Geological Records of a Rhythmic Nature*

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INTRODUCTION

THE New Century dictionary defines rhythm as "a procedure marked by the regular recurrence of particular elements or phases." Rhythms in the history of the earth have attracted the attention of geologists for more than half a century.[1] The lengths of time represented by described rhythms range from a single day and night sequence to a geologic period. Erosional rhythms or cycles are deciphered principally through a study of the land forms of the earth, but they also reflect their successive stages in the quantity and type of sediment in adjacent basins. Rhythms or cycles of sedimentation are observed through the repeated recurrence of certain layers or sequences of layers in a stratified succession, which thus shows the repeated recurrence of nearly identical conditions. A cycle may consist of no more than two beds, whose total thickness is less than 1 millimeter, or of 15 or 20 lithologic units with a combined thickness of more than 100 feet.

My interest in geological rhythms has been aroused through the studies of the "Coal Measures" of the eastern United States during the past several years. These rocks, representing a considerable part of the time scale, exhibit a "regular recurrence of similar elements or phases" so striking that it can scarcely be regarded as the result of a series of coincidences, and so, despite a recent derogatory remark that the discovery of new rhythms may be regarded as a pleasant pastime to occupy the leisure moments of a geologist between more significant tasks, and because I feel that the study of rhythmic records may aid in determining the duration of various parts of geologic time, in determining the rate of accumulation of various kinds of rocks, and perhaps in discovering evidence of the operation of some little-understood forces in the shaping of the earth, I shall take advantage of my position and my required duty to discuss some of the aspects of geologic rhythms. I shall limit my discussion to rhythms of erosion, rhythms of deposition, and climatic rhythms revealed in the growth rings of trees, both living and fossilized.

EROSIONAL RHYTHMS

The great physiographer William Morris Davis developed the concept of the erosion cycle accomplished by streams in a humid region[2]. He conceived a region newly exposed to the action of running water following elevation above the sea, the wasting of a continental glacier, the draining of a lake, the hardening of an extensive lava flow, or some other phenomenon. He demonstrated that first the growth and integration of a drainage system in an area would gradually destroy the initial surface and leave a rugged, well drained, maturely dissected region. The continuance of erosion would develop new plains by broadening the major river valleys, subdue the relief of the uplands, and ultimately produce a new land surface near the level of the principal streams. This surface, which he termed a peneplain, would be permanent until it was either submerged beneath the waters of the sea

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[1] Newberry, J. S., Circles of deposition in American sedimentary rocks; Am. Ass. Adv. Sci., Proc. 22, pt. 2, pp. 185-196, 1874.

[2] Davis, W. M., The rivers and valleys of Pennsylvania: Nat. Geog. Mag. 1, pp. 183-253, 1889.

or elevated and subjected to the beginning of a new erosion cycle. The complex erosional history of some land areas has been interpreted in terms of several partially completed erosion cycles. The interpretation of multiple erosion cycles is further complicated by the possibility that a high level plain may develop on a resistant stratum contemporaneously with a lower plain on a weaker stratum.

Davis[3] also pictured the erosion cycle in an arid region, where most of the sediment from the uplands accumulates in intermontane basins instead of being carried to the ocean. In the earlier part of the cycle the drainage system is poorly integrated, and numerous basins at different levels receive the waste. As the cycle progresses waste from the higher basins spills over into adjacent lower ones, and the drainage becomes more integrated. As the mass of debris rises in the basins it may bury smaller ridges, thus expanding the depositional plain. Temporary saline lakes are likely to occupy the deeper parts of the basins. In cases of extreme aridity wind becomes a more powerful transportive agent than streams and shifting dunes become conspicuous features of the landscape. In cases of greater or increasing humidity the saline lakes increase in size until ultimately they discharge their waters seaward through some notch in the bounding wall of the basin. The Great Basin region of the western United States affords illustrations of various stages in the arid erosion cycle.

