Strontium-isotope and sequence stratigraphy of the Miocene Kirkwood Formation, southern New Jersey

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ABSTRACT
We use Sr-isotope stratigraphy to correlate the Miocene Kirkwood Formation of the New Jersey Coastal Plain to the Geomagnetic Polarity Time Scale (GPTS) and to ascertain the age of Miocene depositional sequences. Sr-isotope stratigraphy confirms diatom biostratigraphy, which delineates three Kirkwood sequences corresponding to East Coast Diatom Zone (ECDZ)1, ECDZ 2, and ECDZ 6 of Andrews (1988). Sr-isotope age estimates of the lowermost sequence (= ECDZ 1) range from 19.2 to 22.6 Ma ± 0.5 m.y. The middle sequence (= ECDZ 2) ranges from 15.5 to 17.4 Ma ± 0.5 m.y.; a disconformity within ECDZ 2 at the Belleplain State Forest borehole and the Wildwood 198A well separates it into two sequences, with a possible hiatus from 17 to 16 Ma. Sr-isotope age estimates of the upper Kirkwood sequence (= ECDZ 6) are not as certain and range from 11.5 to 13.6 Ma ± 0.8 Ma. A shorter age range of 12.2-13.6 Ma for this sequence is supported by its assignment to the D. stauracanthus silicoflagellate Subzone. Sedimentation rates were as high as 40 m per million years during deposition of the Kirkwood Formation, suggesting possible tectonic influences on depositional history. The timing of lower to middle Miocene sequence boundaries from the New Jersey Coastal Plain compares well with other indicators of sea-level change, including oxygen isotopes (Miller and others, 1991b), the global sea-level record of Haq and others (1987), and the offshore New Jersey sequence boundaries of Greenlee and others (1992). Thus, both tectonic and eustatic changes influenced Miocene depositional history of the New Jersey Coastal Plain.

INTRODUCTION
Stratigraphic sequences are composed of unconformity-bounded sedimentary units that are genetically related (Vail and others, 1977; Posamentier and others, 1988). Sequence stratigraphy has revolutionized the way we analyze sedimentary basins. By integrating depositional models based on lithologic and facies analysis with biostratigraphy, sequence stratigraphy, and physical records, the nature and history of a basin can be clearly documented and logically understood.

Analysis of stratigraphic sequences provides a means of establishing the timing and estimating the magnitude of eustatic (= global sea-level) and relative sea-level changes for example, Greenlee and Moore, 1988). Relative sea-level changes on continental margins are inferred from stratigraphic unconformities (and associated hiatuses) and transgressions/regressions of the shoreline as based on various data sources, including facies changes, paleoecology, and seismic profiles. Shallow-water (neritic) sections provide the best indicators of sea-level fluctuations because they are most sensitive (Miller and Kent, 1987; Miller and others, 1990). The juxtaposition of different stratigraphic facies resulting from changing sea level and/or tectonic activity is more easily detected in nearshore and shallow-marine sequences than in deep-marine sequences due to a greater variation in these facies types. In the Atlantic Coastal Plain, typical transitions from shallow-marine environments (shelf, prodelta) to nearshore environments (delta-front, barrier, tidal flat) to nonmarine facies (lower delta plain) offer a wide variety of sedimentary and paleoecological characteristics to distinguish relative sea-level position.

Stratigraphic sequences based on unconformity-bounded cycles of sedimentation have been recognized in the New Jersey Coastal Plain since the 1960s (Owens and Sohl, 1969), not only on the onshore coastal plain (Owens and Gohn, 1985; Olsson, 1991), but also beneath the present-day continental shelf (Greenlee and others, 1988; Greenlee and Moore, 1988; Olsson and Wise, 1987). The typical “New Jersey cycle” (Fig. 1) is an unconformity-bounded coarsening-upward sequence consisting of a basal glauconite sand, a middle silt, and an upper quartz sand. Each cycle ideally represents a transgressive-regressive event in which deltaic deposits (regressive) have prograded over a marine shelf deposit (transgressive). The “New Jersey cycle” has also been interpreted in terms of global sea level by Olsson (1991). Unconformities form when there are rates of sea-level fall (Petman, 1978), whereas deposition occurs on the coastal plain between the maximum rate of sea-level rise and the maximum rate of sea-level fall. According to the terminology of Posamentier and others (1988), the glauconite sand is equivalent to the Transgressive Systems Tract, whereas the silt and sand beds are equivalent to the Highstand Systems Tract; they are separated by a maximum flooding surface (Fig. 1). Although these sequences have chronostratigraphic significance (Owens and Gohn, 1985), they are difficult to correlate to a standard stratigraphy because planktonic index fossils are generally rare or controlled by facies changes (Miller and others, 1990).

