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A 40-Million-Year Lake Record of Early Mesozoic Orbital Climatic Forcing

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Sediments of the early Mesozoic Newark Supergroup of eastern North America consist largely of sedimentary cycles produced by the rise and fall of very large lakes that responded to periodic climate changes controlled by variations in the earth's orbit. Fourier analysis of long sections of the Late Triassic Lockatong and Passaic formations of the Newark Basin show periods in thickness of 5.9, 10.5, 25.2, 32.0, and 96.0 meters corresponding to periodicities in time of roughly 25,000, 44,000, 100,000, 133,000 and 400,000 years, as judged by radiometric time scales and varve-calibrated sedimentation rates. The ratios of the shortest cycle with longer cycles correspond closely to the ratios of the present periods of the main orbital terms that appear to influence climate. Similar long sequences of sedimentary cycles occur through most of the rest of the Newark Supergroup spanning a period of more than 40 million years. This is strong evidence of orbital forcing of climate in the ice-free early Mesozoic and indicates that the main periods of the orbital cycles were not very different 200 million years ago from those today.

THE ORBITAL THEORY OF CLIMATE CHANGE STATES THAT celestial mechanical cycles of the earth's orbit, such as the precession of the equinoxes, the obliquity cycle, and the eccentricity cycle, produce changes in the seasonal and geographical distribution of sunlight reaching the earth which, in turn, affects climate (*1*, *2*). The theory makes specific predictions about the periodicity of climate cycles that should be testable in the geological record. Recently, the predictions of the orbital theory have been convincingly confirmed through studies of climate-sensitive geochemical and biotic indices in deep sea sediments of Quaternary age, especially in middle and high latitudes (*2*). In agreement with present-day celestial mechanical values, proxy indicators of paleoclimate in Quaternary sections show major climate cycles with periods of roughly 21,000 (precession of the equinoxes), 41,000 (obliquity cycle), and 95,000, 123,000, and 413,000 years (eccentricity cycles) (*1*, *2*). These marine proxy records also show strong coherencies with the modern orbital cycles (*1*).

The sediments of closed lakes also provide sensitive records of ancient climate change because lake level and salinity respond directly to changes in precipitation and cloud cover (*3*). In turn, lake level and salinity directly affect sediment fabric and chemical content. In low latitudes, lacustrine records have provided the most convincing and spectacular evidence for Quaternary climatic variations in accord with the orbital theory of climate change (*3*). Because of their relatively simple response to climate change, lacustrine sequences provide fertile ground for testing the predictions of the orbital theory far into the geological past. I describe early Mesozoic cyclic lacustrine sequences in the fluvial and lacustrine Newark Supergroup of eastern North America. These lacustrine sequences span more than 40 million years (*4*), show the full spectrum of climate cycle periodicities predicted by the orbital theory of climate change, and show that the periods of these terms have not changed much, if at all, during the last 200 million years.

Van Houten cycles: Lake level sequences of the Newark Supergroup. Newark Supergroup sediments are the remnants of tropical (10° to 25°N) rift valley sequences formed during the initial phases of extension leading to the breakup of Pangea (*4*, *5*). The sediments are exposed in more than 13 elongate basins from Nova Scotia to North Carolina (Fig. 1). Virtually all these basins contain fine-grained lacustrine sediments. Van Houten (*6*) first recognized the cyclical nature of Newark Supergroup sediments in his studies on the Lockatong Formation of the Newark Basin, where he recognized several orders of cycles interpreted as having periods of roughly 21,000, 100,000, and 400,000 to 500,000 years; he linked these to orbital variations. Similar cyclical lacustrine sequences were subsequently recognized in the other main Newark basins (*7–9*) (Fig. 1).

Most Newark lacustrine deposits consist of simple transgressive-regressive cycles that fall into a single general type of sequence, named a Van Houten cycle (*10*). These cycles consist of three basic, lithologically recognizable divisions, called divisions 1, 2, and 3, which are interpreted (*7*) as lake transgression, high-stand, and regression and low-stand facies (Fig. 2). Division 1 is a calcareous claystone to siltstone with pinch and swell lamination with thin bedding, occasional desiccation cracks and burrowed horizons, stromatolites, and oolites. This represents a lacustrine transgressive sequence with shoreline deposits. Division 2 is a laminated to microlaminated calcareous claystone and siltstone, or limestone, with desiccation cracks rare to absent. This division has the highest organic content of the cycle and fish and other animal fossils are sometimes abundant; it represents the lake's high-stand deposit. Division 3 is a calcareous claystone and siltstone, with abundant desiccation cracks, burrowed and rooted horizons, vesicular and crumb fabrics (*11*), and reptile footprints. Division 3 represents the regressive and low-stand deposit; the lake was at least occasionally dry with incipient soil development.

Van Houten cycles have been shown to be laterally continuous over large areas in several basins, as are their constituent divisions (*7*). The total range of thickness of these cycles over the whole of the Newark Supergroup is between 1.5 and 70 m (*7*, *10*, *12*), but the amount of variability is small within a single formation or a basin (*13*, *14*).

The longest completely unbroken sequence of Van Houten cycles consists of the Lockatong (1100 m) and overlying Passaic (3300 m) formations of the Newark Basin of Late Carnian to earliest Jurassic

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age (Fig. 1). In both formations Van Houten cycles are a mean of 5.9 m thick (*12, 13*), the main lithological difference between the two formations being the higher proportion of red beds in the Passaic.

Individual cycles in the Lockatong and Passaic formations are traceable throughout the basin, indicating that the cycles represent basinwide changes in lake level. The area covered by division 2 (high-stand deposit) indicates that at maximum transgression the lakes covered more than 7000 km^2 (*12, 14*). On the assumption that the finely laminated deep-water sediments could not have been deposited above wave base, the largest lakes would have been more than 100 m deep (*12, 14*).

