THE ORIGIN OF APPALACHIAN DRAINAGE—A REPLY.

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ABSTRACT.

A critical analysis of a recently published theory of origin of Appalachian drainage from a system of southeastward flowing Permian consequents is presented. Questions as to the force of evidence set forth in support of the initial postulate, problematic relations of Triassic and present drainage, and especially, the failure of the theory to explain the positions or trends of major Appalachian streams, indicate that the new theory will not serve to replace the Johnsonian concept of regional superposition of Appalachian streams from a Cretaceous cover.

INTRODUCTION.

Major streams of the northern Appalachian region rise in the Allegheny Plateau and flow southeastward to the Atlantic directly across the northeast-southwest grain of rocks and structures ranging in age from pre-Cambrian to Tertiary. A century of investigation of the origin of this transverse stream system, and of related problems of Appalachian geomorphic development, has yielded results of far more than local importance; in a very real sense the northern Appalachians have occupied a unique position as a source place and proving ground for concepts which, first applied in that region, having come to be adopted throughout the world. Of the several theories of geomorphic evolution that have been proposed, the contrasted explanations of William Morris Davis (1889)[1] and Douglas Johnson (1931)[2] are best known, and serve to define two major stages in the history of the study. A third theory of drainage development, recently set forth by H. A. Meyerhoff and E. W. Olmsted,[3] differs markedly from the earlier views, and is incompatible with the theory of regional superposition of main transverse drainage lines that is embodied in Johnson's interpretation. It is the purpose of this paper to analyze the Meyerhoff-Olmsted theory, in an attempt to determine its merits as a possible alternative to Johnson's view, which is now widely accepted.

[1] Davis, W. M.: The rivers and valleys of Pennsylvania. Geog. Essays, Ginn and Co., New York, pp. 413-484, 1909.

[2] Johnson, Douglas: Stream sculpture on the Atlantic slope, Columbia University Press, New York, 1931.

[3] Meyerhoff, H. A., and Olmsted, E. W.: The origins of Appalachian drainage, This Journal, 5, Vol. 32, pp. 21-42, 1936.

THEORIES OF APPALACHIAN DRAINAGE DEVELOPMENT.

The Davis Theory. Davis believed that the southeastward flowing stream system of the Appalachian Ridge and Valley Province (Fig. 1) resulted from the reversal, by warping and capture during and before Triassic time, of an original northwestward flowing set of consequents[4] which had developed on the growing folds of the Permian Appalachians. In marked contrast, the streams of the Great Valley, Triassic Lowland and Piedmont Provinces (hereafter, for convenience, the Piedmont district), were thought by him to belong to a younger system of consequents, initiated with southeastward courses on a former inland extension of a Cretaceous coastal plain, and later superposed across the complex structures of the region. He held that the Cretaceous mantle from which the Piedmont streams were let down had rested directly on the present hilltop peneplane, the Schooley, which was regarded by him as Jura-Cretaceous in age because it appeared to pass under Cretaceous beds at the Fall Zone. Davis thus recognized two distinct generations of streams in the area as a whole, those of the Ridge and Valley Province being traceable back to initial Permian fold-mountain consequents (but now so greatly modified by capture that little semblance of the original pattern remains), and those of the Piedmont district, including the lower reaches of trunk streams, to a system of Cretaceous coastal plain consequents.

The Johnson Theory. Johnson has presented evidence tending to prove (1) that the captures and reversals postulated by Davis in explaining the evolution of the present drainage pattern in the Ridge and Valley Province from Permian fold-mountain consequents are highly improbable; (2) that certain stream relations in the region of Davis' superposed drainage cannot be explained by direct superposition from a mantle resting on the present hilltop peneplane; (3) that the erosion surface (the Jura-Cretaceous Fall Zone peneplane) which passes beneath the Cretaceous beds at the present inner margin of the coastal plain would, if projected inland, arch well above the surface of the Schooley peneplane, and, (4) that the Schooley surface is Tertiary in age. He has proposed the view that all of the preexisting streams of the area as a whole, of whatever

[4] Davis: Op. cit., p. 449. Davis did not hold, as Meyerhoff and Olmsted state in their discussion of his views, that the Permian drainage of the Pennsylvania region was antecedent.

origin or pattern, were destroyed by a widespread extension of the Cretaceous coastal plain across the surface of the Fall Zone peneplane. A southeastward flowing stream system, initiated on the uparched Cretaceous depositional surface, was modified by capture during the stripping back of coastal plain strata early in the Schooley cycle, was further modified in a new series of adjustments after the streams had been let down across structures of the older rocks later in the Schooley cycle, and in post-Schooley time.

The Meyerhoff-Olmsted theory. The Meyerhoff-Olmsted theory will be discussed fully in the pages which follow; it is outlined here briefly so that the plan of treatment adopted in this paper will be understood. These workers hold that the present southeast flowing stream system of the Ridge and Valley Province and the Piedmont district was inherited directly from a single system of southeast trending, late Permian consequents, whose positions and directions of flow were controlled by the slopes of the surface produced by Appalachian folding. The theory is based (1) on evidence which is supposed to prove that the Permian drainage divide was in the Ridge and Valley Province, rather than in the Piedmont, as Davis believed; (2) on a close correspondence between the positions of present major streams and the positions of the streams which carried waste into Triassic fault basins, this correspondence being supposed to prove that the present streams date from Triassic or pre-Triassic time, rather than from the Cretaceous, as Johnson believes; and (3) on a correlation of locations of present southeast flowing streams with major transverse synclinal axes in the fold mountain belt, and with other transverse structures and zones of weakness, which would account for the positions of the streams without recourse to regional superposition from a Cretaceous coastal plain. These propositions will be discussed in the order named.

POSITION OF THE PERMIAN DIVIDE.