The Miocene Kirkwood Formation of New Jersey is generally considered to be a...
Jersey presents an interesting problem for chronostratigraphic correlation. It is predominantly a shallow-marine unit containing shelf and deltaic facies (Owens and others, 1988). Sediments were deposited on a basin edge in which a terrestrial component (delta) interfingers with a marine component (shelf). Because the Kirkwood Formation generally lacks planktonic calcareous microfossils, biostratigraphic correlation is accomplished primarily with diatoms (Andrews, 1987, 1988). Although diatoms are useful as a biostratigraphic tool in subdividing the Miocene deposits of the Atlantic Coastal Plain (Abbott, 1978; Andrews, 1978, 1988; Wetmore and Andrews, 1990), there are some inherent problems in correlating these sections to the Geomagnetic Polarity Time Scale (GPTS). The index species of diatoms used in the zonation of the Miocene strata along the Atlantic Coast are shallow-water marine species (Abbott, 1978; Andrews, 1978, 1988), making correlation with pelagic biostratigraphy difficult if not impossible.

Silicoflagellates contained within the diatomaceous beds offer one way to calibrate diatoms with deeper marine index sections (Abbott, 1978; Andrews, 1988; Wetmore and Andrews, 1990; Bukry, 1990), which, in turn, are calibrated to magnetostratigraphy. Planktonic foraminifera offer another means to cross-correlate diatom zones with better-calibrated sections and have been used in studies of the Miocene in New Jersey (Olsson and others, 1980; Owens and others, 1988; Poore and Bybell, 1988), Delaware (Benson, 1990), Maryland (Gibson, 1983a, 1983b; Olsson and others, 1987), and Virginia (Pong, 1989). In the Miocene strata of New Jersey, however, planktonic foraminifera are uncommon (Melillo, 1985; Owens and others, 1988). Even in the AMCOR 6011 well, situated 11 km offshore New Jersey, planktonic foraminifera are rare (Melillo, 1985).

Detailed diatom work in New Jersey enabled Andrews (1988) to recognize three of his seven East Coast Diatom Zones: ECDZ 1, ECDZ 2, and ECDZ 3 (Fig. 2). These biostratigraphic zones were used with physical evidence to subdivide the Kirkwood Formation into three distinct unconformity-bounded sequences: lower Kirkwood sequence = ECDZ 1; middle Kirkwood sequence = ECDZ 2; and upper Kirkwood sequence = ECDZ 3 (Owens, 1989; Sugarman and others, 1991).

In this paper, we discuss the characteristics of the three Kirkwood stratigraphic sequences and delineate their distribution in the New Jersey Coastal Plain. We then correlate the three Kirkwood sequences to the GPTS using Sr-isotope measurements of calcareous fossil material. Age estimates are derived from the isotopic reference section developed at Deep Sea Drilling Site 608 (Miller and others, 1991a) that is directly tied to the GPTS (Fig. 2), and at DSDP Site 588 (Hudell and others, 1991).

We also provide additional age estimates for the middle Miocene samples using data from Ocean Drilling Program (ODP) Site 747 (Osilck and others, 1992) because of large age differences in the middle Miocene interval between the Site 588 and Site 608 data. These age estimates enable us to determine the timing of sea-level and/or tectonic events that controlled deposition of the Kirkwood sequences and estimate the age ranges of the Kirkwood formations in New Jersey.

**GEOLOGIC SETTING**

The Kirkwood Formation is the older of two Miocene formations that crop out in the New Jersey Coastal Plain (Fig. 3). In outcrop and in the subsurface it is unconformably overlain by the Miocene Cohansey Formation and unconformably overlies Paleogene sedimentary rocks of several formations. In the subsurface, the Kirkwood Formation unconformably overlies an unnamed Oligocene sand unit (Olsson and others, 1980) that is equivalent to the informal ACGS Beta unit of Owens and others (1988).

The outcropping Kirkwood was subdivided into three members by Ishphording (1970) that are partly facies related. These are (1) Asbury Park, (2) Grenloch Sand, and (3) Alloway Clay Members. The Grenloch Sand and Alloway Clay Members are considered to be the major facies and of inner-shelf origin, whereas the Asbury Park Member is a restricted facies deposited in lagoons, swamps, and estuaries. In parts of Cumberland and...
Salem Counties in southern New Jersey, the Alloway Clay Member includes a fossiliferous clay-silt unit termed the Shiloh Marl. The Miocene invertebrate fauna of this unit is discussed by Richards and Harbison (1942); they assigned the Kirkwood Formation to the middle Miocene on the basis of comparisons of molluscan fauna from New Jersey with the Chesapeake Group of Maryland. We show that in fact the Shiloh Marl is lower Miocene (see below).

The Kirkwood Formation thickenS dip from a maximum of 30 m (100 ft) in outcrop to 213 m (700 ft) in the subsurface at Wildwood, New Jersey. Early subdivisions of the subsurface Kirkwood Formation in New Jersey (Woolman, 1895) were based on a series of cable-tool water wells near the coast and concentrated on correlating massive diatomaceous clay beds and water-bearing sand zones.