Preliminary stratigraphic studies of the Gettysburg and Culpeper basins suggest that lateral equivalents of the Van Houten cycles of the Lockatong and Passaic formations originally extended south into these two basins (*14*). If this proves to be the case, the largest of the lakes would have been at least as large as the present Lake Tanganyika of East Africa or Baikal of Siberia, both of which are rift valley lakes (*15, 16*). However, as shown by the abundant desiccation cracks in division 3 (regressive and low-stand interval) of almost all cycles, even the deepest lakes dried out during the deposition of a single cycle. These very large changes in the depths of lakes are most easily explained by changes in precipitation and cloud cover governing lake level within a deep and closed drainage basin (*3, 14, 16*).

Fourier analysis of lake sediment fabrics. Within the central Newark Basin, the Lockatong and Passaic formations consist of almost exclusively fine-grained calcareous siltstones. Here Van Houten cycles are expressed largely as variations in the fabric of the sediments, originally deposited principally from suspension, which reflect varying degrees of exposure to desiccation and bioturbation. Correlative variations occur in organic carbon and pyrite-sulfur content, and the mode of fossil preservation. I have classified the sediment fabric of these cycles into seven facies called depth ranks, and assigned each a numerical rank from 0 to 6, arranged in order of increasing inferred water depth.

Depth rank 0 is a massively bedded calcareous claystone and siltstone with root, tube, crumb, and vesicular fabric (*11*). Faint remnant parent fabric is present and there are abundant clay cutans. This is an intensely desiccated fabric deposited during the time-averaged lowest lake level (*11*). Depth rank 1 is an intensely brecciated and cracked calcareous claystone and siltstone. Burrows can be common but obvious remnant parent fabric is present. Mud curls are sometimes present as are cracks with vesicular fabric. This fabric shows less intense desiccation and on a time-averaged basis was deposited under relatively deeper water than the facies of depth rank 0 (*11*). Depth rank 2 is a thin bedded calcareous claystone and siltstone with desiccation cracks. Large patches of uncracked matrix are preserved and reptile footprints and burrows are often present. The low density of desiccation cracks shows infrequent desiccation of wet sediment, indicating a yet higher time-averaged lake level (*11*). Depth rank 3 is a thin bedded calcareous claystone and rare siltstone with very small scale burrows; desiccation cracks are rare to

