Eocene-Oligocene sea-level changes on the New Jersey coastal plain linked to the deep-sea record

KENNETH G. MILLER *Department of Geological Sciences, Rutgers University, New Brunswick, New Jersey 08903,* and *Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964*
DENNIS V. KENT
ANDREW N. BROWER } *Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964*
LAUREL M. BYBELL *U.S. Geological Survey, Reston, Virginia 22092*
MARK D. FEIGENSON
RICHARD K. OLSSON } *Department of Geological Sciences, Rutgers University, New Brunswick, New Jersey 08903*
RICHARD Z. POORE *U.S. Geological Survey, Reston, Virginia 22092*

ABSTRACT

We use magnetostratigraphy and Sr-isotope stratigraphy to improve stratigraphic control for the Eocene to Oligocene of the New Jersey coastal plain (ACGS4 borehole). Magnetostratigraphy in many cases is complicated in outcrop sections of shallow-water (<200 m paleodepth) sediments by low remanence and weathering; we minimize these problems by analyzing large samples obtained from the ACGS4 borehole and construct a firm magnetochronology for the early to middle Eocene. Sr-isotope stratigraphy confirms biostratigraphic evidence for a previously unknown uppermost Eocene to lowermost Oligocene unit and delineates a "middle" Oligocene hiatus that is unresolvable using biostratigraphy alone. We recognize hiatuses and associated unconformities on the New Jersey margin near the lower Eocene/middle Eocene boundary, within the middle Eocene, and in the "middle" Oligocene and correlate these events with similar hiatuses observed in other continental-shelf, slope, and epicontinental settings. In addition, a hiatus probably occurred near the middle Eocene/upper Eocene boundary. We conclude that the interregional distribution of these Eocene-Oligocene hiatuses indicates a global cause: eustatic change.

INTRODUCTION

Relative sea-level changes on continents and their margins reflect variations in global sea level, sediment supply, and basin subsidence and have been inferred from transgressions/regressions of the shoreline, changing water depths, and stratal discontinuities (regional unconformities and hiatuses). Unconformities form on passively subsiding continental margins during eustatic lowerings, and their formation is relatively insensitive to sediment supply (Christie-Blick and others, 1989). Tectonic subsidence along old, passive continental margins generally follows a simple thermal subsidence curve (Steckler and Watts, 1982). Hence, studies of unconformities on old, passive margins (such as the Cenozoic margin of New Jersey) potentially provide a way to evaluate the timing, if not the magnitude, of major global sea-level (eustatic) lowerings.

Seismic and sedimentary sequence stratigraphy provides one means for evaluating unconformities on passive margins (for example, Vail and others, 1977; Baum, 1986; Haq and others, 1987). Because of uncertainties in subsidence and paleodepth corrections, the exact relationships among eustasy, seismic stratigraphy, and sedimentary sequence stratigraphy remain controversial; still, seismic disconformities generally form during lowerings of relative sea level (summary in Christie-Blick and others, 1989). Hiatuses are generally associated with disconformities formed during these sea-level lowerings (for example, Aubry, 1985; Graciansky, Poag and others, 1985; Miller and others, 1985b, 1987a, 1987c; Poag, Watts, and others, 1987; van Hinte, Wise and others, 1987). In order to differentiate regional from global causes, the age equivalency among hiatuses on different continental margins must be firmly established, and this requires detailed detailed biostratigraphy, magnetostratigraphy, and isotope stratigraphy (discussion in Miller and Kent, 1987). Herein, we focus on Eocene-Oligocene stratigraphic breaks of the New Jersey coastal plain and correlate these with breaks on other margins, the deep-sea record, and other evidence for eustatic lowerings.

Deciphering the influence of sea-level fluctuations on the stratigraphic record poses a paradox. Shallow-water (neritic) sections are most sensitive to sea-level changes but are generally difficult to correlate to a standard chronostratigraphy because planktonic index fossils are generally rare or controlled by facies changes, and deposition tends to be discontinuous. Conversely, deep-sea (bathyal to abyssal) sections in most cases are more complete and have better stratigraphic control, but the link between deep-sea deposition and sea-level fluctuations is not direct (Tucholke, 1981). The solution to this paradox is to develop chronostratigraphic standards correlated to deep-sea sections (for example, Berggren and others, 1985; Miller and others, 1988); to monitor sea-level changes using shallow, passive continental-margin sequences (for example, Aubry, 1985; Olsson and Wise, 1987); and to use facies-independent means (for example, magnetostratigraphy, Sr-isotope stratigraphy) to correlate the two regions.

The Eocene-Oligocene record on the New Jersey coastal plain contains stratigraphic gaps that have been related to relative sea-level lowerings. Olsson and others (1980) noted a prominent unconformity between the middle Eocene and upper Oligocene that may be related to a "middle" Oligocene glacio-eustatic lowstand (Miller and others, 1985b). Olsson and Wise (1987) recognized six early to middle Eocene hiatuses in the coastal plain associated with paleobathymetric changes. In contrast to this view of a punctuated record, the continuously cored ACGS4 borehole near Mays Landing, New Jersey, indicates that the coastal-plain record may be more complete than previously believed (Owens and others, 1988). At the ACGS4 borehole, Poore and Bybell (1988) identified every nannofossil zone from the upper lower Eocene to lowermost Oligocene (Zones NP12–NP21), including a previously unknown uppermost Eocene–