The ACGS-4 borehole was drilled near Mays Landing, New Jersey, to gather more information on the Paleogene and Neogene units in southern New Jersey for the new state geologic map. More than 91 m of Kirkwood Formation were penetrated and described as a predominantly marine deltaic unit consisting of both shallow shelf and prodelta deposits; the strata were assigned to the lower Miocene (Burdigalian Stage) and lower middle Miocene (Langhian Stage; Owens and others, 1988). Andrews (1987) described the diatom assemblages from the ACGS-4 borehole, and he recognized ECDZ 1 and ECDZ 2 in the Kirkwood Formation; both of these zones are contained within the Calvert Formation of Maryland. He also proposed a 1-million-yr hiatus between deposition of sediments correlated with ECDZ 1 and ECDZ 2.

Examination of additional boreholes penetrating the Kirkwood Formation in southern New Jersey led to the identification of a younger Kirkwood stratigraphic sequence that is correlated with ECDZ 6 (Andrews, 1988; Owens, 1989; Sugarman and others, 1991). This uppermost and youngest Kirkwood sequence is considered middle Miocene (Serravallian Stage) and is equivalent to parts of the Calvert and Choptank Formations of Maryland (Andrews, 1988). On the basis of detailed outcrop and subsurface studies, the three sequences correlate with ECDZ 1, ECDZ 2, and ECDZ 6 each will be given formation status (James Owens, 1992, personal commun.). In this paper, the three sequences are treated as the lower,
middle, and upper parts of the Kirkwood Formation.

METHODS

Sequence Stratigraphy

Wells and boreholes used in this study (Table 1) contain calcareous macrofossils suitable for Sr-isotope analysis. Three key wells used in establishing the overall stratigraphy of the Kirkwood Formation were the ACGS-4 borehole (Owens and others, 1988), the Wildwood 1985A well (Woolman, 1895), and the Belleplain State Forest borehole (Fig. 3A). The ACGS-4 borehole contains a nearly continuous section of the lower Kirkwood sequence (ECDZ 1), whereas the Belleplain contains a continuous core of the entire upper Kirkwood sequence (ECDZ 6) and a nearly continuous section of the middle Kirkwood sequence (ECDZ 2). Although Wildwood is a cable-tool well drilled in 1894, its samples provided the most complete record of all three sequences in one well and a good representative section of ECDZ 2. Additional boreholes and wells (Table 1; Fig. 3A) were used to expand the data set needed to bracket the age of the three Kirkwood stratigraphic sequences with Sr-isotope age estimates.

Sedimentary sequences were established by analyzing the wells for lithology, mineralogy, bedforms, and fossil remains and by incorporating these characteristics into depositional units. Correlation of these depositional units was accomplished primarily with diatom biostratigraphy and Sr-isotope stratigraphy. Published biostratigraphic data (Andrews, 1987, 1988; Wetmore and Andrews, 1990) were supplemented by unpublished diatom data (George Andrews, 1992, written commun.) and silicoflagellate biostratigraphy (Bukry, 1990; 1991, written commun.). Unconformities were identified on the basis of physical stratigraphy, including reworking and bioturbation, major changes in sedimentologic characteristics, and positive gamma ray spikes. In addition, unconformities were inferred from hiatuses recognized biostratigraphically, based on Andrews' (1988) East Coast Diatom Zones, and with Sr-isotope age estimates. Because the three Kirkwood sequences contain many similar sediment types, biostratigraphy and/or Sr-isotope age estimates are essential in separating these sequences.

Sr-Isotope Stratigraphy

Sr-isotope analyses made on calcareous mollusk shells. A piece 0.1 in (3 mm) in diameter 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 (for example, Hart and Brooks,
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1974) were used to separate strontium for analysis on a VG Sector mass spectrometer at Rutgers University. Internal precision (intrarun variability) on the Sector is approximately ±0.000008 (mean error for analyses in this study); external precision (intrarun variability) is approximately 0.000026 to 0.000030 (Miller and others, 1991a). At Rutgers, NBS is routinely measured at 0.710252 (2σ standard deviation 0.000026; n = 35) normalized to 88Sr/86Sr of 0.1194 (Miller and others, 1991a).

Sr-isotope values were converted to age estimates using the regression equations of Miller and others (1991a) and Hodell and others (1991). Early Miocene age estimates are similar using either regression. A discussion of the limits of stratigraphic-age resolution using Sr isotopes in the Miocene can be found in these papers. Because of the age discrepancies in the middle Miocene between the published regressions (Table 1), the age regression equation from ODP Site 747 (Oslick and others, 1992) was also used because it has an excellent magnetostratigraphic record. The GPTS of Berggren and others (1985) is used throughout.