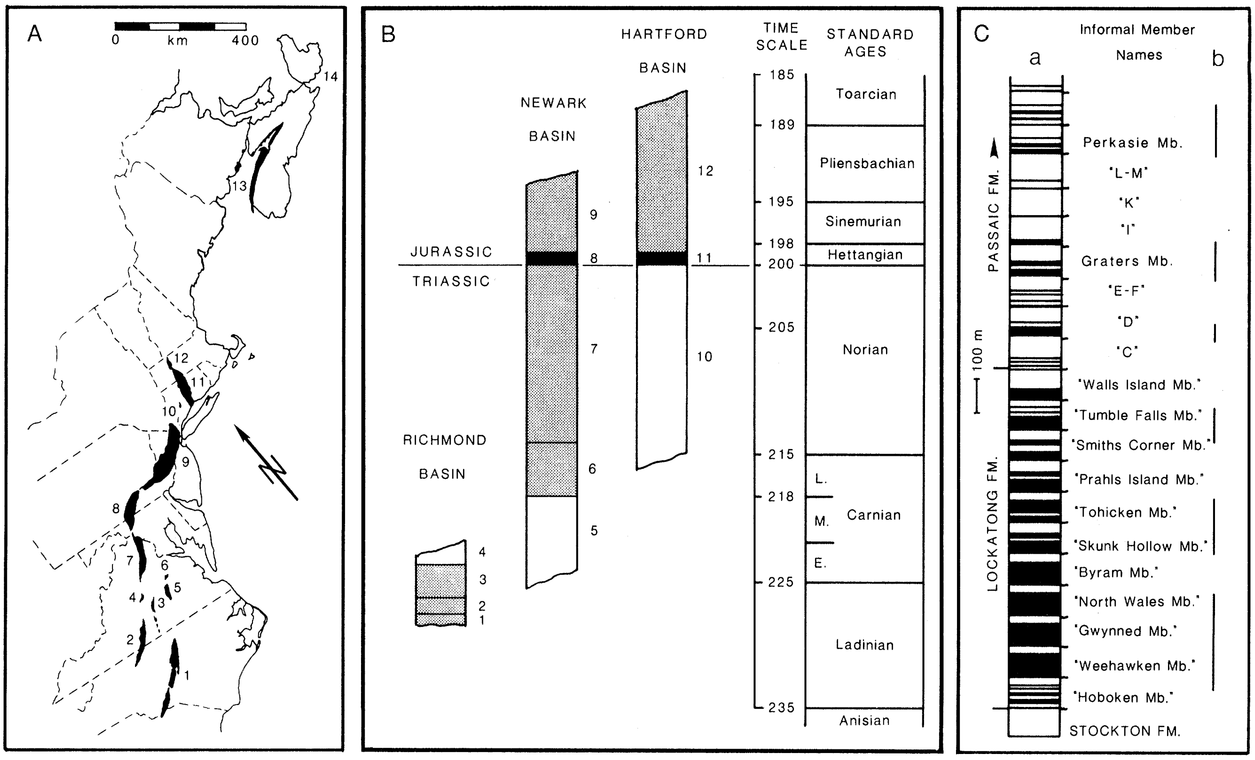

Fig. 1. The Newark Supergroup and sections mentioned in text. (A) Exposed extent of the Newark Supergroup (in black). Basin names are 1, Deep River Basin; 2, Dan River Basin; 3, Farmville and subsidiary basins; 4, Scottville Basin; 5, Richmond Basin; 6, Taylorsville Basin; 7, Culpeper Basin; 8, Gettysburg Basin; 9, Newark Basin; 10, Pomperaug Basin; 11, Hartford Basin; 12, Deerfield Basin; 13, Fundy Basin; and 14, Chedebucto Basin (Orpheus Graben). (B) Correlation of major portions of the Newark Supergroup (*4, 31, 36*). Time scale compiled from Webb (*23*) and Odin and Kennedy (*24*). In stratigraphic columns, gray intervals represent dominantly lacustrine sediments, white intervals represent dominantly fluvial sediments, and black intervals represent interbedded extrusive basalts and lacustrine sediments. Abbreviations of units are 1, lower Barren Beds; 2, Productive Coal Measures; 3, Vinita Shale; 4, Otterdale Sandstone; 5, Stockton Formation; 6, Lockatong Formation; 7, Passaic Formation; 8, Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, and Hook Mountain Basalt; 9, Boonton Formation; 10, New Haven Arkose; 11, Talcott Basalt, Shuttle Meadow Formation, Holyoke Basalt, East Berlin Formation, and Hampden Basalt; and 12, Portland Formation. (C) Lockatong and lower Passaic formations: (a) composite stratigraphic section Lockatong and lower Passaic formations (horizontal black intervals represent principally gray and black sediments and white intervals represent mostly red sediments); (b) vertical black bars indicate intervals of Lockatong and Passaic formations in which Van Houten cycles show especially thick and finely laminated black sediments in division 2, an approximately 1.6-million-year cycle is indicated by the spacing of these zones.

Table 1. Ratio of the mean period of the cycle of the precession of the equinoxes to the other main orbital periods and comparison with the mean period of thickness of Van Houten cycles to the other main periods in the Lockatong and Passaic formations (from Fig. 3). Abbreviations of orbital periods: P, precession of the equinoxes; O, cycle of the obliquity of the earth's axis; E1, E2, and E3, first, second, and third main terms of eccentricity of the earth's orbit (*32*).

Item	Orbital periods				
	P	O	E1	E2	E3
Present-day periods ($\times 10^3$ years)	21.7	41.0	95.0	123.0	412.1
Average thicknesses of cycles (m)	5.9	10.5	25.2	32.0	96.0
Ratio of modern periods of precession to other modern orbital periods	1.0	1.9	4.4	5.8	19.0
Ratio of Van Houten cycles to other cycles					
Eureka Section	1.0	1.7	4.3		
Gwynned Section	1.0	1.9	3.9		15.5
Delaware River Section	1.0	1.7	4.1	5.5	16.6
Ottsville Section	1.0		4.7		
Ratios of average periods of Van Houten cycles to averages of other cycles	1.0	1.8	4.3	5.5	16.3

absent and pinch and swell lamination is often present. Although only rarely or never desiccated, this fabric was deposited under relatively shallow water, as evidenced by the frequent erosion and deposition above wave base (*14*). Depth rank 4 is an evenly laminated calcareous claystone with some small-scale burrows and abundant discontinuous microlamination. There are no desiccation cracks. Bottom water ventilation, and hence degree of bioturbation, is directly related to water depth in steep sided lakes (*14*) and, therefore, the decrease in bioturbation reflects an increasing bottom water oxygen deficit in deepening water. Depth rank 5 is an evenly and finely laminated calcareous claystone or limestone with abundant discontinuous microlaminations; there are no desiccation cracks. This facies was deposited under water that was usually anoxic with only infrequent ventilation and was hence deeper than that which produced depth rank 4 (*14*). Depth rank 6 is a microlaminated calcareous siltstone with only rare disruptions and no desiccation cracks. This represents the facies deposited under the least oxygenated water when the lake was deepest and when the bottom was most insulated from wind- and wave-generated turbulence (*7, 14*).

When these depth ranks are plotted as a function of sediment thickness in single sections, both individual Van Houten cycles and several higher order cycles are apparent in the resulting curves (Figs. 2 and 3). These depth rank curves allow a qualitative classification of facies that reflect changes in lake level to be handled by numerical analysis of relative changes in lake depth with thickness or time, much as $\delta^{18}O$ curves have been used for variations in ice volume and temperature in deep sea cores (*3*).

Four different sections of the Lockatong and Passaic formations have been measured from these depth rank curves (Figs. 3 and 5). All have nearly complete exposure and very little overlap. The three Lockatong sections make up most of the lower three-quarters of the formation and the single Passaic Formation section at Ottsville, Pennsylvania, makes up the Perkasie Member, located about 600 m above the top of the Lockatong Formation. These sections were selected because of their complete exposure, position in the basin, and prevalence of suspension-dominated sediments (*11*).

The periodic components of the depth rank curves of the Lockatong and Passaic formations are described by Blackman and Tukey-type Fourier analysis (*17*), following a modification of the procedure established by Hays, Imbrie, and Shackleton (*3, 18*) for their analysis of Quaternary deep sea cores. The analysis consists of two parts: an examination of the periodic components of the depth rank curves in terms of thickness, and selection of a sedimentation rate so that the periodic components in the time domain can be examined. In both cases, a power (or variance) spectrum is produced that expresses the variance of the data curve as a function of the frequency of the cycle.

Periods in the thickness of cycles. Power spectra of depth rank curves constructed for the four Newark Basin sections are very similar, with

