataway, NJ (Table 1). Cores from Florida (Fig. 2) were sampled at the Florida Geological Survey's core repository in Tallahassee and are indexed according to the Florida Geological Survey's well accession numbering system (Table 2).

Sr-isotope analyses were made on calcareous mollusk shells (note: one sample was collected from foraminifers). A 0.1-in diameter (5 mm) piece was taken from the most pristine part of the shell and ultrasonically cleaned in distilled water for 5-10 s, crushed, and dissolved in 1.5-N HCl. Standard ion-exchange techniques (Hart and Brooks, 1974) were used to separate strontium for analysis on a VG Sector mass spectrometer at Rutgers University. At Rutgers, NBS-987 was measured as 0.710255 ^{87}Sr/^{86}Sr (20 analyses, $1\sigma = \pm 0.000008$, normalized to ^{86}Sr/^{88}Sr = 0.1194) during analysis of Leg 150X samples. Two recent measurements on EN-1, an informal Sr-isotope standard, are 0.709196 ± 9 and 0.709186 ± 6.

Average internal error (intrarun variability) at Rutgers was ±0.000009 for the 103 and 17 samples analyzed and tabulated in Tables 1 and 2. External error at Rutgers has previously been reported as ±0.000020 to ±0.000030 (Miller et al., 1991a). In a recent study from the Rutgers laboratory, average error of 17 duplicates analyzed was ±0.000020 (Oslick et al., 1994); this is probably a good estimate for external precision.

Sr-isotopic values for Florida shells were measured at the Rutgers Laboratory, and the U.S. Geological Survey's Isotope Laboratory in Menlo Park, CA. At Menlo Park, samples were dissolved in 2-N HCl. Strontium-isotope ratios were determined using a MAT 261, 90° sector mass spectrometer, using the double rhenium filament mode of ionization. All Sr-isotopic ratios are also normalized to a ^{86}Sr/^{88}Sr = 0.1194. Lab average of ^{87}Sr/^{86}Sr for the NBS standard is 0.710239 ± 14; we add 0.000016 to ^{87}Sr/^{86}Sr measurements from the U.S. Geological Survey Isotope Laboratory for comparison with ^{87}Sr/^{86}Sr values from the Rutgers Laboratory (Table 2).

Sr-isotope values were converted to age estimates using the regression equations of Oslick et al. (1994) for the Oligocene through Miocene, and Miller et al. (1988) for the late Eocene. Late Miocene and Pliocene ages were determined using the data sets in Farrell et al. (1995), and converting these into age equations using the techniques outlined in Miller et al. (1991a). The equations are given in Table 3. The Oslick et al. (1994) regressions were computed for the Cande and Kent (1992) time scale, which has minor differences from the Berggren et al. (1995) time scale. The geomagnetic polarity time scale (GPTS) of Berggren et al. (1995) is used throughout.

Stratigraphic resolution in the Oligocene is as good as ±0.5 m.y. in the early Oligocene and as poor as ±0.8 m.y. for the late Oligocene interval between ~28 and 24 Ma (Oslick et al., 1994). The early Miocene is especially suitable for Sr-isotope stratigraphy, with a ^{87}Sr/^{86}Sr rate of change of 60–80 ppm/m.y. (Hodell et al., 1991; Miller et al., 1991a; Oslick et al., 1994), and age estimates with a resolution of ±0.4 m.y. for replicate analyses (Oslick et al., 1994). Age resolution for the middle Miocene decreases to about ±0.9 m.y because of a corresponding lower ^{87}Sr/^{86}Sr rate of change (~22 ppm/m.y; Oslick et al., 1994), but still provides moderate chronostratigraphic resolution.

Diagenetic alteration of the source material for the different data sets is a concern. For New Jersey samples, few diagenetic problems have been documented (Sugarman et al., 1993; Miller, et al., 1994). However, diagenetic problems were encountered in the Maryland Miocene section (Miller and Sugarman, 1995) and attributed to post-depositional exchanges in aragonitic shells. In Florida, Jones et al. (1993), McCartan et al. (1995c), and this paper present analyses of calcareous shallow-water shells, whereas Mallinson et al. (1994) analyzed dolomitic sediment and phosphorite grains and crusts. Nevertheless, all the authors conclude that their ^{87}Sr/^{86}Sr values reflect the times when sea level was at or near its maximum for the depositional cycle during which the sample was formed.

Age inversions are present in certain intervals from boreholes in Florida. The nonsystematic pattern of Sr-isotopic values in Borehole W-16505 above 663.2 ft (202.1 m) may indicate diagenetic overprinting or reworking. With the exception of these problems, the Florida data can be interpreted in a stratigraphically meaningful way.

RESULTS

New Jersey Depositional Styles

Both Oligocene and Miocene sequences from the Leg 150X onshore boreholes show similar overall coarsening-upward trends above basal unconformities. These asymmetric transgressive/regressive cycles of sedimentation have been documented by Owens and

Table 1. $^{87}Sr/^{86}Sr$ values and age estimates for the Atlantic City, Island Beach, and Cape May boreholes.

Rutgers lab no.	Depth (ft)	$^{87}Sr/^{86}Sr$	Error (±)	BKV age (Ma)	CK age (Ma)	Age error Ma (±)
Cape May						
2039	358.4	0.708856	0.000006	12.5	12.7	1.2
2033	370.4	0.708880	0.000008	11.4	11.8	1.2
2034	386.7	0.708885	0.000008	11.2	11.6	1.2
2035	390.6	0.708870	0.000009	11.9	12.2	1.2
1966	417.1a	0.708878	0.000007	11.5	11.9	1.2
1967	417.1b	0.708887	0.000013	11.1	11.5	1.2
1968	421.4	0.708878	0.000006	11.5	11.9	1.2
1969	431.5	0.708878	0.000007	11.5	11.9	1.2
2213	514.3	0.708790	0.000008	15.5	15.2	1.2
2214	527.5	0.708812	0.000013	14.5	14.4	1.2
1970	529.5	0.708805	0.000025	14.8	14.6	1.2
2111	573.6	0.708816	0.000011	14.3	14.2	1.2
2112	581.5	0.708766	0.000008	16.2	15.9	0.6
2162	582.6	0.708784	0.000027	16.0	15.7	0.6
2036	600.0	0.708764	0.000011	16.3	16.0	0.6
2040	677.3	0.708721	0.000006	16.9	16.6	0.6
2298	690.1	0.708685	0.000012	17.4	17.1	0.6
2113	706.4	0.708659	0.000007	17.8	17.5	0.6
2041	722.5	0.708601	0.000008	18.6	18.4	0.6
2037	810.9	0.708558	0.000010	19.3	19.0	0.6
2042	832.6	0.708540	0.000007	19.5	19.3	0.6
2030	851.3	0.708499	0.000014	20.1	19.9	0.6
2038	882.7	0.708498	0.000008	20.1	19.9	0.6
2043	982.2	0.708476	0.000011	20.4	20.2	0.6
2044	1012.7	0.708448	0.000007	20.8	20.6	0.6
2027	1058.0	0.708446	0.000009	20.9	20.6	0.6
2045	1058.0	0.708438	0.000077	21.0	20.7	0.6
2046	1085.0	0.708323	0.000014	22.6	22.4	0.6
2028	1085.0	0.708318	0.000029	22.7	22.5	0.6
2031	1098.0	0.708327	0.000016	22.6	22.4	0.6
2047	1098.0	0.708334	0.000020	22.5	22.3	0.6
2114	1135.8	0.708290	0.000006	23.1	23.6	1.1
2032	1209.0	0.708228	0.000014	25.0	24.8	1.1
2048	1209.0	0.708229	0.000029	24.9	24.7	1.1
2183	1209.0	0.708315	0.000019	22.5	23.1	1.1
2029	1247.0	0.708257	0.000006	24.1	24.2	1.1
2185	1249.0	0.708251	0.000011	24.3	24.3	1.1
2180	1268.0	0.708335	0.000038	21.9	22.7	1.1
2139	1271.0	0.708216	0.000008	25.3	25.0	1.1
2140	1299.0	0.708223	0.000014	25.1	24.9	1.1
2141	1302.0	0.708178	0.000006	26.4	25.7	1.1
2142	1340.0	0.708034	0.000013	30.6	28.5	1.1
2186	1340.0	0.707995	0.000030	31.7	30.1	2.0
2143	1350.0	0.707939	0.000008	33.3	31.6	2.0
2181	1350.0	0.70794	0.000031	33.3	31.6	2.0
2182	1354.5	0.707973	0.000020	32.3	30.7	2.0
Island Beach						
1700	503.3	0.708390	0.000015	21.7	21.4	0.6
1701	504.5	0.708379	0.000004	21.8	21.6	0.6
1702	522.5	0.708252	0.000005	24.3	24.3	1.1
1703	663.8	0.707958	0.000006	32.7	31.1	2.0
1745	668.0	0.707957	0.000012	32.8	31.1	2.0
1746	677.0	0.707944	0.000014	33.1	31.5	2.0
1704	683.6	0.707983	0.000006	32.0	30.4	2.0
2187	703.0	0.707743	0.000034	38.9	37.0	2.0
Atlantic City						
1786	401.7	0.708839	0.000013	13.3	13.4	1.2
1792	411.1	0.708836	0.000009	13.4	13.5	1.2
1907	442.5	0.708842	0.000012	13.1	13.2	1.2
1908	462.6	0.708827	0.000008	13.8	13.8	1.2
1787	462.6	0.708833	0.000010	13.5	13.6	1.2
1884	476.5	0.708765	0.000006	16.6	16.0	0.6
1965	479.0	0.708798	0.000008	15.1	15.5	0.6
1885	492.3	0.708762	0.000007	16.7	16.0	0.6
1819	515.0	0.708765	0.000033	16.6	16.0	0.6
1913	519.5	0.708722	0.000009	18.5	16.6	0.6
1788	520.0	0.708713	0.000011	17.0	16.7	0.6
1793	559.7	0.708668	0.000011	17.7	17.4	0.6
1820	605.1	0.708656	0.000011	17.8	17.6	0.6
1794	644.0	0.708672	0.000008	17.6	17.3	0.6
1909	644.1	0.708669	0.000009	17.6	17.4	0.6
1826	661.1	0.708640	0.000008	18.1	17.8	0.6
1825	661.2	0.708494	0.000010	20.2	19.9	0.6
1795	708.5	0.708476	0.000011	20.4	20.2	0.6
1914	708.5	0.708485	0.000007	20.3	20.1	0.6
1796	723.2	0.708490	0.000010	20.2	20.0	0.6
1910	723.2	0.708488	0.000010	20.3	20.0	0.6
1821	821.2	0.708469	0.000010	20.5	20.3	0.6
1822	831.4	0.708468	0.000011	20.6	20.3	0.6
1915	831.4	0.708482	0.000015	20.3	20.1	0.6
1789	854.1	0.708453	0.000011	20.8	20.5	0.6
1911	854.1	0.708484	0.000010	20.3	20.1	0.6
1847	869.2	0.708438	0.000020	21.0	20.7	0.6
1953	875.1	0.708461	0.000012	20.7	20.4	0.6
1790	884.8	0.708372	0.000012	21.9	21.7	0.6
1916	884.8	0.708419	0.000020	21.3	21.0	0.6
1889	898.0	0.708339	0.000009	22.4	22.2	0.6
1848	908.3	0.708299	0.000011	22.9	23.4	1.1
1791	913.0	0.708303	0.000011	22.8	23.3	1.1
1954	913.0	0.708273	0.000011	23.7	23.9	1.1
2297	917.5	0.708154	0.000038	27.1	26.2	1.1
1890	922.5	0.708207	0.000026	25.6	25.2	1.1
1823	932.2	0.708199	0.000013	25.8	25.3	1.1
1955	948.0	0.708172	0.000007	26.6	25.9	1.1
1797	974.5	0.708142	0.000011	27.4	26.4	1.1
1956	974.5	0.708147	0.000012	27.3	26.3	1.1
1824	1056.5	0.708135	0.000013	27.6	26.6	1.1
2184	1072.0	0.708121	0.000011	28.1	26.8	1.1
1827	1117.0	0.708097	0.000014	28.7	27.3	1.1
1886	1140.9	0.708048	0.000007	30.2	28.3	1.08
1887	1164.5	0.708056	0.000008	29.9	28.1	1.08
1828	1178.2	0.707936	0.000008	33.4	30.4	2.0
1829	1204.1	0.707823	0.000013	36.6	32.6	2.0
1830	1301.1	0.707784	0.000013	37.7	33.4	2.0
1888	1334.8	0.707763	0.000007	38.3	33.8	2.0