Diagenetic alteration of the shell material used in this study is considered to be minimal, with no observed recrystallization. In most intervals of the upper Kirkwood sequence (ECDZ 6), shell material was commonly weathered enough to be scratched with a fingernail. These shells were analyzed for mineralogy with X-ray diffraction and were found to be completely aragonitic. It is possible that weathering of some of the shells in the Kirkwood is due to the corrosive (low pH) ground water in the upper Kirkwood sequence.

RESULTS

Sr-isotope values and age estimates (Table 1) confirm the three distinct Kirkwood sequences discussed below.

Lower Kirkwood Sequence

The lower Kirkwood sequence, placed in ECDZ 1, represents the earliest Miocene deposition in New Jersey. It is the most areally extensive of the three Kirkwood sequences in New Jersey, and it is exposed in the outcrop belt (Fig. 3B). It has a maximum thickness of more than 122 m (400 ft), and its depocenter is situated beneath Long Beach Island.

This sequence is similar to the classic "New Jersey cycle" (Fig. 1). At the ACGS-4 borehole (Fig. 4), a thin bed of clayey, fine, glauconite sand (= Transgressive Systems Tract) rests on the basal unconformity, as is the case at the Wildwood 198A well (Fig. 5). This bed is overlain by a thick, laminated-to-massive clay-silt sequence (= lower Highstand Systems Tract) that is commonly micaceous and carbonaceous and contains scattered, thin, densely packed shell beds. The shells are generally broken and rarely in life position, indicating transport into deeper waters during storm events. The clay-silt interval is conformably overlain by a thick section of sand (= upper Highstand Systems Tract). The sand is the volumetrically dominant component of the cycle, being 30 m thick at the ACGS-4 borehole (Fig. 4) and about 61 m thick at the Wildwood 198A well (Fig. 5). This sand correlates with the "800 foot sand" of earlier workers (Woolman, 1895; Richards and Harbison, 1942), a major aquifer in southeastern New Jersey.
The thick ECDZ 1 unit from the ACOS-4 borehole may contain a record of parasequence sets within the Highstand Systems Tract. For example, we assume that the recurrence of silt layers at 107-117 m (350-385 ft) and 87-90 m (285-295 ft) represents the base of regressive parasequences within the generally regressive Highstand Systems Tract; this requires placement of flooding surfaces (FS) at 117 m (385 ft) and 90 m (295 ft), respectively (Fig. 4). Both flooding surfaces are associated with positive gamma ray kicks (Fig. 4). These parasequences represent a higher order variation (that is, with two parasequences occurring in <1 m.y.; Fig. 4) observable only in cores with the highest sedimentation rates. Without identification of these parasequences at other localities, however, their significance remains uncertain.

The age of the lower Kirkwood sequence is well defined by Sr-isotope age estimates and microfossil data at the ACOS-4 borehole. Sr-isotope ages of 19.7-21.4 Ma (±0.5 m.y.) were obtained for the Kirkwood 1 sequence at this borehole, indicating an early Miocene age. Age estimates at the ACOS-4 borehole show an apparently linear trend with depth (Fig. 6). Sedimentation rates were 40 m per million years for this interval, a relatively high rate. At the base of this cycle, at 144 and 143 m (473 and 469 ft) in the ACOS-4 borehole, planktonic foraminifera were assigned to lower Miocene Zone N5 of Blow (1969) on
### ACGS-4 Borehole

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Figure 4. Schematic stratigraphic section of the ACGS-4 borehole. Sr-isotope age estimates are based on the age equations from Miller and others (1991a). ECDZ = East Coast Diatom Zones of Andrews (1988). MFS = maximum flooding surface; FS = flooding surface; unc. = unconformity.
the basis of the presence of *Globigerinoides altiapertus* (Poore and Bybell, 1988; age estimate for its first appearance is 20.9 Ma; Berggren and others, 1985). Preliminary magnetostratigraphic analyses of the Miocene section at this borehole reveal that the sediments are weakly magnetized, and many samples exhibited erratic behavior during thermal and alternating field demagnetization (D. V. Kent, 1992, personal commun.). Nevertheless, the lower Kirkwood sequence from 146–113 m (479–370 ft) contains an interpretable polarity history with a transition from reversed polarities below 134 m (439 ft) to normal polarities above (D. V. Kent, 1992, personal commun.). With the support of the Sr-isotope and biostratigraphic data, this polarity transition is identified as the base of Chronzone C3n (20.45 Ma; Berggren and others, 1985).

Sr-isotope age estimates for the lower Kirkwood sequence from other boreholes and wells yield ages similar to those at ACGS-4 (Fig. 6). Ages are restricted between 19.2–22.6 Ma (±0.5 m.y.) on the basis of the Site 608 age equation (Miller and others, 1991a). The age estimates based on the regression developed at Site 588 (Hodell and others, 1991) and Site 747 (Oslick and others, 1992) are almost identical to those from Site 608, yielding ages ~0.2 m.y. younger (Table 1). One mollusk shell was found in the outcropping Shiloh Marl. An age estimate of 20.3 Ma obtained from this sample is consistent with the subsurface data. Sandy-silt fillings from the shell contained *Actinoptychus heliopelia* (George Andrews, 1988, written commun.), the index species for ECDZ 1 (Andrews, 1988).