Analysis of Arguments. Meyerhoff and Olmsted devote a considerable part of their paper to presentation of evidence which, they hold, indicates that the Permian streams of the Appalachians *must* have flowed to the southeast. In this connection they state:—(1) that "the Blue Ridge . . . was the backbone of Appalachian uplift," and again, (2) "that the

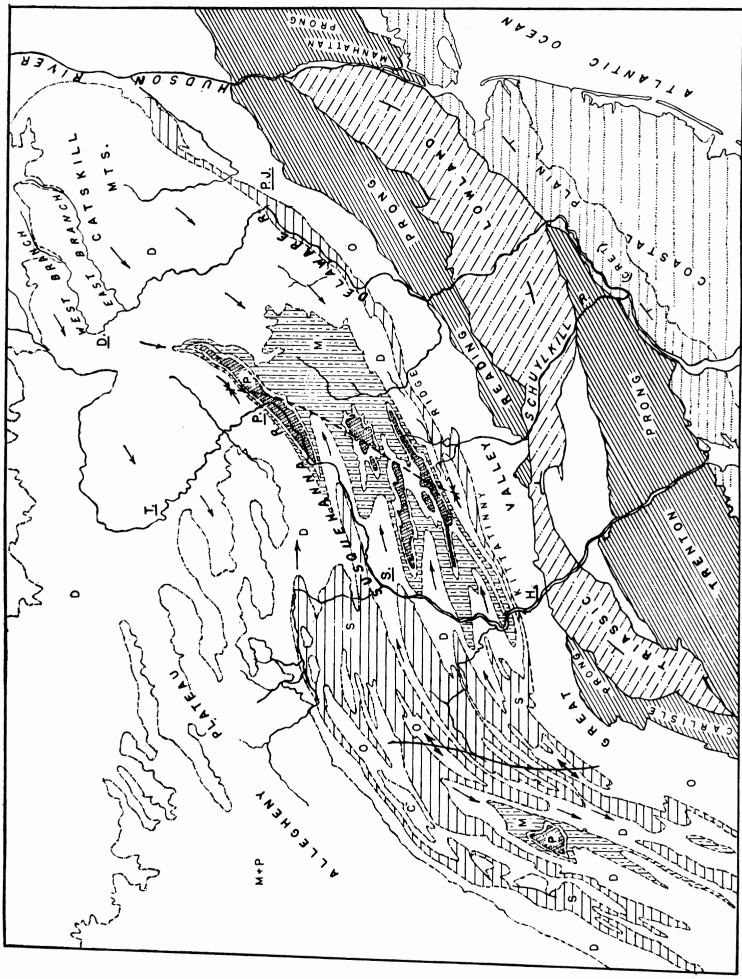

Fig. 1. Map of the Northern Appalachian region, from the Geological Map of the United States (1932). The Ridge and Valley Province is the fold mountain belt between the Allegheny Plateau and Kittatinny Ridge. The "Piedmont district" includes the Great Valley, four Prongs of lower Paleozoic and pre-Cambrian crystallines and metamorphics, and the Triassic Lowland. Carlisle Prong is the northern extension of Blue Ridge. Initial letters of names of Paleozoic periods indicate the age of rocks in the Ridge and Valley Province. Direction of pitch of folds is shown by arrows, and the positions of transverse anticlinal and synclinal axes are indicated by solid and dashed lines, respectively. Underlined letters in heavy type mark the location of cities mentioned in the text: D, Deposit; T, Towanda; P J, Port Jervis; S, Sunbury; H, Harrisburg.

highest elevations and the drainage divide of the late Permian and early Triassic Appalachians was situated no farther east than the more or less continuous range formed by Blue Ridge, Reading Prong, and the Green and Taconic Mountains,"[5] and again, after several explanatory paragraphs which are treated below, (3) that "the axis of maximum uplift and the Permo-Triassic watershed are believed to have been located northwest of Kittatinny Ridge, but not as far as the southeastern front of the Allegheny Plateau."[6]

Statements 1 and 2 are supported by a discussion of the bearing of the structure and Paleozoic stratigraphy of the Piedmont district on the form of the initial constructional surface of that region. The conclusion, that the highest lands of Permian time were located somewhere in the Piedmont crystalline belt, is the traditional American view; it is in all essential respects identical with the concept that caused Davis to direct the Permian drainage of the Ridge and Valley Province northwestward, in spite of the manifold difficulties which this postulate introduced into his scheme of drainage evolution. Since this conclusion automatically limits the possible extent of southeast drainage of the Permian lands to the southeastern part of the Piedmont district, it is directly opposed to the major thesis of the Meyerhoff-Olmsted article.

It appears, therefore, that statements 1 and 2 must be regarded as intermediate steps[7] in the Meyerhoff-Olmsted structural argument, and that statement 3, which places the Permian divide farther to the northwest, must be considered the fundamental postulate of the theory. This change in the location of the divide from the Piedmont to the Ridge and Valley Province, that is, to a position somewhat more favorable to the development of an extensive southeasterly directed consequent drainage system, is based, (A) on the prevailing northwest asymmetry and overturning of Appalachian fold structures, *and* (B) on hypothetical extension of low angle thrust plates northwest across an undefined part of the Ridge and Valley Province.[8] It is at once evident that these two explanations are mutually exclusive, rather than cumulative, in their effect on the trend of drainage lines at any one place at the time of mountain building; the same stream cannot be at once consequent on

[5] Op. cit., p. 27.
[6] Op. cit., p. 29.
[7] Meyerhoff, H. A.: personal communication.
[8] Op. cit., p. 27-29.

folded strata and consequent on a thrust plate that covers the folds.

(A) Asymmetry or overturning of a single fold may well control the position of the *local divide*[9] formed by the fold in its growth, the theoretical distance of shifting of the initial divide from the present outcrop of the axial plane of the fold being a function of the dip of the axial plane and the initial height of the fold crest above the present erosion surface. The problem under discussion relates, however, not to a local divide, but to the main divide of the Appalachian region as a whole, and there is no evident reason why asymmetry of many folds should cause an appreciable shifting in the position of the major divide of the fold mountain belt. All of the major transverse streams of the Appalachians cross many folds.

(B) Low angle overthrusts and other structures indicating considerable horizontal translation of rock masses have been mapped in the Hudson Valley and Piedmont districts. The existence of some of the major thrusts is a problem now under discussion. Even if the faults are present as mapped, there is no structural or stratigraphic evidence that any of those described in the Pennsylvania Piedmont ever extended northwestward to or beyond the position of Kittatinny Ridge. Finally, the dates of the supposed low angle thrusts are largely unknown.