Sohl (1969) for the Cretaceous and Sugarman et al. (1993) for the Miocene of New Jersey.

The Oligocene and Miocene sections reflect two different depositional systems: shelf and delta (see fig. 4 in Miller, Chapter 1, this volume). Oligocene sequences were deposited in neritic (shelfal) environments and often contain glauconite throughout. The presence of glauconite in the medial silts and upper quartz sands (Highstand Systems Tracts) is attributed to stratigraphic reworking (Pekar et al., Chapter 15, this volume). Miocene sequences were deposited in shelfal and deltaic environments, and overall are characteristically shallower water deposits. Oligocene sediments often contain sufficient planktonic foraminifers for biostratigraphic correlation, whereas the Miocene strata mostly lack planktonic foraminifers (Liu et al., Chapter 10, this volume).

Oligocene sedimentation in the New Jersey Coastal Plain displays an overall coarsening-upward trend over several sequences. Owens et al. (1995a) mapped two subsurface Oligocene cycles, a lower Oligocene To_1 cycle and an upper Oligocene To_2 cycle, which approximately correspond to the Sewell Point and Atlantic City Formations (Pekar et al., Chapter 8, this volume). Pekar et al. (Chapter 15, this volume) recognized at least five Oligocene sequences using shifts in benthic foraminiferal biofacies along with hiatuses delineated biostratigraphically or with Sr isotopes. The lower Oligocene (Sewell Point/To_1 cycle) is generally finer grained and characterized by outer neritic biofacies, whereas the upper Oligocene (Atlantic City/To_2 cycle) is generally coarser grained and characterized by inner (and some middle) neritic biofacies (Owens et al., 1995a; Pekar et al., Chapter 15, this volume). Thus, the Oligocene of New Jersey shows a general coarsening and shallowing upsection that marks a major change in sedimentation. This increased input of coarse clastic material is associated with regional uplift of the Appalachians, which provided a renewed source of sediment (Poag and Sevon, 1989).

The lowermost Miocene Kw0 sequence is similar to Oligocene sequences in that it is dominated by glauconite deposited in inner to middle neritic paleodepths (Miller, et al., 1994). It has only been mapped downdip in continuously cored boreholes (e.g., Atlantic City and Cape May; Miller and Sugarman, 1995).

Miocene sedimentation younger than 22 Ma in New Jersey reflects strong deltaic influence. The Kw1 (Kirkwood 1) and younger Miocene sequences record shoaling-upward transitions from inner neritic and prodelta environments to delta front and near-shore marine environments. The lower Miocene Kw1 sequences (Kw1a and Kw1b) are the most extensive sequences in New Jersey and are exposed updip in the outcrop belt (Sugarman et al., 1993; Owens et al., 1995a, 1995b). Both the Kw1a and Kw1b sequences are dominated by silt facies deposited in neritic environments in their lower and me-

Table 2. New ^{87}/Sr^{86}Sr values, age estimates, and sequence correlation for boreholes studied in central and southern Florida (Fig. 2).