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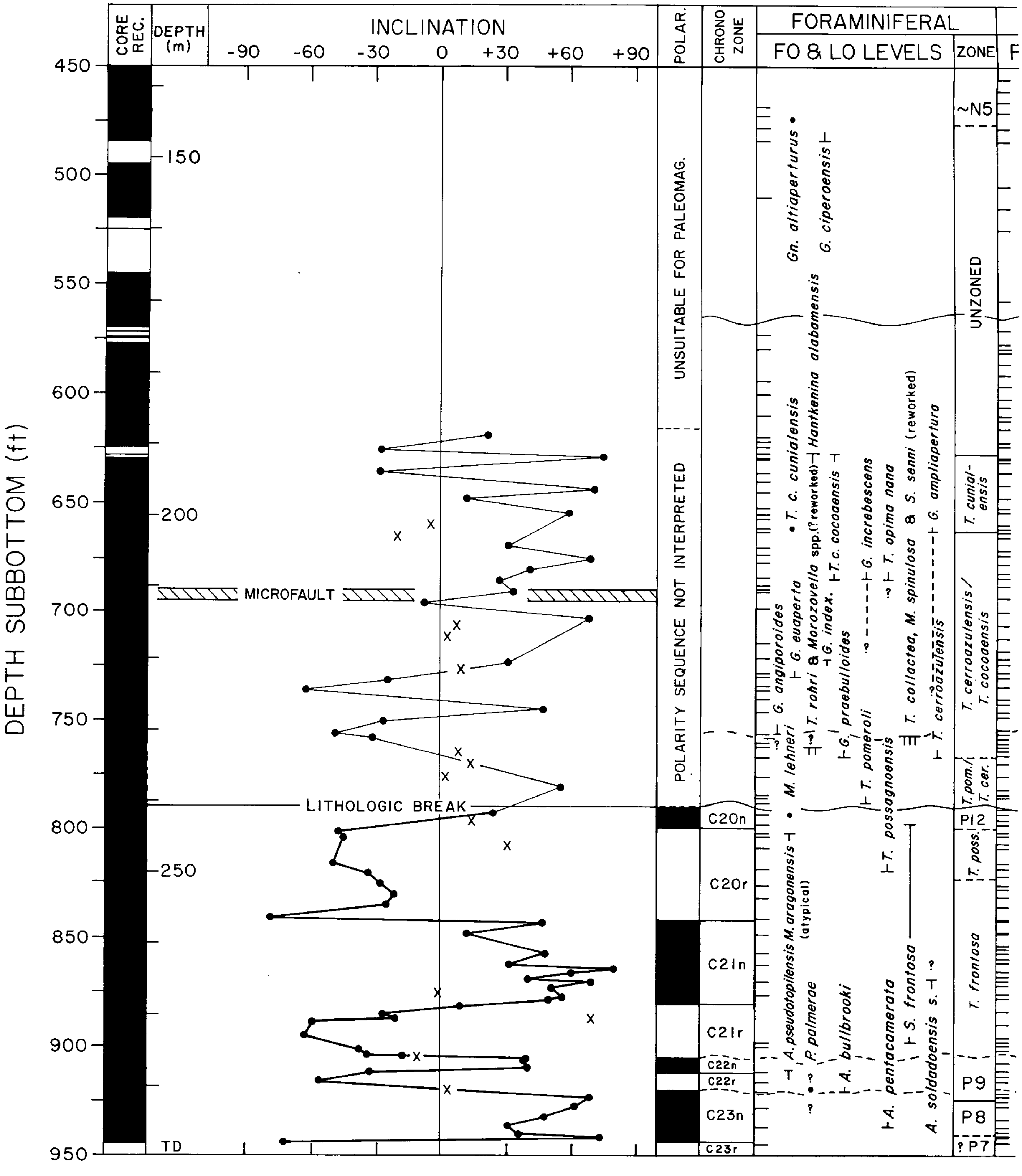
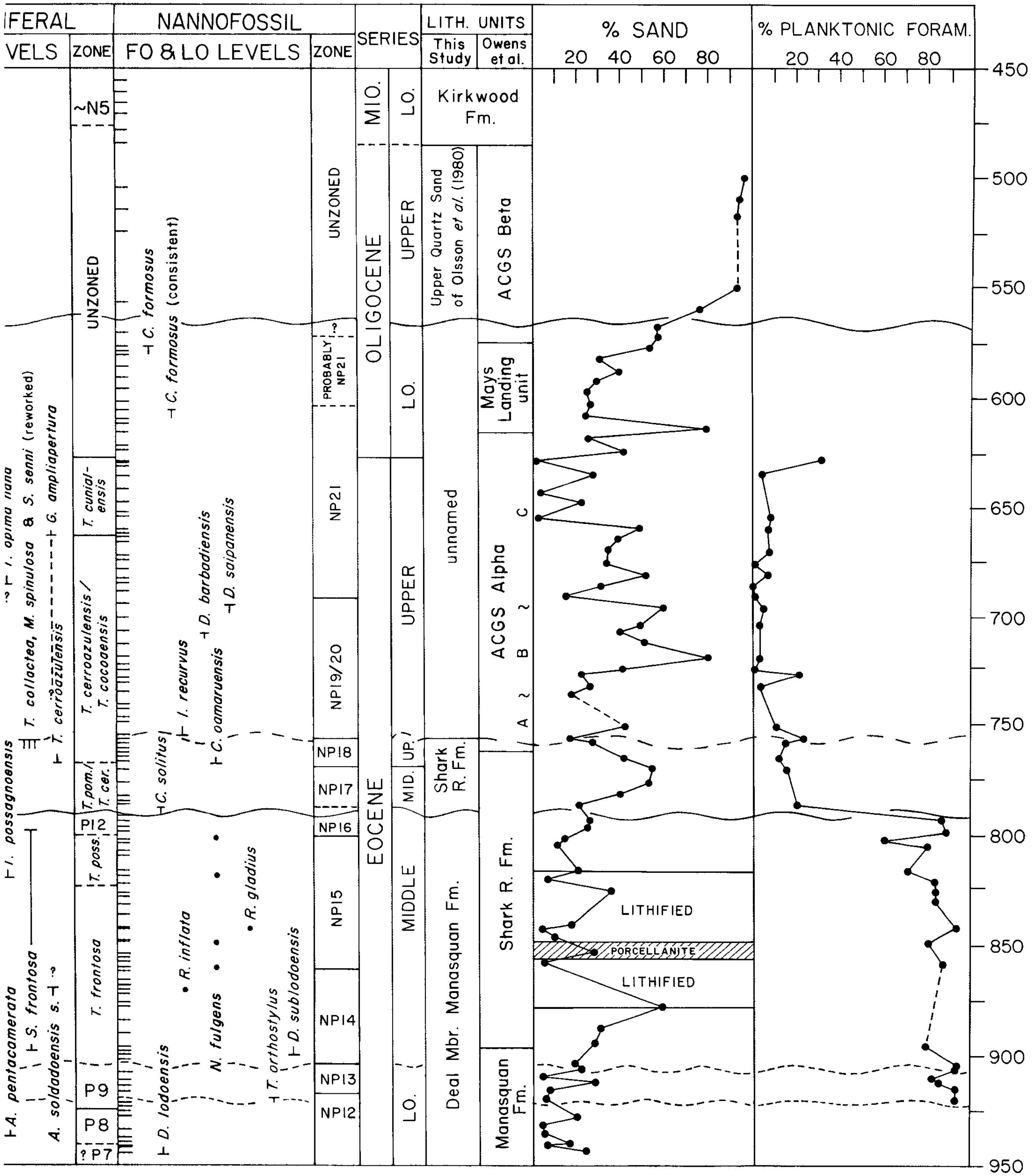