Douglas Johnson[4] has described coastal erosion cycles initiated either by elevation or subsidence of the land with reference to sea level. Wave-cut cliffs are formed along recently elevated coasts, and if the rocks are of unequal resistance to wave attack, headlands and coves may develop. After a time a series of offshore bars or a barrier beach is formed, separated from the mainland shore by a lagoon. The beach is interrupted at intervals by tidal inlets. As the emergent cycle passes from maturity to old age, the offshore bars migrate landward until they merge with the beach. The coast, now fronted by a broad wave-cut bench, straightened of irregularities due to unequal hardness, and protected by a sandy beach, has achieved stability until there is another movement of the land or a change in sea-level.

If the sea-level is raised or the land lowered a deeply embayed coast with irregularly branching promontories characterizes the initial stage. Erosion of the headlands and the building of bay-mouth bars continues until maturity. The coast is ultimately straightened in old age and resembles the corresponding stage for an emergent coast.

Hobbs[5] described an erosion cycle for mountain glaciers. At the outset, glaciers form from snowfields in deep shaded ravines on the mountain slopes. The surfaces between these glaciers are rounded hills or divides. As glacial erosion proceeds, deep U-shaped valleys are carved out and the divides are narrowed until they become steep-sided, saw-toothed ridges with high peaks or horns at intervals along the range. Later erosion reduces the height of the peaks and the area of the névé fields or gathering grounds for the glacier, and the glacier gradually decreases in size due to lack of nourishment, terminating the cycle. Examples illustrating the various stages of this cycle are to be found in the mountain ranges of western United States.

A somewhat different form of erosion cycle is found in areas of limestone bedrock, where solution-widened joints admit the surface water to a labyrinth of subterranean passages. Erosion in such regions is accomplished by solution and the collapse of materials above limestone caverns. Natural bridges, sink-holes, disappearing streams, and giant springs are all features of this karst erosion cycle.

Milner[6], Boswell[7], and others have showed that an erosion cycle on a land area may be interpreted through the sequence of sedimentary units deposited in an adjacent basin. At the beginning of the cycle, deeply

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[3] Davis, W. M., The geographic cycle in an arid climate: Jour. Geol. 13, pp. 381-407, 1905.

[4] Johnson, D. W., Shore processes and shore line development, pp. 199-392, 1919.

[5] Hobbs, W. H., Characteristics of existing glaciers, pp. 25-39, 1922.

[6] Milner, H. B., Sedimentary petrography, pp. 361-371, 1929.

[7] Boswell, P. G. H., On the mineralogy of sedimentary rocks, pp. 37-59, 1933.

weathered residual soils would be the principal source of sedimentary materials, and stable mineral species would predominate. Later, during youth and early maturity, while the streams deepen their courses rapidly into unweathered materials, the sediments will contain numerous unstable mineral species which will afford a clue to the types of rocks exposed in the region providing the sediment. During late maturity and old age, erosion proceeds less rapidly and there is more opportunity for weathering, so that only the more stable mineral species survive destruction. The study of mineral assemblages in sedimentary formations of known geologic age thus affords a check on the number and geologic age of erosion cycles in nearby regions.

TREE RING RHYTHMS

The variable width of annual growth rings in trees seems intimately related to the relative abundance of moisture during successive growing seasons. Studies of growth rings, especially of such old trees as the sequoias of California, affords one of our best records of climatic variations within the last few thousand years. Huntington[8], Douglass[9], and others have done much careful work on tree ring sequences. Douglass found it possible to date the Indian cliff dwellings of the arid southwest through matching growth rings in timbers used in their construction with those of very old trees still growing. He also proved that aridity led to the abandonment of these settlements. By matching humid and arid periods of the California "Big Tree" groves with high and low levels of shore-lines on the Caspian Sea as revealed by the records of historic settlements there, Huntington showed that climatic changes recorded in the tree rings are world-wide rather than local. Tree rings afford an opportunity to study the effects of sun-spot and other solar cycles and have yielded evidences of cycles of lengths ranging from about 10 months to more than 30 years. Petrified wood from various geologic periods indicates by variations in growth rings whether or not seasonal climates prevailed and sun-spots like those of the present day occurred during former periods. The petrified wood from the Pennsylvanian rocks generally shows no growth rings, leading some geologists to believe that the climate of that period was uniformly mild without cold seasons, although others state that the types of plants composing the coal flora would not develop growth rings even with a seasonal climate.