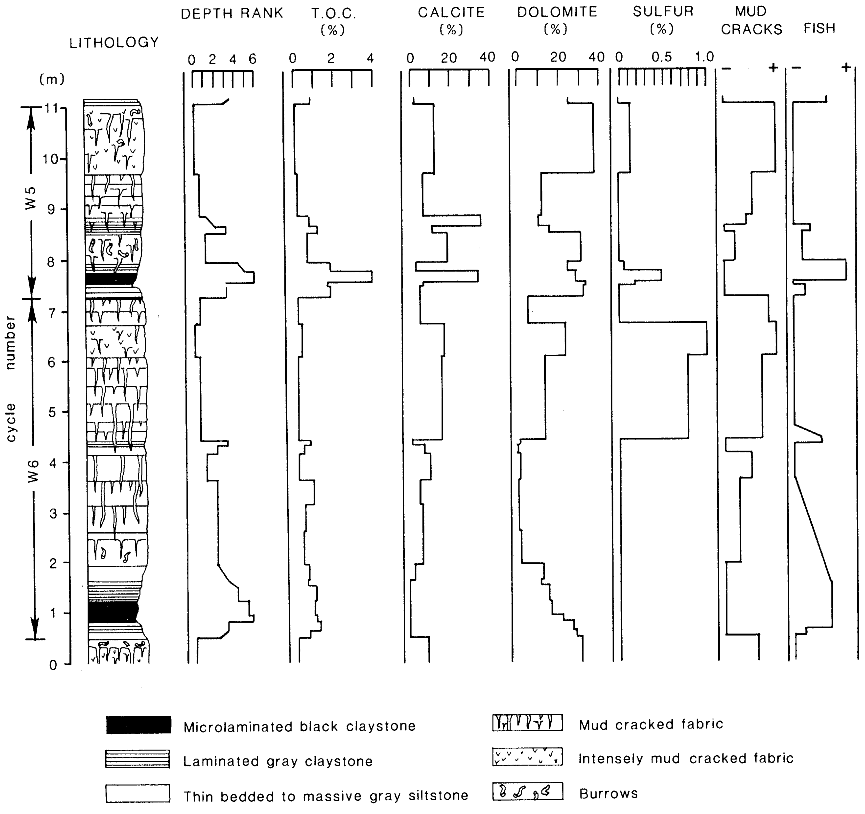

Fig. 2. Two representative Van Houten cycles from the Lockatong Formation of the Eureka Quarry, Tradesville, Pennsylvania (from interval marked "a" in The Eureka section of Fig. 3). Chemical data from (*14, 37*). T.O.C. refers to total organic carbon content that is measured as percentage by weight.

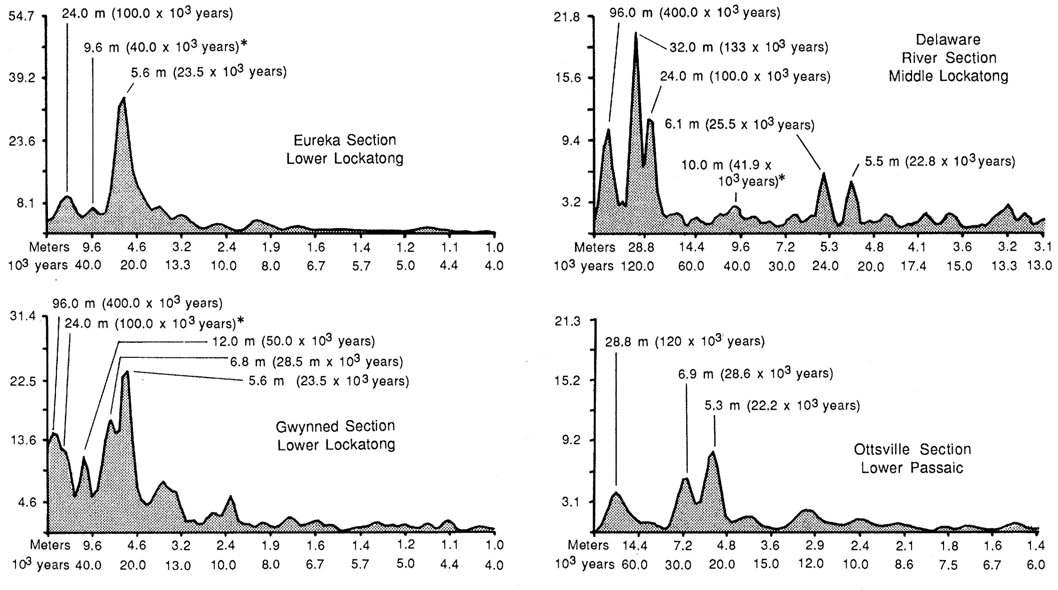

Fig. 3. Power spectra of the sections of the Lockatong and Passaic formations in Fig. 4 showing the main periods in both thickness and time. Periods marked with an asterisk are not significant at the 5% level.

prominent periods at approximately 5.5, 6.5, 25.0, 32.0, and 96.0 m (Fig. 3). A less significant peak appears around 10.5 m. The 5.5- and 6.5-m cycles average to 5.9 m, which represents the thickness of individual Van Houten cycles and the 24.0- plus 32.0-m cycles and the 96.0-m cycle are two kinds of long cycle types identifiable at most outcrops and also originally noted by Van Houten (*6*). The 96-m cycles are very obvious at map scale and constitute the named members of the Lockatong and Passaic formations (Figs. 1 and 4). These were originally mapped by McLaughlin (*19*) more than 40 years ago throughout much of the Newark Basin.

An even longer term cycle is suggested by the occurrence of a series of Van Houten cycles, most with an especially thick, well-laminated, and fossiliferous division 2, at roughly 400-m intervals (Fig. 1). These results are preliminary and appropriately long time series have not yet been subjected to spectral analyses.

Comparison with modern orbital periods. To compare the Late Triassic power spectra with the predictions of the orbital theory, I used first the ratios of thickness of periods in the Lockatong and Passaic formations and the ratios of the orbital periods. This method is based on the strongly hierarchical structure of the power spectra and is independent of vagaries of time scale and sedimentation rate estimates (Table 1).

The celestial mechanical functions producing the periods of precession, obliquity, and eccentricity are free to vary independently throughout geologic time (*20*). Varying any of the periods independently would distort the thickness ratios and the power spectra. The close agreement of the thickness ratios to the predictions of the orbital theory, therefore, suggests that the early Mesozoic periods of these celestial mechanical elements were similar to those of the present day.

Estimating the sedimentation rate. In order for the periodicity of the Lockatong and Passaic formations to be examined in terms of time, however, a sedimentation rate must be applied to the sections so that thickness may be expressed as time. Current radiometric dating techniques lack the accuracy and precision to estimate the duration of these Triassic sections by internal dates alone. Two less robust methods are available: use of published radiometric time scales, based on globally compiled data, and varve calibration (*21, 22*).

