PERIODICITY OF LAKE-LEVEL CYCLES IN THE LATE TRIASSIC LOCKATONG FORMATION OF THE NEWARK BASIN (NEWARK SUPERGROUP, NEW JERSEY AND PENNSYLVANIA

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The short (ca. 5m) sedimentary cycles which Van Houten first described from the Lockatong Formation of the Newark Basin were produced by the climate controlled rise and fall of large lakes. During their high stands many of these lakes covered over 7000 km^2 and were over 100 m deep, but during their low stands they were reduced to playas or dried out completely. Annual laminations (varves) present in many short cycles show that the lakes which produced them oscillated in depth with a periodicity of about 21 800 years. Lockatong short cycles make up longer, compound cycles, 25 m and 100 m thick, which reflect periodic changes in the magnitude of high-stands of the 21 800 year lake-level cycles. These lower frequency cycles show a 101 400 and a 418 000 periodicity, respectively. These periodicities are within the tight independent constraints placed on the duration of these cycles by radiometric dates and sediment thickness. During the Triassic the Newark Basin was located at about 15 N, paleolatitude and the periodicities and the ratios of the short and compound cycles are in very close agreement with the Milankovitch predictions for that paleolatitude.

During the early Mesozoic, Pangea rested on the equator (Fig. 1) and a long series of rift valleys formed around the zone which was to become the Atlantic Ocean. These rift valleys filled with thousands of meters of sediments and igneous rocks and the North American contingent of what remains of these deposits is called the Newark Supergroup (1). The exposed portions of the Newark Supergroup consist largely of lacustrine deposits and these rocks preserve a record of changing climate spanning some 35 million years over a distance of over 2000 kilometers. The largest and thickest sequences are preserved in the Newark

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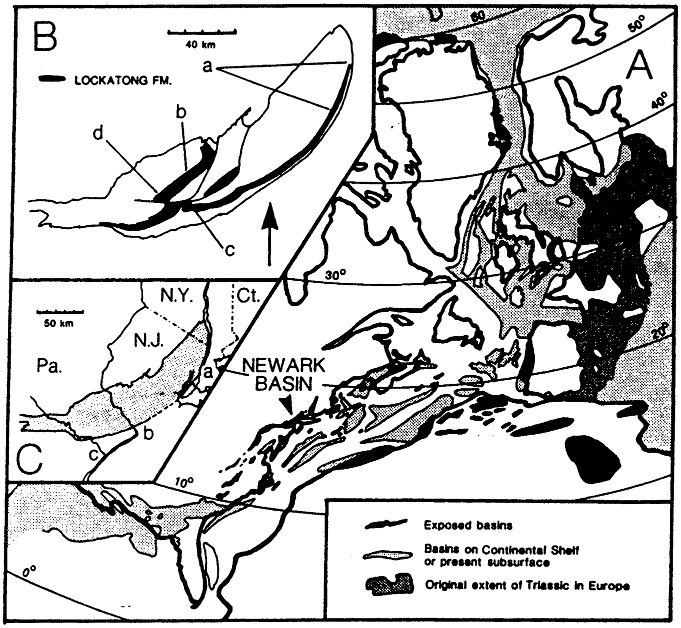

Figure 1 Lockatong Formation in the Newark Basin : A, Predrift (Late-Triassic, Early Jurassic) position of rift basins (Newark Supergroup consists of basins exposed in eastern North America - continental positions from (6) - geology adapted from (1,6,7)) ; B, distribution of Lockatong Formation in Newark Basin - intrusions omitted (a, position of sections in Weehawken area (sections A-F in Figure 5); b, Delaware River section; c, Rushland I quarry section; d, Eureka Quarry section); C, major cities around Newark Basin (a, New York City; b, Trenton; c, Philadelphia).

Basin division of the Newark Supergroup in New York, New Jersey and Pennsylvania. Van Houten (2,3) was one of the first to recognize that much of the Newark Basin record is cyclic and that this cyclicity reflected periodically changing climate. He suggested that this climate change was in turn controlled by the precession of the equinoxes. This paper is essentially a reexamination, extension, and confirmation of Van Houten's original work.

There are 9 formations in the Newark Basin section (4,5) (Fig. 2) and of these the Late Triassic Lockatong and overlying Passaic formations comprise the longest continuous lacustrine record. The Lockatong (Figs 1 and 2) consists almost entirely of a spectrum of thin (ca. 5 m) sedimentary cycles, the end