Figure 1. Magnetostratigraphic, biostratigraphic, and lithologic data for ACGS4 borehole, Mays Landing, New Jersey. Wavy lines indicate disconformities (solid) or inferred disconformities (dashed). Inclinations of samples with reliable magnetic behavior are plotted as solid circles and connected by lines; x's indicate samples with erratic magnetic behavior. Biostratigraphic data from Tables 1 and 2 in Poore and Bybell (1988); foraminiferal zonation after Poore and Bybell except for assignments to Zones P7–P9 and P12, which are based upon their identifica-



tions and the revised zonal scheme of Berggren and Miller (1988). Lithologic units column compares our interpretation of the formational assignments with that of Owens and others (1986) (see text). Percent sand computed relative to total weight except for the lithified interval between 250 and 265 m, where the sand fraction was normalized to the <1 mm size fraction (the >1 mm size fraction contained unprocessed fragments). Percent planktonic foraminifera computed relative to total foraminifera. (Note overlap in center.)

lowermost Oligocene unit. Still, they suspected that hiatuses occurred during the Eocene-Oligocene. These previous biostratigraphic studies differ because of problems inherent in shallow-water sections: scarcity of marker microfossils, sample coverage in wells, reworking, lateral facies variations, and local differences in basinal development. We applied magnetostratigraphy and Sr-isotope stratigraphy to the Eocene-Oligocene section recovered at the ACGS4 borehole in order to refine coastal-plain correlations, to estimate the ages of the major unconformities, and to place the strata into a global chronostratigraphic framework.

LITHOLOGY AND SETTING

The ACGS4 borehole was drilled near Mays Landing, New Jersey, by the U.S. Geological Survey and the New Jersey Geological Survey. Total depth was 288 m (945′). The Paleogene section can be divided into three general parts (Fig. 1).

(1) From the base (288 m; 945′) to 241 m (790′), the section consists of lower to middle Eocene yellow-ash gray clay and silt with a mean sand content of 26.6%. The high percentage of planktonic foraminifera (mean: 84.3% planktonic/total foraminifera) (Fig. 1) suggests deposition in deep water (middle bathyal depths, >600 m; for example, Grimsdale and van Morkhoven, 1955); however, benthic foraminiferal biofacies studies indicate deposition in outer neritic water depths (~150 m; Biofacies 4 of Olsson and Wise, 1987, dominated by *Pyramidina subrotundata* and *Siphonina claibornensis*; Christensen and others, 1989). We suggest that this discrepancy in paleodepth estimates is caused by penetration of anomalously high numbers of planktonic foraminifera into the Eocene neritic zone, owing to its ramp-type physiography (Poag and Low, 1987); alternatively, many Eocene species were able to tolerate shallower water than can the Recent species, which were the basis for the study of Grimsdale and van Morkhoven (1955).

(2) From 241 m (790′) to 174 m (570′), the section consists of middle to upper Eocene and lowermost Oligocene green to gray silty sand to sandy silt (mean 35.5% sand). This section was deposited in middle neritic depths (30–100 m), as indicated by the low numbers of planktonic foraminifera (10.5% mean planktonic/total foraminifera) and by the presence of benthic foraminiferal Biofacies 1 of Olsson and Wise (1987), which is dominated by *Epistominella minuta* and *Hanzawaia mauricensis* (Christensen and others, 1989).

(3) From 174 m (570′) to the top of the Paleogene section (148 m; 485′), the section consists of upper Oligocene sands (mean 85.4%) deposited in inner neritic to beach conditions (virtually no planktonic and rare benthic foraminifera consisting almost entirely of *Nonionellina pizzarensis*, *Buliminella curta*, and *Uvigerina juncea*).

The lowermost section penetrated at the ACSG4 borehole is assignable to the Deal Member of the Manasquan Formation (Enright, 1969). We place the boundary with the overlying Shark River Formation at 241 m (790′). There is a striking change in color, grain size, percentage of planktonic foraminifera (from 84.3% to 10.5%) (Fig. 1), and water depth (from outer neritic to middle neritic, approximately 60 m of relative sea-level lowering; Christensen and others, 1989) at this level, and we infer that this is a major disconformity. This differs from the placement of the formational boundary at 271 m (890′) by Owens and others (1988) and Poore and Bybell (1988) (Fig. 1), who used the first occurrence of glauconitic sand layers to mark the base of the Shark River Formation, as did Enright (1969). Still, on the basis of numerous criteria, the 241 m level constitutes the major Eocene lithologic change at the ACGS4 borehole, justifying the placement of the formation boundary here.

A porcellanite layer noted at 261 m (855′) (Fig. 1) correlates with the younger part of a time-transgressive upper lower to lower middle Eocene porcellanite-chert layer distributed throughout the deep western North Atlantic (equal to Horizon A^c; Tucholke and Mountain, 1979; Thein and von Rad, 1987). This porcellanite is observable in outcrop in the New Jersey coastal plain (for example, Manasquan River, Howell Park).