The duration of the combined Lockatong and Passaic formations can be estimated by comparison of the paleontologically dated base and top of the units to radiometrically based time scales of the early Mesozoic; Newark Basin igneous rocks are limited to a very restricted portion of the Early Jurassic section (*4, 7*) and thus direct dating of the interval is not possible. The biostratigraphic boundary between the late and middle Carnian falls within 100 m of the base of the Lockatong, and the Triassic-Jurassic boundary falls within the upper 100 m of the Passaic Formation (*14*) (Fig. 3). The duration of the two formations is between 20 and 14 million years according to recently published time scales (Table 2). The total thickness of the Lockatong and Passaic formations is about 4400 m; this thickness divided by the estimated duration of this interval results in a net sedimentation rate of between 0.22 mm per year and 0.31 mm per year. The periods of the main sedimentary cycles calculated for these different time scales are shown in Table 2.

For the varve calibration method it is assumed that the carbonate-organic claystone couplets in division 2, with a depth rank of 5 or 6, are produced by seasonal changes in sedimentation and are hence lacustrine varves. The average sedimentation rate thus derived for the microlaminated sediments of the central Newark Basin is 0.24 mm per year (Table 3). This is the same value used by Van Houten

Table 2. Comparison of the modern main orbital periods with the main periods derived from the Lockatong and Passaic formations on the basis of various times scales. The varve sedimentation time scale is based on a sedimentation rate of 0.24 mm per year and orbital periods were calculated from average thickness periods shown in Table 1. Numbers in parentheses are the ages (in millions of years) for the Triassic-Jurassic boundary and the Late Carnian-Middle Carnian boundary. Abbreviations of orbital periods: P, precession of the equinoxes; O, cycle of the obliquity of the earth's axis; E1, E2, and E3, first, second, and third terms of eccentricity of the earth's orbit (*32*).

Time scale	Orbital periods (×10^3 years)					Reference
	P	O	E1	E2	E3	
Present day	21	41	95	123	413	
Varve sedimentation	25	44	100	125	400	
Radiometric scale 1 (200–218 × 10^6 years ago)	25	44	100	125	400	(*23*)
Radiometric scale 2 (208–227 and 204–223 × 10^6 years ago)	26	46	109	139	417	(*25, 29*)
Radiometric scale 3 (208–228 × 10^6 years ago)	27	48	115	145	436	(*26*)
Radiometric scale 4 (213–227 × 10^6 years ago)	19	34	81	103	309	(*27*)

(*6*). The sections measured here are almost exclusively suspension-dominated and while the sediment fabric changes drastically under different water depths, the net sedimentation rate may remain on the average constant. Under the rather tenuous assumption that the 0.24 mm per year value is also representative of the nonvarved suspension-dominated sediments, I have used it to calibrate the depth rank curves.

Despite the obvious uncertainties of both approaches, the difference between the sedimentation rates derived from published time scales and varve counts are not significant. For the power spectra time calibration I have selected the varve method for a sedimentation rate because it is based on information from the sections themselves and agrees with what appears to be the most robust of the published radiometric time scales (*23, 24*). This time scale (*23*) places the Triassic-Jurassic boundary at 200 million years, which also agrees with dates from the earliest Jurassic Newark Basin basalt flows.

It is also important to note that the longer term cycles are composed of successions of Van Houten cycles and thus changes in sedimentation rates in single Van Houten cycles were plausibly repeated in successive cycles. Therefore, those periods in thickness (and time) greater than a single Van Houten cycle as identified by Fourier analysis are not affected by short-term inconstancies in sedimentation rates.

When the sedimentation rate of 0.24 mm per year (from the varve counts) is applied to the four sections, power spectra show prominent periods in time at 22,000 to 24,000, 26,000 to 29,000, 40,000 to 50,000, 100,000 to 133,000, and 400,000 years (Fig. 3). The ranges of these periods calibrated by most published time scales are not significantly different from each other, as shown in Table 2 (*23–28*). This is in full agreement with the arguments based solely on ratios of the thicknesses of the cycles. The remainder of the Lockatong and Passaic formations closely resembles the four sections examined here. Therefore, the available data suggest that the lakes that deposited the Lockatong and Passaic formations responded in depth to changes in climate with periods of around 25,000, 45,000, 100,000, 133,000, and 400,000 years.

Lacustrine cycles in the rest of the Newark Supergroup. The Jurassic portions of the Newark Supergroup continue the pattern of sedimentary cycles seen in the Triassic Lockatong and Passaic formations (Fig. 5). The longest intervals of Jurassic age Newark Supergroup rocks are preserved in the Hettangian to Toarcian age (Early Jurassic) portions of the Hartford Basin (Fig. 1). Correlation with the Newark Basin is afforded by the geochemistry of the extrusive igneous units (*29, 30*), pollen and spore data, and the pattern of Van Houten cycles themselves (*14*). The dissimilarity between the fish assemblages in the sequentially matching Van Houten cycles in correlative formations in the extrusive zone shows, however, that the basins were not in the same drainage systems. Therefore the two lake systems must have responded synchronously but independently