The age of the base of this sequence is not well defined. Although the age estimate for the base at the best section, the ACGS-4 borehole, is 21.4 Ma, two measurements from two isolated samples (Berkeley MUA well, Lacey MUA borehole) yield slightly older ages (22.2 and 22.6 Ma, respectively; Table 1). This may indicate that the base of the sequence is ~22.6 Ma and that the oldest strata lie in the central to northern New Jersey Coastal Plain. We place less faith in isolated analyses, however, because a consistent upsection increase in $^{87}$Sr/$^{86}$Sr values provides one of the primary criteria in evaluating Sr-isotope measurements. We speculate that these older ages may represent a depositional sequence older than the ECDZ 1 sequence at the ACGS-4 borehole because this borehole records a relatively complete “New Jersey cycle” (Fig. 4). This implies that the older ages must either reflect Lowstand Systems Tracts of
this cycle (unlikely, given that Lowstand Systems Tracts have not been recorded this far updip in any cycle) or an older sequence. This possible sequence is still within ECDZ 1.

Andrews (1988) estimated the age of his ECDZ 1 (A. heliopelta Assemblage Zone) to be about 19.1–18.9 Ma (Fig. 2). This zone is correlative with Bed 3A of the Calvert Formation in Maryland (Andrews, 1988). Sili
coflagellate markers in Bed 3A include Na
viculopsis quadrata and N. ponticula. At the Wildwood 198A borehole, rare specimens of N. quadrata occur with A. heliopelta (Wet
more and Andrews, 1990). N. quadrata is assigned to the early Miocene Sphenolithus belemnus (= CN2; ~NN3) and Helico
sphaera amplexa (= CN3; ~NN4) coccolith zones (Bukry and Foster, 1974).

One of the major goals of this study was to de
fine the age ranges of the East Coast Dia
tom Zones of Andrews (1988) in New Jersey using Sr-isotope stratigraphy to correlate them to the GPTS. Our data set indicates an age range of 19.2–22.6 Ma (~0.5 m.y.) for Kirkwood deposits assigned to the ECDZ 1. This extends by 3.5 m.y. Andrews' (1988) lower age estimate for the base of ECDZ 1. Benson (1990) gave the range of A. heliopelta in Delaware as 17–24 Ma based on its o
verlap with Globorotalia kugleri. However, the last occurrence of G. kugleri is 21.7 Ma (Berggren and others, 1985), suggesting that the base of the A. heliopelta Zone may be slightly older than this (that is, within the ±0.5 m.y. age error, the Sr-isotope age estimates may be as old as 23.1 Ma).

Bukry (1990) assigned samples from 48–52 m (157–172 ft) at the Clayton borehole to the upper lower Miocene on the basis of the presence of Helicosphaera amplexa s. s. He assigned this interval to calcareous nanno
plankton Zone CN3 (16.2–17.1 Ma; Berggren and others, 1985). Sr-isotope analysis of shell material from 52 m (170 ft) yields an age es
timate of 21.0 Ma (Table 1), substantially older than the nanofossil assignment. In fact, Sr-isotope data (this study) and plank
tonic foraminifera (Zone N5, Poore and By
bell, 1988) both indicate an older age for this interval. This discrepancy is unresolved, al
though consistency of the foraminifer biogr
atigraphy and Sr-isotope stratigraphy indi
cates that the nanofossil correlation may be in error.

Middle Kirkwood Sequence

The middle Kirkwood 2 sequence is correl
ative with ECDZ 2 of Andrews (1988). It unconformably overlies the Kirkwood 1 se
quence (Figs. 4 and 5). The part of the base
containing sediments of the Kirkwood 2 se
quence covers a smaller area of the coastal plain than the lower Kirkwood sequence (Fig. 3C). The depocenter is situated between Cape May and Atlantic City where the Kirk
wood 2 sequence reaches a thickness of just under 92 m (300 ft).

ECDZ 2 is a range zone based on the first
and last occurrence of Delphineis ovata and has an age estimate of 15.6 Ma to 17.4 Ma (Andrews, 1988; Fig. 2). It also contains the silicoflagellate N. navicula (Andrews, 1988), which is in the late early Miocene N. ponticula zone (Fig. 2) of Bukry (1981).