Core	Depth (ft)	^{87}Sr/^{86}Sr	±	Interlab correction +0.000016	BKV85 Age (Ma)	BKV95 Age (Ma)	Sequence
W-11669	39.0	0.708381	25	0.708397	21.6	21.3	FM1
W-11669	54.0	0.707994	19	0.708010	31.2	29.7	FM1-diagenesis
W-11669	166.2	0.707923	18	0.707939	33.3	31.6	FM1-diagenesis
W-11669	219.0	0.708359	13	0.708375	21.9	21.7	FM1
W-11669	275.0	0.708381	42	0.708397	21.6	21.3	FM1
W-11669	276.5	0.708374	15	0.708390	21.7	21.5	FM1
W-11669	323.5	0.708327	23	0.708343	22.4	22.1	FM1
W-11669	369.0	0.708069	12	0.708085	29.1	27.5	FO2b
W-11669	388.5	0.708136	19	0.708152	27.2	26.3	FO3
W-11669	414.0	0.708032	19	0.708048	30.2	28.6	FO2
W-11669	436.0	0.707989	15	0.708005	31.4	29.8	FO2
W-11946	181.5	0.708101	18		28.6	27.2	FO2b
W-11946	460.0	0.707853	8		35.8	35.7	Unnamed Eocene
W-12050	56.0	0.708679	14	0.708695	17.3	17.0	Diagenesis
W-12050	82-87	0.708980	6	None		5.1	Unnamed
W-12050	85.0	0.708980	11	0.708996		6.2	Unnamed
W-12050	124.0	0.708569	18	0.708585	18.9	18.6	FM2
W-12050	160.0	0.708524	20	0.708540	19.5	19.3	FM2
W-12050	188.0	0.708534	10	None	19.7	19.3	FM2
W-12050	226.0	0.708505	14	0.708521	19.8	19.5	FM2
W-12050	268.0	0.708421	17	0.708437	21.0	20.8	FM2
W-12050	277.0	0.708390	18	0.708406	21.4	21.2	FM1
W-12050	286.0	0.708379	4	None	22.3	21.6	FM1
W-12050	355.5	0.708046	16	0.708062	28.0	28.0	FO2b
W-12050	400.0	0.707984	13	0.708000	29.7	30.0	FO2
W-12050	432.0	0.708002	11	0.708018	29.5	29.4	FO2
W-12050	507.0	0.707835	17	0.707851	34.0	34.0	Unnamed Eocene
W-12050	586.0	0.707927	8	None	33.6	33.6	Unnamed Eocene
W-15166	286.4	0.708324	8	None	22.9	22.2	FM1
W-15168	381.5	0.708127	5	None	27.9	26.7	FO3
W-15303	105.0	0.708588	10	0.708604	18.6	18.3	FM2
W-15303	230.0	0.708052	41	0.708068	29.6	27.9	FO2b
W-15303	309.5	0.707985	27	0.708001	31.5	29.9	FO2
W-15303	342.5	0.707968	16	0.707984	32.0	30.4	FO2
W-15303	433.0	0.708015	13	0.708031	30.6	29.1	FO2-diagenesis
W-15303	528.5	0.707920	19	0.707936	33.4	31.7	FO1
W-15303	594.0	0.707904	19	0.707920	33.8	32.1	FO1
W-15303	693.0	0.707888	19	0.707904	34.3	32.6	FO1
W-15303	825.0	0.707828	10	0.707844	36.5	34.2	Unnamed Eocene
W-15286	25.0	0.709003	19	0.709019		5.7	Unnamed
W-15286	80.0	0.709033	16	0.709049		5.0	Unnamed
W-15286	153.0	0.708894	13	0.708910	10.1	10.7	FM5
W-15286	161.0	0.708859	13	0.708875	11.7	12.0	FM5
W-15286	239.0	0.708761	17	0.708777	16.1	15.8	FM4
W-15286	276-278.0	0.708699	15	0.708715	17.0	16.7	FM3
W-15286	307-309.0	0.708770	14	0.708786	16.0	15.7	Diagenesis
W-15286	361.0	0.708704	14	0.708720	16.9	16.6	FM3
W-15286	474.0	0.708619	16	0.708634	18.2	19.9	FM2
W-15286	551.0	0.708431	28	0.708447	20.9	20.6	FM2
W-15286	569.0	0.708415	17	0.708431	21.1	20.9	FM2
W-15286	630.0	0.708187	19	0.708203	25.7	25.3	FO3
W-15286	709.5	0.708162	17	0.708178	26.4	25.7	FO3
W-15287	14.0	0.709075	14	0.709091		2.2	Unnamed
W-15287	30.0	0.709075	13	0.709091		2.2	Unnamed
W-15287	88.5	0.709014	18	0.709030		5.4	Unnamed
W-15287	116.5	0.709041	12	0.709057		4.8	Unnamed
W-15287	131.0	0.709041	20	0.709057		4.8	Unnamed
W-15287	162.0	0.709020	15	0.709036		5.3	Unnamed
W-15287	197.0	0.709025	18	0.709041		5.2	Unnamed
W-15287	320.0	0.708936	34	0.708952		7.2	Unnamed
W-15636	295.0	0.708595	13		18.9	18.4	FM3
W-16505	20.0	0.709039	15	0.709054		4.9	Unnamed
W-16505	58.5	0.709067	20	0.709083		2.3	Unnamed
W-16505	72.5	0.709094	13	0.709110		1.8	Unnamed
W-16505	273.9	0.708912	17	0.708928	9.3	10.0	Unnamed
W-16505	460.0	0.708813	22	0.708829	13.7	13.7	Diagenesis?
W-16505	483.0	0.708719	27	0.708935	9.0	9.7	Diagenesis?
W-16505	520.0	0.708581	18	0.708597	18.7	18.4	Diagenesis
W-16505	570.0	0.708734	14	0.708750	16.5	16.2	FM4
W-16505	595.0	0.708692	22	0.708708	17.1	16.8	FM3
W-16505	610.0	0.708650	30	0.708666	17.7	17.4	FM3
W-16505	648.0	0.708643	13	0.708659	17.8	17.5	FM3
W-16505	663.2	0.708796	15	0.708812	14.5	14.4	Diagenesis
W-16505	673.0	0.708630	17	0.708646	18	17.7	FM3
W-16505	696.0	0.708626	17	0.708642	18	17.8	FM3
W-16782	230.0	0.708192	6		26.0	25.5	FO3
W-16782	260.0	0.708182	6		26.3	25.7	FO3
W-16782	310.8	0.708153	6		27.1	26.2	FO3
W-16782	317.1	0.708163	8		26.8	26.0	FO3

Table 2 (continued).

Core	Depth (ft)	$^{87}Sr/^{86}Sr$	±	Interlab correction +0.000016	BKV85 Age (Ma)	BKV95 Age (Ma)	Sequence
W-16814	234.0	0.708504	12	0.708520	19.8	19.5	FM2
W-16814	341.5'	0.708181	6	0.708197		25.4	FO3
W-16814	388.5	0.808166	5		26.8	26.0	FO3
W-16814	630.0	0.708030	12	0.708046		28.7	FO2
W-16814	659.0	0.708042	5		30.3	28.4	FO2
W-16814	684.0	0.707980	20	0.707996		30.1	FO2
W-17000	313.0	0.708730	7		16.7	16.5	FM3
W-17000	347.0	0.708409	20	0.708425	21.2	20.9	FM2
W-17000	374.0	0.708216	9		25.3	25.0	FO3
W-17000	423.0	0.707965	13	0.707981	32.1	30.5	FO2
W-17000	536.0	0.707863	19	0.707879	35.0	33.3	FO1
W-17000	636.5	0.707871	17	0.707887	34.8	33.0	FO1
W-17000	698.5	0.707773	24	0.707789	37.6	35.7	Unnamed Eocene
W-16890	80.0	0.709075	22	0.709091		2.2	Unnamed
W-16890	143.0	0.709054	20	0.709070		3.6	Unnamed
W-16890	409.0	0.708876	12	0.708892	10.9	11.3	FM5
W-16890	570.5	0.708764	27	0.708780	16.1	15.7	FM4
W-16890	614.0	0.708754	16	0.708770	16.2	15.9	FM4
W-16890	765.5	0.708535	21	0.708551	19.4	19.1	FM2
W-16890	797.5	0.708494	29	0.708510	19.9	19.7	FM2
W-16890	898.0	0.708448	29	0.708464	20.6	20.4	FM2
W-16890	960.0	0.708383	13	0.708399	21.5	21.3	FM1

dial parts and are capped by inner neritic and delta front quartz sands. The upper lower Miocene to lower middle Miocene Kw2 sequences (Kw2a and Kw2b) are predominantly fine-grained facies deposited in inner neritic shelf and prodelta environments and are capped by quartz sands (maximum 50 ft [15.2 m]) in localized depocenters. One depocenter is localized in southeastern New Jersey (Cape May County); updip from this deposits of quartz sand from the Kw2 sequence occur, although their distribution is still poorly mapped. Miocene sequences younger than the Kw2 (the Kw3 and Kw-Cohansey) have limited distribution in basins in southeastern New Jersey (Sugarman et al., 1993), where they contain predominantly inner neritic, deltaic, and tidal flat facies. Descriptions of these facies can be found in Miller, et al. (1994), Miller et al. (Chapter 14, this volume), Miller and Sugarman (1995), and Sugarman and Miller (1997).

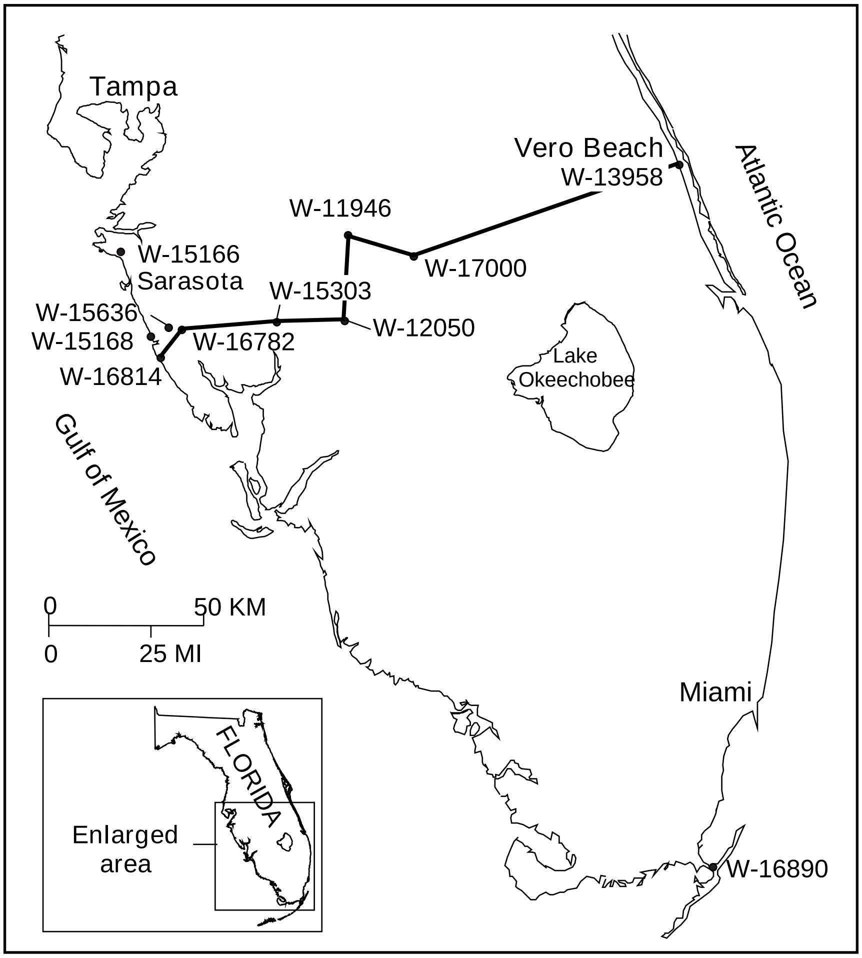

Figure 2. Location of boreholes studied in Florida. Heavy line indicates location of cross section shown in Fig. 3.