Meyerhoff and Olmsted's tacit assumption that the initial drainage of hypothetical Permian overthrust sheets flowed southeast appears to be based on a belief that the initial surface of a thrust mass necessarily slopes in the same direction as the dip of the fault plane. In some simple bedding thrusts this relation may be true, but it seems improbable that it would hold in internally complex thrust masses rooted in the metamorphic terranes of the Piedmont district. Structure sections of the Alps and the Scottish Highlands support the alternative suggestion that, because of a piling up or slicing of thrust plates, the height of land and the drainage divide at the time of faulting might be many miles back from the edge of the most extended thrust plate. Moreover, it seems highly questionable whether the initial drainage of the translated sheet or sheets of southwest-striking metamorphics would exhibit the parallel southeast stream trends that characterize the present Atlantic slope.

[9] Meyerhoff and Olmsted: Op. cit., fig. 2.

These uncertainties as to the former extension of thrust plates over the folds of the Ridge and Valley Province, and the problematic effect of such thrusts, and of asymmetric folds, on the trend of consequent drainage at the time of mountain building, raise a decided question as to the force of the arguments presented by Meyerhoff and Olmsted as the "structural basis" of their statement No. 3, "that the axis of maximum uplift and the Permo-Triassic divide were located northwest of Kittatinny Ridge."

Surface form of the Permian Appalachians. Restoration of the initial surface of an orogenic belt, on the assumption that major structures at the present erosion level had distinct topographic expression on the first surface of uplift, is a highly complex problem even under the most favorable circumstances. Davis[10] and Chamberlain,[11] who attempted to reconstruct Appalachian folds on the basis of the structural relations of their truncated roots, confined their efforts to the Ridge and Valley Province, where the relatively simple form of folds controlled by massive middle and upper Paleozoic quartzites makes application of the method feasible. Extension of the same method to the complex mountain belt southeast of Kittatinny Ridge is complicated: (1) by uncertainty as to the original thicknesses and stratigraphic relations of the intensely deformed early Paleozoic beds that now underlie parts of the Piedmont district, (2) by the presence of a major unconformity between these beds and the upper Paleozoic strata that may have formed the Permian surface, (3) lack of knowledge as to the dates of structures in the Piedmont, and consequent uncertainty as to which of the structures might have had a controlling influence on the Permian surface, and (4) the fact that the rocks of the area have been displaced by vertical movements amounting to thousands of feet in post-Permian time, especially during the Triassic, and consequent doubt as to how much of the present altitude of any given stratigraphic horizon must be ascribed to Permian, as opposed to post-Permian, movements.

Conclusions. It appears, therefore, that even the most generalized restoration of the Permian surface in the Piedmont

[10] Op. cit., pp. 449-453.

[11] Chamberlin, R. T.: The Appalachian folds of central Pennsylvania, Jour Geol., Vol. 18, pp. 228-251, 1910.

region, on the basis of structures at the present erosion level, is impossible. Discussion of other lines of evidence bearing on the broader problem of the relative height of the Piedmont and the Ridge and Valley districts during Permian time consists largely of a balancing of indefinite possibilities and probabilities which do not, in this paper, merit the space they would occupy. The conclusion, which is largely negative, may be stated briefly: The weight of indirect evidence and deductive reasoning favors the generally accepted view that the highest lands of the Permian Appalachians were in the intensely deformed belt southeast of Kittatinny Ridge, but this view is not susceptible to direct proof. It is impossible to state that Permian drainage of the growing Appalachians *must* have been either consequent or antecedent, or that it *must* have flowed to the northwest or to the southeast. It is possible that the initial system was consequent, and it is possible that some or all of the drainage of the Ridge and Valley Province escaped southeast to the Atlantic, as required by Meyerhoff-Olmsted theory. But these possibilities certainly cannot be considered as part of the "structural basis" of an Appalachian drainage theory.

Almost complete lack of knowledge of Permian surface form does permit a wide range of postulates as to initial drainage *direction.* But the crux of the problem of the origin of Appalachian drainage is the explanation of numerous parallel southeast trending segments of major streams, which show a complete disregard for rock structures. It should be especially noted that in seeking to derive this pattern from a system of Permian consequents Meyerhoff and Olmsted *assume* that the Permian streams had numerous parallel southeast trending segments. They do not explain why this should have been so.

TRIASSIC DRAINAGE.

General Statement. Each of the streams of the Northern Appalachians, on its way to the sea, crosses the outcrop of the thick sequence of Triassic shales and sandstones preserved in downfaulted basins in the Pennsylvania and New Jersey Piedmont (Fig. 1). According to Meyerhoff and Olmsted, an extraordinary correlation between the positions of these present streams and the positions of Triassic streams (as denoted by the lithology of Triassic beds along the northwestern border of the fault basins), indicates that the southeastward flowing streams of the Atlantic Slope occupied their present position in

Newark (Triassic) time.[12] This relationship, if true, would tend to support the theory of preserved Permian drainage; in such measure as the degree of matching might exceed that which would be expected on the basis of chance, it would be unfavorable to Johnson's theory of superposition of present streams across the Triassic belt from a Cretaceous coastal plain. The correlation is said to be so striking that Johnson's theory is untenable.

It is by no means certain that the Newark series as a whole was deposited by southeast flowing streams. Partly because of an abundance of mica and feldspar in the Triassic sediments, Stose has argued that the bulk of the materials were derived from crystalline terranes to the southeast of the fault basins, rather than from the Paleozoic beds which underlie the region to the northwest. He believes that the Newark beds were laid down in basins that deepened westward as deposition continued, and that it was only during the latter part of Newark time that uplift to the northwest formed highlands from which were shed the quartzite and limestone conglomerates which occur along the western side of the basins.[13] It appears that this conclusion, based on extensive field work, should not be lightly set aside,[14] but no attempt is made here to weigh the merits of the problem of the derivation of the Triassic sediments. It is sufficient to point out that Stose's conclusions, if even partly correct, are fatal to the theory of pre-Triassic origin of present Appalachian streams.