DEPOSITIONAL RHYTHMS

Varves

Varves are pairs of laminations differing from each other in color and texture, and thought to have accumulated during one year. They were first observed[10] in lake clays associated with glacial deposits in Sweden and Finland and consist normally of a lighter colored, more sandy bed and a darker colored, more clayey layer. Each pair of laminae was interpreted as a single year's deposit formed in a lake fed by glacial melt waters. The coarser textured, lighter colored layer is the summer and the finer, darker colored layer is the winter deposit.

Varves range in thickness from less than 1 millimeter to more than 1 foot. They were correlated from one exposure to another by the distribution of abnormally thin or thick single varves or groups. A correlation with successive positions of the ice front was found possible and the varves were found to thicken and to be composed of coarser material nearer the position of the ice margin. Johnston[11] carried on a study of recent sediments in Lake Louise, Canada, a lake fed by glacial waters. He discovered that the

[8] Huntington, E., The climatic factor as illustrated in arid America: Carnegie Inst. Wash., Publ. 192, pp. 95-157, 1914.

[9] Douglass, A. E., Climatic cycles and tree growth; a study of the annual rings of trees in relation to climate and solar activity: Carnegie Inst. Wash., Publ. 289, vol. II, 1928.

[10] Geer, Gerard de., A geochronology of the last 12,000 years: Comptes rendus, Cong. geol. intern., sess. 11 (1910), pp. 241-253, 1912.

[11] Johnston, W. A., Sedimentation in Lake Louise, Alberta, Canada: Am. Jour. Sci., 5th ser., vol. 4, pp. 376-386, 1922.

sediments exhibit paired laminations except in the delta where the glacial stream enters the lake. Calculations based on the known discharge of water into the lake, the volume of lake water, and the average amount of suspended sediment showed that the paired laminations are of the right order of thickness to be considered annual accumulations. In Sweden postglacial varves were discovered in sediments deposited in a lake which was drained in the 18th century. It proved possible to correlate these postglacial varves with late glacial varves and to reconstruct and date the history of the glacial recession northward across Sweden by means of the varves. Antevs[12] and others have attempted to correlate varve sequences between the Scandinavian countries and North America, but the tentative correlations made have been challenged on several grounds. Antevs[13] worked out varve sequences in the Connecticut River valley, upon which he based a chronology of ice recession in that area, indicating an average retreat of 1 mile in about 10 years. Flint[14] has studied the Connecticut valley glacial records and believes the glacier did not retreat, but became a stagnant mass of ice and that the varves were formed in a series of lakes at progressively lower levels, held in by temporary ice barriers. He does not accept the varves of that region as a basis for chronology. Andersen[15] has similarly criticized de Geer's conclusions in Denmark and suggested that the varves may record day and night, rather than annual rhythms. This controversy has not yet been settled to the satisfaction of all concerned. Sayles[16], Coleman[17], and others have discovered varve-like sediments associated with deposits formed during earlier glacial periods, now indurated and altered to banded shales and slates. These have been found in connection with late Paleozoic glacial deposits in South America, South Africa, Asia, Australia, and Massachusetts, and in connection with pre-Cambrian glacial deposits in Canada and elsewhere. Glacial varves are generally considered annual deposits and valuable for recording chronology and calculating rates of sedimentation.

Non-glacial Varves

Workers engaged in studies of recent and ancient lake sedimentation outside glacial regions have discovered various conditions in lakes which may be responsible for annual paired laminations or varves. Kindle[18] has noted that lake water becomes thermally stratified during the summer months, the warm light water (epilimnion) overlying colder and heavier water (hypolimnion). Fine muds and debris from aquatic vegetation will not sink through the denser water, but remain suspended until the fall overturn when all the water achieves an uniform temperature before freezing. This fall overturn is responsible for the settling of fine debris which may form a lamina overlying a coarser band deposited during the summer.