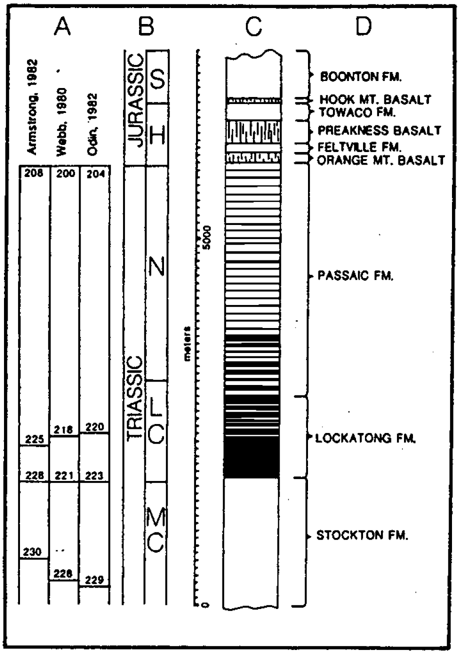

Figure 2 Formations of the Newark Basin and their ages : A, radiometric scales for the Late Triassic (Late Carnian is here assumed to be 1/3 of Carnian time and the Mid-Late Carnian and Triassic-Jurassic boundaries are correlated with the basin section by biostratigraphic data); B, system and stage boundaries based on biostratigraphy, radiometric dates, and paleomagnetics; C, diagram of Newark Basin section (black horizontal lines and black bars represent gray and black units of the Triassic portion of the section and white areas and bars are principally red beds) ; D, formations of the Newark Basin (from 4,5).

members of which Van Houten (2,3) termed detrital and chemical (Fig. 3). The vertical sequence of fossils and sedimentary structures found in the cycles show that they owe their origin to the rise and fall of lakes. Each detrital cycle averages 5.7 m and can be divided into three lithologically distinct divisions (Fig. 3) (7) : division 1 consists of platy to massive gray mudstone sometimes showing current bedding deposited during lake transgression; division 2 is a fine calcareous black mudstone often platy to microlaminated and organic rich, deposited during lake high-stand; and division 3 is made up of platy to massive gray mudstone deposited during lake regression, low-stand, and lake bottom exposure. Chemical cycles are, on the average thinner than detrital cycles (4.5 m) and consist of a lower platy gray mudstone and an upper much more massive gray or red mudstone often rich in sprays of analcime and dolomite crystals and pseudomorphs after gypsum, glauberite and halite - hence Van Houten's epithet chemical cycles.

Van Houten (2,3) reasoned that the vertical sequence of bed types with short cycles reflected the expansion and contraction of lakes. Detrital cycles were produced by lakes which were deep enough to have reached their outlet and were hence through-flowing. Chemical cycles, in contrast, were produced by lakes which never reached their outlet and therefore they concentrated salts during their entire existence. Van Houten argued that all these lakes were relatively shallow and that their depths were governed by changes in precipitation and thus the individual short cycles record regional cyclic changes in precipitation.

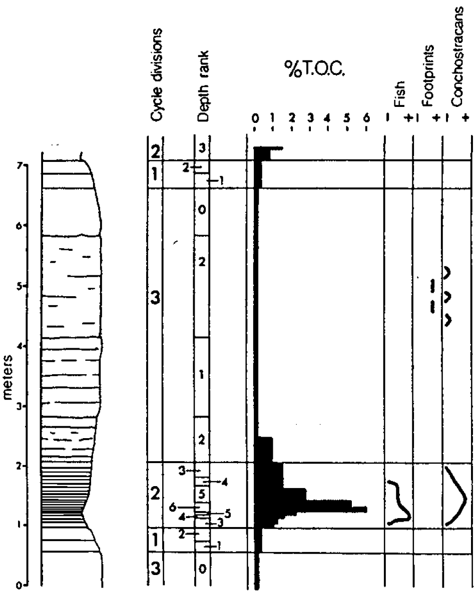

Figure 3 Major features of Lockatong detrital cycles. This cycle is marked SH in Figure 9.

The alternative explanation to changing climate is that the short sedimentary cycles were produced by the filling in of small shallow lakes by sediments, the differences between the cycles being due to local hydrographic differences, and the development of the lake basins being due to local tectonics. Chemical cycles might then form geographically adjacent to

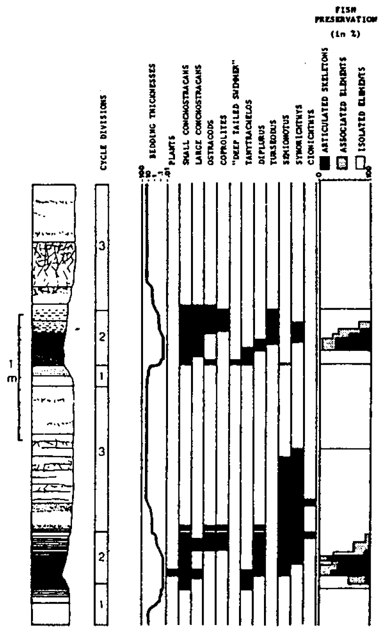

Figure 4 Detrital cycles W-5 (above) and W-6 (below) at excavation at Weehawken, New Jersey showing distribution of major fossils and their preservation : "deep tailed swimmer" and Tanytrachelos are small reptiles, and Diplurus, Turseodus, Semionotus, Synorichthys, and Cionichthys are fishes. This is locality A in Figure 5.

detrital cycles. Information on the lateral extent of cycles is needed to select between these two explanations.