Table 3. ^{87}Sr/^{86}Sr age regressions from 0 to 7 Ma.

Age (Ma)	Equation
0–2.5	Age (Ma) = 15235.09 – (^{87}Sr/^{86}Sr) × 21482.28
2.5–4.8	Age (Ma) = 59941.95 – (^{87}Sr/^{86}Sr) × 84530.85
4.8–7.0	Age (Ma) = 15640.06 – (^{87}Sr/^{86}Sr) × 22050.72

Note: Based on data from Farrell et al. (1995).

New Jersey Oligocene Sequences

New Jersey Oligocene sequences determined from the Island Beach, Atlantic City, and Cape May boreholes have been identified by Pekar (1995) and Pekar et al. (Chapter 15, this volume). A short synthesis of these Oligocene sequences, termed O1 through O6, is given below. In New Jersey, the Oligocene rests unconformably over the Eocene with a hiatus of at least 1.0 m.y. (33.8–32.7 Ma).

Lowermost Oligocene Sequence O1

Sequence O1 is present at Island Beach and Cape May; it may be equivalent with the Mays Landing unit named at the ACGS#4 borehole by Owens et al. (1988), although it is possible that the latter is a slightly older sequence. Its age is 32.8–32.2 Ma, and it is assigned to Zones P18 and NP22 (Pekar and Miller, 1996; Pekar et al., Chapter 15, this volume).

Lower Oligocene Sequence O2

Sequence O2 is separated from Sequence O1 by a hiatus of ~1 m.y. (at Island Beach) to 3 m.y. (at Atlantic City; Pekar et al., Chapter 15, this volume). Sequence O2 represents less than 1 m.y. (30.8–29.9 Ma) and is assigned to Zones P19 and perhaps P20 partim (Pekar and Miller, 1996; Pekar et al., Chapter 15, this volume).

Lower Oligocene Sequence O3

A hiatus of ~1 m.y. (29.9–29.0 Ma) separates Sequence O3 from Sequence O2. Sequence O3, with an age of 29.0–28.3 Ma, is only observed at the Atlantic City borehole, where it is equivalent to Zone P21a (Pekar and Miller, 1996; Pekar et al., Chapter 15, this volume).

Lower Upper Oligocene Sequence O4

Sequence O4 is late Oligocene (27.5–27.0 Ma) and unconformably overlies sequence O3, from which it is separated by a hiatus of ~1 m.y. The sequence, equivalent to Zone P21b (Pekar et al., Chapter 15, this volume), is found in the Cape May, Atlantic City, and Island Beach boreholes.

Upper Oligocene Sequences O5/O6

Sequence O5 is found only at Atlantic City, where its age is 27.0–25.6 Ma. It is equivalent to Zone P22. The hiatus between Sequences O5/O4 is below the resolution of Sr-isotope stratigraphy. Sequence O5 is an excellent example of a “New Jersey” sequence in that it coarsens upward from a glauconite sand with outer neritic biofacies to a coarse glauconitic quartz sand with inner neritic biofacies. Sequence O6 (25.1–24.2 Ma), also equivalent to Zone P22, was identified at Atlantic City and Cape May. There is no definite hiatus between Sequences O5 and O6, although a hiatus of 0.5 m.y. is possible. Sequences O5 and O6 may, in fact, be one sequence (Pekar et al., Chapter 15, this volume).

New Jersey Miocene Sequences

Miocene sequences have been dated with Sr-isotope stratigraphy at the Atlantic City and Cape May boreholes (Table 1), where at least seven, and possibly as many as nine, lower to middle Miocene sequences have been identified.

Lowermost Miocene Sequence Kw0

The basal Miocene sequence (Kw0), dated as ~23.6–23.3 Ma at Cape May, is a glauconite sand. At Atlantic City, three shell beds (>0.5 m thick) with glauconite sand (937–924 ft [285.6–281.6 m]) spanning the Oligocene/Miocene boundary (Sr ages of 25.3–21.7 Ma) may represent three truncated sequences (Miller, et al., 1994), including one (23.6–21.4 Ma) that may correlate to Kw0 at Cape May.

Lower Miocene Sequences Kw1a and Kw1b

The Kw1a sequence, deposited between 21.1 and 20.1 Ma, is the most pervasive sequence in the New Jersey subsurface (Sugarman et al., 1993). Shell beds (~1 m thick) and glauconitic sands mark the base of Kw1a. At Atlantic City, the Kw1a sequence (183 ft thick [56 m]) shallows upward, with shelf and prodelta silty clays in the base and delta front sands at the top.

At Atlantic City, the Kw1b sequence is dated as 20.1–19.9 Ma. Sr isotopes cannot be used to resolve a hiatus between Kw1a and Kw1b sequences, although a distinct disconformity is indicated by gamma logs, facies shifts, and an irregular surface at the contact (see also Owens et al. [1988], ACGS#4 borehole; Fig. 1). The section from 850 to 710 ft (259–216 m) at Cape May appears to be younger (19.3–18.4 Ma) than the Kw1b sequence at Atlantic City; it may represent a thicker upper Kw1b section, or a previously unrecognized sequence (Kw1c).

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

A major unconformity (0.5- to 2.0-m.y. hiatus) occurs at the base of Kw2. The overall Kw2 sequence of Sugarman et al. (1993) can be split into a Kw2a (17.8–16.6 Ma) and a Kw2b (16.1–15.6 Ma) sequence separated by a hiatus of ~0.5 m.y.

Unnamed Middle Middle Miocene Sequence

At Cape May, there appears to be a middle middle Miocene (previously unnamed) sequence (Kw2c) that is not present at Atlantic City. The sequence is a shelfal quartz sand with Sr-isotopic ages of 15.2–14.2 Ma. If the uppermost sample at 514 ft (156.7 m) is excluded because of a stratigraphic age inversion, then the sequence is better dated at 14.6–14.2 Ma.

Middle Middle Miocene Kw3 Sequence

A major unconformity separates the Kw2c and Kw3 sequences. The Kw3 sequence is dated as 13.8–13.4 Ma at Atlantic City.

Upper Middle Miocene Kw-Cohansey Sequence

The upper middle Miocene Kirkwood-Cohansey sequence is present at Cape May and dated at 12.1–11.5 Ma (see Miller, et al., 1996a, for discussion).

Florida Depositional Styles

Oligocene and Miocene sedimentary rocks in west-central, peninsular Florida consist of two major lithofacies that differ mainly in their proportions of carbonate and siliciclastic sediment. One lithofacies consists of a series of carbonate beds containing relatively low percentages of siliciclastic and phosphatic minerals. This lithofacies forms most of the lower Oligocene Suwannee Limestone and the Tampa Member of the Arcadia Formation (Hawthorn Group of Scott, 1988). The second lithofacies consists of cycles of silty claystone (locally phosphatic) or carbonate-cemented quartz sandstone interbedded with carbonate beds (also locally phosphatic). This lithofacies characterizes the upper Oligocene and lower to lower middle Miocene deposits, which include most of the Arcadia Formation of Scott (1988), except the Tampa Member.

The two lithofacies reflect the changing influence of terrigenous sedimentation in the depositional history of the region. The biogenic carbonate and phosphatic deposits were generated within the depositional basins, typically at or near the site of accumulation and burial. Terrigenous sediments provided by south-flowing rivers originating in crystalline rocks and coastal plain beds in Georgia and adjacent states moved southward along both coasts of the Florida peninsula by longshore marine currents (McCartan and Owens, 1991; McCartan et al., 1995b, 1995c; Mallinson and Compton, 1995). During periods of high influx of sand, silt, and clay, the relative proportion of carbonate shell fragments diminished. The main locus of siliciclastic sediment transport and accumulation is now along the east coast, as it was along preexisting east-coast shorelines. The secondary locus is the modern west coast and its precursors (McCartan and Owens, 1991; McCartan et al., 1995a, 1995b). Biogenic carbonate shoals occupy much of the area between the main siliciclastic pathways, and carbonate debris from the shoals interfingers laterally with siliciclastic debris along the east and west margins of the Florida Peninsula.