Bradley,[19] in studying the Green River oil-shales of Utah and Colorado, discovered paired laminations ranging from 0.05 to 0.2 millimeters thick and generally consisting of a band of dark clay very rich in organic matter and a lighter band with less organic matter, but in some parts of the shale particularly rich in calcium carbonate. Considering the area of the ancient

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[12] Antevs, E., Probable correlation between the last ice retreat in North America and in Europe (abstr.): Geol. Soc. Amer., Bull., vol. 36, pp. 153-154, 1925.

——— The last glaciation, with special reference to the ice retreat in northeastern North America: Am. Geog. Soc., Research ser. No. 17, 1928.

[13] Antevs, E., The recession of the last ice sheet in New England: Am. Geog. Soc., Research ser. No. 11, 1922.

[14] Flint, R. F., The stagnation and dissipation of the last ice sheet: Geog. Rev., vol. 19, pp. 256-289, 1929.

——— The glacial geology of Connecticut, Conn. State Geol. and Nat. Hist. Surv., Bull. 47, 1930.

[15] Andersen, S. A., The waning of the last continental glacier in Denmark as illustrated by varved clay and eskers: Jour. Geol., vol. 39, pp. 609-624, 1931.

[16] Sayles, R. W., Seasonal deposition in aqueoglacial sediments: Mus. Comp. Zool. (Harvard Univ.), vol. 47, pp. 5-63, 1919.

[17] Coleman, A. P., Ice ages, recent and ancient, pp. 234-236, 1929.

[18] Kindle, E., The role of thermal stratification in lacustrine sedimentation: Proc. Royal Soc., Canada, Trans., 3rd ser., vol. 21, pp. 1-35, 1927.

[19] Bradley, W. H., The varves and climate of the Green River epoch: U. S. Geol. Surv., Prof. Paper 158, pp. 87-110, 1929.

lake in which the shale accumulated and the probable quantity of suspended load introduced into it, Bradley concluded that the thickness of the varves was reasonable for annual deposits. He argued that organic matter, which is seasonal in production, should be concentrated in part of the annual varve, and that calcium carbonate would be precipitated in greater quantity in the summer than in the winter because of the evaporation of carbon dioxide from the water during the warmer season. Bradley decided there were about 3,000,000 varves in the Green River shale, and found that they displayed long period rhythms in alternations between organic rich oil-shales and marlstones. There are about 22,000 varves in each of these rhythms, and as this corresponds with the cycle of precession of the equinoxes he interpreted the rhythm as of that origin.

Stamp[20] described varved sediments from the Tertiary of Burma. He stated that the sediments were accumulated in the sea into which the ancestor of the Irrawaddy River discharged and that one lamina corresponds with the flood season of the river and the other with the low-water season. He found that there were on the average about 5 varves per inch, indicating a total period of at least 2½ million years for the whole series of rocks which is about 12,000 feet thick.

Under favorable conditions a saline lake undergoing evaporation may deposit a lamina of gypsum or anhydrite during one season and some other saline during another. Gypsum and salt alternations have been described from the Permian of Kansas, and anhydrite and dolomite varves of very regular development from the Permian of Texas, in a drill core.[21]

The speaker has observed presumably nonglacial varves in a fine-grained sandstone or siltstone of Carboniferous age in Wyoming, in which pure white laminae alternate with reddish laminae of somewhat finer texture. A fine-grained siltstone occurring near the base of the Pennsylvanian system and quarried for whetstones in Orange County, Indiana, is also regularly laminated or varved. The laminations in this formation seem to record numerous short-period rhythms which may be associated with sun-spot cycles.

LARGER RHYTHMS OR CYCLES IN SEDIMENTATION

Newberry[22] described a "circle" of sedimentation as consisting of sandstone at the base, followed successively by shale and limestone and separated from other "circles" by unconformities. He interpreted the "circles" as being initiated by diastrophic movement, following which coarse sediment was carried into nearby depositional basins. As the elevated land mass became worn down the particles transported to the basin became finer and deposition proceeded less rapidly. Eventually erosion of the source area ceased and limestone followed shale in the basin. The "circle" is terminated by renewed uplift, which again brings a supply of coarser sediment into the basin. This is a succession of events rather similar to the ideal concept of a geologic period, which should be initiated and terminated by uplift but otherwise marked by general stability.