The upper Eocene–lowermost Oligocene section extending from 234 m (767′) to 174 m (570′) (Fig. 1) has been identified previously in the New Jersey coastal plain only at the ACGS4 borehole and has been informally designated the ACGS Alpha and Mays Landing units (Fig. 1) (Owens and others, 1988; Poore and Bybell, 1988). Nemickas and Carswell (1976) first applied the term "Piney Point Formation" to sands in the New Jersey subsurface; Olsson and others (1980) established that these sands were upper Oligocene. In the type well in Maryland, however, the Piney Point Formation is middle Eocene as suggested by Brown and others (1972), whereas Benson (1989) showed that it is not the same lithologic unit as the upper Oligocene of New Jersey. Thus, we agree with Hazel and others (1984) that a new formational name is needed for these upper Oligocene sands. These sands are overlain by gray silts of the Miocene Kirkwood Formation (Fig. 1).

MAGNETOSTRATIGRAPHY AND BIOSTRATIGRAPHY

Good magnetostratigraphic records have been obtained from Cenozoic pelagic sediments (for example, Lowrie and others, 1982; Tauxe and others, 1983). In contrast, difficulties are generally encountered in obtaining high-quality paleomagnetic results in shallow-marine deposits such as at the ACGS4 borehole (for example, Townsend and Hailwood, 1985). In such settings, dilution of magnetic minerals and relatively coarse grain sizes tend to result in weak magnetization and poor stability. In addition, outcrop studies of shallow-marine strata are complicated in many cases by weathering processes, which alter the paleomagnetic record (for example, Ellwood and others, 1984).

We analyzed larger samples than normal from the ACGS4 borehole (~50–100 cc versus ~10 cc), effectively increasing the sample remanent magnetization signal by as much as an order of magnitude. Eighty-nine 5-cm-long samples were obtained from the ~5-cm (2.5 in.)-diameter core; paleomagnetic samples were obtained from the base of the borehole at 288 m (945′) to approximately 190 m (625′) (Fig. 1; Owens and others, 1988). Above this, the section consisted of poorly consolidated sands unsuitable for paleomagnetic studies (Fig. 1). Paleomagnetic samples were analyzed using a large-access (6.8 cm) ScT cryogenic magnetometer and a large-access (12 cm) solenoid for AF demagnetization to 45 mT. Because the borehole was not azimuthally oriented, the directions of magnetization were referred to the vertical orientation and an arbitrary horizontal.

The natural remanent magnetization (NRM) intensities are low (mean about 0.2 mA/M). Each sample was subjected to several (typically 5) progressive levels of AF demagnetization. After the 20 mT treatment, the intensities were reduced to about 0.1 mA/M; 13 samples with intensities of less than 0.005 mA/m after treatment were rejected from further consideration. Seventy-six remanent inclinations obtained after partial demagnetization of the remaining samples were plotted versus depth in the borehole (Fig. 1). Because of erratic demagnetization behavior of 14 samples (shown as unconnected x's; Fig. 1), only 62 samples were suitable for interpretation (solid circles connected by line; Fig. 1).

Reasonable magnetobiostratigraphic correlations can be made for the deeper-water (outer neritic) facies penetrated between 241 m (790′) and the base of the recovered section (288 m; 945′). Biostratigraphy suggests that this section is relatively complete (Poore and Bybell, 1988), encompassing nannofossil Zones NP12 to early NP16 (Fig. 1). Hence, the magnetozones observed in this upper lower to lower middle Eocene interval can be correlated to Chrons C23r to C20r of the Geomagnetic Polarity Time Scale (GPTS; the time scale of Berggren and others, 1985, is used throughout). For example, given the general stratigraphic constraints, the thick normal-polarity interval from 268.5 m (881′) to 257 m (842′) is identified as Chronozone C21n, and the succeeding long reversed-polarity interval from 257 m (842′) to 244 m (800′) with the long reversed interval of Chronozone C20r.

Detailed biostratigraphic criteria support the identification of the magnetochrons and their correlations to the GPTS. For example, the following magnetobiostratigraphic relationships observed at the ACGS4 borehole reasonably agree with the criteria compiled by Berggren and others (1985).

(1) The NP12/NP13 boundary [= last occurrence (LO) *Tribrachiatus orthostylus*] occurs at the base of Chronozone C22r (280 m; between samples 916.5′ and 920.5′).[1]

(2) The NP13/NP14 boundary [= first occurrence (FO) *Discoaster sublodoensis*] occurs in an interval (276 m; 902′–908′) spanning the Chronozone C22n/C21r boundary (ca. 52 Ma), whereas elsewhere it appears in lower C22n (52.6 Ma; Berggren and others, 1985).

(3) The NP14/NP15 boundary (= FO *Nannotetrina fulgens*) occurs in the lower part of Chronozone C21n (263 m; 860′–862′).

(4) The FO of *Planorotalites palmerae* occurs in Chronozone C22r (281 m; 921′–928′).

(5) The LO of *N. fulgens* (= Zone NP15/NP16 boundary) (244 m; 798′–802′) suggests that the apparent polarity transition at 243 m (793′–801.5′) is the boundary between Chronozones C20r/C20n; the LO *Morozovella aragonensis* (= boundary of Zones P11/P12) at this level is consistent with this, although the forms are not typical (Poore and Bybell, 1988).

(6) The FO of *Turborotalia possagnoensis* (250 m; 818′–826′) is in the middle of Chronozone C20r at the ACGS4 borehole, slightly higher than observed elsewhere (lower Chronozone C20r).