Over the last six years I have been attempting to trace individual Lockatong cycles laterally. This is made difficult principally because of : 1) the scarcity of large, continuous exposures; 2) the presence of lateral facies changes; and 3) the general similarity of all the sedimentary cycles. Detailed investigations of single sections, however, have shown that each cycle can be uniquely defined by the details of the vertical changes in the kinds, preservation, and diversity of fossils (Figs 4 and 5). It has become evident that it is a property of detrital cycles that these vertical changes seen in single cycles remain consistent laterally (Fig. 5). This property allows for individual cycles to be identified in vertical sections of many cycles and allows individual cycles to be traced over large distances (Figs 5 and 6). I first worked out a cycle-by-cycle

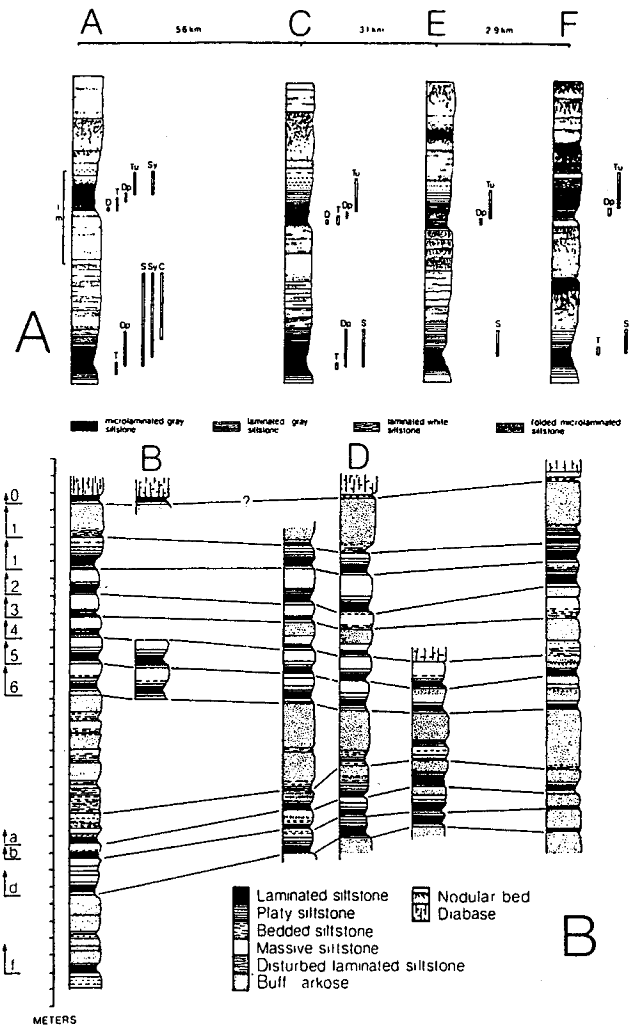

Figure 5 Lateral extent of Lockatong detrital cycles from Weehawken to Fort Lee, New Jersey: A, detailed correlation by the vertical distribution of fossil fishes of cycles W-5 (above) and W-6 (below) [abbreviations of vertebrate fossils - D, "deep tailed swimmer", T, Tanytrachelos, Dp, Diplurus, Tu, Turseodus, Sy, Synorichthys, S, Semionotus, and C, Cionichthys] B, correlation of all exposed cycles laterally based on the vertical distribution of fossil fishes. Localities of sections A - F shown in Figure 1 and given in detail in (8).

stratigraphy for 18 cycles in the Hoboken to Fort Lee area (7) where outcrops are closely spaced (about 1 per 2 km for 20 km (Figs 5 and 6)). Recently, a large series of new outcrops have been identified in the central and southern Newark Basin which permit the cycles found in the Hoboken - Fort Lee area to be traced over most of the basin. In addition, these newly found exposures allow the same cycles originally worked on by Van Houten to be traced over large areas of the central Newark Basin (Fig.6). It is now apparent that many individual detrital cycles can be traced over most of the Newark Basin and that these cycles retain their particular faunal identities over these areas. It is also apparent that the short sedimentary cycles of the Lockatong reflect changes in the depths of lakes which covered much, if not all, of the Newark Basin and that changes in precipitation and evaporation rates are the most plausible cause of the lake-level change.