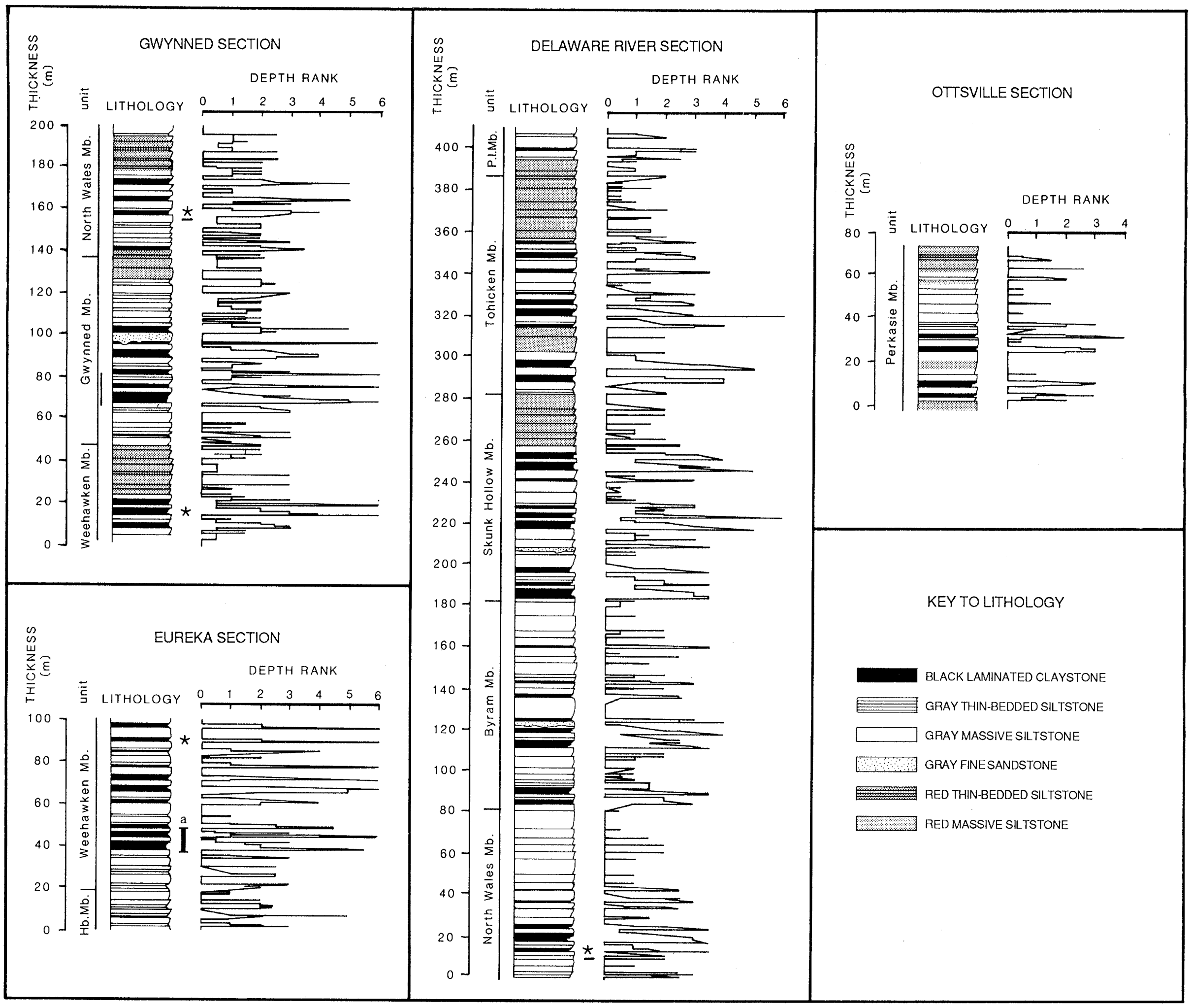

Fig. 4. Measured sections of Lockatong and Passaic formations (*38*) with depth rank curves. In the Eureka Section, "a" indicates the two Van Houten cycles shown in Fig. 2. The asterisk in the Eureka Section indicates the units thought to correlate with the beds indicated by the asterisk in the Gwynned Section; the underlined asterisk in the Gwynned Section corresponds to that in the Delaware Section.

to some regional control, presumably cyclically changing climate (*19*).

The oldest Newark Supergroup sediments known to be made up of Van Houten cycles occur in the relatively poorly known Ladinian and early Carnian age (Middle and Late Triassic) strata of the Richmond Basin in Virginia (*31*). The time span represented in these Middle Triassic rocks through the Newark Basin section, to the late Early Jurassic rocks of the Hartford Basin is more than 40 million years (Fig. 1). This entire interval is dominated by the pattern of Van Houten cycles typified by the Lockatong and Passaic formations (Fig. 5), although the cycles differ in thickness, presumably due to differences in basin subsidence and sedimentation rates.

Orbital forcing of early Mesozoic lake depth. The periods seen in Fourier analysis of the Lockatong and Passaic formations are similar to those predicted by the orbital theory of climate change and those seen in Quaternary deep sea cores (*1, 2*). In particular the Lockatong and Passaic 25,000-year cycle corresponds to the average cycle of the precession of the equinoxes (mean, 21,000 years), the 45,000-year cycle to the axial tilt cycle (41,000 years), and the 100,000-, 133,000-, and 400,000-year cycles to three main celestial mechanical terms of the cycle of the eccentricity of the earth's orbit (95,000 123,000 and 413,000 years) (*32*). The tendency for the Lockatong and Passaic formations to show two peaks in their power spectra around 25,000 years may be particularly significant because it parallels the two modes of precession, 19,000 and 23,000 years, averaging 21,000 years. The suggestions of a 1.6-million-year cycle in the Lockatong and Passaic also finds a close match in the Milankovitch periodicities as the sixth celestial mechanical term of the eccentricity cycle (*32*) (Table 1).

Table 3. Sedimentation rates (±SEM) derived from varve counts for the central Newark Basin (*39*).

Section	Couplets (*n*)	Sedimentation rate (mm per year)
Eureka	29	0.22 ± 0.01
	41	0.25 ± 0.01
	35	0.25 ± 0.01
Gwynned	42	0.24 ± 0.01
Delaware River	25	0.22 ± 0.01
	47	0.23 ± 0.02
	43	0.27 ± 0.01

Climate cycles in the ice-free Mesozoic world. Explanations of the physical mechanism relating orbital forcing to cyclic and periodic climate change have traditionally focused on the nonlinear response of ice to relatively small changes in insolation (*3*). However, such explanations of the Newark Supergroup cycles are untenable; there is little evidence of continental glaciers or sea ice in the early Mesozoic (*33*).