The Kirkwood 2 sequence is best de
veloped at the Wildwood 198A well (Fig. 5) where it is almost 92 m thick. The base of the cycle is predominantly a micaceous silt with some fine sand and fine carbonaceous material. Most of the cycle is dominated by quartz sand. At the AGCS-4 borehole (Fig. 4), the cycle is dominated by silt, with no overlying sand. The silt is clayey, micaceous, laminated-to-massive bedded, and commonly contains small fragments of wood. Thin seams of sand, generally very fine to fine, may be present. Diatoms are abundant in the middle Kirkwood sequence (ECDZ 2) at the AGCS-4 and are dominated by Paralia sulcata, which is common in marine shallow-shelf environ
ments (Andrews, 1987). The bottom of the Belleplain State Forest borehole contained 23 m (75 ft) of ECDZ 2 assigned to the middle Kirkwood sequence (Fig. 7). The deposit consists predominantly of burrowed, fine,
Belleplain State Forest Borehole

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Figure 7. Schematic stratigraphic section of the Belleplain State Forest borehole. Sr-isotope age estimates are based on age equations from Miller and others (1991a) and are average values for the two shell beds in the middle Kirkwood sequence. Bukry (1992, written commun.) assigned samples from 68 m (222 ft) and 75 m (247 ft) to the *D. Sauracanthus* silicoflagellate subzone. ECDZ = East Coast Diatom Zones of Andrews (1988). unc. = unconformity.

Micaceous sand with some interbedded clay-silt.

Sr-isotope age estimates for 12 middle Kirkwood sequence samples (Table 1) ranged from 15.5 to 17.4 Ma (±0.5 m.y.), closely approximating the age estimate for ECDZ 2 by Andrews (1988). The best Sr-isotope control is afforded by the Belleplain State Forest borehole. The data indicate an unconformity at a depth of 91 m (298 ft), at the base of a densely packed shell bed (Figs. 7 and 8). On the basis of an age error of ±0.5 m.y. and ages of 16 Ma above and 17 Ma below the possible unconformity, Sr isotopes cannot unequivocally resolve a hiatus here (Fig. 8). However, the consistently higher Sr ratios above the unconformity and the lithologic break in the core indicate that the middle Kirkwood sequence, as well as ECDZ 2, contains a significant unconformity and a short (<1 m.y.) hiatus. This unconformity divides ECDZ 2 into two sequences. A coeval unconformity is apparently present at the Wildwood 198A well (Fig. 5) between depths of 212–219 m (694–718 ft), where Sr-isotope age estimates are 16.2 Ma and 17.4 Ma above and below the unconformity, respectively. Assuming a 0.5-m.y. hiatus at 91 m (298 ft), sedimentation rates would be 22.5 m per million years for ECDZ 2 at the Belleplain State Forest borehole.

**Upper Kirkwood Sequence**

The Kirkwood 3 sequence—the youngest of the three sequences—unconformably overlies the middle Kirkwood 2 sequence. It correlates with the East Coast Diatom Zone 6 of Andrews (1988), which is a partial range zone whose base is at the first occurrence of *Rhaphoneis clavata* and top is at the last occurrence of *R. geminifera*. It is the least extensive of the three Kirkwood sequences and has a limited distribution in the New Jersey Coastal Plain (Fig. 3D). Its depocenter is just south of Atlantic City, where it is 61 m (200 ft) thick.

The most complete stratigraphic section of the upper Kirkwood sequence is from the Belleplain State Forest borehole, where it is ~46 m (150 ft) thick (Fig. 7). The unit is unconformably bounded, with a phosphatic pebble layer marking the basal unconformity. About 9–12 m of micaceous, burrowed clay-silt with two thin, loosely packed shell horizons are overlain by 18 m (60 ft) of massive micaceous burrowed sand. This is interpreted here as a marine shell deposit that coarsens upward. The sequence is capped by ~12 m (40 ft) of laminated clay-silt to fine sand typical of a tidal-flat facies.

ECDZ 6 is middle Miocene with an estimated age of 13.8 to 12.8 Ma (Andrews, 1988). This zone is in the top of Bed 15 of the Calvert Formation, in Beds 17–18, and in parts of Bed 19 of the Choptank Formation. In the Belleplain State Forest borehole, diatom biostratigraphy of samples at 73 m (240 ft) and 67...
stratification of Miocene Kirkwood Formation, New Jersey

Figure 8. Results of the Sr-isotope stratigraphy of the Belleplain State Forest borehole plotted versus the GPTS of Berggren and others (1985) and the foraminifera zones of Blow (1969).

m (220 ft) yielded an assemblage low in ECDZ 6 and very close to the ECDZ 5 boundary, equivalent to the lower part of Bed 15 of the Calvert Formation (Andrews, 1992, written commun.). In fact, the lowermost part of the ECDZ 6 section at the Belleplain State Forest borehole may be better assigned to ECDZ 5. Changes in the diatom assemblages across the boundary of ECDZ 5/ECDZ 6 are very gradual, however, and may be paleoecologically controlled (Andrews, 1988), and the differentiation of the boundary between the two zones is difficult.

