[AMERICAN JOURNAL OF SCIENCE, VOL. 260, OCTOBER 1962, P. 561-576]

American Journal of Science

OCTOBER 1962

CYCLIC SEDIMENTATION AND THE ORIGIN OF ANALCIME-RICH UPPER TRIASSIC LOCKATONG FORMATION, WEST-CENTRAL NEW JERSEY AND ADJACENT PENNSYLVANIA

FRANKLYN B. VAN HOUTEN

Department of Geology, Princeton University, Princeton, New Jersey

ABSTRACT. The Upper Triassic Lockatong formation is a huge lens (3500 feet x 25 miles x 90 miles) of lacustrine deposits composed mainly of massive dark gray or reddish brown argillite and subordinate platy dark gray mudstone and black shale arranged in asymmetrical short cycles of two kinds.

One variety, averaging 17 to 22 feet in thickness, consists of several feet of black shale succeeded by platy carbonate-rich mudstone in the lower part and massive calcareous mudstone (argillite) in the upper part. Lenses of thin-bedded fine-grained sandstone commonly occur in these "detrital" cycles.

A second, more common kind of short cycle, averaging 7 to 14 feet in thickness, contains less detrital and more chemical sediment. The lower beds are platy carbonate-rich mudstone and marlstone, some of which are varved. The upper part is massive carbonate- and analcime-rich mudstone (argillite), which contains as much as 7 percent soda and as little as 47 percent silica.

Analcime, which constitutes as much as 35 to 40 percent of the argillite, or its sodium-rich colloidal precursor were primary products of sedimentation in a lake from whose water calcium and magnesium carbonates had been extracted during deposition of the chemical variety of short cycle.

Progressive reduction in water depth and decrease in redox potential associated with the development of a distinctive sequence of sedimentary structures through the course of a short cycle presumably resulted from a cyclic variation in rainfall accompanied by periodically accentuated compaction imposed on lacustrine mud accumulating in a continuously sinking basin. Varve counts of black mudstone suggest control by the 21,000-year precession cycle.

Groups of detrital and chemical cycles occur in rhythmic couples 325 to 350 feet thick. These apparently resulted from alternating wetter and drier phases of a long cycle, producing either through-flowing drainage in the lake basin and a group of detrital short cycles, or a closed basin and a group of chemical short cycles characterized by the concentration of sodium in the upper part of each cycle. In some chemical cycles reddish brown mud accumulated in an oxidizing environment induced by saline waters that inhibited organic growth.

INTRODUCTION

The Lockatong formation is a huge lens of lacustrine deposits, originally about 25 miles wide and 90 miles long, and a maximum of about 3500 feet thick (fig. 1). which contains one of the largest known accumulations of sedimentary analcime of nonvolcanic origin. It lies conformably on the Stockton arkose and reddish brown sandy mudstone (maximum of 5000 feet thick) and under the reddish brown Brunswick shale (maximum of 6000 feet thick). Together, these three nonmarine lithofacies constitute the upper Triassic Newark group (Kümmel, 1940, p. 101-111; McLaughlin, 1959).

Sedimentary cycles[1] are a fundamental feature of the Lockatong formation and were a basic factor in the origin of its abundant analcime. A general

[1] "Sedimentary cycles are recurrent sequences of strata each consisting of several similar lithologically distinctive members arranged in the same order" (Weller, 1960, p. 367).