Relations of Major Streams. Meyerhoff and Olmsted's strongly worded conclusions as to the correlation between the positions of Triassic and present streams are based on supposed localization of conglomerates in the Triassic sequence at points where modern streams enter the Triassic belt. In the case of the Susquehanna they state that:

"In one outcrop three and a half miles east of Yellow Breeches Creek near Susquehanna River, an exceptionally wide stratigraphic range is represented in the constituents of the (Triassic) conglomerates, and every fragment can be traced to its source in the

[12] Op. cit., p. 39.

[13] Stose, George W.: Description of the Fairfield and Gettysburg quadrangles. U. S. Geol. Surv., Atlas. Fairfield-Gettysburg Folio. No. 225, 22 pp., 1929. For stratigraphic relations of the conglomerates see also: McLaughlin, Dean B.: The thickness of the Newark series in Pennsylvania and the age of the border conglomerate. Mich. Acad. Sci., Papers, Vol. 16, pp. 421-427, 1931.

[14] Meyerhoff and Olmsted: Op. cit., p. 37.

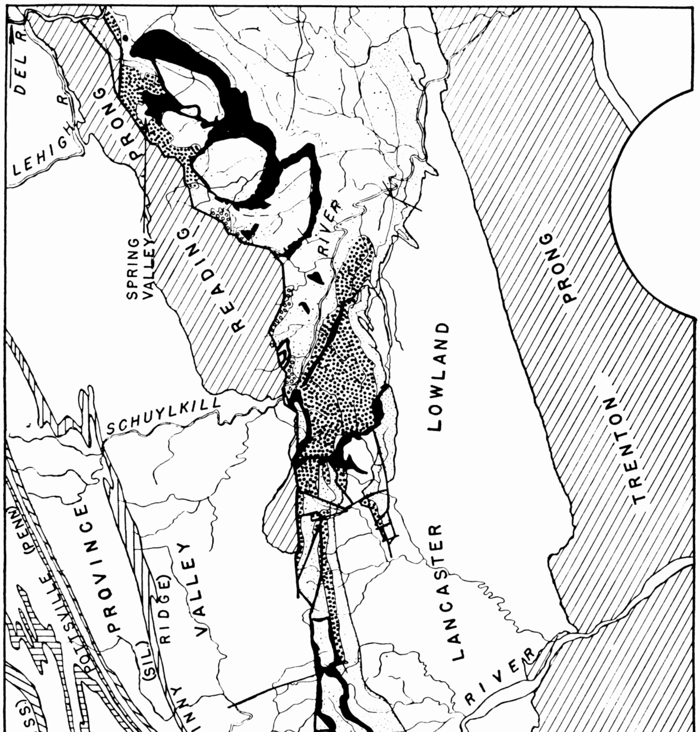
DEL R.
LEHIGH R.
READING PRONG
SPRING VALLEY
RIVER
SCHUYLKILL
LANCASTER LOWLAND
TRENTON PRONG
YORK
RIVER
RIDGE AND VALLEY PROVINCE
POCONO SS (MISS)
POTTSVILLE (PENN)
MEDINA (SIL) RIDGE
KITTATINNY
GREAT VALLEY
SUSQUEHANNA
YELLOW BREECHES CREEK
CARLISLE PRONG
0 6 30 MILES

Fig. 2.

several Paleozoic formations through which the Susquehanna has cut its way."[15]

Triassic conglomerates, interbedded in a sequence that consists predominately of shale and sandstone, do occur just southeast of the Triassic border fault in an area extending from three to five miles west of the Susquehanna (Fig. 2). There is no doubt that the quartzite pebbles were derived from the Paleozoic sequence to the northwest, but it is not clear how the "stratigraphic range" represented by the pebbles (which bears on the length of the depositing stream) was determined. In an earlier study of Susquehanna River terraces[16] the writer found that the range of lithologic types in each of the three great Appalachian quartzites and in other sandstones in the Paleozoic sequence was such that not more than one per cent of the quartzose pebbles in terrace deposits could be traced, by sight identification, to any specific source bed.

As pointed out in the direct statement and in the quotation above, these Triassic conglomerates are found west of the Susquehanna Valley. Quartzite pebbles are, however, notably rare in numerous stream cuts and road cuts *in* the Susquehanna Valley, where Triassic sediments adjacent to the boundary fault are predominantly fine shales and sandstones. If conglomerates serve as an index to the location of Triassic streams, it appears that no stream occupied the present position of the Susquehanna during the deposition of this shale-sandstone sequence. There is no modern cross-cutting stream to match the conglomerates west of the Susquehanna Valley.

[15] Op. cit., p. 38.
[16] Mackin, J. Hoover: Terraces in the Susquehanna Valley below Harrisburg, Pennsylvania, Science, Vol. 80, p. 141, 1934.

Fig. 2. Map of southeastern Pennsylvania, from Geological Map of Pennsylvania (1931). The three ridge-forming quartzites of the Ridge and Valley Province are named, and the direction of pitch of the folds in which they are involved is indicated by arrows. The Great Valley and the York-Lancaster Lowland are underlain, in large part, by weak lower Paleozoic shales and limestones; the Carlisle, Reading, and Trenton Prongs, by resistant lower Paleozoic and pre-Cambrian crystallines and metamorphics. Triassic sediments, indicated by a stippled pattern, rest unconformably on the older rocks along the southern margin of the Triassic Lowland, and are in fault contact along the northern margin. Triassic igneous rocks are indicated by solid black, shales and sandstones by a light stipple, "quartzose conglomerates" by a dark stipple, and "limestone conglomerates" by small circles. The symbols give an erroneous impression of the distinctness of the several lithologic units; mapping of the "quartzose conglomerates," in particular, appears to have been based on a litter of pebbles in soil, and large areas are so mapped where fresh road cuts show uniformly fine shales and sandstones.