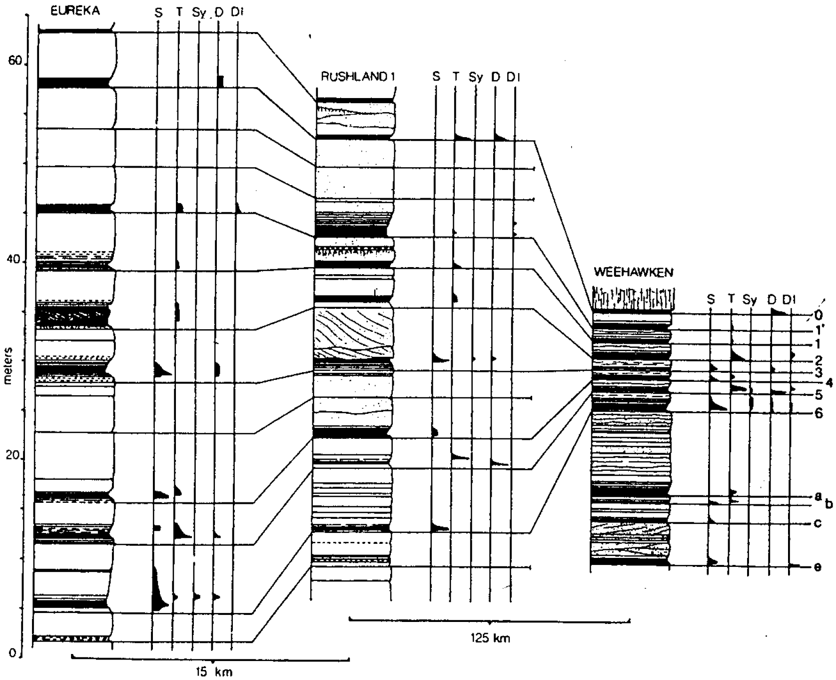

Figure 6 Correlation across Newark Basin of detrital cycles of Weehawken member of lower Lockatong (see Figure 7) showing distribution of most abundant fish. Abbreviations of fish taxa as follows : S, Semionotus, T, Turseodus, Sy, Synorichthys, D, Diplurus, and Dl, large coelacanth. Positions of sections shown in Figure 1.

A consequence of the ability to trace individual cycles laterally is that lithological and paleontological features which are associated with various degrees of lateral continuity can be identified. Those cycles fitting Van Houten's detrital category prove to be traceable individually over much longer distances than those fitting the chemical category which are restricted to the central 60 km of the basin. Furthermore, those detrital cycles which contain a microlaminated division 2 are traceable over the largest distances with the least change. The microlaminated portions of these cycles contain the best preserved vertebrate remains. The very fine laminae and the fine preservation of fossil fish and other delicate organisms in the microlaminated portions of division 2 show that deposition of these units could only have occurred below wave base (7,9).

The lateral continuity of the microlaminated portions of division 2 allows for an estimation of the minimum extent and depth of the Lockatong lakes during their maximum transgression. I have developed a new method of estimating the depths of ancien lakes which uses the familar relationship between the maximum fetch of a water body, wind speed and the depth of wave mixing (9). Using this method, the fact that the microlaminated (i.e. varved) fish-bearing portion of individual Lockatong cycles cover over 7000 km^2 means that the lake which deposited that unit must have covered more than 7000 km^2 and must have been more than 100 m deep. the fact that the portions of Lockatong cycles which were deposited during lake low stand can also be traced over the extent of the formation illustrates that the lakes actually did become very shallow and frequently dried out entirely. Thus, those detrital cycles with a microlaminated division 2 resulted from tremendous fluctuations in water depth, similar to or greater in magnitude than the changes known to have occurred in many of the lakes of the Great Basin in the western United States (10,11) and the Great Lakes of Africa (12,13,14).

Detrital and chemical cycles do not occur randomly in vertical section. Clusters of 1 to 4 detrital and 1 to 4 chemical cycles make up 25 m cycles (added up to a total of 4 to 6 short cycles) (Fig. 7) and clusters of these 25 m cycles alternately dominated by chemical or detrital cycles clusters make up 100 m cycles (Fig. 7) (2,3). The pattern of 100 m cycles allows the Lockatong formation to be broken up tentatively into 11 members (Fig. 7). This pattern of 100 m cycles continues into the overlying Passaic Formation. In the latter, however, the chemical cycles disappear and their position is taken by red beds (Figs 2 and 7).

The classification of sedimentary cycles types developed by Van Houten and followed in my own previous papers is