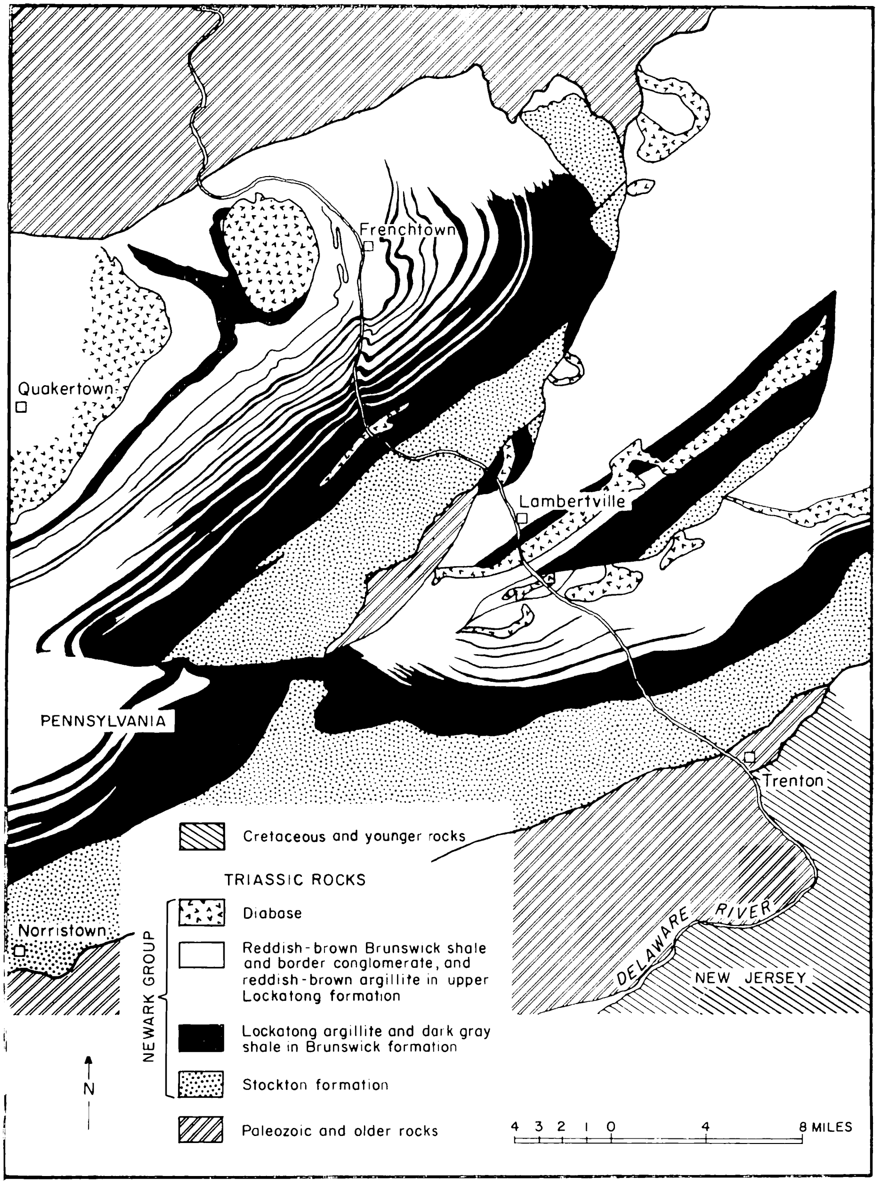


Fig. 1. Geologic map of west-central New Jersey and adjacent Pennsylvania. Interfingering of Lockatong and Brunswick lithofacies based largely on mapping by McLaughlin (1948, 1959).

description of the Lockatong cycles and a preliminary interpretation of the cyclic sedimentation[2] based on data from more than 150 thin sections and 750

[2] Cyclic sedimentation . . . "the deposits of which imply repetition of a series of events rather than their mere recurrence" (Wells, 1960, p. 390).

X-ray analyses are presented here as part of a detailed study of the formation that has been supported by a grant from the National Science Foundation (project G 5032). It is a pleasure to acknowledge the help of Erling Dorf, A. G. Fischer. and Sheldon Judson during the preparation of this paper.

ROCK TYPES

The principal rock types in the Lockatong formation are:

1. Tough. massive, very fine-grained to aphanitic argillite,[3] mostly dark gray. with disseminated pyrite. It is the predominant rock type in the formation and comprises two varieties, both of which exhibit extensively disturbed or disrupted laminae on a microscopic scale. Some of the disturbance is the work of organisms; most of it apparently is of inorganic origin.

(a). One kind is a calcareous feldspathic mudstone with a hackly or gnarly fracture, and with indistinct, irregular carbonaceous laminae; some of it has been deformed into a crenulate or contorted fabric on a microscopic scale (pl. 2-C). This argillite is essentially a detrital deposit composed of illite and rarely chlorite, feldspar, calcite, and a very minor amount of quartz.

(b). The other kind of argillite breaks with a subconchoidal fracture and is composed of illite, feldspar, analcime, and carbonates of which dolomite generally predominates (Van Houten, 1960). The rock contains as much as 7 percent soda and as little as 47 percent silica, and a maximum of 35 to 40 percent analcime.

The groundmass, which is either homogeneous or has a brecciated aspect on a microscopic scale (pl. 2-D), is commonly speckled with white patches of crystalline analcime and carbonates producing a fabric rather like that of "birdseye" limestone. Some of this unique argillite is reddish brown.

(2) Platy very dark gray to black laminated mudstone and marlstone[4] (pl. 2-A) extensively disrupted by shrinkage cracks (pl. 1-C,D,E; pl. 2-B). It is composed of illite, rare chlorite, feldspar, and relatively abundant carbonates of which dolomite commonly predominates. Minor amounts of analcime and

[3] Argillite is a hard, nonfissile aphanitic mudstone indurated beyond the hardness of associated shale.

[4] Marlstone is an aphanitic argillaceous carbonate rock or a carbonate-rich mudstone.

PLATE 1

Short cycles and sedimentary features, Lockatong formation.

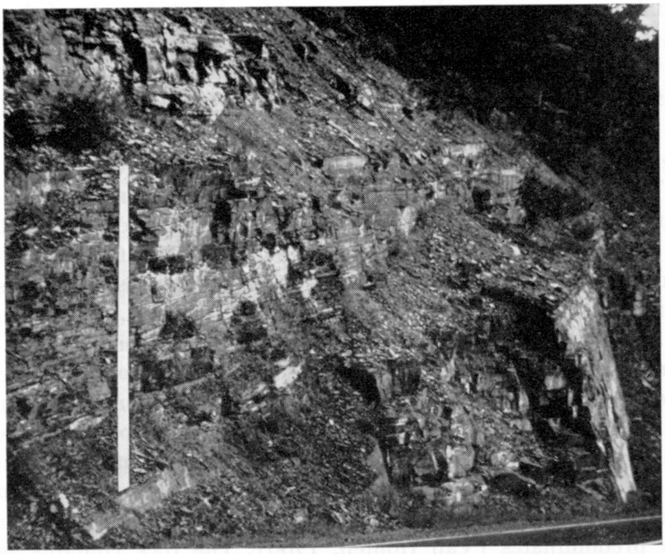
A. Three short cycles in upper part of Lockatong formation, along New Jersey State Highway 29, 7 miles south of Frenchtown, N. J. Middle cycle indicated by white line is detrital variety 20 feet thick. Location of cycles in section shown on figure 2.

B. Short cycles in Lockatong formation, exposed in quarry at Rushland, east-central Pennsylvania. Black bands mark base of cycles.

C. Interbedded tan-weathering gray marlstone and very dark gray to black carbonate-rich mudstone (unit 2) in lower part of chemical cycle. Marlstone is disrupted by shrinkage cracks filled with black mudstone that were crumpled during compaction. Lowest layer of marlstone is about 3 inches thick.