A plausible mechanism for direct control of the climate of an ice-free world by Milankovitch-type changes in insolation has been proposed by Rossignol-Strick and others (*34*) for low latitude Quaternary climate changes and will suffice. According to this model, changes in heating intensity of northern continental masses caused directly by precession of the equinoxes alter the intensity of low pressure cells that drive the monsoonal winds in the more southern areas. At any one location, precipitation is under the direct

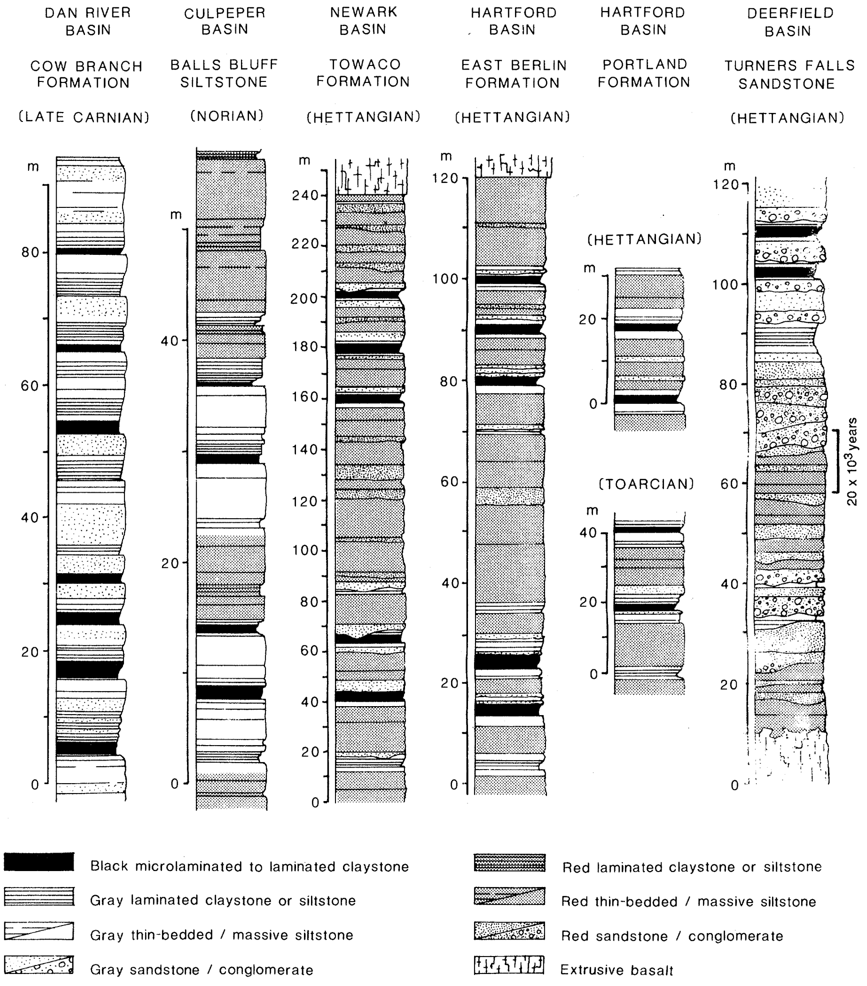

Fig. 5. Comparisons of sequences from various portions of the Newark Supergroup other than the Lockatong and Passaic formations (*37, 38*), all shown with the Van Houten cycles drawn to the same time scale. With the exception of the Portland Formation intervals, each section shows two 100,000-year cycles.

control of the precession cycle, which is in turn modulated by the eccentricity cycle.

The Newark Supergroup lay between 10° and 25°N latitude (*5*) during the early Mesozoic and would have experienced a monsoonal climate. According to the Rossignol-Strick model, precipitation, and hence lake level, would respond most strongly to the precession and eccentricity cycles, which is the observed pattern, although presumably orographic effects would modify both the magnitude and the expression of the climate changes (*5*). In the Newark Supergroup, the shape of the depth rank curves (Fig. 3) implies that precession controlled lake depth, with the expected modulation by the longer eccentricity cycles. The relative unimportance of the obliquity cycle confirms the prediction that the obliquity cycle has little direct effect on insolation in low latitudes dominated by the monsoonal climate (*34*).