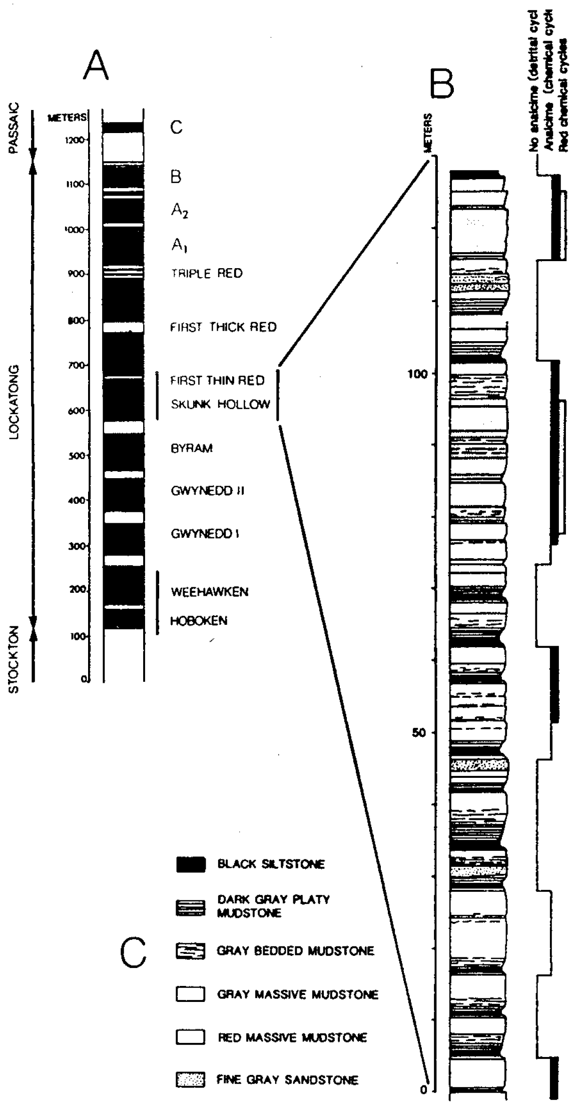

Figure 7 A, tentative division of the Lockatong Formation into 100 m members as exposed along the Delaware River in the Hunterdon Plateau Fault Block: Black horizontal bars represent portions of the Lockatong dominated by detrital cycles, white bars indicate portions of Lockatong made up mostly of red chemical cycles or red beds, gray bars indicate portions made up mostly of gray chemical cycles. Black vertical bars indicate portions of Lockatong shown in Figures 9 and 10. B, measured section of McLaughlin's (17) First Thin Red and the Skunk Hollow Member of this report. C, key for B.

essentially a typological one. The method of classification forces cycles to be identified either as chemical or as detrital. The operational definition of chemical cycles requires that evaporitic minerals, especially zeolites and dolomite, be present in the cycle. Thus, even if in all other respects a cycle without evaporitic minerals looks exactly other chemical cycles and is the lateral equivalent of a "true" chemical cycle it is classified as detrital because it lacks the essential aspect of a chemical cycle. This purely semantic problem produces confusion in interpretation when by definition, chemical cycles turn into detrital cycles laterally. In addition, in this sort of typological classification system all the information inherent in intermediate cycles is lost. This is the nature of typological classifications.

As suggested by Van Houten (2,3) and Olsen (7) various features of the sedimentary fabric of the rock types which make up Lockatong short cycles have characteristics which can be interpreted in terms of water depth, at least in a relative sense. Thus, division 2 of detrital cycles is interpreted as having been deposited in deeper water than divisions 1 or 3 because of the absence of indications of exposure to the air, presence of undisturbed laminations, lack of roots, etc. The vertical sequences of sediment fabric types through a cycle shows directional change in several characters which reflect the expansion and contraction of the lakes in which they were deposited. I have developed a tentative classification of sedimentary fabrics within Lockatong cycles with seven categories (Fig. 8) ranked from 0 to 6 in order of the relative depth of water in which they were deposited. This sequence is seen in vertical succession through typical detrital cycles as 1 2 3 4 5 4 3 2 1 0 (from the bottom up). Walther's law suggests that these same

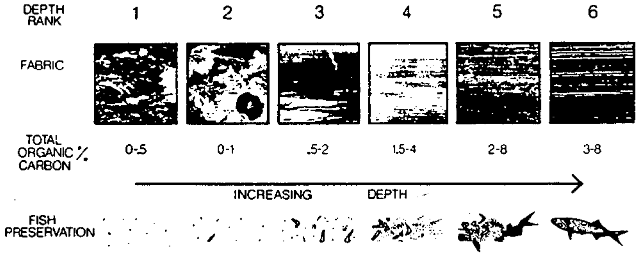

Figure 8 Ranks of sedimentary fabrics of mudstones and siltstones of Lockatong Formation arranged in order of the interpreted relative depth of water in which they were deposited and their relationship to organic carbon content and fossil fish preservation. Rank 0 (not shown) is a microbrecciated and disrupted massive mudstone sometimes with evaporitic minerals.

fabrics might be reflected in lateral changes from the center of the basin outwards, as well, and for the most part they are (7).

When the rank of the fabrics of beds which compose Lockatong short cycles are graphed against the measured section (Figs 9 and 10), the rank can be read as a indicator of water depth and hence a proxy indicator of (at least) local climate. The curve produced by this method is analogous to curves produced