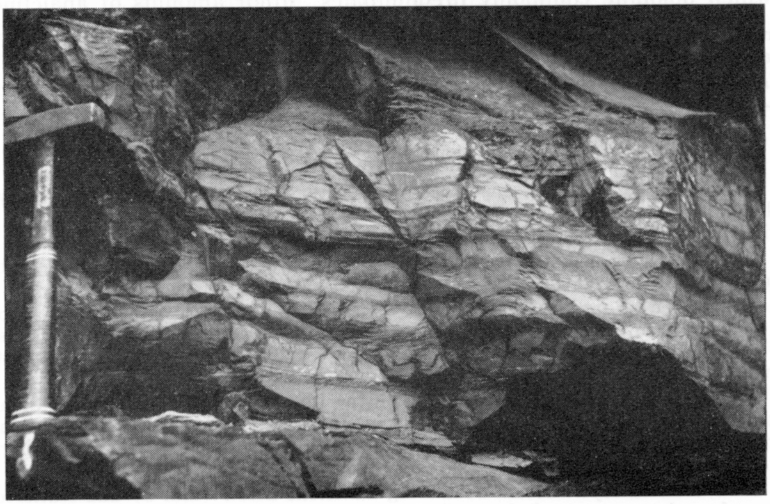
D. Intraformational breccia (unit 3) in argillite in middle of chemical cycle. Disrupted tan-weathering marlstone layers widely scattered through very dark gray analcime-bearing mudstone. The pattern of dispersal suggests forceful disruption after burial by upward moving water and mud in sol state. White tape in 6 inches.

E. Brecciated layers of tan-weathering marlstone below (unit 3) and scattered fragments of marlstone set in dark gray analcime-rich argillite above (unit 4), in middle of chemical cycle. Polished specimen 7 inches long.



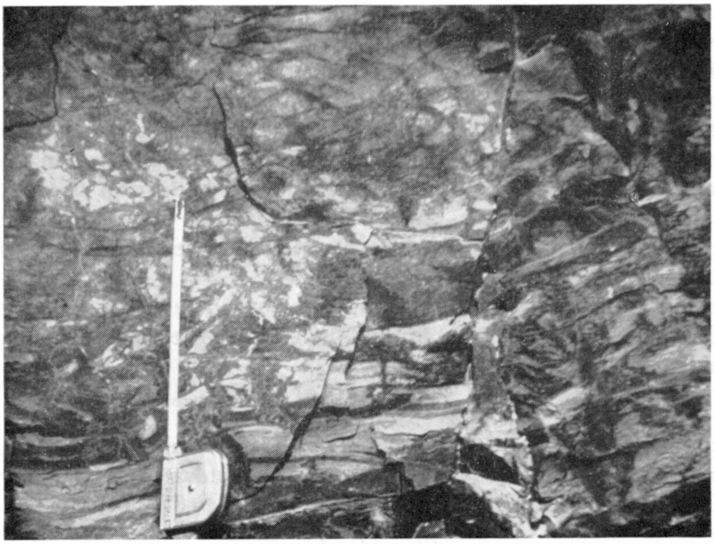
A

B



C

PLATE 1 Short cycles and sedimentary



D

E

features, Lockatong formation. For explanation see bottom of page 563.

lenses and layers of pyrite and crystalline carbonates 1/16th to 1 inch thick occur locally.

(3) Black laminated shale composed of illite, chlorite, and feldspar, a minor amount of calcite and quartz, and scattered pyrite.

(4) Gray, thin-bedded calcareous, well sorted fine-grained feldspathic sandstone and siltstone with distinct black carbonaceous laminae and irregular small-scale cross-lamination are common in the lower third of the formation and occur in the upper part as 2- to 5-foot layers and lenses associated with detrital argillite (type 1a). In these rocks there are scattered horizontal organic burrows averaging 1 to 3 mm in diameter.

The overlying reddish brown Brunswick shale is a fissile, rather poorly sorted, feldspathic mudstone containing illite and chlorite, feldspar and quartz, and a minor amount of calcite cement.

LOCKATONG CYCLES

Patterned sequences of two different orders of magnitude occur in the Lockatong formation. One consists of short sedimentary cycles ranging from about 10 to 20 feet thick, the other of long cycles 325 to 375 feet thick.

Short Cycles

An orderly asymmetrical repetition of rock types is reflected in weathered profiles (pl. 1-A) as well as in the vertical distribution of color, composition, and distinctive sedimentary structures. Approximately 80 short cycles are present in a 1300-foot section of the upper part of the formation exposed in a long roadcut on New Jersey State Highway 29, 6 to 8 miles south of Frenchtown on the Delaware River. Short cycles are also well displayed in large quarries in east-central Pennsylvania (pl. 1-B).

In general form short cycles consist of lower black shale and platy mudstone and marlstone and of upper massive gray or reddish brown argillite which makes conspicuous jointed ledges. In detail, however, there are two rather distinctive sorts (fig. 2). Unfortunately, the sequence and relationship of the two kinds of short cycles revealed in the long outcrop on N. J. State Highway 29 cannot readily be checked or amplified elsewhere because of a lack of accessible, well exposed thick sections of the formation.

Detrital variety.—One variety of short cycle (fig. 3), rather clearly delineated in outcrop, consists of several feet of pyritic black shale at the base

---

Fig. 2. Generalized stratigraphic section of upper Lockatong formation exposed along New Jersey State Highway 29, 6 to 8 miles south of Frenchtown, N. J., showing short detrital and chemical cycles. Distribution pattern of short cycles is indicated by scale along right side of section. Data derived from measurement of section to 1-foot intervals and from about four X-rayed samples per cycle and 70 thin sections of representative rocks.

Fig. 3. Diagrammatic sketch of detrital (A) and chemical (B) varieties of short cycles in Lockatong formation. Detrital cycles average 17 to 22 feet thick; chemical cycles average 7 to 14 feet thick. Closely spaced thin lines—black shale; thick lines—platy gray marlstone interbedded with very dark gray to black carbonate-rich mudstone. Massive argillite in upper part of detrital cycle has indistinct laminae contorted on a microscopic scale and lens of fine-grained sandstone with small-scale cross- and contorted-bedding. Massive analcime-rich argillite in upper part of chemical cycle is brecciated on microscopic scale. Units 1 to 6 of chemical cycle described in text.