Sr-isotope measurements on 15 samples from the upper Kirkwood sequence were converted to age estimates (Table 1). These estimates range from 15.2 to 10.8 Ma (±2.3 m.y.) based on the Sr-age calibration of Miller and others (1991a); they range from 13.1 to 9.4 Ma (±1.4 m.y.) based on the age calibration of Hodell and others (1991). Clearly, the age estimates from Hodell and others (1991) for this middle Miocene interval are about 1 to 2.5 m.y. younger (Table 1). Although Site 608 contains the best magnetostratigraphic record, it is not completely satisfactory (Miller and others, 1991a). Site 588 middle Miocene data are much less scattered (Hodell and others, 1991), but the chronology is poorly controlled. Oslick and Miller (1992) resolved this disagreement by generating a Sr-age calibration at Site 747 that contained a very good magnetostratigraphic record.

Age estimates based on the Site 747 regression (Table 1, column C) ranged from 14.6 to 11.5 Ma (±0.5 m.y.). The age estimate for a sample from the Avalon Marshes borohole (14.6 Ma) appears to be too old, suggesting reworking of shell material from ECDZ 2. If this age estimate is excluded, ECDZ 6 ranges in age from 13.6 to 11.5 Ma.

Silicoflagellate biostratigraphy also provides support for the older age estimates for shells from ECDZ 6 (Table 1, columns A and C). Bukry (1990, 1991, written commun.) placed samples at ACW#1 borohole from 129 m (424 ft) and Belleplain State Forest borehole (Fig. 7) from 75 m and 68 m (247 ft and 222 ft) in the middle Miocene Disteophanus stauracanthus Subzone of the Corbisema tricantoha Zone (Bukry, 1985). This Subzone is correlative with nannoplankton Zone NN6 (Fig. 2) and ranges from about 14.2 to 12.3 Ma (Barron and others, 1985) or from 14.4 to 13.0 Ma (Berggren and others, 1985). This is in excellent agreement with age estimates based on Site 608 and Site 747 regressions.

DISCUSSION

Sediments of the Kirkwood Formation were deposited during a period of 10 m.y. During this time, the sedimentary environment was characterized by two depositional megasystems—marine shelf and delta. The interfingering and repetition of sedimentary facies characteristic of these two environ-
The lower Kirkwood sequence (Kirkwood 1 sequence = ECDZ 1) is the most completely developed sedimentologic cycle of the three Kirkwood sequences and contains a basal glauconite sand, a middle silt, and an upper sand. Its age is well defined by Sr-isotope age estimates between 19.2 and 21.4 Ma, with the base possibly extending to 22.6 Ma (using age regression of Miller and others, 1991a). This is also supported by the assignment of the foraminifera at the base of this cycle at AGCS-4 to Zone N5 (Poore and Bybell, 1988). The correlation of the Clayton borehole sample (Sr-isotope age estimate of 21.0 Ma) to calcareous nannoplankton zone CN3 by Bukry (1990) implies that *H. ampliaperta* and secondary markers *Discocaster variabilis* and *Helicosphaera scissura* may occur earlier in this shallow Atlantic Basin than in other marine basins (for example, Berggren and others, 1985).

The middle Kirkwood sequence, or Kirkwood 2 sequence, correlates with ECDZ 2 of Andrews (1988) and is also an unconformity-bounded, generally coarsening-upward sedimentary cycle. A hiatus of 2 m.y. separated deposition of the Kirkwood 1 and 2 sequences (Fig. 9). Sr-isotope age estimates for the Kirkwood 2 sequence based on the age equation of Miller and others (1991a) range from 17.4 to 15.5 Ma (±0.5 m.y.). This places the base of this sequence in the lower Miocene and the top of the sequence in the middle Miocene.

The base of the Kirkwood 2 sequence apparently correlates with sequence boundary TB2.2, a third-order type-2 cycle of Haq and others (1987). The base of the sequence correlates with the δ¹⁸O increase associated with Zone Mi1b (Fig. 9). This indicates a linkage between the glacioeustatic record and the erosion of unconformities on the New Jersey Coastal Plain, and it supports the suggestion of Haq and others (1987) of a eustatic lowering at ~18 Ma (the TB2.1/2.2 boundary). Considering uncertainties in the ages of the eustatic record of Haq and others (1987), it is possible that the unconformity separating ECDZ 2 from ECDZ 1 correlates not with TB2.2, but with TB2.3 (Fig. 9). Assuming the ages provided by Haq and others are correct, however, this unconformity best correlates with the TB2.2 event.

ECDZ 2 is split into a lower and an upper sequence separated by an unconformity.
Data from the Belleplain State Forest borehole and the Wildwood 198A well indicate an unconformity within ECDZ 2 (Figs. 5 and 7). The duration of the hiatus associated with this surface is 1 m.y. or less (from ~17 to 16 Ma), at the limits of Sr-isotope resolution for this interval. However, Sr-isotope values firmly establish the age of the surface as 16 to 17 Ma (Fig. 9). This unconformity within ECDZ 2 in New Jersey apparently correlates with the PP-0 disconformity of Kidwell (1984); this latter surface occurs between Bed 3B and Beds 4 to 9 in the Calvert Cliffs of Maryland, where the diatom assemblages for ECDZ 2 were developed. Within the age uncertainty, this surface correlates with the 818O increase associated with Zone Mi2 (Fig. 9) and with the eustatic lowering of the TB2.3 sequence boundary (Haq and others, 1987; Fig. 9). It may correlate with the offshore New Jersey Bice-1 sequence boundary (Fig. 9), although age errors on the latter are large (±1 m.y.; Greenlee and others, 1992).