Florida Sequences

The sequences developed in this study are from a transect of boreholes across the Florida Peninsula (Fig. 2). We illustrate the lithologies and sequences from seven of these boreholes (Figs. 3A, 3B). The lithostratigraphic units were published by Scott (1988) and slightly revised in McCartan et al. (1995c). We identify Oligocene Sequences FO1 through FO3 and Miocene Sequences FM1 through FM5 based on integration of the lithostratigraphy and Sr-isotopic data (Figs. 3, 4, 5; Table 2).

Early Oligocene Sequence FO1

Sequence FO1, contained within the “Suwannee” Limestone, unconformably overlies the upper Eocene Ocala Limestone. Limited Sr-isotopic age estimates from upper Eocene strata (W-15303 = 34.2 Ma; W-11946 and W-17000 = 35.7 Ma) provide a tentative age range of 35.7–34.2 Ma (Fig. 4; Table 2) for the uppermost Eocene sequence in Florida. In Core W-17000, an unconformity with a maximum hiatus of 2.7 m.y. (35.7–33.6 Ma) is present between the upper Eocene sequence and lower Oligocene Sequence FO1. W-15303 provides the best set of Sr-isotopic ages for this sequence, which are between 32.6 and 31.7 Ma. The overall ages for Sequence FO1 are 33.3–31.7 Ma (Table 2). In general, this sequence is a relatively pure limestone with low-amplitude, low-frequency spikes on the gamma logs (Fig. 3).

Upper Lower Oligocene Sequence FO2

The Sr-isotopic age range for Sequence FO2 is 30.5–28.4 Ma (Fig. 4). It is often correlated with strata assigned to the Nocatee Member of the Arcadia Formation, except along the west coast, where it is correlated with the lower undivided part of the Arcadia Formation. The hiatus separating Sequences FO2 and FO1 is significant. For example, in Borehole W-15303 (Table 2), a maximum hiatus of 2.6 m.y. is associated with a sequence boundary between 528.5 ft (161.1 m; 31.7 Ma) and 433 ft (132 m; 29.1 Ma). The hiatus may be as short as 1.3 m.y. because of diagenetic alteration of the 433-ft sample. Samples from Sequence FO2 in Borehole W-16814 have a Sr-isotopic age range of 30.1–28.7 Ma (Table 2).

Lower Upper Oligocene Sequence FO2b

Three data points from separate boreholes suggest the possibility of another sequence in the early late Oligocene of Florida with a Sr-isotopic age range of 28.0–27.5 Ma (Fig. 4). A sample from 230 ft (70.1 m) in Corehole W-15303 yielded a Sr-isotopic age of 27.9 Ma. Another sample from Corehole W-11669 at 369 ft (112.5 m) had a Sr-isotopic age of 27.5 Ma, whereas the 355.5-ft sample (108.4 m) from W-12050 had a Sr-isotopic age of 28.0 Ma (Table 2). Because the possible hiatus of 0.4 m.y. between this sequence and the FO2 sequence is below the resolution for Sr-isotope stratigraphy, we consider Sequence FO2b as the upper part of sequence FO2.

Upper Oligocene Sequence FO3

Sequence FO3 has a Sr-isotopic age range of 26.3–25.3 Ma (Fig. 4). A reliable series of Sr-isotopic age estimates for this sequence was derived from Borehole W-16782, where four samples ranged from 26.2 to 25.5 Ma (Table 2). A 1.2-m.y. hiatus separates the FO3 and FO2b sequences. Sequences FO2, FO2b, and FO3 consist of a mixture of siliciclastic, phosphatic, and carbonate deposits with higher amplitude, higher frequency spikes on the gamma logs (Fig. 3).

Lower Miocene Sequence FM1

A major hiatus of ~2 m.y. (25.5–22.9 Ma) separates Oligocene Sequence FO3 from Miocene Sequence FM1 in south Florida. Sequence FM1 has a Sr-isotopic age range of 22.9–20.9 Ma (Fig. 5).

Upper Lower Miocene Sequence FM2

Miocene sequence FM2 has a Sr-isotopic age range of 20.8–18.2 Ma. The duration of the hiatus at the FM2/FM1 sequence contact could not be resolved in this study. FM2 is well dated using Sr-isotopes in the W-12050 borehole at 20.8–18.6 Ma (Table 2). It is possible that an unconformity exists between the 124-ft (37.8 m; 18.6 Ma) and 160-ft samples (48.8 m; 19.3 Ma). We were unable to locate the lithologic contact that corresponds to the FM2/FM1 sequence contact; however, additional cores might recover it. In northeast Florida, Mallinson and Compton (1995) identified two depositional sequences with maximum sea-level fluctuations at 20.5 and 18.7 Ma.

Upper Lower Miocene Sequence FM3

Sequence FM3 has a Sr-isotopic age range from 17.5 to 16.5 Ma (Fig. 5). An excellent section of this sequence from Borehole W-16505 yielded Sr-isotopic ages of 17.8–16.8 Ma.

Lower Middle Miocene Sequence FM4

Sequence FM4 has an age range from 16.2 to 15.7 Ma (Fig. 5). The hiatus between FM3 and FM4 (~0.3 m.y.) is below the resolution of Sr-isotope stratigraphy, but is present in Borehole W-16505 between 570.0 and 595 ft (173.7 and 181.4 m).

Upper Middle to Lower Upper Miocene Sequence FM5

Sequence FM5 is tentatively identified only in Boreholes W-15286 and W-16890 in the southern peninsula. Sr-isotopic age estimates are 12.0–11.3 Ma (Fig. 5).

DISCUSSION

Correlation of Coastal Plain Sequences with Global Sea-Level Proxies

The age of Oligocene and Miocene sequence boundaries determined in cores from New Jersey and Florida show excellent correlation with deep-sea δ^{18}O increases, which are inferred glacioeustatic lowerings (Figs. 4, 5). Lower Oligocene sequence boundaries in Alabama also appear to correlate with δ^{18}O increases (Miller et al.,

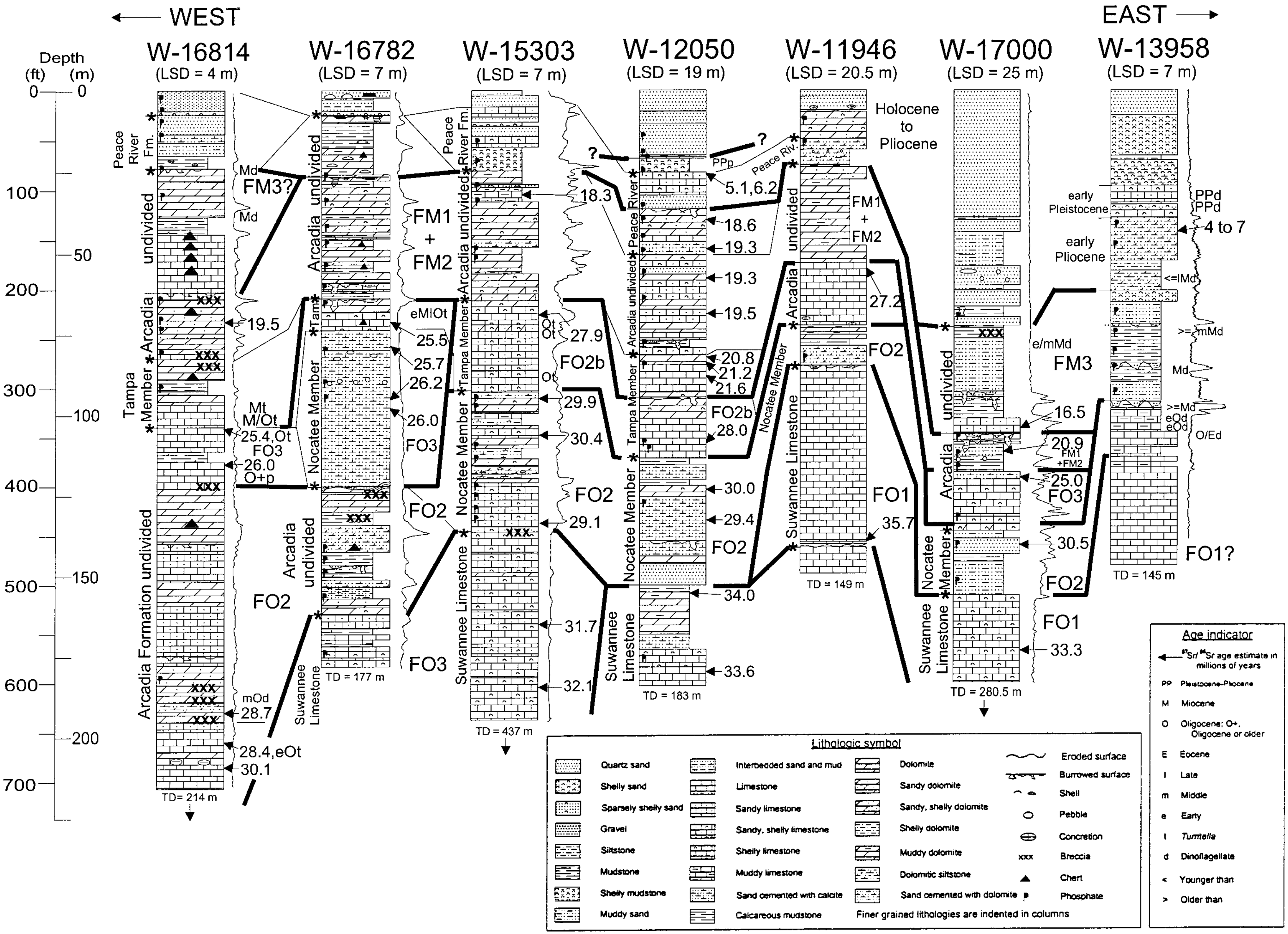

Figure 3. East–west cross section across the central Florida peninsula showing well lithologies, gamma-ray geophysical logs (where available), sequence terminology, and stratigraphic nomenclature. LSD = land surface datum.