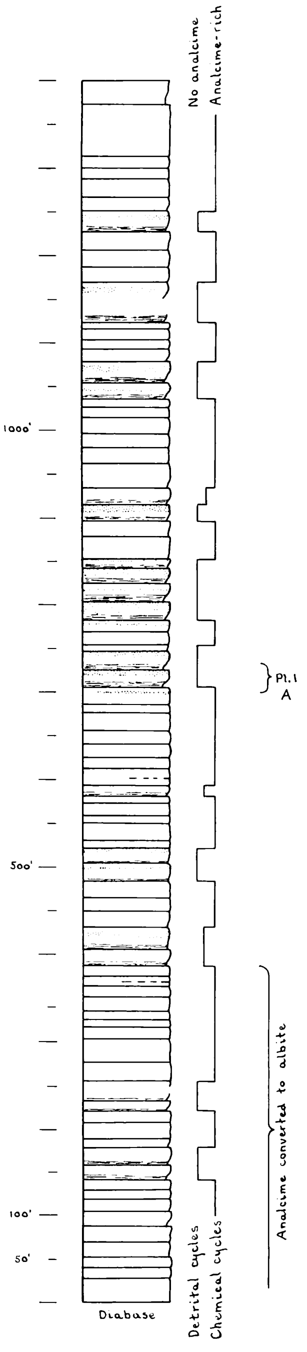

No analcime
Analcime-rich
1000'
500'
100'
50'
Pl. I
A
Analcime converted to albite
Diabase
Detrital cycles
Chemical cycles

Fig. 2.

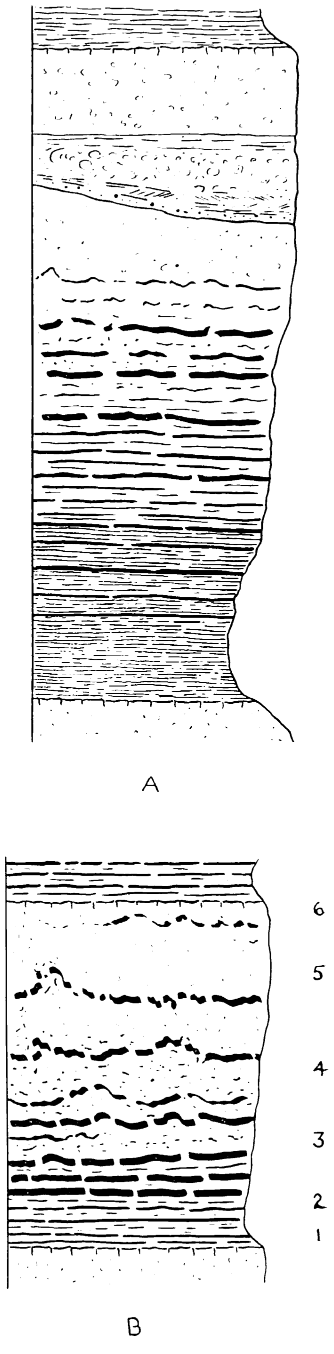

A
6
5
4
3
2
1
B

Fig. 3.

succeeded by platy black mudstone and interbedded tan-weathering disrupted dark gray calcitic and rarely dolomitic marlstone in alternating layers ¼ to 2 inches thick. The upper part is massive, calcareous silty mudstone with indistinct irregular laminae and commonly with a crenulate or contorted fabric produced by flowage on a microscopic scale (pl. 2-C). The crenulate fabric is largely the product of crumpling of slender silty mudcrack casts during compaction (Bradley, 1930b). Some of the disturbance is undoubtedly the work of organisms. Interbedded with this detrital mudstone are 2- to 5-foot layers and lenses of distinctly thin-bedded, fine-grained sandstone and siltstone, which locally also have a contorted fabric and are disturbed by scattered horizontal organic burrows. Some of the fine-grained sandstone occurs in graded beds 1 to 2 mm thick.

Detrital cycles, generally ranging from to 17 to 22 feet in thickness, comprise the thicker ones but they constitute only about one third of all the short cycles in the measured section (fig. 2).

Chemical variety.—A second, more common kind of short cycle differs principally in containing less detrital and more chemical sediment, and most cycles of this variety range from 7 to 14 feet in thickness (fig. 3). The lower part consists of interbedded black to dark gray platy dolomitic and calcitic mudstone and marlstone; the upper part is massive analcime- and carbonate (predominantly dolomite)-rich argillite. Because easily weathered black shale is not present at the base these cycles are less evident in outcrop.

Short cycles of the chemical variety commonly exhibit a succession of distinctive sedimentary structures, described here in a sequence of rather arbitrary units (fig. 3).

(*Unit 1*): The lowest several inches of platy black dolomitic and calcitic mudstone and marlstone contains interbedded 1/16th to 1 inch layers and lenses of crystalline dolomite and calcite, and less commonly, pyrite. Moreover, many of the platy layers are composed of regularly alternating black carbonaceous and light gray carbonate-rich laminae (pl. 2-A). These couplets of laminae resemble varves in the Eocene Green River lacustrine deposits (Bradley, 1930a, p. 95-96).

(*Unit 2*): In the lower several feet of the cycle platy carbonate-bearing beds with thin layers and lenses of crystalline carbonates commonly show a distinct pattern of ½- to 3-inch layers of black mudstone alternating with ½- to 4-inch layers of tan-weathering gray marlstone and aphanitic dolomite. In the lower part thinner layers of both black mudstone and gray dolomitic marlstone are extensively mudcracked and the cracks are now filled with short crumpled casts.