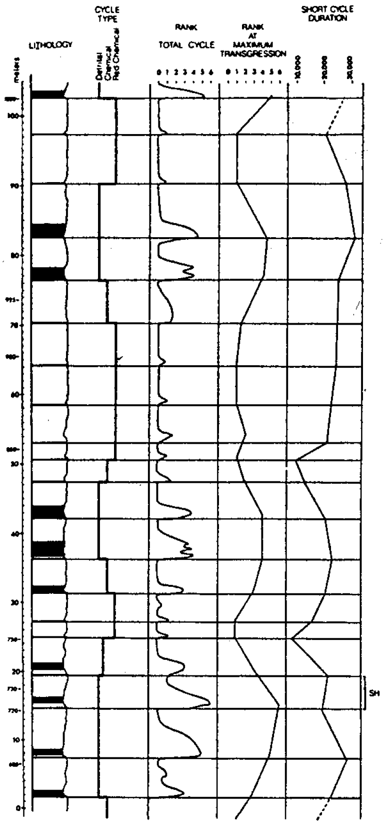

Figure 9 Section of First Thin Red and Skunk Hollow members of Lockatong along Delaware River (see Figure 7) showing the classification of cycle type according to Van Houten (2,3), the application of depth ranks based on Figure 8, and the duration of short sedimentary cycles. Duration is equal to 0.24 mm X cycle thickness and this value is placed at base of cycle. SH is cycle drawn in Figure 3.

by graphing oxygen isotope ratios or the derived bottom water temperatures against core depth in cores of the ocean bottom (15,16). By use of this depth rank, it is no longer necessary to identify sedimentary cycles or to classify the cycle types into end members, although this is still a useful tool. The larger cycles of 25 m and 100 m also show up in the curve as modulations of the maximum magnitude of the higher frequency cycles. All the information present in the typological classification of cycles and the higher order cycles are preserved in this curve. Because the ranks are based on sedimentary fabrics which are related to water depth, the rank curve canbe interpreted as a lake-level curve with rank 6 equivalent to depths in excess of 100 m and ranks 0-1 corresponding to very shallow, saline water, or complete dessication.

Two long sections through different portions of the Lockatong (the Skunk Hollow Member and the Weehawken and Hoboken members (Figs 9 and 10)) are dealt with here, but the same pattern can be seen at other outcrops within the center of the basin and in the Passaic Formation as well. Peaks in depth rank occur at about 5 m intervals, and when these peaks alone are graphed against the section, a 25 m cycle of maximum rank becomes clear. Peaks in this 25 m cycle occur at 100 m intervals, although the two measured sections presented here are too short to show this fully. The peaks occurring at 5 m intervals are the short cycles identified by Van Houten. At the Delaware River section, most of those peaks occuring at 5 m intervals which do not exceed rank 3 belong to cycles identified by Van Houten as chemical cycles. Most of those peaks which have ranks of 4 to 6 belong to Van Houten's detrital cycles. The 25 m cycles seen in depth rank correspond to Van Houten's 25 m alternations of chemical and detrital cycles and the 100 m cycles are also equivalent. The main advantage of this method is that the structure of these curves contains much more information than a typological classification, especially in sections where no evaporitic minerals are present in cycles which otherwise look like chemical cycles but which do not fit the definition. These curves are also amenable to the type of wave theory analysis used with so much success in the deep sea curves (16,18); such procedures are not possible with a typological classification of cycles.

The microlaminated portions of division 2 of short cycles (corresponding to the peaks of 5 and 6 in rank) are composed of couplets of a lamina of very low carbonate - high organic carbon mudstone and a lamina of higher carbonate - low organic carbon mudstone. These couplets are traceable over very large areas and are indistinguishable from the annual laminations produced today in anoxic aquatic environments such as the bottoms of deep lakes (7,19). If these couplets are of annual origin, and there is no reason to believe they are not, they are non-glacial varves (each couplet = 1 varve) and the average thickness of a varve is the sedimentation rate per year after compaction. This sedimentation rate can then be used to calibrate both the curves of ranks and the individual cycles (Figs 9 and 10) (Table 1). Van Houten used exactly this property of microlaminated portions of Lockatong short cycles and concluded that the short cycles had a period of about 21 000 years, the 25 m cycles a period of 100 000 years, and the 100 m cycles a period of 500 000 years.

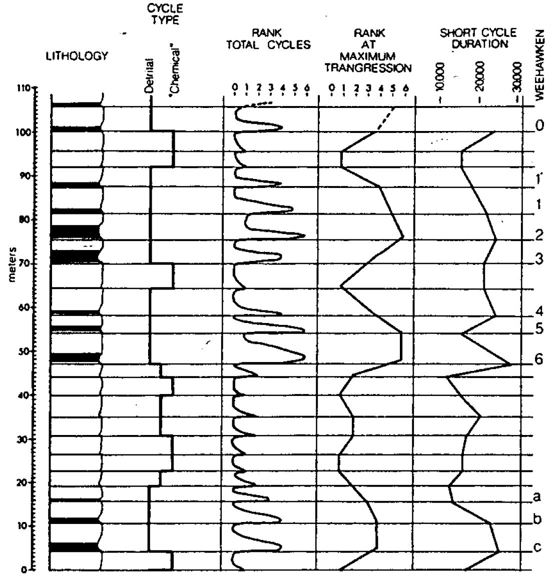

Figure 10 Measured section of Weehawken and Hoboken members in Eureka Quarry near Chalfont, Pennsylvania. Same conventions as Figure 9. Cycle designations on left based on correlation with cycles in Weehawken area (Fig. 6).