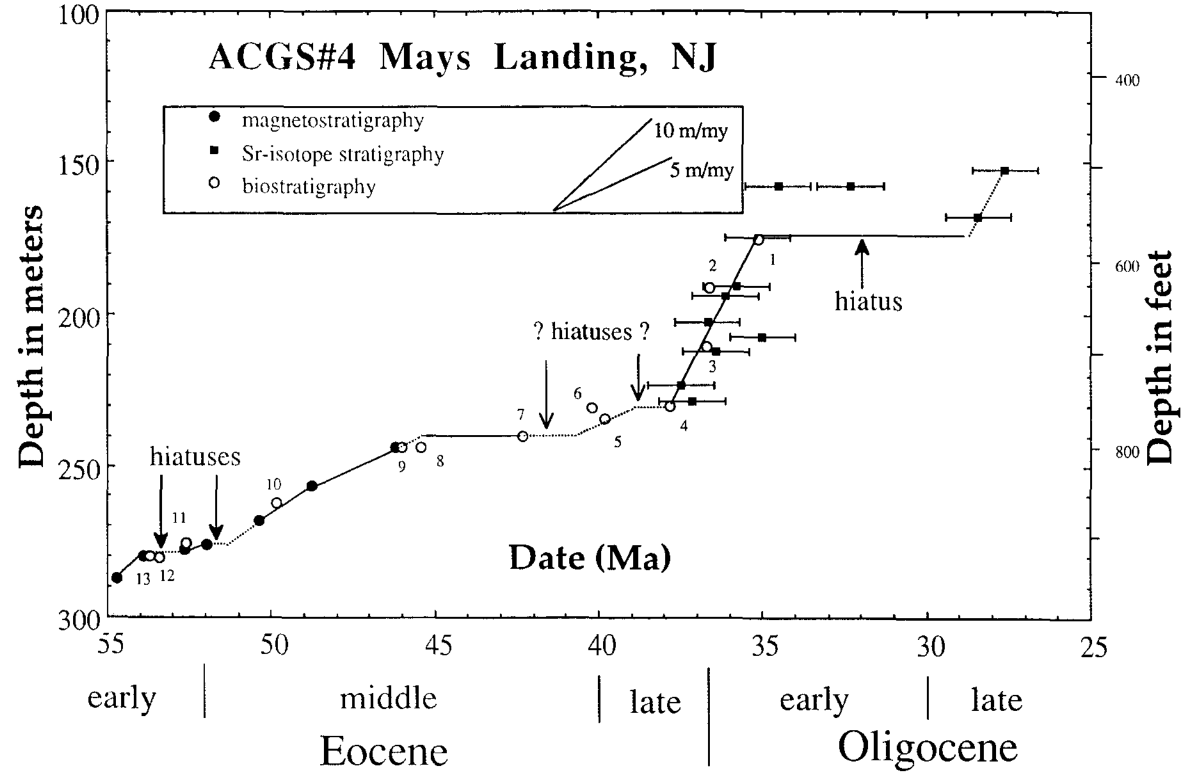


Figure 2. Age versus depth for magnetostratigraphic, biostratigraphic, and Sr-isotope stratigraphic age estimates. Zonal boundaries are drawn between samples. Sr-isotope age estimates from Table 1; error bars are ±1.0 m.y., our estimate of stratigraphic resolution for the Oligocene. Magnetostratigraphic age estimates: Chronozone C20n/C20r, 244.1 m, 46.17 Ma; Chronozone C20r/C21n, 256.8 m, 48.75 Ma; Chronozone C21n/C21r, 268.5 m, 50.34 Ma; Chronozone C21r/C22n, 276.1 m, 51.95 Ma (probably not a real datum level owing to removal of section); Chronozone C22n/C22r, 277.7 m, 52.62 Ma (probably not a real datum level owing to removal of section); Chronozone C22r/C23n, 280.0 m, 53.88 Ma; Chronozone C23n/C23r, 287.5 m, 54.70 Ma Biostratigraphic age estimates: (1) LO *Cyclococcolithus formosus*, 175.0 m (570.5′–574′), 35.1 Ma; (2) LO *Hantkenina* spp., 190.9 m (624.5′–627.5′), 36.6 Ma; (3) LO *Discoaster saipanensis*, 210.7 m (688′–694′), 36.7 Ma; (4) FO *Isthmolithus recurvus*, 230.1 m (754.5′–755′), 37.8 Ma; (5) FO *Chiasmolithus oamaruensis*, 234.4 m (767.5′–770′), 39.8 Ma; (6) LO *Truncorotaloides* spp., 230.5 m (746′–756′; placed at 756′ to be consistent with the FO *I. recurvus* at 754.5′), 40.2 Ma (not a datum level, owing to reworking as shown by its offset in figure); (7) LO *C. solitus*, 240.0 m (786′–788.5′), 42.3 Ma; (8) LO *Nannotetrina fulgens*, 243.9 m (798′–802′), 45.4 Ma; (9) LO *Morozovella aragonensis*, 243.9 m (798′–802′), 46.0 Ma (forms are not typical; Poore and Bybell, 1988); (10) FO *N. fulgens*, 262.5 m (860′–862′), 49.8 Ma; (11) FO *D. sublodoensis*, 275.9 m (902′–908′), 52.6 Ma; (12) FO *Planorotalides palmerae*, 280.6 m (920.5′–928′), 53.4 Ma; (13) LO *Triabrachiatus orthostylus*, 280.0 m (916.5′–920.5′), 53.7 Ma. Time scale and biostratigraphic calibrations were taken from Berggren and others (1985). The two Sr-isotope analyses at 158 m (515′–520′) are considered anomalous (see text) and are not connected by a line.

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[1] The depths of biostratigraphic datum levels are provided in feet (reflecting the depth range between samples) and meters (reflecting the mean depth of the sampled interval).

(7) The FO's of *Acarinina bullbroki*, *A. pentacamerata*, and *Subbotina frontosa* are consistent with the magnetobiostratigraphic relationships observed at Pacific Deep Sea Drilling Project Site 577 (Miller and others, 1987b).