In the upper part of unit 2 thicker layers of the tan-weathering marlstone predominate (pl. 1-C) and these are ruptured by slender irregular shrinkage cracks now filled with black mudstone that was crumpled during compaction. Locally, minor amounts of crystalline analcime mixed with carbonates occur in thin lenses and in densely scattered white patches in the black mudstone layers in units 2 and 3.

Black shale and platy carbonate-rich mudstone of the sort in units 1 and 2 have yielded most of the fossils found in the Lockatong formation. These include the remains of elasmobranch, coelocanth, and palaeoniscid fish, several kinds of reptiles, estheriids, phyllocarids, and ostracodes, and plants.

(*Unit 3*) : Above the relatively undisturbed "banded" sequence there are a few feet of extensively disrupted 1- to 3-inch layers of tan-weathering marlstone embedded in very dark gray analcime-bearing mudstone. Evidently the carbonate-rich layers hardened and shrank after burial relatively more rapidly than the surrounding dark gray colloidal mud. This fragmentation by post-burial shrinkage upset the physical system so that dark gray colloidal gel reverted thixotropically to a sol. With loss of support the carbonate-rich fragments drifted apart and colloidal mud in a sol state was forced around the firmer pieces (pl. 1-E; pl. 2-B).

Locally the intraformational breccia is dispersed through the overlying mudstone in an "explosive" pattern (pl. 1-D), suggesting forceful disruption of layers of quick-setting carbonate-rich mud by upward-moving water released during compaction.

In chemical cycles that are predominantly reddish brown, units 1 to 3 are abbreviated and contain beds of disrupted greenish gray to medium gray mudstone generally less than 1 inch thick. Many of these layers now form a mosaic type (Bradley, 1931, p. 28-29) of intraformational breccia with flat fragments oriented nearly parallel to bedding.

(*Unit 4*) : Above unit 3 a few feet of dark gray analcime-rich mudstone may appear uniform in outcrop, but actually it is disrupted on a microscopic scale (pl. 2-D) and contains scattered small angular fragments of marlstone (pl. 1-E) apparently derived from completely disrupted layers. In cycles that are reddish brown in the upper part, the color change occurs in unit 4 where small greenish gray mudstone fragments are scattered through dark reddish brown argillite.

In units 4 and 5 irregularly disrupted layers of tan-weathering marlstone recur about every 3 or 4 feet in gray argillite. In reddish brown argillite most of the recurring layers are thin beds of disrupted greenish gray mudstone.

PLATE 2

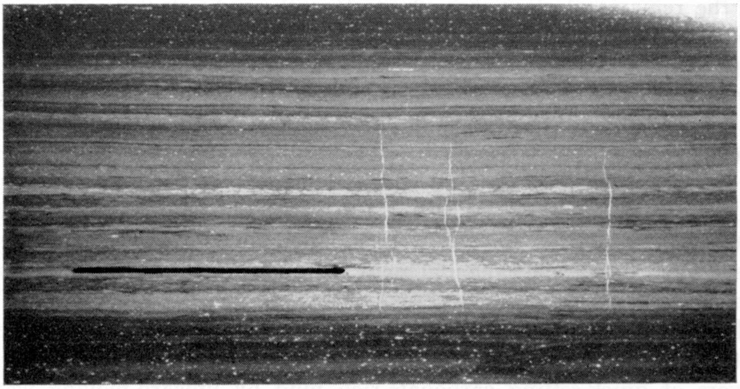
Photomicrographs of Lockatong formation.

A. Platy black varved marlstone in lowest part (unit 1) of chemical variety of short cycle. Thin dark member of varve is organic-rich; thicker light member is muddy dolomite. Varves in upper third of specimen range from 0.05 to 0.2 mm in thickness. Black line is 1 cm.

B. Brecciated medium gray dolomite- and analcime-rich argillite (unit 3) in middle of chemical cycle. Cracks formed by postburial shrinkage and disruption are filled with dark reddish brown dolomite- and analcime-rich mudstone. Some cracks were crumpled during compaction. Minute scattered crystals and larger white patches are dolomite. Vertical black line is 1 cm.

C. Massive indistinctly laminated silty argillite in upper part of detrital variety of short cycle, with crenulate and lobate or contorted fabric produced by postburial flowage on a microscopic scale. Contorted structures as in lower left are mudcrack casts crumpled during compaction. Coarse silt in uppermost contorted argillite; remainder of specimen is fine silt and clay. Vertical black line is 1 cm.

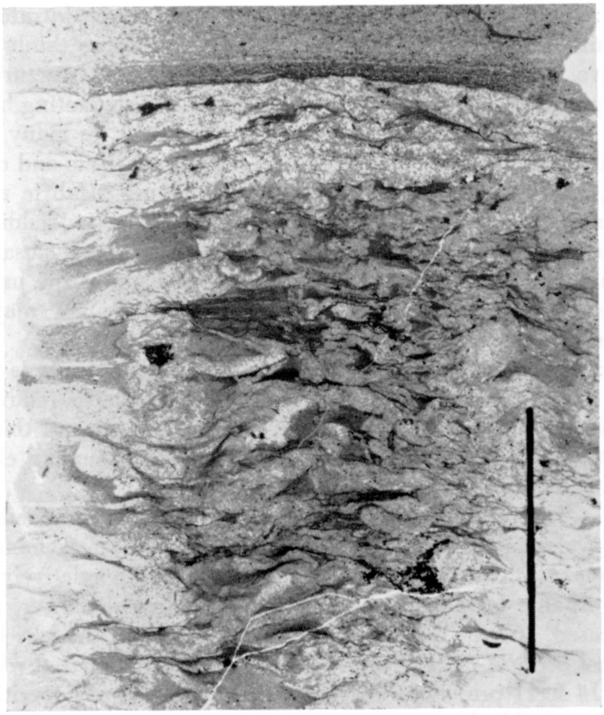
D. Massive dark gray analcime-rich argillite in upper part (units 4 and 5) of chemical variety of short cycle, showing microbrecciation produced during burial and dewatering of colloidal mud. Scattered patches of analcime lie mainly in shrinkage or disruption cracks. Largest patches are about 2 mm long. A few small dolomite rhombs occur in argillite and in some of the analcime patches. Vertical black line is 1 cm.