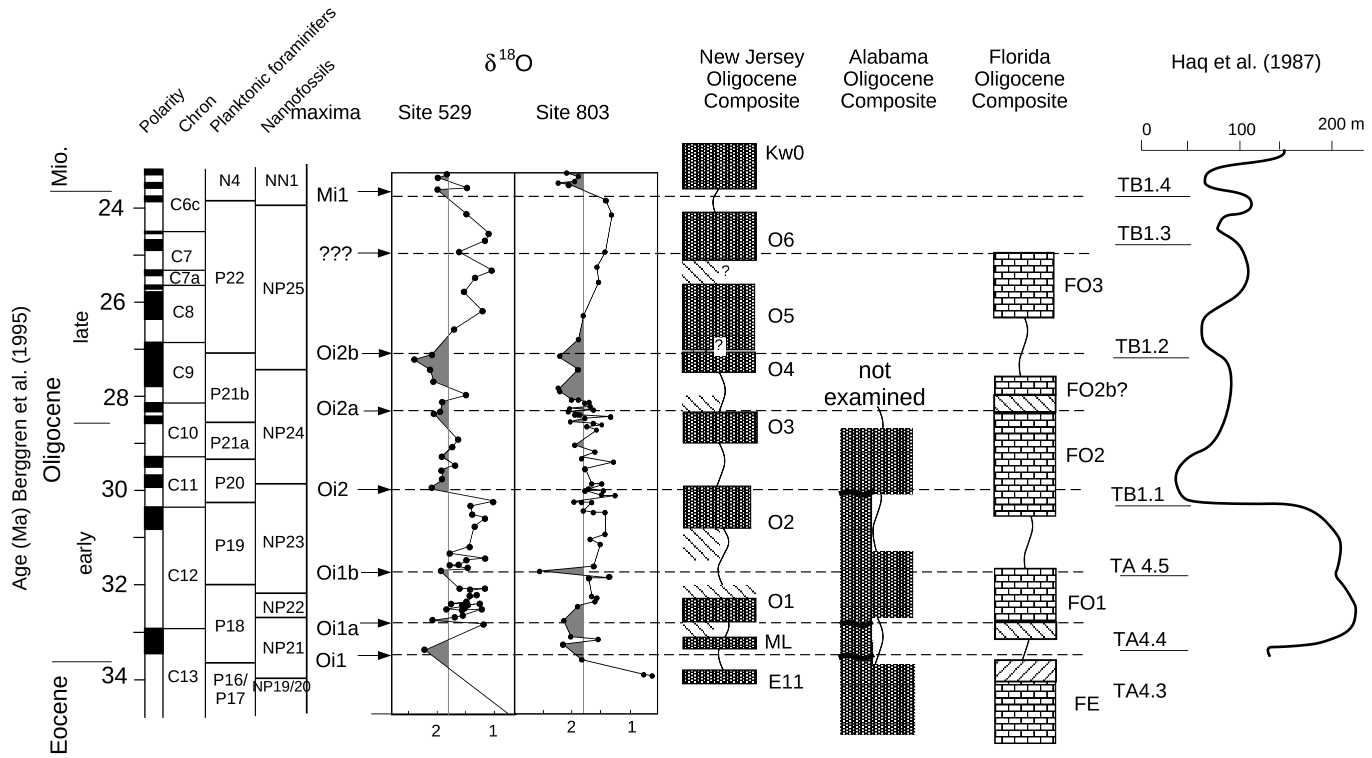

Figure 4. Comparison of New Jersey, Florida, and Alabama Oligocene sequences and the deep-sea $\delta^{18}O$ record and the Haq et al. (1987) inferred eustatic record. Ages are based on the GPTS of Berggren et al. (1995). Isotope maxima are from Miller et al. (1991b) and Pekar et al. (Chapter 15, this volume). Alabama data from Miller et al. (1993). Thinner boxes in the Alabama column are areas of uncertainty.

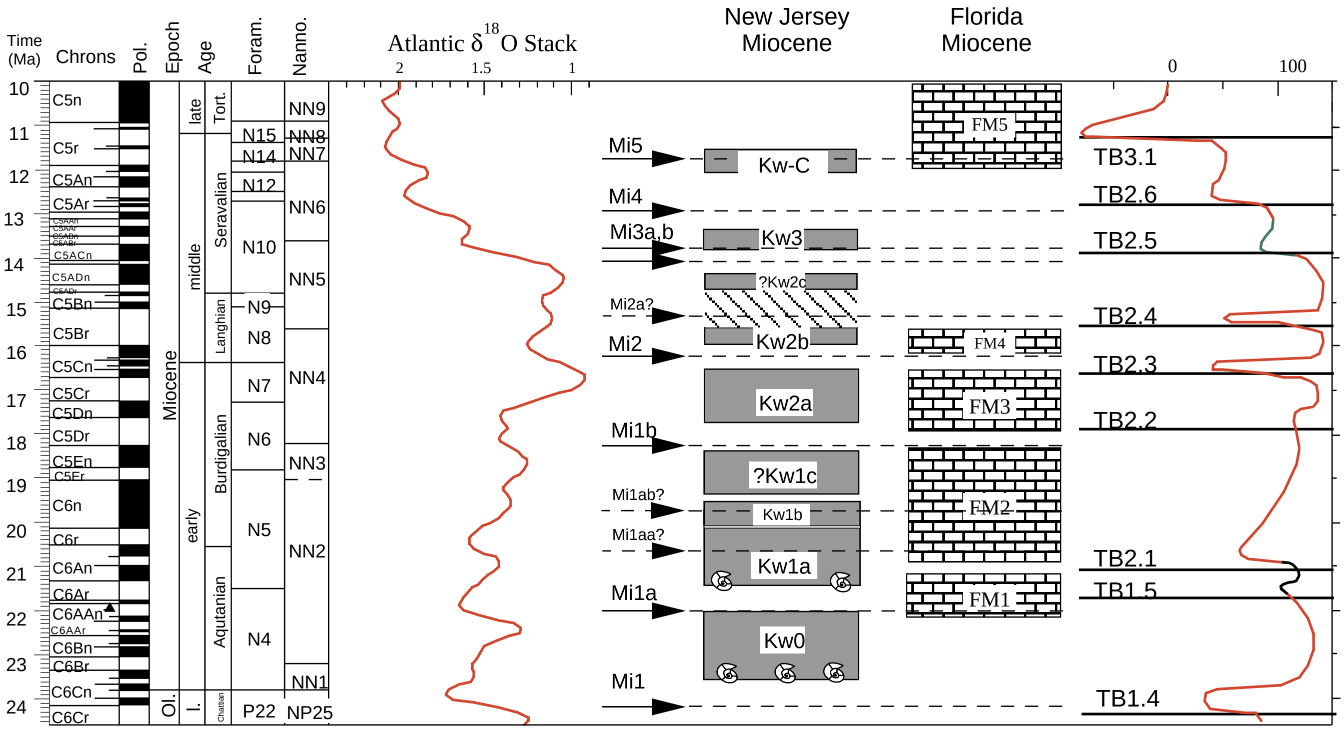

Figure 5. Comparison of New Jersey and Florida Miocene sequences with the deep-sea $\delta^{18}O$ record (Miller et al., 1991b, 1996b) and the Haq et al. (1987) inferred eustatic record.

1993; Fig. 4). Assuming that these correlations are valid (see below for discussion of uncertainties in correlations), this is strong confirmation that global sea-level change is a primary control on the timing of Oligocene sequence boundaries for the coastal plain sections studied here.

Hiatuses separate Eocene sequences from the oldest Oligocene sequences in New Jersey and Florida, and there is a probable hiatus in Alabama (Fig. 4). These earliest Oligocene hiatuses correlate with the Oi1 and Oi1a δ^{18}O increases (33.5 and 32.8 Ma) and with the TA4.4 sequence boundary of Haq et al. (1987; Fig. 4). The Oi1 event is a major earliest Oligocene increase that represents at least 30–50 m of glacioeustatic lowering (Miller et al., 1991b).