Above approximately 241 m (790′), the sample coverage and general data quality in the sandier facies are not sufficient to interpret polarity history or to attempt correlation of the magnetozones to the GPTS. At least a 3-m.y. hiatus (from 45 to at least 42 Ma) occurs at 241 m, for the lower part of Magnetochron C20n (244–241 m; ~46.2–45.6 Ma by extrapolating sedimentation rates) is overlain by the LO *Chiasmolithus solitus* (240 m; 786′–788.5′; 42.3 Ma). In addition, nannofossil biostratigraphy suggests (Poore and Bybell, 1988) (1) correlation of the interval from 241 m (790′) to 230 m (756′) to the latest middle to earliest late Eocene Zones NP17 to NP18 and (2) that this section is condensed or contains one or more hiatuses, for the LO *C. solitus* (42.3 Ma), the FO *C. oamaruensis* (39.8 Ma), and the FO *Isthmolithus recurvus* (37.8 Ma) occur within a 10-m interval (mean sedimentation rate, assuming that continuous sedimentation for this interval is ~2 m/m.y.). The overlap of *Truncorotaloides* spp. and *C. oamaruensis* is anomalous and is due to upsection reworking of the former taxon (Poore and Bybell, 1988). We estimated ages for this section by assuming that the FO *C. oamaruensis* is a real datum level, that the LO of *C. solitus* is reworked upward by one sample above the disconformity at 241 m, and that the sedimentation rate is 5 m/m.y. (Figs. 2 and 3). From these assumptions, we estimate that there are two hiatuses: from 45 to 40 Ma and from 39 to 37 Ma (Figs. 2 and 3).

The interval from 228 m (750′) to 191 m (627′) represents upper Eocene Zones NP19/20 and lower Zone NP21 (Poore and Bybell, 1988). The LO *Hantkenina* spp. at 191 m (624′–627′) is used to recognize the top of the Eocene (Berggren and Miller, 1988). The interval from 191 m (627′) to 175 m (575′) is assigned to lowermost Oligocene Zone NP21 (that is, from 36.6–35.1 Ma). No further biostratigraphic subdivision of the Oligocene is possible, although lowermost Miocene sediments (Zone N5) are recognized at 144 Ma (473′) (Poore and Bybell, 1988).

Sr-ISOTOPE STRATIGRAPHY

Studies by Burke and others (1982), DePaolo and Ingram (1985), and Hess and others (1986) have shown the potential for using the record of $^{87}Sr/^{86}Sr$ preserved in marine carbonates as a stratigraphic tool. The Sr-isotope ratio in sea water is believed to be uniform at a given time, as the residence time is much longer than oceanic mixing times (Broecker and Peng, 1982). A large increase in $^{87}Sr/^{86}Sr$ (~0.001300) occurred from the late Eocene to Recent (Burke and others, 1982; DePaolo and Ingram, 1985; Hess and others, 1986). Hence, measurement of $^{87}Sr/^{86}Sr$ ratios in marine carbonates affords a powerful correlation tool for this interval, especially for tying shallow-water sequences to better-constrained deep-sea records (for example, Miller and others, 1988).

Sr-isotope studies were performed upon mixed benthic and planktonic foraminifera (>200 specimens) picked from the greater than 150 μm size fraction and from molluscan shells and fragments. The carbonate was dissolved in 1.5N HCl. Standard ion-exchange techniques were used to separate strontium for analysis on a VG Sector mass spectrometer at Rutgers University, New Brunswick, New Jersey. Internal precision (intrarun variability) on the Sector is approximately ±0.000011, and external precision (interrun variability) is ±0.000030 or better; the NBS 987 standard is routinely measured at Rutgers as 0.710250 (Miller and others, 1988). Ages (Table 1) were estimated from the Sr-isotope measurements using the empirical age-$^{87}Sr/^{86}Sr$ relationship established at Deep Sea Drilling Project Site 522 (Miller and others, 1988); this linear relationship is apparently valid from about the late Eocene (~38 Ma) into the earliest Miocene (~22 Ma). Given the rate of change of $^{87}Sr/^{86}Sr$ and our external precision, our stratigraphic resolution for this interval is ±1 m.y. or better (Miller and others, 1988).

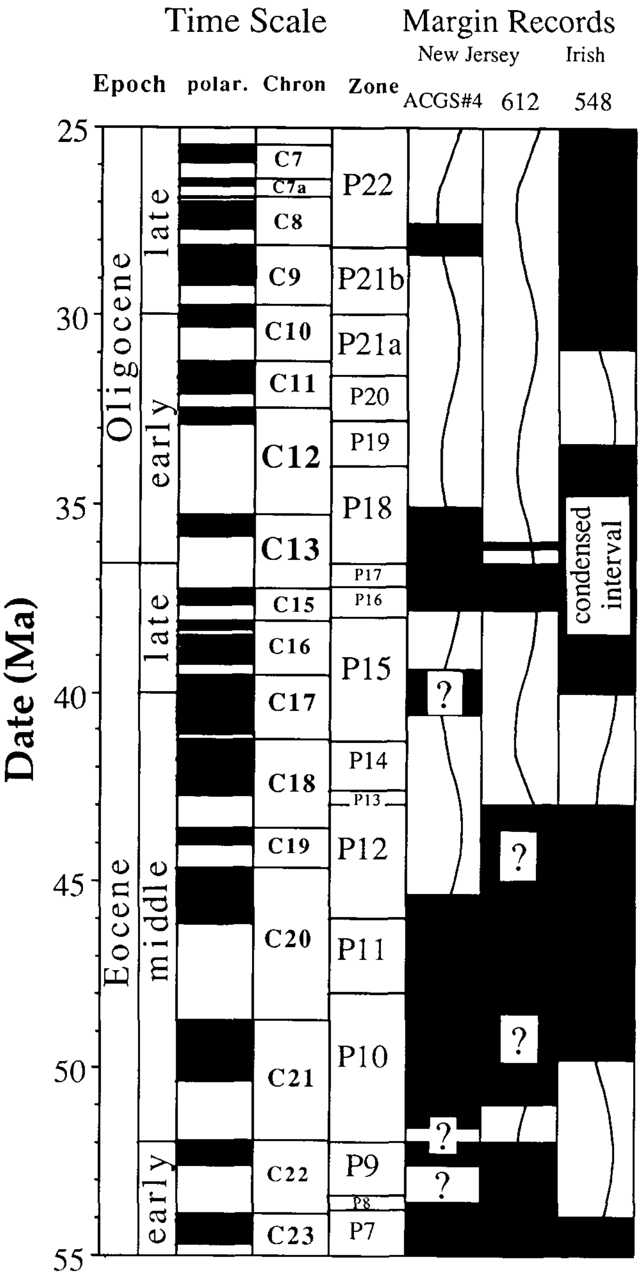

Figure 3. Comparison of the stratigraphy at the ACGS4 borehole and at DSDP Site 612 (New Jersey slope). Black intervals indicate time represented; vertical lines indicate hiatuses. The estimates for the hiatuses at the ACGS4 were derived from Figure 2. Age estimates for Site 612 were taken from Miller and Katz (1987). Time scale was taken from Berggren and others (1985).