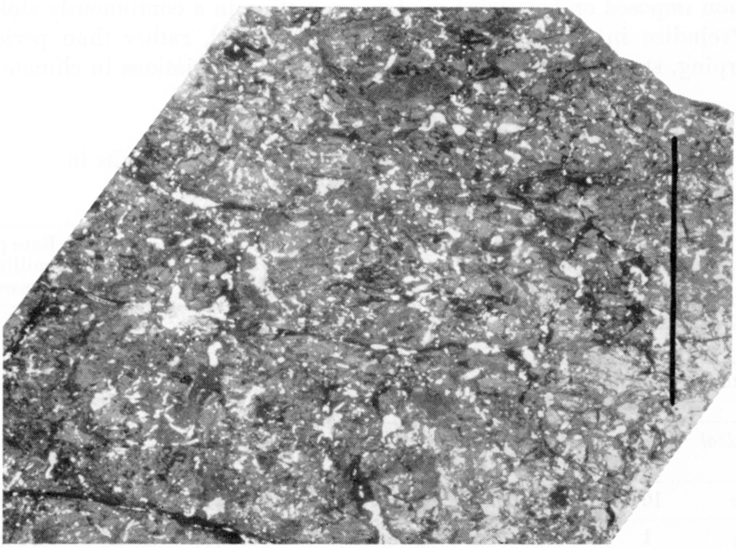
A

B

PLATE 2



C



D

Photomicrographs of Lockatong formation. For explanation see bottom of page 569.

(*Unit 5*): In the upper several feet of a chemical cycle, intraformational fragments diminish to less than ⅛th inch in length and are thinly dispersed through massive, aphanitic argillite, which is either nearly structureless or is completely fragmented on a microscopic scale (pl. 2-D), suggesting brecciation during burial and dewatering of colloidal mud. Moreover, in many cycles the rock is shot through with white patches of crystalline analcime and carbonates as much as 1/16th to ¼th inch in diameter, producing a fabric rather like "birdseye" limestone. These patches are especially large in reddish brown argillite and in the uppermost part of the formation where a mosaic type of intraformational breccia is common. The outline of some of the patches and the occurrence of some in mudcrack filling suggest that many may fill salt-crystal (glauberite?) cavities.

(*Unit 6*): The uppermost 2 to 4 inches of a cycle commonly is very dark gray to black above gray argillite and medium gray above reddish brown argillite, and its top surface is mudcracked. The darker color of this unit apparently resulted from downward penetration of strong reducing effects prevailing at the beginning of the succeeding cycle.

Summary.—The sedimentary features of both detrital and chemical varieties of short cycles in the Lockatong formation record an asymmetrical sequence of events. Each began with filling the basin with relatively stagnant water rich in organic ooze. Gradually, the lake became shallower, the redox potential decreased, and the cycle ended with emergence of the lake bottom. A greater thickness of most detrital cycles (17 to 22 feet) compared with chemical ones (7 to 14 feet) probably reflects a more rapid rate of deposition of the detrital sediments (table 1).

Preliminary interpretation of these short cycles suggests that they resulted from a cyclic variation in rainfall accompanied by periodically accentuated compaction imposed on lacustrine mud accumulating in a continuously sinking basin. Prejudice in favor of a cyclic climatic control, rather than periodic downwarping, stems largely from an assumption that variations in climate are

TABLE 1

Estimates of rates of sedimentation and duration of units in Lockatong formation

	Number of units in formation	Thickness of units	Duration of units	Years per foot	Rate per thousand years	Rate per million years
Short cycle	220-230	15 ft av.	22,000 yr av. (19,000-25,000 yr)	1470 yr	.68 ft	
Detrital		19 ft av. (17-22 ft)		1160 yr	.86 ft	
Chemical		11 ft av. (7-14 ft)		2000 yr	.50 ft	
Long cycle	10	345 ft av.	500,000-510,000 yr	1480 yr	.68 ft	
Lockatong formation	1	3500 ft	5,100,000 yr	1450 yr	.69 ft	690 ft

apt to be more regular and persistent than intermittent subsidence (see Gilbert, 1895, p. 123. 127). A tentative estimate of the duration of a short cycle gives an average of 22,000 years (table 1), which agrees rather well with the 21,000-year precession cycle. Support for this interpretation is afforded by cycles of oil shale and marlstone in the Eocene Green River lacustrine deposits of Wyoming and Colorado. Varve counts of these 5- to 10-foot cycles indicate an average duration of 21,630 years, suggesting control by the precession cycle (Bradley, 1930a, p. 105-106).

Assuming that the short sedimentary cycles in the Lockatong formation were caused by cyclic variation in climate, the following reconstruction is proposed:

Chemical cycles accumulated when the lake had no outlet, and chemicals derived from a deeply weathered source area were concentrated and precipitated in the basin. A cycle began with increased rainfall and inflow. As the lake level rose, laminated carbonate-rich black mud and layers of pure carbonate were deposited on the stagnant bottom. Through the course of a cycle rainfall began to wane; the water became shallower and less stagnant. Deposition of uniform colloidal clay predominated as the continued precipitation of calcite and dolomite left the water enriched in sodium. In this setting analcime or its precursor accumulated in the mud. In the late dry stage of many of the chemical cycles, and throughout most of the course of some, reddish brown mud was preserved in an oxidizing environment, apparently indirectly induced by noxious saline waters that inhibited organic growth. At such times the size of the lake probably was greatly reduced, leaving extensive oxidizing mudflats with pools of concentrated brine. In the final stage of minimum rainfall, exposed deposits were suncracked, saline compounds crystallized on the mudflats, and the newly deposited cycle underwent relatively rapid compaction that accentuated the lowering of the basin by continuous gentle sinking.