The Oi1a and Oi1b δ^{18}O increases are smaller amplitude (<0.5‰) increases identified in higher resolution deep-sea records (Pekar et al., Chapter 15, this volume), and their global significance is unknown. Nevertheless, we assume that they represent probable sea-level lowerings of ~20–30 m, and there is a reasonable correlation of events in New Jersey, Florida, and Alabama with these increases. The O1 sequence in New Jersey and FO1 sequence in Florida are bracketed by the Oi1/Oi1a (33.5/32.8 Ma) and Oi1b (31.7 Ma) δ^{18}O increases. A possible lowermost Oligocene sequence in New Jersey at the ACGS#4 borehole (Owens et al., 1988) may be bracketed by the Oi1 and Oi1a increases (ML in Fig. 4). Although both the Oi1a and Oi1b δ^{18}O increases apparently correlate with no discernible hiatuses in Alabama, the former correlates with a possible sequence boundary at the top of the Forest Hill/Red Bluff Formations (top of Chronozone C13n) and the latter with the base of the Glendon Formation (Miller et al., 1993).

The major Oi2 (30.3 Ma) δ^{18}O increase (Fig. 4) correlates (1) reasonably well with a hiatus in New Jersey, (2) moderately well with a hiatus in Florida between the FO2 and FO1 sequences, and (3) very well with a major sequence boundary at the base of the Chickasawhay Formation in Alabama (Miller et al., 1993). The O2 sequence in New Jersey correlates with the TA4.5 cycle of Haq et al. (1987).

The Oi2 (30.3 Ma) and Oi2a (28.1 Ma) δ^{18}O increases are almost identical in age to the FO2 sequence boundaries (Fig. 4). The O3 sequence in New Jersey represents a much shorter sequence that was deposited between δ^{18}O increases. The upper surface of the O4 New Jersey sequence correlates well with the Oi2a/Oi2b (27.0 Ma) zonal boundary. A possible sequence of short duration may also be present in Florida during the time interval between the Oi2a and Oi2b δ^{18}O increases.

The uppermost Oligocene O5/O6 sequences are bracketed by the Oi2b and Mi1 δ^{18}O increases, with the upper surface of the O6 sequence being coeval with the Mi1 increase (23.8 Ma). The O5/O6 sequence boundary may correlate with a minor, unnamed δ^{18}O increase (Fig. 4; Pekar et al., Chapter 15, this volume). The FO3 sequence in Florida may correlate with the New Jersey O5 sequence. The O5 and O6 sequences correlate well with the TB1.2 and TB1.3 cycles of Haq et al. (1987). The FO3 sequence correlates with their TB1.2 sequence.

Miller and Sugarman (1995) and Miller, et al. (1996a) documented correlation between New Jersey Miocene onshore sequences, δ^{18}O increases, and Haq et al. (1987) sequences using the Berggren et al. (1985) time scale. Using the Berggren et al. (1995) time scale improves the comparisons further. For example, the Mi1, Mi1a, Mi1b, Mi2, Mi3a/b, and Mi4 δ^{18}O increases correlate with hiatuses associated with the New Jersey sequence boundaries Kw0, Kw1a, Kw2a, Kw2b, Kw3, and Kw-Cohansey, respectively, and the Haq et al. (1987) Sequences TB1.4, TB1.5/2.1, TB2.2, TB2.3, TB2.5, and TB2.6, respectively (Fig. 5). Smaller δ^{18}O increases not previously identified (Mi1aa, Mi1ab, Mi2a on Fig. 5) may correlate with the remaining Kw1b, Kw1c, and Kw2c sequence boundaries, although the significance of these increases and higher order sequences is uncertain.

The New Jersey onshore sequences also correlate reasonably well with the Florida Miocene sequences described here and with the northeastern Florida sequences described by Mallinson and Compton (1995). The bases of the FM2, FM3, and FM4 sequences correlate with the bases of Kw1a, Kw2a, and Kw2b sequences, respectively (Fig. 5).

There are still uncertainties in the correlations presented here. First, the significance of the higher order sequences (e.g., Kw1b, Kw1c, Kw2c) is not certain. Second, correlation with several of the Haq et al. (1987) cycles still remains equivocal. For example, Miller et al. (1996b) correlated the TB2.4 Haq et al. (1987) cycle with the Mi3a and 3b oxygen-isotope events, a correlation that we still prefer; however, we show that it may be possible to correlate TB2.4 with an older, albeit smaller scale, oxygen-isotopic event (“Mi2a”). Third, Sr-isotopic stratigraphy has age resolution of ±0.6–0.4 m.y. for the early Miocene and ±1.2–0.8 m.y for the middle Miocene at the 95% confidence interval using 1 and 3 analyses per level, respectively (Oslick et al., 1994).

To evaluate the validity of Sr-isotopic correlations of sequence boundaries and δ^{18}O increases, we tied sequence boundaries at Cape May and Atlantic City directly to the benthic foraminiferal δ^{18}O record at ODP Site 608 (Fig. 6; Miller et al., 1991a). We did this by projecting New Jersey Sr-isotopic values onto a linear fit of Sr vs. depth at Site 608 (Fig. 6), circumventing any uncertainties in the Sr age calibrations. With the exception of the Kw2b-Mi2 correlation, all of the other correlations are actually improved using this method (Fig. 6). This also suggests that some of the slight (<0.5 m.y.) mismatches between the smoothed δ^{18}O records and sequences (Figs. 4, 5) results from problems in stacking and smoothing the stable isotopic records from three sites. We conclude that our correlations of sequence boundaries with δ^{18}O increases are valid and that glacioeustasy is responsible for forming these unconformities.

Sedimentation and Tectonics

Siliciclastic sediments in the New Jersey Margin record the dynamics between sediment supply, subsidence, and eustasy. The typical New Jersey sequence (Sugarman et al., 1993; 1995) is an unconformity-bounded, shoaling-upward, sedimentary column whose architecture offers some clues to the dynamics of sea level, subsidence, and sediment supply. The lowermost parts of sequences consist of beds of glauconite sand or quartzose glauconite sand (~3–6 m thick) deposited in middle to outer shelf environments. These beds accumulated at a relatively low rate of 1–5 m/m.y. (Sugarman et al., 1995; Miller and Sugarman, 1995). These low sedimentation rates suggest sediment supply was limited. The clay-silts and quartz sands found in the middle to upper part of sequences record a progradational phase in which sediment supply was more plentiful in shallower water environments (e.g., inner shelf, delta front). Sedimentation rates in these Highstand Systems Tract deposits were relatively rapid (25–100 m/m.y.), with the majority of the sediment deposited more quickly when compared with the Transgressive Systems Tract. In order for the bulk of the sequence to be deposited in a relatively short amount of time, some combination of increased sediment supply (tectonics?; proximity to the depocenter?) coupled with increased subsidence seems necessary to allow accommodation in shallow-water depths (<30 m).

Although global sea level has been shown to have a significant influence on coastal plain sequences (Figs. 4, 5), comparisons of sequences within the same depositional basin and between basins have been shown to vary significantly (e.g., Pekar et al., Chapter 15, this volume; Miller and Sugarman, 1995). In a comparison of New Jersey and Maryland Miocene sections from the Salisbury Embayment, Miller and Sugarman (1995) demonstrated that most of the lower Miocene present in New Jersey is missing in outcrop and the subsurface of Maryland. In contrast, the upper Miocene to Pliocene is largely nonmarine and thin in New Jersey, but is thicker and largely marine in Maryland (Gibson, 1983). These differences are likely the result of tectonics. One possible mechanism that could explain the distribution of sequences is progressive downwarping of the Salisbury Embayment to the south (Owens et al., Chapter 2, this volume). This would