We found good agreement between Sr-isotope age estimates made upon foraminifera and shell material and biostratigraphic age estimates (Zones NP19/20–NP21) for the upper Eocene–lowermost Oligocene at

TABLE 1. ^{87}Sr/^{86}Sr VALUES FOR ACGS4 BOREHOLE

Depth (ft)	(m)	^{87}Sr/^{86}Sr	Estimated age (Ma)	Material
495–505	152.44	0.708137 ± 6	27.6	S
515–520	157.77	0.707972 ± 5	32.3	S
515–520	157.77	0.707894 ± 5	34.5	S
545–555	167.68	0.708108 ± 8	28.4	S
572.25	174.47	0.707875 ± 4	35.1	S
624.5	190.40	0.707852 ± 14	35.8	F
635.0	193.60	0.707840 ± 4	36.1	S
664.5	202.59	0.707821 ± 7	36.7	F
680.5	207.47	0.707879 ± 13	35.0	F
695.7	212.10	0.707830 ± 5	36.4	F
731.5	223.02	0.707793 ± 4	37.5	S
750.0	228.66	0.707805 ± 5	37.1	F
757.5	230.95	0.707821 ± 11	36.7	F*
781.0	238.11	0.707831 ± 5	36.4	F*

Note: F, separated foraminifera (mixed benthic and planktonic ssp.); S, shell (whole and debris); estimated age computed using measured ^{87}Sr/^{86}Sr values and the equation Age (Ma) = 20392.79 – 28758.84 (^{87}Sr/^{86}Sr).

*Numbers not used in age-depth plot (see text).

the ACGS4 borehole (Table 1; Fig. 2). The measurements of two samples from the middle Eocene unit (231 and 238 m) are not stratigraphically useful because the empirical age-^{87}Sr/^{86}Sr relationship is not unique for the interval older than ~38–37 m.y. (Table 1); these two samples are separated from samples immediately above by an unconformity (Fig. 1). Otherwise, Sr-isotope values generally decrease with depth as expected for the upper Eocene–lowermost Oligocene section (that is, between 229 m, 750′, and 174 m, 572′; Table 1).

There is little biostratigraphic evidence to constrain the age of the sediments between ~168 m (545′–555′) and 152 m (495′–505′) (this section is younger than Zone NP23 but older than Zone N5; Poore and Bybell, 1988), but Sr-isotope values indicate that these sediments are definitely Oligocene. An apparent discontinuity in the ^{87}Sr/^{86}Sr values between ~168 m (545′–555′) and ~174 m (572′) occurs at a level interpreted as a physical unconformity separating inner-neritic beach sands above and middle-neritic sandy silts below. Sr-isotope analyses at 168 m (545′–555′) and 152 m (495′–505′) suggest that the hiatus associated with this unconformity occurred between ~35 and ~28 m.y. ago (Fig. 2; Table 1), consistent with previous biostratigraphic age estimates of the hiatus on the New Jersey margin (Olsson and others, 1980; Miller and others, 1985a). Duplicate analyses of mollusc shells at ~158 m (515′–520′), however, yielded anomalously low values and older ages (32.3 and 34.5 m.y.; Table 1), and the age estimate of 28 m.y. of the surface above the unconformity is tentative.[2]

DISCUSSION

Integration of biostratigraphy (Poore and Bybell, 1988), magnetostratigraphy, and Sr-isotope stratigraphy at the ACGS4 borehole indicates the presence of at least four Paleogene hiatuses (Figs. 1–3). Extrapolation of sedimentation rates using magnetostratigraphically determined chron boundaries (that is, magnetochronology) delineates one or more short hiatuses near the early Eocene/middle Eocene boundary (within Chron C22, which spanned 53.9–52.0 Ma). Integration of magnetostratigraphy and biostratigraphy reveals a hiatus within the middle Eocene (~46 Ma to 42 or 40 Ma). Integration of biostratigraphy and Sr-isotope stratigraphy suggests a possible hiatus in the early late Eocene (~39–37 Ma) and a hiatus within the Oligocene (~35–28 Ma; Figs. 2 and 3).

The record at the ACGS4 borehole is one of the most complete shallow-water sections for the upper lower to lower middle Eocene, albeit at relatively low sedimentation rates (~5 m/m.y.). Still, some of the uppermost lower Eocene is probably missing. The interval of Chronozone C22 (54–52 Ma; Fig. 2) at this borehole is condensed, for sedimentation rates were low during Chrons C22n and C22r (~2 versus >5 m/m.y. in the rest of the lower–middle Eocene). This indicates that either one hiatus occurred in late Chron C22r to early Chron C22n, or two (or more) hiatuses occurred during Chron C22. Olsson and Wise (1987) used biostratigraphy to delineate two hiatuses in the latest early Eocene in the New Jersey coastal plain. Two hiatuses probably occurred at the ACGS4 borehole (as drawn in Figs. 1–3) on the basis of (1) the juxtaposition of the LO *Tribrachiatus orthostylus* and the FO *Planorotalites palmerae* suggests a short break during early Chron C22r and (2) the juxtaposition of the FO's of *Subbotina frontosa* and *Discoaster sublodoensis* suggests that late Zone P9 may be missing and that a hiatus occurred in late Chron C22n.