Detrital cycles resulted from a similar cyclic increase and decrease in rainfall, but they accumulated when the lake was fed by through-flowing drainage, which carried most of the soluble material to the sea.

A similar asymmetrical trend, from minor transgression and submergence to emergence, has dominated many cyclic sequences, such as the mid-Devonian Caithness flagstone (Middle Old Red Sandstone) of northeastern Scotland (Crampton, 1914), the Jurassic deposits of Yorkshire (Hemingway, 1951) and of Utah (Richards, 1958), and the Cretaceous rocks of the Swiss Alps (Brückner, 1953). But there is no agreement as to whether cycles of this sort reflect climatic episodes of varying rainfall repeatedly filling a continuously sinking basin, or whether they are primarily products of periodic downwarping of the basin.

Of all the asymmetrical cycles described in some detail, those of the Mid-Devonian Caithness flagstone of Scotland (Crampton, 1914) most clearly resemble the short Lockatong cycles. The striking similarity is manifest in the following features: Both are lacustrine lithofacies that were deposited after an episode of arkose accumulation and both have marginal reddish brown mudstone facies. They are essentially deposits of mud containing abundant carbonates and dark organic matter presumably derived from microphytic

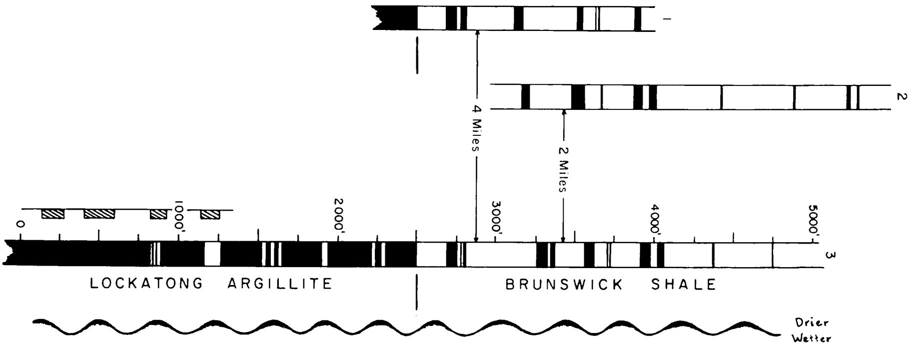


Fig. 4. Generalized stratigraphic sections of uppermost Lockatong argillite and overlying Brunswick shale (after McLaughlin, 1959, tables 19 and 25). Black—gray units; white—reddish brown units. Diagonal-lined blocks represent major sequences of short chemical cycles shown in figure 2. Long cycles of wetter and drier phases are sketched at right of sections. (1) Section along Tohickon Creek, Pennsylvania. (2) Section along Tinicum Creek, Pennsylvania. (3) Section along Delaware River, New Jersey.

plankton. The lower part of the cycles is platy calcareous, pyritic mudstone with thin layers of crystalline carbonate. Moreover, the restricted fossil content of these formations, which consists primarily of fish, estheriids, ostracodes, and plant fragments, occurs largely in the platy mudstone. In both, sandstone layers and lenses are confined to the upper part of the cycles, and mudstone near the top is mudcracked. Compared in detail, the Caithness cycles, and especially those in the Papigoe beds and Thurso flagstone, are like the short detrital cycles of the Lockatong formation, except that the Caithness cycles are two to three times thicker.

The Lockatong chemical cycles, on the other hand, recall the setting of 5- to 10-foot cycles in the Eocene Green River lake beds of Wyoming and Colorado (Bradley, 1930a, 1931; Milton and Eugster, 1959, p. 119-123), sharing alike such distinctive features as varving, the concentration of carbonates, pyrite, and analcime, and accumulating under the control of the precession cycle. In contrast, the Green River formation preserves an exceedingly rich fauna and flora.

Long Cycles

Detrital and chemical varieties of short cycles in the long outcrop of the upper Lockatong formation (fig. 2) are grouped so that the more numerous chemical cycles form the longer sequences with interspersed clusters of detrital cycles. The arrangement suggests a pattern of long sedimentary cycles, each about 325 to 350 feet thick, and each comprising a sequence of chemical cycles and the adjacent group of detrital cycles.

Interbedded Lockatong and Brunswick lithofacies.—The Lockatong formation grades upward into the Brunswick shale through a thick section of rather regularly alternating reddish brown and dark gray units (fig. 4). Moreover, the interbedded gray layers above the main body of the Lockatong formation finger laterally into reddish brown Brunswick shale (fig. 1). This extensive interfingering of the Lockatong and Brunswick lithofacies, first re-

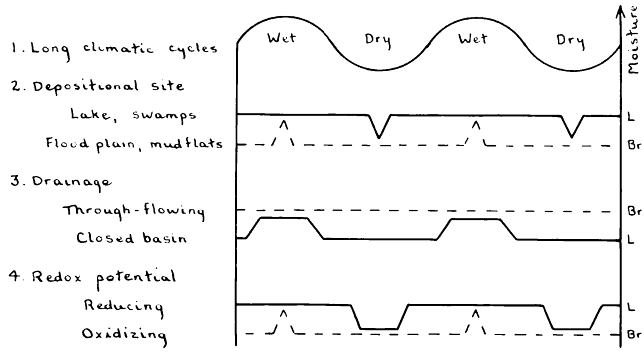


Fig. 5. Comparison of environmental conditions during wetter and drier phases of long climatic cycles reflected in the Lockatong (solid line) and Brunswick (dashed line) lithofacies.

ported by McLaughlin in 1932 (1933) and subsequently mapped and described by him (1944, 1948, 1959). reflects a long succession of changes in the shape and size of the Lockatong lake.