Meyerhoff and Olmsted do not discuss the lithology of the Triassic sequence at the point where the present Schuylkill River enters the Triassic lowland; a fan shaped area of "quartzose conglomerates,"[17] depicted on the Pennsylvania geologic map (Fig. 2), suggests that a large stream discharged into the Triassic basin of deposition in the vicinity of the present Schuylkill *when these pebble-bearing beds were being formed.* But, if conglomerates mark the location of Triassic streams, no stream could have followed the present course of the Schuylkill at another time, during the deposition of a thick sequence of fine shales and siltstones, without pebbles, which outcrop *in* the Schuylkill Valley near the border fault. Most significant of the Triassic sediments of the Schuylkill area are a series of limestone and dolomite fanglomerates, at least 1,000 feet in thickness, which occur at the exact point where the river issues from the Reading Prong.[18] Steep dips and complex structures of Paleozoic strata northwest of the boundary fault indicate that a Triassic stream heading any considerable distance in these terranes would have crossed the outcrop of both quartzites and limestones; the absence of quartzite pebbles in the limestone fanglomerates, and the angularity of the limestone blocks, indicate that they were laid down by a local stream, probably at the foot of an active fault scarp. This local stream built its fan at the point where the Schuylkill now crosses the boundary fault. The essential conclusion, to be drawn from the occurrence of these three markedly different rock types in the Schuylkill area, is that local conditions of sedimentation varied widely from time to time during the Triassic, and that no single Triassic stream maintained a course in any way comparable with that of the Schuylkill throughout the deposition of the Newark series.

Apparently in connection with the Lehigh River, Meyerhoff and Olmsted state:

"One large deposit of quartzite conglomerates situated south of Spring Valley, Pennsylvania, is not associated with a modern river, but its position south of the broad gap at Bethlehem leaves no doubt as to its origin and initial fluvial connections."[19]

The inference is that the Spring Valley conglomerates were formed by the Triassic Lehigh River, and that the stream has

[17] Geologic map of Pennsylvania. Harrisburg, 1931.
[18] Geological map of Pennsylvania.
[19] Op. cit., p. 38.

been captured by the Delaware during the present erosion cycle (Fig. 2). Whether or not the Lehigh River cut the broad gap south of Bethlehem seems open to question, for the gap lies along the outcrop of Paleozoic limestones infolded in the resistant rocks of the Reading Prong, and may well owe its existence to the etching out of these weak rocks by minor streams. Nevertheless, the sharp elbow of the Lehigh may be an elbow of capture, and that stream may well have once flowed southeastward toward the Spring Valley area, either through the Bethlehem gap, or at some level above the Schooley peneplane. But the lithology of the Spring Valley Triassic sequence does not, in the opinion of the writer, serve to prove that the Lehigh occupied such a course during Triassic time, for, in addition to quartzose conglomerates, the Spring Valley deposits include shales, limestone conglomerates, and talus and landslide breccias. It is, in other words, a typical border sequence, and can be duplicated in closely spaced unit areas along the full length of the western margin of the Newark belt.

Relations of Minor Streams. A close correspondence between distribution of Triassic conglomerates and the positions of certain minor streams which enter the Triassic area from the northwest proves, according to Meyerhoff and Olmsted, that these streams date from Triassic time. No specific cases are described. The fact that the minor streams are closely spaced and that, as stated above, conglomerates of various types are continuous for the greater part of the distance along the western margin of the Triassic Lowland makes the use of this criterion in the case of the small streams even more difficult than in the cases of the major streams. Distribution of conglomerates shown on the Pennsylvania state map, and especially on detailed quadrangle maps of the Pennsylvania and United States Geological Surveys, fails to show any consistent relationship; none was found by the writer in five days field work along the fault front.

The trend of present minor streams provides an alternative approach to the problem of their origin, for if they date from Triassic time they should flow southeast from upthrown blocks of older rocks to downthrown blocks of Triassic sedimentation. Where the Triassic beds are in fault contact with resistant crystallines of the Reading Prong most minor streams do flow southeastward, down the slope of the resequent fault line scarp that has been developed by selective erosion of relatively weak Triassic sediments. Where Paleozoic limestones of the upthrown blocks have been reduced to a lower level than the Triassic shales many of the minor streams flow across the fault in the opposite direction, from downthrown to upthrown blocks. These small streams could not have flowed northwestward throughout Triassic time.

Yellow Breeches Creek, mentioned by Meyerhoff and Olmsted in a paragraph quoted above, flows for many miles directly along the trace of the boundary fault, crossing and recrossing the fault line (Fig. 2). This stream, and the many other northeast-southwest trending streams of the district, could not have occupied their present course during the Triassic.

These relations, and the trellis drainage pattern that is well developed in parts of the Triassic Lowland, indicate that most of the minor streams of the area as a whole owe their positions and directions of flow to headward erosion (in post-Triassic time) controlled by differential rock resistance.

Conditions of deposition along the western margin of the Newark Basin. Juxtaposition of talus breccia, conglomerates and fanglomerates of many types, and fine shales, at the present erosion surface in small unit areas near the western margin of the Triassic Lowland is due to shifting of different stratigraphic horizons to a common plane (the present surface) by minor block fault movements of Triassic date. Wide variation in the rock types that would appear in a columnar section of the Triassic beds near the fault, taken together with local fault zones showing intense crushing of Triassic sediments, prove that movements on the major boundary faults were recurrent and that conditions of deposition varied widely during the accumulation of the Newark sediments. Laminated shales are now in fault contact with ancient rocks at many points. Since these shales could not have been deposited at the base of active fault scarps, it appears that, during some stages of Triassic sedimentation, the western border of the basin of deposition was some distance west of the fault zone which marks the present western boundary of the Triassic Lowland.[20] During such stages any streams entering from the northwest would

[20] For independent stratigraphic evidence leading to the same conclusion see Stose, G. W., and Jonas, A. I.: Triassic sedimentary rocks and basaltic flow northwest of Lebanon, Pennsylvania. Bull. Geol. Soc. Am., Vol. 36, pp. 160-161, 1925 (abstract).

Longwell, and others, present evidence of beveling, and renewal by recurrent faulting, of the Triassic scarps at the east margin of the Connecticut lowland. Longwell, C. R. Notes on the structure of the Triassic rocks in southern Connecticut. This Journal, 5, Vol. 4, p. 235, 1922.

have wandered widely over alluvial plains, and could not have maintained fixed positions at what is now the western boundary of the Lowland.