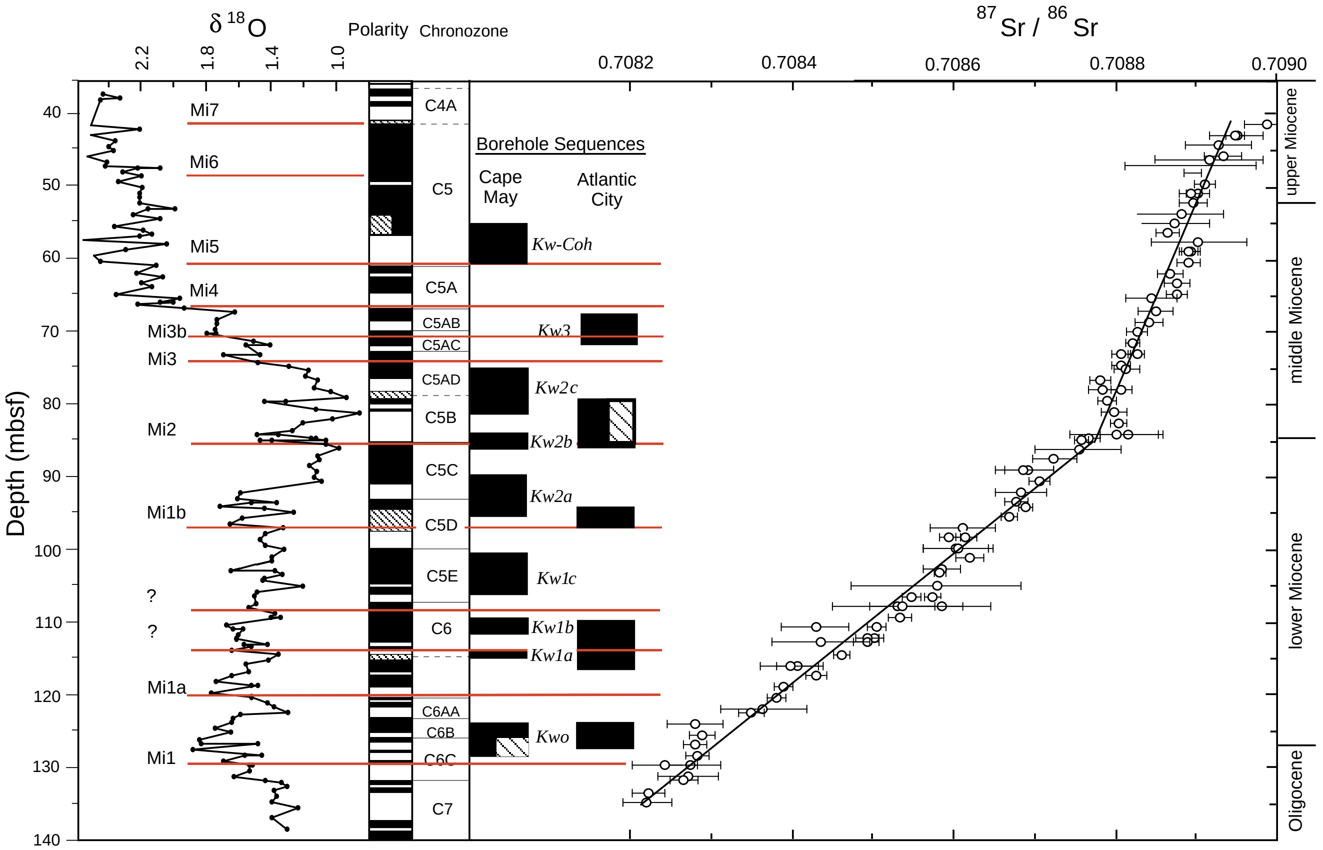

Figure 6. Projection of Leg 150X Miocene Sr-isotopic values on the Sr- and oxygen-isotopic and magnetostratigraphic record at Site 747 (Oslick et al., 1994). Two linear regressions were fit through the Site 747 Sr-isotopic data, and Sr-isotopic values for the Leg 150X sequences (Table 1) were projected from their corresponding values on the regression to the equivalent depths. Sequences projected into the Site 747 depths are indicated as black boxes; equivalent hiatuses are indicated with open intervals. Such projections allow direct comparison of the sequence with the oxygen-isotopic proxy for glacioeustasy, independent of age models and time scales.

have allowed thicker lower Miocene accumulations in New Jersey than in Maryland, where a possible arch prevented sediment accumulation (Owens et al., 1988; Owens et al., Chapter 2, this volume). As the basin subsided to the south, thicker marine deposits would have been preserved in the southern Salisbury Embayment (Maryland) compared with thinner marginal to nonmarine deposits in New Jersey in the upper middle and upper Miocene. Other possible explanations for the absence of lower Miocene strata in Maryland include faulting of crustal blocks (Brown et al., 1972), local flexural subsidence (Pazzaglia and Gardner, 1994), or differential subsidence caused by sediment loading (Miller and Sugarman, 1995).

Regional differences among sequences in Florida also may reflect local nondeposition caused by tectonic emergence or significant postdepositional erosion. For example, a significant break that occurred across the Oligocene/Miocene boundary (about 23.7 Ma) in Florida (Table 4; e.g., between Sequences FO3 and FM1 in central Florida; Figs. 4, 5) can be unequivocally attributed to the Mi1 glacioeustatic fall (Miller et al., 1991b); however, the long hiatus associated with this boundary (e.g., ~3 m.y. in central Florida; Figs. 4, 5) may reflect regional tectonic accentuation. The distribution of other Floridian Oligocene to Miocene strata also may reflect tectonic effects on the following:

1. In the northwest, the entire upper Oligocene and most of the middle and upper Miocene appear to be missing. Mallinson et al. (1994) believed that the northeast corner of Florida was emergent during most of the Oligocene, and emergence may also account for the general absence of upper Oligocene strata in the northwest.
2. In the northeast, the lower Oligocene and most of the upper Oligocene are missing, and the middle and upper Miocene are well represented (Mallinson et al., 1994; Table 4).
3. In the central part of the peninsula, most of the middle Miocene is not represented. This region was emergent during the middle to early late Miocene (16 Ma to about 6 or 5 Ma), judging from biostratigraphic data, including land and estuarine vertebrate paleogeography (Webb et al., 1981; Webb and Hulbert, 1986; Hulbert, 1987), and the absence of marine deposits (Fig. 4).

Changes in sediment provenance and supply also contribute to sequence differences within and between basins. Starting in the early Oligocene, siliciclastic and phosphatic deposition gradually increased as carbonate deposition declined in northern and central Florida. Today, carbonate deposits accumulate only in the Florida Keys and in Florida Bay. Complicating the basic interplay between carbonate, siliciclastic, and phosphatic sedimentation is the effect of locally subsiding basins and uplifting arches (Owens et al., 1988; Owens et al., Chapter 2, this volume), epeirogenic uplift (Opdyke et al., 1984), and limestone dissolution that may cause isostatic rebounding (Opdyke et al., 1984). Despite the importance of changes in sediment provenance and supply and tectonics on deposition in Florida, we note that the similar timing of sequence boundaries between New Jersey and Florida and their close association with δ^{18}O increases (Fig.

Table 4. ^{87}Sr/^{86}Sr ages estimates of Oligocene and Miocene sea-level highstands in Florida.

Stratigraphic age (Ma)	Northcentral and northwestern (S)^a	Northeastern (P&D)^{b*}	Northeastern (P&D)^{b†}	Central peninsula (S)^c	Central peninsula (S)^a	Southern peninsula (S)^c
middle middle to late Miocene	12.1, 12.2	6–8 9.1–10.9, 12.4	7.7? 8.8–13.6 14.8–14.9			7.2? 9.3–11.7 13.7, 14.5
late early to early middle Miocene	17.5	13.2–16.9	15.6–17.3	16.7–17.3		16.0–17.1
early Miocene	18.5, 18.7 19.2–20.5	17.9–19.2 20.0–21.3	17.9–19.3 20.0–21.2 20.6–21.5	18.6–19.8 21–21.9		17.7–18.7 19.4–19.9
late Oligocene	24.4–24.7	24.2–25.9	24.7–26.7	25.3–28	25.3–25.6 28.6–32.1	25.7–26.4
early Oligocene	33.3–35.5			33.3–35.8	34.1	

Notes: S = shallow-water carbonate shells; P&D = dolomite and phosphorite grains and crusts. ^{a} = Jones et al., 1993; ^{b} = Mallinson et al., 1994; Mallinson and Compton, 1995 (0.708830, 0.708629, and 0.708317 were omitted to emphasize gaps in age estimates); * = calculated using the regression equation of Hodell et al., 1991; † = calculated using the regression equation of Oslick et al., 1994; ^{c} = Wingard et al., 1994, values only; McCartan, Weedman, et al., 1995.

4) demonstrates that glacioeustasy is a primary control on deposition in these regions.

CONCLUSIONS

1. Oligocene to lower middle Miocene siliciclastic sequences in New Jersey correlate well with carbonate and mixed carbonate-siliciclastic sequences in central Florida and with lower Oligocene mixed carbonate-siliciclastic sequences in Alabama.
2. There is an excellent correlation between Oligocene to lower middle Miocene sequence boundaries in New Jersey and Florida, lower Oligocene sequences in Alabama, and deep-sea δ^{18}O increases, which are inferred glacioeustatic lowerings. These correlations indicate that global sea-level change was a primary control on the timing of Oligocene to Miocene "Icehouse World" sequence boundaries for the Atlantic Coastal Plain.
3. Although Oligocene to Miocene sequences generally correlate throughout the Atlantic Coastal Plain, there are differences among locations. Regional differences are evident in the better preservation of upper lower Oligocene sequences in Florida and Alabama, the absence of the uppermost Oligocene, lowermost Miocene, and upper middle Miocene sequences in Florida, and the absence of the lowermost Miocene sequence in Maryland. The timing of sequence boundaries is better established in the New Jersey Miocene because of more detailed Sr-isotopic age estimates from shell beds. Poor correlation exists after the early middle Miocene (post ~15 Ma) between New Jersey and Florida because the majority of the middle Miocene is missing from central Florida. The early late Miocene is probably represented in New Jersey, although correlation of Sr isotopes to the late Miocene of Florida is not possible, because the majority of upper Miocene strata in New Jersey are nonmarine and contain unsuitable material for Sr-isotope stratigraphy.

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