A hiatus and/or change in bathymetry occurred near the early Eocene/middle Eocene boundary in several other regions, although the synchrony of these events has not been proven. A hiatus occurred across the early Eocene/middle Eocene boundary in much of the United States Atlantic coastal plain (Olsson and others, 1988). In shallow-water epicontinental areas of northwest Europe, Chronozone C22n is missing (Aubry, 1985). Baum (1986) and Hazel and others (1984) suggested that a hiatus occurred near the early Eocene/middle Eocene boundary in Alabama, although they placed the break in different parts of the section. Significant hiatuses associated with distinct lithologic unconformities developed at the early Eocene/middle Eocene boundary on the Irish continental slope (Site 548; Poag and others, 1985; Snyder and Waters, 1985) (Fig. 3) and the New Jersey continental slope (Miller and Hart, 1987; Poag and Low, 1987). Distinct shallowing events occurred in the latest early Eocene of Libya (Barr and Berggren, 1981), Egypt (Abul-Nasr and Thunell, 1987), and California (Berggren and Aubert, 1983).

These records indicate that the widespread unconformities and relative sea-level falls developed near the early Eocene/middle Eocene boundary in many different areas. Vail and others (1977) and Haq and others (1987) also suggested that one of the most important Cenozoic sea-level falls occurred near the early Eocene/middle Eocene boundary. Although the data of Vail and others (1977) and Haq and others (1987) are largely unpublished, there is a good correspondence between their major coastal offlap/eustatic lowering events and hiatuses delineated on passive margins such as the early Eocene/middle Eocene boundary (Poag and others, 1985; Miller and others, 1987a; Christie-Blick and others, 1989; this study, among others). The widespread distribution of this erosional event identified by seismic stratigraphy (Vail and others, 1977), sequence stratigraphy (Haq and others, 1987; Baum, 1986), and chronostratigraphy points toward a similar cause: eustatic lowering.

A hiatus occurred within the middle Eocene (from about 46 Ma to 42 or 40 Ma) at the ACGS4 borehole, and we speculate that a hiatus also occurred near the middle Eocene/late Eocene boundary (tentative age estimate from ~39 to 37 m.y.) (Figs. 2 and 3). The older break corresponds with hiatuses inferred at other New Jersey coastal-plain wells (Olsson and Wise, 1987), channeling noted on the New Jersey continental slope (Mountain, 1987), and one or more minor eustatic lowerings of Haq and others (1987). The younger hiatus may correspond with a break near the middle Eocene/late Eocene boundary on the New Jersey coastal plain and slope and Irish continental slope (Snyder and Waters, 1985; Miller and Hart, 1987; Poag and Low, 1987) and a major inferred eustatic lowering (Haq and others, 1987). Bear in mind that interpretation of the

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[2] We rely upon the analyses from 168 and 152 m because the duplicate analyses at 158 m show differences from each other. Such variability may result from inclusions of glauconite in the shell. We encountered such inclusions in a sample from 157 m (505′–515′), which was rejected owing to Rb interference from glauconite. In addition, the Sr-isotope analyses used here show a discontinuity at the same level as the physical unconformity.

middle to late Eocene transition (the interval between 42 and 37 Ma) is difficult at the ACGS4 borehole because (1) the GPTS is predominantly normal polarity through this interval, (2) Sr-isotope stratigraphy does not appear to be useful (Miller and others, 1988); and (3) the ACGS4 section is complicated by reworking in this interval (Poore and Bybell, 1988).

We document that the "middle" Oligocene hiatus extended from ca. 35 to 28 Ma on the New Jersey margin, consistent with a hiatus that occurred on the Irish margin from 34 to 30 Ma (Miller and others, 1985b, 1988). A similar break occurred on margin and epicontinental locations from throughout the world, including Israel (Martinotti, 1981), Australia (Loutit and Kennett, 1981; for a different view, see Carter, 1985), eastern Canadian margin (Gradstein and Agterberg, 1982), Alabama (Baum, 1986), and northwest Europe (Aubry, 1985), and it seems to correspond with one of the largest inferred eustatic lowerings of Haq and others (1987).

One implication of the foregoing is that shallow-water hiatuses such as those in the New Jersey coastal plain also occur in deep-water depositional settings (for example, slope and rise). Comparison of the stratigraphic records from the New Jersey coastal plain (ACGS4) with the New Jersey and Irish continental slopes (DSDP Sites 612 and 548; paleodepths ~1,200 m; Snyder and Waters, 1985; Miller and Katz, 1987) shows a striking similarity (Fig. 3). On the Irish and New Jersey offshore margins, the early Eocene/middle Eocene and middle Eocene/late Eocene boundaries are associated with biostratigraphically identified hiatuses and physical disconformities noted in DSDP boreholes (Miller and others, 1985a; Poag and others, 1985; Snyder and Waters, 1985; Poag and Low, 1987; Miller and Hart, 1987). Distinct channeling events at the early Eocene/middle Eocene boundary, within the middle Eocene, and within the Oligocene have been noted in seismic stratigraphic data from the New Jersey continental slope (Poag and Mountain, 1987; Mountain, 1987). Because all of these DSDP sites were located in paleodepths of greater than 1,000 m, the erosion cannot have been due to subaerial exposure. Several possible mechanisms have been suggested for these submarine hiatuses other than eustatic change (Mountain, 1987). One implication of our observation of such coeval erosional events in shallow-water and continental-slope locations is that continental slopes provide monitors, albeit indirect, of global sea-level lowering.

CONCLUSIONS

We have successfully applied established stratigraphic techniques of magnetostratigraphy and Sr-isotope stratigraphy to a difficult setting: shallow-water (neritic) deposits. By integrating magnetostratigraphy, Sr-isotope stratigraphy, and biostratigraphy, we are able to document hiatuses in the New Jersey coastal plain (ACGS4 borehole) that were not resolvable using biostratigraphy alone. If this improved stratigraphic control is used, these stratigraphic breaks can be compared with similar breaks on this and other passive margins and epicontinental settings. Such baseline stratigraphic studies are needed to evaluate the global synchrony of erosional events and the role of eustatic changes. Although there is still uncertainty in the timing of erosional events, we have found good agreement between the timing of hiatuses in the Eocene-Oligocene New Jersey coastal plain (ACGS4 borehole), the timing of hiatuses in other regions, and the major eustatic lowering inferred by Vail and others (1977) and Haq and others (1987). The interregional synchrony of these Eocene-Oligocene hiatuses and unconformities suggests that they resulted from global lowerings of sea level.

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