Conclusions: (1) Study of the sedimentary sequence along the northwestern margin of the Triassic Lowland fails to confirm Meyerhoff and Olmsted's statement as to the striking correlation between distribution of Triassic conglomerates and the positions of present streams, major or minor. The seemingly rigid test of channel for channel correlation, utilized here in the cases of the major streams, is the only test known to the writer that can be applied to the statements of Meyerhoff and Olmsted. Conglomerates of several types occur at many points, at and between streams, but, in a sequence that consists of interbedded shales, sandstones, conglomerates and breccias, the mere proximity of a Triassic gravel lens to a present stream means nothing. (2) Consideration of conditions of deposition of the varied Triassic sequence indicates that all streams which entered the basin of deposition from the northwest must have shifted their courses markedly, from time to time, at the western boundary of the present Triassic Lowland, which did not always correspond with the western margin of Triassic sedimentation. The distribution of conglomerates at the western boundary of the present Triassic Lowland does not, therefore, serve as a reliable index to the entry points of streams flowing into the Triassic basin of sedimentation; in so far as the conglomerates are concerned, the present major streams of the Ridge and Valley province might, or might not, have occupied their present positions during Triassic time.

Relations of conglomerates in the Newark sequence do not (1, above), and could not (2, above), prove or disprove the thesis that the present major streams of the Atlantic slope date from a system of southeastward flowing Permian consequents.

RELATIONS OF APPALACHIAN STREAMS TO STRUCTURE.

General statement. Meyerhoff and Olmsted's statement of their theory as one which holds that the modern drainage of the Atlantic slope evolved directly from the original consequent system which drained the Permian Appalachians leaves much to be desired in the way of clarity, for in the long course of post-Permian erosion major streams might have retained their original courses with little essential change, or they might have been so completely modified by capture and other adjustments that little or no trace of the initial pattern is preserved. The problem is not solved by their treatment of individual streams. They suggest: (1) that the Susquehanna (as indicated by structural relations) is an inherited Permian consequent in the Ridge and Valley Province and in the Piedmont[21]; and, (2) that all minor streams which cross Kittatinny Ridge were let down across present structures from the backslope of an asymmetrical fold, or from a hypothetical overthrust sheet,[22] but that the Susquehanna and other major streams which cross the ridge may have gained their courses by subsequent erosion guided by transverse zones of weakness.[23] Since a single stream, in the same ridge crossing, cannot be at once consequent and subsequent, it appears that two distinctly different theories are proposed. The theory which holds that the present major transverse streams are inherited Permian consequents is generally favored in the Meyerhoff-Olmsted article, and will be examined first.

Tests of the theory of preserved Permian consequent drainage. The first and most obvious test of the theory that Appalachian streams inherited their courses directly from a system of Permian consequents is a comparison of the positions of present stream courses with the positions that should have been occupied by major streams on the Permian surface, restored on the basis of present structures. This test is predicated on the basic assumption on which the theory itself is founded, namely, that structures at the present erosion had sufficient topographic expression on the Permian surface to produce and control a consequent pattern. It is evident from the foregoing discussion of the problem of the Permian divide that the test can be applied only in those parts of the Appalachians where the upper Paleozoic sequence is sufficiently preserved to make the restoration practicable. The Ridge and Valley Province of eastern Pennsylvania, where the contrasted theories of Davis, Johnson and Meyerhoff and Olmsted have been applied, meets this requirement.

In such a region we might expect that major transverse consequents should cross belts of folds in or near transverse sags in the folded structures, if such structural sags are present. The value of this test depends on whether a given structural sag was reflected in the initial surface. Since, as pointed out

[21] Op. cit., p. 31.
[22] Op. cit., p. 34.
[23] Op. cit., p. 32.

above, the whole concept of consequent drainage is based on the assumption that larger structural elements did have sufficient surface expression to control drainage ways, it appears that the correspondence or lack of correspondence of stream courses with well marked structural sags is a valid test of the consequent theory. It must be applied, of course, only to major streams which cross a number of folds, for local crossings of single limbs of asymmetric folds may be due to local superposition or other accidents.

Streams or segments of streams which flow parallel with fold structures need not be expected to occupy synclinal valleys, for the axial planes of many Appalachian folds are inclined, and a shifting of a longitudinal synclinal consequent to a homoclinal or anticlinal position, without capture or other interruption that would destroy the identity of the stream, is entirely possible. But if such longitudinal streams be true consequents, they should flow in the direction of the *pitch* of related structures, provided only that the structural pitch is of such amount that convergence of horizons higher in the sequence could not have eliminated its effect on initial surface slopes. If, in a closed structure, pitch is marked and continuous for any considerable distance, the direction of flow of inherited consequent streams must correspond with it.

With these considerations in mind, we may examine the specific cases advanced in support of the theory of preserved consequent drainage:

RELATIONS OF LONGITUDINAL STREAMS TO STRUCTURE.

The East and West Branches of the Delaware River, the headwater reaches of the Susquehanna, and a segment of the Susquehanna between Pittston and Sunbury (P and S, Fig. 1) flow southwest from the Catskills along the trend of fold structures. In 1933 Ruedemann suggested that these streams had inherited their courses from a set of southwestward flowing synclinal consequents, the "ancestral Susquehanna system," of Permian age.[24] He believed that the present southeast flowing master stream of the region, the Delaware River, had extended itself headward from the Atlantic by a series of captures, the most recent of which had gained for that stream its East and West Branches at the expense of the Susquehanna

[24] Ruedemann, Rudolf: Development of Drainage of Catskills, This Journal, 23, 337-349, 1932.

system. Mackin replied to Ruedemann's paper, comparing the theory of preserved synclinal consequent drainage with Johnson's theory of regional superposition, and concluding that the latter theory provided the better explanation of the drainage pattern in question.[25] The reply was sent to Ruedemann before publication and benefitted greatly by the incorporation of suggestions and corrections offered by him in the most cordial spirit. The Meyerhoff-Olmsted treatment of Delaware-Susquehanna problems in the area under consideration must be quoted in full:

"The adherents of the theory of regional superposition dismiss Appalachian structure as the initiating factor in localizing modern stream courses and as a determinant of the present geomorphic pattern, although in doing so they must ignore many structural and stratigraphic facts of fundamental importance. This is evident in Mackin's attack on Ruedemann's exposition of southwest drainage from the Catskill Mountains. In the first place, it may be questioned whether Ruedemann intended to imply that the present streams are longitudinal consequents; they are subsequents, as Mackin postulates, but there is more reason to believe in their derivation from post-Permian longitudinal consequents than Mackin realizes. There has been deep erosion in the Catskills, yet the late Devonian still rises to heights approximately 4,000 feet. In the Pocono Plateau, 130 miles to the south, the early Mississippian conglomerate which caps the plateau surface has a peak elevation of 2,300 feet, and at this point the Upper Devonian lies approximately 3,000 feet lower than in the Catskills. Granting that the thickening of the Lower Mississippian deposits southward tends to make the stratigraphic relief greater than the original topographic relief, none the less, the doming of the Catskill country and the sagging of the Pocono-Susquehanna section was sufficiently marked to decant Catskill drainage in the latter direction, regardless of the behavior of individual folds or their specific relations to present streams. But this obvious and plausible explanation of a local situation has been discarded in favor of complicated fluvial jockeying in a theory wherein the local geology weighs so lightly."[26]

It should be noted in passing that the age of the sandstone beds of the Catskill-Pocono region is a problem now under discussion; Chadwick[27] has advanced evidence tending to prove

[25] Mackin, J. Hoover: The evolution of the Hudson-Delaware-Susquehanna drainage. This Journal, 26, pp. 319-331, 1933.
[26] Op. cit., p. 29.
[27] Chadwick, G. H.: What is "Pocono"?, This Journal, 5, Vol. 29, pp. 133-143, 1935.

that the capping sandstones of the Catskills are middle, rather than late Devonian, and that the so-called Mississippian Pocono may be Devonian in age. There is an additional question as to how much of the southwest dip of the beds must be attributed to "doming of the Catskill country" and how much may be the initial slope of deposition of the stream laid sandstones and conglomerates of the Catskill-Pocono region. These questions do not alter the fact that there is a regional dip (or, more properly, regional pitch of broad folds) southwest from the Catskills, but they may alter the amount of the dip that must be ascribed to Permian movements.

The streams of the southwestern Catskills, particularly the East and West Branches of the Delaware and the headwaters of the Susquehanna, flow parallel with, and down the pitch of structures of Permian age. Meyerhoff and Olmsted, in accepting the fact that the streams flow in the same direction that would have been taken by Permian consequents as an indication that the streams date from Permian time, fail to appreciate the full significance of their statement that these streams are subsequents. If the streams are subsequents they extended themselves headward along weak rock belts and should, for this reason alone, follow structural trends, whatever may have been the drainage pattern before they were developed. They might have been "derived from" a system of southwestwardly flowing Permian consequents, or they might equally well have extended themselves at the expense of any other drainage pattern, and their development might have occurred at any time from Permian to Pliocene. Mackin did not take issue with Ruedemann as to the date of origin of these streams. He states:

"The structural relations of the southwest flowing headwaters of the Susquehanna and of the East and West Branches of the Delaware are non-committal as to the genesis of these segments, which flow parallel with the folds, in weak rock belts that are, in part at least, anticlinal. They are clearly subsequents, but whether they are of the same generation of subsequents as the great majority of the post-Cretaceous streams of eastern Pennsylvania, or whether they represent parts of an older drainage system on higher land never covered by the Cretaceous sea, must remain an interesting speculation."[28]

The formidable objection to the theory of preserved Permian consequent drainage in the Delaware-Susquehanna region is the

[28] Mackin: op. cit., p. 324.

fact that the Susquehanna, in the 36 mile stretch between Pittston and Sunbury (P and S, Fig. 1), flows directly against the pitch of folded structures that are, according to the theory, supposed to have controlled the course of the stream. This specific relation of a major fold to a major stream can hardly be disregarded; if the southwest pitch of the Catskill strata caused the Permian drainage of the Catskills to flow southwest, the northeast pitch of the Pittston-Sunbury folds should have caused the Pittston-Sunbury drainage to flow northeast, and the present drainage, if inherited from Permian consequents, should flow in the same direction. This consideration, stressed by Mackin, is not mentioned by Meyerhoff and Olmsted in their restatement of the Ruedemann view. Mention, elsewhere in their paper, of a "natural movement of intermontane streams toward an orogenic depression in the vicinity of Harrisburg,"[29] fails as an explanation of the anomaly, first, because it is not clear how the "natural shifting" was accomplished, and second, because, as will be shown below, there is no evidence of an orogenic depression in the vicinity of Harrisburg.

No other specific longitudinal streams are mentioned by Meyerhoff and Olmsted. Statistical analysis of trends of streams in the Pennsylvania Appalachians fails to show any correlation between direction of flow of longitudinal streams and direction of pitch of related structures. This is interpreted as meaning that there is no genetic relation between direction of stream flow and structural pitch. The longitudinal streams appear to be, not Permian consequents, but subsequents controlled by weak rock belts.

Relations of transverse streams to structure. Meyerhoff and Olmsted discuss the specific structural relations of only one of the major transverse streams of eastern Pennsylvania, namely, the Susquehanna River. The Susquehanna serves well as a test case, for it is the largest stream of the area and, in its repeated crossings of ridges underlain by resistant Paleozoic quartzite, it epitomizes the problems of other southeast flowing drainage lines of the Northern Appalachians. They state:

> "In picking its way across the folds to the Piedmont, the Susquehanna plainly utilized and still approximately follows the deepest structural sag in the entire central Appalachian belt."[30]

[29] Meyerhoff and Olmsted: op. cit., p. 33.
[30] Op. cit., p. 31.

The evidence for the presence of the sag supposed to have controlled the position of the stream is not explained. The folds crossed by the Susquehanna in the Ridge and Valley Province pitch to the northeast, from a major transverse upwarp in the fold mountain belt which lies some 40 miles southwest of the stream, to a major transverse downwarp which lies some 35 miles northeast of the stream (Figs. 1 and 2). Both of these structural elements are included by Keith on his structural map of Appalachian folds,[31] and both are clearly shown by the outcrop pattern on the United States and Pennsylvania geologic maps (Figs. 1 and 2). Pennsylvania owes its most extensive anthracite fields to preservation of the coal measures in "canoe shaped" synclines that lie along the transverse downwarp. The amplitude of the sag is indicated by the fact that these beds, which extend far below sea level in the coal fields, would, if projected southwest, be high above the present ridge tops near the Susquehanna Valley. It appears, therefore, that far from following a major transverse sag, the Susquehanna actually crosses pitching folds, well up on the flanks of a high upwarp in the folded belt. If even the most general relation existed between the initial surface expression of the folds, and structures at the present erosion level, the Susquehanna could not have taken its present course as a Permian consequent.