In a valuable contribution to the literature on rhythmic sedimentation Barrell[23] outlined a sequence of events including periodic downwarping of basin areas with reference to a hinge line, and intervening periods when, without deformation, the basins became filled with sediment. He noted that because the downwarping would be greatest farthest from the hinge line, numerous stratigraphic units of the deeper part of the basin should wedge out against the edge of the basin or hinge line.

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[20] Stamp, L. D., Seasonal rhythm in the Tertiary sediments of Burma: Geol. Mag., vol. 62, pp. 515-528, 1925.

[21] Udden, J. A., Laminated anhydrite in Texas. Geol. Soc. Amer., Bull., vol. 35, pp. 347-354, 1924.

[22] Newberry, J. S., Circles of deposition in American sedimentary rocks, Am. Assoc. Adv. Sci., Proc. 22, pt. 2, pp. 185-196, 1874.

[23] Barrell, J., Rhythms and the measurement of geologic time: Geol. Soc. Amer., Bull., vol. 28, pp. 745-809, 1917.

Stamp[24] has described cyclic sediments of Eocene age in the London and Paris basins, which consist of successive groups of marine strata in one direction intertonguing with nonmarine strata in the other direction.

CARBONIFEROUS CYCLES OF SEDIMENTATION

The latter part of the Paleozoic era, consisting of the later Mississippian, the whole Pennsylvanian, and the early Permian periods, seems to have been characterized by some form of rhythmic sedimentation over many parts of the world. These rhythms represent a time interval much less than a geologic period, as the later Mississippian (Chester series) of the Mississippi valley includes 9 rhythms, the Pennsylvanian 30 or more, and the early Permian (Big Blue series)[25] of Kansas about 10. Born[26] in describing the upper Carboniferous (Pennsylvanian) of the Upper Silesian basin stated that 477 cycles have been found in that region. American Pennsylvanian cycles were first noted by Udden[27] in the Peoria quadrangle, Illinois, where a similar series of beds was found associated with coals 5, 6, and 7, and the Lonsdale limestone. Cyclic sedimentation was the subject of later investigation by J. M. Weller in Illinois and adjacent states.[28] Somewhat similar rhythms of the same age have been described from Ohio,[29] West Virginia,[30] Kansas and Nebraska,[31] England,[32] and the Donetz coal basin of Russia.[33] The speaker has also observed sedimentary rhythms in the Pennsylvanian rocks of Kentucky, Indiana, Iowa, Missouri, Oklahoma, and several states in the Rocky Mountains. The phenomenon thus seems very widespread in the northern hemisphere, though it has not yet been recognized in the southern hemisphere.

Weller stated that the cycle of sedimentation of the Pennsylvanian of Illinois when fully developed consists of the following lithologic units:

10. Gray shale with ironstone concretions
9. Marine limestone
8. Carbonaceous (black) shale
7. Marine limestone (local)
6. Gray shale with plant remains (local)
5. Coal
4. Underclay
3. Fresh water limestone
2. Shale or sandy shale
1. Sandstone

Erosional unconformity above No. 10 of next cycle below

Weller[34] proposed the name cyclothem for this group of strata and considered it to be approximately equivalent to a geologic formation. Beds 7-10

[24] Stamp, L. D., On cyles of sedimentation in the Eocene strata of the Anglo-Franco-Belgian Basin: Geol. Mag., vol. 58, pp. 108-114, 194-200, 1922.

[25] Jewett, J. M., Evidence of cyclic sedimentation in Kansas during the Permian period, Kans. Acad. Sci., Tr., vol. 36, pp. 137-140, 1933.

[26] Born, A., Periodizitat epirogener Krustenbewegungen: XVI Intern. geol. congr., Rept., vol. 1, p. 172, 1936.