The upper Kirkwood sequence, or Kirkwood 3 sequence, is correlative with ECDZ 6 of Andrews (1988) and the D. stauracanthus Subzone of Bukry (1985), which has an age of 14.2–12.3 Ma (Barron and others, 1985). Preferred age estimates for this cycle obtained from Site 747 are 13.6–11.5 Ma (~±0.8 m.y.), although its age limits are not well defined in any borehole. The hiatus associated with the basal unconformity correlates with the base of oxygen isotope Zone M3 and could correlate with the lower boundary of sequence TB2.5 or TB2.4 of Haq and others (1987) and the Aqua or Red-2 offshore New Jersey sequence boundaries (Fig. 9). The age estimates for the upper boundary of this sequence are poorly defined: if the Wildwood 198A data are excluded because they are regarded as somewhat younger than the other Sr-age data for ECDZ 6, the upper range is 12.2 Ma. This age estimate of the upper boundary is supported by the silicoflagellate biostratigraphy. On the basis of maximum sedimentation rates of 40 m per million years (from ECDZ 1), ECDZ 6 at Belleplain would comprise 1.2 m.y.; the slowest sedimentation rates used here (22.5 m per million years) would require 2 m.y. of deposition. These are within the data range of 13.6–12.2 Ma for the age of the upper Kirkwood sequence. Considering these uncertainties, we cannot evaluate if the hiatus at the top of this sequence correlates with 818O Zones Mi4 or Mi5 or neither, although a tentative correlation with Mi4 is preferred. We also tentatively correlate the hiatus at the top of this sequence with the lower boundary of sequence TB2.6 of Haq and others (1987), and the Yellow-2 offshore New Jersey sequence boundary of Greenlee and others (1992).

Although it is possible to ascertain whether eustasy is a controlling factor in the deposition of the Kirkwood sequences by comparing Sr-isotope age estimates with the oxygen isotope record, global sea-level curves, and the offshore New Jersey record, the role and timing of tectonics are more difficult to evaluate. Clearly, depositional and erosional histories in the Miocene Atlantic Coastal Plain differ between Maryland and New Jersey. For example, ECDZ 3, 4, and 5 are present in the Maryland stratigraphic record, but absent in New Jersey (with the possible exception of the upper part of ECDZ 5), suggesting that tectonism may be an important factor controlling intrabasinal stratigraphic differences in the Atlantic Coastal Plain (Owens and Gohn, 1985). The high sedimentation rates measured in the Kirkwood sequences also suggest a tectonic effect through uplift, resulting in large volumes of sediment delivered in several pulses.

CONCLUSIONS

Sr-isotope stratigraphy has made possible age estimates of shallow-water New Jersey Coastal Plain sections on the basis of two DSDP and one ODP reference sections and correlation to the GPTS. This enabled us to define the ages of depositional sequences in the Kirkwood Formation and to compare timing of these Miocene sequences with other sea-level proxies, including offshore New Jersey (Greenlee and others, 1992), the oxygen isotope record (Miller and others, 1991b), and the inferred eustatic record of Haq and others (1987). The correlation of the onshore unconformities with other indicators is consistent with a global-crustal, eustatic change. We also suggest that tectonics plays an important role in the development of the Kirkwood sequences in New Jersey, although the interaction of sea level and tectonics is difficult to determine at this time. Future studies, including additional onshore drilling, offshore drilling, and seismic stratigraphic studies, should provide a transect across the margin needed to evaluate the role of tectonics and sea-level change (Mountain and Miller, 1992).

ACKNOWLEDGMENTS

Discussions and collaborative work with D. V. Kent were particularly helpful. We thank W. Newell for supplying samples from the ACGS-4 and Belleplain boring; R. K. Olsson for samples from the Jobs Point and Leggette boreholes; G. Andrews, D. Bukry, and D. V. Kent for supplying unpublished diatom, nannofossil, and magnetostratigraphic data, respectively; and M. French, W. Graff, D. Harper, C. Liu, and J. Browning for graphical support. Supported by National Science Foundation Grants OCE89-11810 and OCE92-03282 (Miller). We thank Thomas Gibson, I. G. Grossman, and Douglas Jones for reviewing the manuscript.

REFERENCES CITED


Geological Society of America Bulletin, April 1993


Olson, J. F., 1989, Marine Tertiary depositional history of the New Jersey Coastal Plain: Geological Society of America Abstracts with Programs, Northeastern Section, v. 21, no. 5, p. 56.