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13. Van Houten cycles of the Lockatong Formation of the Newark Basin change in thickness from about 5.9 m in the central Newark Basin to 1.5 m on the northeastern sediment-starved portion of the basin (*7*).
14. P. E. Olsen, thesis, Yale University, New Haven, CT (1984).
15. The Culpeper and Gettysburg basins are separated by a small break in Maryland, but the facies patterns and ages of strata in the adjacent portions of both basins show no indications that this was a barrier during sedimentation; Van Houten cycles are present on both sides of the break. The Newark and Gettysburg basins are connected by a narrow neck. Van Houten cycles are present in this area (B. Cornet, personal communication) and the adjacent Gettysburg and Newark basins.
16. The Newark, Gettysburg, plus Culpeper basins occupy an area of 29,000 km^2 and Lake Tanganyika occupies 31,900 km^2 and Baikal occupies 31,500 km^2 [G. E. Hutchinson, *Treatise on Limnology* (Wiley, New York, 1957), vol. 1]. Within the three Newark Supergroup basins, Van Houten cycles extend to the basin edges, indicating the minimum area covered by lakes flooding all three basins must have been at least as large as their present area.
17. R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra from the Point of View of Communications Engineering* (Dover, New York, 1958).
18. Power spectra were derived from a program compiled by N. G. Pisias and other members of SPECMAP based on the Blackman and Tukey (*17*) "truncated autocovariance method" and the subroutines of G. M. Jenkins and D. G. Watts [*Spectral Analysis and Its Applications* (Holden-Day, San Francisco, 1969)]. The statistical procedure involves calculation of a thickness or time series by linear interpolation, lagging, calculation of an autocovariance function, smoothing with a Hamming lag window, power spectrum production, and statistical evaluation. The following sampling intervals and lags were used to calculate the spectra: Eureka, Gwynned, and Ottsville, $t = 2000$ years or 0.4 m and 100 lags; Delaware, $t = 6000$ years or 1.4 m.
19. D. B. McLaughlin, *Pa. Acad. Sci. Proc.* **20**, 89 (1946); *Mich. Acad. Sci. Proc.* **32**, 295 (1948).
20. A. Berger, in *Milankovitch and Climate*, A. L. Berger *et al.*, Eds. (Reidel, Dordrecht, 1984), part 1, pp. 3–39.
21. R. Y. Anderson, *State Geol. Surv. Kans. Bull. 169*, **1** (no. 169, 1 1964).
22. This is precisely what Van Houten originally did with the Lockatong (*6*).
23. J. A. Webb, *J. Geol. Soc. Aust.* **28**, 107 (1981).
24. The Triassic time scale of Webb (*23*) is used here because its Triassic-Jurassic boundary age agrees with the K-Ar and ^{40}Ar/^{39}Ar dates for Newark igneous rocks and all the stage boundaries agree with the U-Pb dates of D. L. Kimbrough and J. M. Mattinson [*Geol. Soc. Am. Abstr. Program* **16**, 559 (1985)] from New Zealand. The Jurassic time scale is adapted from W. J. Kennedy and G. S. Odin [in *Numerical Dating in Stratigraphy*, G. S. Odin, Ed. (Wiley, New York, 1982), pp. 557–592] by fixing the Triassic-Jurassic boundary at 200 million years ago and scaling the position of the Hettangian-Sinemurian boundary by the ratio of the number of ammonite zones that each stage contains. The other boundary dates are unaltered.
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26. R. L. Armstrong, *ibid.*, pp. 509–514.
27. W. B. Harland, *A Geologic Time Scale* (Cambridge Univ. Press, Cambridge, 1982).
28. A. R. Palmer, *Geology* **11**, 503 (1983).
29. J. H. Puffer, *Geol. Soc. Am. Abstr. Program* **15**, 665 (1983); ______, D. Hurtubise, F. Geiger, P. Lechler, *Geol. Soc. Am. Bull. 92* (1981), part 1, pp. 155–159, and part 2, pp. 515–553.
30. A. R. Philpotts and I. Reichenbach, *Geol. Soc. Am. Bull. 96* (1985), p. 1131.
31. V. Edinger and B. Cornet (personal communication) report Van Houten cycles and compound cycles based on drill-hole data from the Richmond Basin.
32. A. Berger, *Nature (London)* **269**, 44 (1977).
33. A. Hallam, *J. Geol. Soc. Lond.* **142**, 433 (1985).
34. M. Rossignol-Strick, *Nature (London)* **303**, 46 (1983); *Palaeogeogr. Palaeoclimat. Palaeoecol.* **49**, 237 (1985); J. E. Kutzbach and B. L. Otto-Bliesner, *J. Atmos. Sci.* **39**, 1177 (1982).
35. R. Y. Anderson [in *Milankovitch and Climate*, A. L. Berger *et al.*, Eds. (Reidel, Dordrecht, 1984), part 1, pp. 147–162], using varves from Permian evaporite sequences, has convincingly shown that the mean period of climate cycles in the range of precession was about 20,000 years. Experiments tuning the Lockatong and Passaic power spectra thickness peaks of 5.5 and 6.5 m to a mean of 21,000 years produces periods of 20,000 and 23,000 years without affecting the 100,000-, 133,000-, and 400,000-year peaks at this level of resolution.
36. P. E. Olsen, A. R. McCune, K. S. Thomson, *Am. J. Sci.* **282**, 1 (1982).
37. Data for calcite, dolomite and sulfur were provided by G. R. Robinson and J. Hosterman (personal communication) and are based on x-ray diffraction data. The sulfur data were normalized to samples run by the combustion and barium chloranilate method of R. J. Bertolachini and J. E. Barney [*Anal. Chem.* **29**, 281 (1957)] and have a probable precision of 50%. Carbon and carbonate data were analyzed by the standard Leco method and are considered accurate to ±5%.
38. Locations and stratigraphic position of sections are: Eureka Section, Eureka Quarry, Tradesville, Bucks County, Pennsylvania (40°15′30″N, 75°11′00″W) consisting of lower 200 m of the Lockatong Formation (upper half of the Hoboken Member and lower half of the Weehawken Member); Gwynned Section, cut on old Reading Railroad line, Gwynned, Montgomery County, Pennsylvania (40°12′15″N, 75°16′10″W) consisting of the upper third of the Weehawken Member, the entire Gwynned Member, and the lower half of the North Wales Member; Delaware River Section, cut on east side of Route 29, Byram, New Jersey (40°26′00″N, 75°03′45″W) consisting of the upper half of the North Wales Member, all of the succeeding Byram, Skunk Hollow, and Tohicken members, and the base of the Prahls Island member; Ottsville Section, quarry at Harrow, Bucks County (40°29′40″N, 75°10′10″W) and road cut on Route 611 in Ottsville, Bucks County (40°28′35″N, 75°09′55″W) and is in the lower Passaic Formation, roughly 1000 m above the top of the Delaware River section (about 600 m above the top of the Lockatong).
39. Varve thicknesses were measured with a Wild M5 binocular microscope with a drawing tube attachment.

40. I thank J. Imbrie and A. Duffy for performing the spectral analysis on the Eureka and Gwynned sections and J. Imbrie again for many hours of discussion; C. J Banach for field assistance; H. Houghton for showing me the quarry at Harrow (Ottsville), Pennsylvania; G. R. Robinson for supplying the calcite, dolomite, and sulfur data for Fig. 2 and for help with the organic carbon data; R. Berner for Fig 2; J.D. Hays, T. Janecek, J. Morely, J. Smoot, and F. Van Houten for many enlightening discussions; and R. L. Hayden, J. V. Hays, T. Janecek, J. Morely, D Peteet, S. Rachootin, J. Smoot, and F. Van Houten for critiquing the manuscript. Supported by the Miller Institute for Basic Research in Science, an Arco Petroleum Research Fellowship, a W. P. Sloan Foundation Fellowship, and NSF grant DEB 79-21746 (to K. S. Thomson).
41. This paper is Lamont-Doherty Geological Observatory Contribution 4066.

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COVER Footprint with skin impressions of a small (1 meter) Late Triassic lizard-like form (probably spenodontid) that walked along the shores of a rising lake. The lake level rose and fell during the early Mesozoic in response to orbital forcing of climate. See page 842. [Paul E. Olsen, Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY 10964]