[27] Udden, J. A., Geology and mineral resources of the Peoria quadrangle, Illinois: U. S. Geol. Surv., Bull. 506, pp. 47-50, 1912.

[28] Weller, J. M., Cyclic sedimentation in the Pennsylvanian and its significance: Jour. Geol., vol. 38, pp. 97-135, 1930.

——— The conception of cyclical sedimentation during the Pennsylvanian period: Ill. State Geol. Surv., Bull. 60, pp. 163-177, 1931.

[29] Stout, W., Pennsylvanian cycles in Ohio: Ill. State Geol. Surv., Bull. 60, pp. 195-216, 1931.

[30] Reger, D. B., Pennsylvanian cycles in West Virginia: Ill. State Geol. Surv., Bull. 60, pp. 217-239, 1931.

[31] Moore, R. C., Pennsylvanian cycles in the northern mid-continent region: Ill. State Geol. Surv., Bull. 60, pp. 247-257, 1931.

[32] Hudson, R. G., On the rhythmic succession of the Yoredale series in Wensleydale: Yorkshire Geol. Soc., Pr., vol. 20, pt. I, pp. 1-11, 1923-24.

[33] Grabau, A. W., The Permian of Mongolia: Am. Mus. Nat. Hist., Natural History of Central Asia, vol. 4, pp. 432-442, 1931.

[34] Wanless, H. R., and Weller, J. M., Correlation and extent of Pennsylvanian cyclothems: Geol. Soc. Amer., Bull., vol. 43, p. 1003, 1932.

of the cyclothem are considered marine in origin as they generally contain marine fossils. Beds 1-6 are considered nonmarine, largely because they contain traces of land or fresh water plants or animals, and because marine fossils are not found. The successive cyclothems are not all composed of the full sequence of beds. As one cyclothem is traced over a large territory certain members may be found to disappear or other new members may be introduced. In some regions, like southern Illinois, eastern Kentucky, and Virginia, the cyclothems consist almost wholly of non-marine members, while in other regions such as in the upper Pennsylvanian of northern Illinois, Kansas, and Nebraska, the non-marine beds of the cycle may be greatly reduced in thickness or entirely absent, making the record largely one of marine sedimentation. Traced into other regions the sedimentary rhythms include coarse conglomerates, as in central Colorado and Virginia; red beds, as in the upper Pennsylvanian of Ohio, West Virginia, and Oklahoma; chert or flint, as in the lower Permian of Kansas; and gypsum as in Kansas and Colorado. The lithologic composition and thickness of the cyclothem is a record of (1) the proximity of the area to highlands providing sedimentary materials, (2) the rate of subsistence, (3) the average elevation of the locality in respect to sea-level, and (4) the climate, both of the source area of the sediment and the depositional basin. Geosynclinal areas marked by rapid subsistence have a thicker rhythmic record than regions with less rapid subsistence and if they were close to old land masses, as the Appalachian geosyncline was, they include coarser sediments. During the Pennsylvanian period, the eastern United States evidently had, as it has now, a more humid climate than the Rocky Mountain region. This is indicated by more numerous and thicker coals, more abundant horizons yielding fossil plant impressions, and a predominance of shales, the product of deep chemical weathering of the lands providing sedimentary particles. In contrast the cyclothems of the Rocky Mountain region contain very few coals or plant horizons, the sandstones and conglomerates contain abundant feldspars and other unstable mineral species, shales are infrequent and wholly lacking in some areas, red beds are common, and gypsum and salt are found in a few places. The tracing of a particular cyclothem from the Appalachian region to the Rocky Mountains with a study of the varied conditions of sedimentation would provide a significant picture of conditions of regional climate and physiography of the Carboniferous.

Moore[35] has described a still more complex rhythm from the upper Pennsylvanian of Kansas, to which he has applied the name megacycle. This includes as many as 5 marine limestones and locally as many as three coals. Each limestone or shale of the megacycle is characterized by some textural, structural, or faunal features resembling those of corresponding shales or limestones in other megacycles but differing from others in the same megacycle. A critical analysis of the upper Pennsylvanian succession in southern and central Illinois suggests the presence of a corresponding complex rhythm, characterized by more shale, coal, and sandstone and less limestone than in Kansas.