I have examinated all the microlaminated units in short cycles in the sections presented in Figures 9 and 10, as well as other cycles within the central Newark Basin. The mean sedimentation rate derived from 10 measurements of non-overlapping portions of 4 different cycles exposed in 2 different members in the Lockatong is 0.24 mm/yr. When this sedimentation rate is applied to the sections measured in Figures 9 and 10 the periodicities for the short and longer frequency cycles are derived (Table 1). The mean periods of the cycles in the Lockatong as shown by the curves of rank and the mean sedimentation rate are thus about 20 900, and 101 400. There are about 220 short cycles in the Lockatong and in the 1100 m of this formation, there are 11 100 m cycles. There are thus about 20 short cycles per 100 m cycle and assuming 20 900 years per cycle the 100 m cycle takes about 418 000 years.

Table 1 Periods of cycles in Lockatong based on varve calibration.

Main periods of all cycles

20 800 : 101 400 : 418 000 years

Main periods of short cycles

Eureka :
All short cycles, N=26, 20 500 ± 643 years
Detrital cycles, N=15, 22 800 ± 1659 years
Chemical cycles, N=11, 17 300 ± 841 years

Delaware River :
All short cycles, N=19, 21 300 ± 1449 years
Detrital cycles, N=7, 25 200 ± 1667 years
Chemical cycles, N=12, 19 900 ± 1810 years

Periods of "25 m" cycles

Eureka :
N=5, 101 500 years
Delaware River :
N=4, 101 400 years

Period of "100 m" cycles

418 000 years (see text for explanation)

Van Houten's classification of cycles into chemical and detrital types is applied to the sections in Figures 9 and 10, chemical cycles have a mean periodicity of 23 800 years and detrital cycles have a mean periodicity of 18 800 years. Unfortunately, this difference only reflects the fact that chemical cycles tend to be thinner than detrital and it is very difficult for me to believe that sedimentation rates were so constant between cycles that such a small difference in thickness can be significant in terms of time. It seems much more likely that the small differences in cycle thickness reflect differences in rates of sedimentation during the arid intervals represented by the upper parts of chemical cycles.

The above calibration of cycles in the Lockatong does, of course, depend on the assumption of a constant sedimentation rate - an assumption which might be right on a large scale, but which is certainly wrong on a very fine scale. Fortunately, there is another means than varve counts available for approximating the periodicity of Lockatong lake-level cycles. Newark Basin stratigraphy has, over the last 10 years been investigated on increasingly finer levels. The age of the Lockatong is early Late Triassic (Late Carnian) on the basis of both correlation by pollen and spores (20,21) and reptiles and amphibians (5,8) and the top of the overlying Passaic Formation corresponds, more or less to the Triassic - Jurassic boundary on the basis of abundant radiometric dates from the overlying lava flows (8,22), paleomagnetic reversal sequences (23), pollen and spores (20), and reptile remains (8). Using these correlations, the duration of the Lockatong plus Passaic formations can be estimated by using published radiometric scales (Fig. 2). Three somewhat different radiometric scales have been published for the Triassic but, using either, the Lockatong plus Passaic column took about 20 million years to deposit. The pattern of 100 m cycles seen in the Lockatong (Fig. 7) continues up through the Passaic Formation. There, they show up as intervals of gray and black detrital cycles separated by red beds. These gray and black intervals have been traced over much of the Newark Basin by McLaughlin (17) and they show up clearly on a map of 1:250,000 scale as well as on LANDSAT photos. The top of the Passaic Formation is not preserved in the area in which the sections described in this paper occur because of post-Early Jurassic erosion. However, the entire thickness is preserved in adjacent fault blocks and after correction for systematic decreases in thickness of 100 m cycles outside the center of the basin (5) the total sediment column in the center of the basin is estimated to be about 4190 m. Since there are about 42, 100 m cycles in this interval (most have been mapped) the periodicity of the 100 m cycles was, on the average, 476 000 years. Dividing by the number of 25 m cycles per 100 m cycle (i.e.4), and 5 m cycles per 25 m cycle (i.e. 5), the 25 m cycles take up 119 000 years and the 5 m cycles 24 000 years. Using either varve counts of radiometric - paleontological methods to obtain calibration for Lockatong cycles, the main periods which show up are fairly close to 21 000, 100 000 and 400 000 years.

The main periodicities seen in the lake-level cycles of the Lockatong are also seen in the deep-sea proxy records for the

Pleistocene and both records agree with major periods predicted by the Milankovitch astronomical theory of climate. During the Triassic the Newark Basin was located at about 17 N paleolatitude (Fig. 1). On the basis of celestial mechanics, at this latitude solar insolation changes should reflect the cycles of precession (21 000 yrs) and eccentricity (100 000 and 400 000 yrs) but not obliquity (42 000 yrs) (24) and there is no sign of a 42 000 year cycle in the Lockatong record. The ratio of thickness (and inferred duration) of the short Lockatong cycles to the thicker compound cycles is 1 : 5 and 1 : 20. Even if sedimentation rates were strongly variable within short cycles, these ratios match only the precession and eccentricity portions of the spectrum of Milankovitch astronomical periodicities.