In the lower 1600 feet of the interbedded reddish brown and gray sequence that is assigned to the Lockatong formation, argillite predominates, analcime is present in most of the rocks and is unusually abundant in some, the thicker interbedded units are gray, and the couples range from 325 to 375 feet in thickness. In the upper 2200 feet, assigned to the Brunswick formation, the dominant rock type is feldspathic shale rarely containing analcime, the thicker interbedded units are reddish brown, and the couples range from 350 to 425 feet in thickness.

Significantly, these couples of reddish brown and gray units continue the pattern of long cycles based on the grouping of chemical and detrital varieties of short cycles (fig. 4). The fact that groups of chemical short cycles fit with reddish brown units in one phase of the long cycles, and groups of detrital cycles and gray units coincide with the other phase points to long cycles of alternating drier and wetter episodes (fig. 4).

CONCLUSIONS

During aggradation of the Newark Basin in late Triassic time accumulation of a thick sequence of arkosic sand gave way to deposition of reddish brown mud and sand presumably derived from deeply weathered source areas some distance from the center of the basin. Some of the mud carried to the basin by sluggish streams accumulated on broad floodplains to form the Brunswick lithofacies, and some of it was transported to an extensive central lake. Here the Lockatong lithofacies accumulated in a gently subsiding basin, where the same general conditions of deposition persisted for several million years. Short and long climatic cycles prevailing at this time are recorded in the Lockatong formation, but only the long cycles are clearly reflected in the overlying lower part of the Brunswick formation.

Throughout the life of the Lockatong lake, variations in rainfall produced variations in source-area erosion and inflow to the basin. In wet phases of long cycles (fig. 5), through-flowing drainage was maintained and detrital sediments predominated. In drier episodes of long cycles, a closed basin developed and chemical sedimentation prevailed. During these long climatic cycles the lacustrine deposits accumulated in a pattern of short asymmetrical cycles recording short cycles of alternating wetter and drier climate.

Lacustrine conditions prevailed until an increased supply of mud and sand, perhaps resulting from increased erosion in the source area, filled the basin. With waning of the lake, floodplains with external drainage spread across the basin. Under these conditions the long climatic cycles were expressed in prolonged periods of oxidizing environments alternating with brief returns to reducing conditions (fig. 4).

In retrospect, the principal features of the Lockatong and Brunswick formations resulted largely from interaction of lacustrine and floodplain environments with alternating wetter and drier phases of long climatic cycles. Moreover, during the drier phases 21,000-year precession cycles produced a cyclic concentration of soda in the lacustrine deposits that is now preserved in analcime-rich argillite.

Preliminary estimates of rates of sedimentation and duration of units in the Lockatong formation, presented in table 1, are based on several varve counts and on measurements of cycles in the upper half of the formation only. The figures must be taken as suggestive at best.

References

Bradley, W. H., 1930a, The varves and climate of the Green River epoch: U. S. Geol. Survey Prof. Paper 158, p. 87-110.

——— 1930b, The behavior of certain mudcrack casts during compaction: Am. Jour. Sci., 5th ser., v. 20, p. 136-144.

——— 1931, Origin and microfossils of the oil shale of the Green River formation of Colorado and Utah: U. S. Geol. Survey Prof. Paper 168, 58 p.

Brückner, W. D., 1953, Cyclic calcareous sedimentation as an index of climatic variations in the past: Jour. Sed. Petrology, v. 23, p. 235-237.

Crampton, C. B., 1914, Lithology and conditions of deposit of the Caithness flagstone series, *in* The geology of Caithness: Scotland Geol. Survey Mem., p. 80-103.

Gilbert, G. K., 1895, Sedimentary measurement of Cretaceous time: Jour. Geology, v. 3, p. 121-127.

Hemingway, J. E., 1951, Cyclic sedimentation and the deposition of ironstone in the Yorkshire Lias: Yorkshire Geol. Soc. Proc., v. 28, pt. 2, p. 67-74.

Kümmel, H. B., 1940, The geology of New Jersey: New Jersey Dept. Conserv. and Devel. Bull. 50, 203 p.

McLaughlin, D. B., 1933, A note on the stratigraphy of the Brunswick formation (Newark) in Pennsylvania: Michigan Acad. Sci. Papers, v. 18, p. 421-435.

——— 1944, Triassic stratigraphy in the Point Pleasant district, Pennsylvania: Pennsylvania Acad. Sci. Proc., v. 18, p. 62-69.

——— 1948, Continuity of strata in the Newark Series: Michigan Acad. Sci. Papers, v. 32, p. 295-303.

——— 1959, Mesozoic rocks, *in* Geology and mineral resources of Bucks County, Pennsylvania: Pennsylvania Geol. Survey, 4th ser., Bull. C9, p. 55-114.

Milton, Charles, and Eugster, H. P., 1959, Mineral assemblages of the Green River formation, *in* Researches in geochemistry: New York, John Wiley and Sons, p. 118-150.

Richards, H. G., 1958, Cyclic deposition in the Jurassic Carmel formation of eastern Utah: Jour. Sed. Petrology, v. 28, p. 40-45.

Van Houten, F. B., 1960, Composition of upper Triassic Lockatong argillite, west-central New Jersey: Jour. Geology, v. 68, p. 666-669.

Weller, J. M., 1960, Stratigraphic principles and practice: New York, Harper and Bros., 725 p.

Wells, J. A., 1960, Cyclic sedimentation: a review: Geol. Mag., v. 97, p. 389-403.