INTERPRETATIONS

Several students of Carboniferous cyclic sedimentation have suggested explanations for the rhythmic changes involved. Stout[36] and Cady[37] have postulated a broad interior basin subject to periodic downwarping during which shales, limestones, and sandstones were deposited and ultimately built up to a profile of equilibrium on which coal swamps established themselves, to persist until a renewal of downwarping. Stout attaches little significance

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[35] Moore, R. C., Stratigraphic classification of the Pennsylvanian rocks of Kansas: State Geol. Surv. of Kans., Bull. 22, pp. 29-35, 1936.

[36] Stout, W., Pennsylvanian cycles in Ohio: Ill. State Geol. Surv., Bull. 60, pp. 204-205, 1931.

[37] Cady, G. H., Alternative interpretation of the subdivision of the Pennsylvanian series in the Eastern Interior province (abstract): Geol. Soc. Amer., Proc. for 1933, p. 71, 1934.

to the breaks at the bases of numerous sandstones and believes the sandstones to be marine. Weller,[38] on the other hand, believes that the surfaces below the sandstone were the result of erosion above sea-level and that the sandstones are non-marine deposits. In order to fit these views into the interpretation of the rhythmic movements Weller postulated cycles of alternating elevation and subsidence for the interior of the United States, the subsidence exceeding the elevation in amount. The maximum emergence in each cycle is placed at the erosional surface initiating the rhythm and the maximum subsidence at the deposition of the upper marine limestone (member 9). Born[39] interpreted the Carboniferous cycles of Europe as due to accumulation of stresses to the breaking point, when they were relieved by movement. He believes the movements of similar sorts occurred at similar intervals, and compared the procedure with "breathing" of the earth. The speaker, with Professor F. P. Shepard[40] suggested that the movements of the depositional basin were dominantly downward, but that the sea-level repeatedly rose and fell, causing frequent wide migrations of the strand-line. The sea-level fluctuations were tentatively interpreted as due to the alternative growth and wastage of late Paleozoic continental glaciers principally in the southern hemisphere. They suggested that climatic cycles related to the precession of the equinoxes or some other extra-terrestrial cause might be responsible for the growth and melting of the glaciers and for changes in conditions of sedimentation outside glaciated areas. Critics of this latter view point out that late Paleozoic glaciation is not definitely known to coincide in time with the Carboniferous cyclic sedimentation, nor is it known that there were as many glacial epochs as there were cycles. The length of time required for the individual Carboniferous rhythms has not been determined, nor is it known whether all are of approximately the same duration. The great similarity in sequence in numerous successive cyclothems and their approximate equivalence in thickness suggests that they record approximately equal periods of time and the operation of some regular rhythmic forces.

Rhythmic and Nonrhythmic Periods of Earth History

In contrast with the Pennsylvanian and Pleistocene periods during which there were frequent changes in climate, sea level, and types of sedimentary rocks, other portions of the geologic time scale seem to have been characterized by the persistence of similar conditions for long periods of time. The middle Ordovician, the middle Silurian, and the middle Mississippian periods were characterized by continuous limestone or dolomite deposition throughout the central parts of the United States. There were thus intervals of geologic history when earth movements and climatic changes attained a rather regular periodicity recording itself in erosion cycles, cycles of sedimentation, and glacial and interglacial epochs. There were other somewhat longer intervals when periodic earth movements and climatic changes apparently were subdued or lacking.

[38] Weller, J. M., Cyclical sedimentation in the Pennsylvanian and its significance: Jour. Geol., vol. 38, pp. 110-135, 1930.
[39] Born, A., Periodizitat epirogener Krustenbewegungen: XVI Intern. geol. Congr., Rept., vol. 1, pp. 169-189, 1936.
[40] Wanless, H. R., and Shepard, F. P., Sea level and climatic changes related to late Paleozoic cycles: Geol. Soc. Amer., Bull., vol. 47, pp. 1177-1206, 1936.