Hypothetical alterations of the periodicity of short cycles are constrained by the radiometric-paleontological data from the sediments. The implications of assignments of the short cycles (and hence the compound cycles as well) to periodicities of even 2 x 21 000 years would involve gross changes in the duration of the Late Triassic, age of the Lockatong, thicknesses of the Lockatong and Passaic Formations, or stratigraphic position of the Triassic-Jurassic boundary. The magnitude of the changes necessary to accomodate a doubling of the duration of a Lockatong short cycle would be out of proportion of what appears to be even a very pessimistic view of the confidence in the correlations and radiometric ages. What can be safely said at this time is that very large lakes in the Newark Basin fluctuated in depth over periods on the order of magnitude of 21 000 years and that the ratios of the higher frequency fluctuations to modulations of the magnitude of those fluctuations correspond to 1 : 5 and 1 : 20 which are the same as the ratios of the terms of precession and eccentricity. These intepretations of Lockatong lake-level cycles appear to be strong evidence of Milankovitch type forcing of climate in the Late Triassic. They also provide evidence that the main periods of precession and eccentricity were not very different 220 million years ago from today.

REFERENCES

1. Olsen, P.E. : 1978, Newsletters on Stratigraphy. 7, pp. 90-95.
2. Van Houten, F.B. : 1962, Amer. Jour. Sci. 260, pp. 561-576.
3. Van Houten, F.B. : 1980, in : "Field Studies in New Jersey Geology and Guide to Field Trips", 52nd Annual Meeting of the New York State Geological Association, W. Manspeize (Ed.), Newark College of Arts and Sciences, Rutgers University, pp. 264-276.
4. Olsen, P.E. : 1980, New Jersey Academy of Science, Bulletin 25, pp. 25-51.

5. Olsen, P.E. : 1980, in : "Field Studies in New Jersey Geology and Guide to Field Trips", 52nd Annual Meeting of the New York State Geological Association, W. Manspeizer (Ed.), Newark College of Arts and Sciences, Rutgers University, pp. 2-39.
6. Smith, A.G. : 1981, Geol. Rundschau 70, pp. 91-127.
7. Olsen, P.E. : 1980, in : "Field Studies in New Jersey Geology and Guide to Field Trips", 52nd Annual Meeting of the New York State Geological Association, W. Manspeizer (Ed.), Newark College of Arts and Sciences, Rutgers University, pp. 352-398.
8. Olsen, P.E., McCune, A.R., and Thomson, K.S. : 1982, Amer. Jour. Sci. 282, pp. 1-44.
9. Manspeizer, W. and Olsen, P.E. : 1981, in : "Field Guide to the Geology of the Palaeozoic, Mesozoic, and Tertiary Rocks of New Jersey and the Central Hudson Valley", G.W. Hobbs (Ed.), Petroleum Exploration Society of New York, New York, pp. 25-103.
10. Benson, L.V. : 1981, Quat. Res. 16, pp. 390-403.
11. Gilbert, G.K. : 1890, Lake Bonneville, U.S. Geol. Surv., Monogr. 1, 438pp.
12. Hamilton, A.C. : 1982, Environmental History of East Africa : A Study of the Quaternary. New York, Academic Press, 328pp.
13. Kutzbach, J.E. : 1980, Quat. Res. 14, pp. 210-223.
14. Livingston D.A. : 1965, Limnol. Oceanogr. 10, pp. 607-610.
15. Emiliani, C. : 1966, Jour. Geol. 74, pp. 109-126.
16. Imbrie J. : 1982, Icarus 50, pp. 408-422.
17. McLaughlin, D.B. : 1946, Mich. Acad. Sci. Papers 32, pp. 295-303.
18. Hays, J.D., Imbrie, J., and Shackleton, N.J. : 1976, Science 194, pp. 1121-1132.
19. Twenhofel, W.H. : 1932, Treatise on Sedimentation, 2nd ed. Baltimore, Williams and Wilkens, 926pp.
20. Cornet, W.B. : 1977, The palynostratigraphy and age of the Newark Supergroup. Ph.D. Thesis, University of Pennsylvania, State College, 506pp.
21. Cornet, W.B. : 1977, In : "Geobotany", Romans, R.C. (Ed.), New York, Plenum Press, pp. 165-172.
22. Armstrong, R.L. : 1982, in : "Numerical Dating in Stratigraphy", G.S. Odin (Ed.), John Wiley and Sons, London, pp. 509-513.
23. McIntosh, W.C. : 1976, Paleomagnetic reversals in the Newark Group Brunswick Formation of eastern Pennsylvania and central New Jersey. Senior Thesis, Princeton University, Princeton, 72pp.
24. Berger, A.L., Quat. Res. 9, pp. 139-167.

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