Second in order of size among the transverse streams of eastern Pennsylvania is the Delaware River. The segment of that stream between Deposit and Port Jervis (D and P J, Fig. 1) flows southeast, directly across the regional southwest dip from the Catskills that was stressed by Meyerhoff and Olmsted in a paragraph quoted above. If, as they state, the doming of the Catskills was sufficient to decant the Permian drainage of that country to the southwest, the southeast flowing Delaware cannot be considered a Permian consequent. Even if the warping was not so strong as they suppose, the position of the stream athwart the regional dip, and well up on the flanks of the Catskill dome, is fatal to the theory that its position was determined by the form of the Permian surface. Ruedemann's suggestion that the stretch of the Delaware in question is subsequent, although not accepted by the writer, is far more in keeping with structural relations, for the stream might have extended itself headward along an intercuesta lowland on the outcrop of relatively weak Catskill sandstones and

[31] Keith, Arthur: Outlines of Appalachian Structure, Geol. Soc. Am., Bull., Vol. 34, pp. 309-380, 1923.

shales when, at a higher level, the resistant conglomerates of the Pocono Plateau extended farther to the northeast.

It will be recalled that the initial postulate of the Meyerhoff-Olmsted theory was that the divide between northwest and southeast flowing streams of the Permian Appalachians was "northwest of Kittatinny Ridge, but not so far northwest as the edge of the Allegheny Plateau." But some of the major streams of the fold mountain belt head far back in the Plateau. The Pittston-Towanda (P and T, Fig. 1) segment of the Susquehanna, which falls in this group, is one of the most striking of the southeast trending drainage lines of the Pennsylvania region. Evidently this stream cannot be explained as a Permian consequent on the basis of the initial postulate as to the position of the divide.

It thus appears that the theory which would derive the present stream system of eastern Pennsylvania from a system of Permian consequents does not stand the test of critical analysis, for it fails to provide any consistent explanation for the directions of flow of longitudinal streams, or for the positions of transverse streams.

THE THEORY OF MODIFIED PERMIAN CONSEQUENT DRAINAGE.

A possible alternative view remains: that the southeast drainage of eastern Pennsylvania has evolved from a southeastwardly directed Permian system, with so complete modification by capture that few of the streams retain their initial consequent courses. It will be recognized at the outset that this view differs but little from the theory proposed by Davis. His major Permian "Anthracite River"[32] would have flowed southeast, rather than northwest as he supposed, and its direct descendent would be the Schuylkill River. The structural position of the Schuylkill permits this interpretation, for the stream lies near the transverse sag discussed in the last section. The lateral branches of the Anthracite-Schuylkill would have been trimmed off by the Delaware and Susquehanna Rivers, which would thus owe their positions to headward erosion and their present size to conquest. In so radically altered a drainage system there is no reason to expect that longitudinal streams should flow in the direction of pitch of related fold structures, for these streams would be largely subsequent. The principal test of the merits of the theory is whether the captures required in the development of the transverse streams are practicable.

[32] Davis: op. cit., pp. 451-453.

Johnson, in his presentation of the theory of regional superposition of Appalachian drainage from a Cretaceous coastal plain, has published a full analysis of this problem, and has shown that it is in the highest degree improbable that the major transverse streams, particularly the Susquehanna, could have gained their present courses by capture. Mackin, following Johnson, has stressed theoretical difficulties bearing on the possibility of headward growth of the Delaware River across such barriers as Kittatinny Mountain. The arguments set forth in these two papers have not been questioned, and need not be repeated here.

The single new line of evidence presented by Meyerhoff and Olmsted in this connection is the statement, quoted from Ashley,[33] that the water gaps of major transverse streams in the Ridge and Valley Province correspond, in position, with transverse zones of weakness in the ridge-forming strata. Their interpretation of the bearing of Ashley's observations on Johnson's theory of regional superposition must be examined briefly. They state that:

". . . to fit the facts (namely, the relations noted by Ashley, and other structural relations of streams that have been discussed elsewhere in this paper) into a theory of regional superposition from a coastal plain, one must attribute to the consequent drainage on the marine cover such an uncanny insight into the foibles of the buried structures that the theory becomes incredible."[34]

It is evident that this argument depends on the presence of a far higher degree of correlation between zones of weakness and stream courses than could be expected on the basis of chance; like the supposed correspondence between Triassic conglomerates and present streams, the problem is essentially statistical. The merits of the argument must be based, therefore, not only on the presence of zones of jointing and faulting at stream ways, but on the *relative absence of such structures between streams.* For if a given bed were generally faulted or fractured, or if zones of faulting and fracturing were closely spaced, the correspondence of a number of transverse valleys with fractured zones would have absolutely no bearing on the problem of whether or not the transverse streams were superposed from an uncomformable cover.

[33] Ashley, G. H.: Studies in Appalachian Mountain sculpture, Geol. Soc. Am., Bull., Vol. 46, p. 1406, 1935.
[34] Op. cit., p. 32.

For every geologist who has studied the relatively inaccessible interstream stretches of Pennsylvania ridges, scores have examined roadside exposures in transverse stream valleys. Certain types of structural and stratigraphic work, which require transverse cuts, have been confined largely to the valleys. Furthermore, for every good exposure of structures on the heavily forested ridges between the watergaps, there are many in the gaps, where vigorous stream cutting and the works of man have combined to produce ideal conditions for geological observations. It appears, therefore, that the recognition of minor structural features in water gaps does not at all mean that such features are actually localized in the gaps. The apparent localization may be due wholly to the fact that these areas are more accessible, better exposed, and have been most carefully studied.

A further point may bear on relations of streams to minor structures. Gilbert and others have shown that certain joints in the Sierra granites are localized near stream valleys because of relief of internal stresses in the granites by the cutting of the valleys.[35] Whether such joints occur in the Pennsylvania quartzites is not known, although Johnson has noted exfoliation of the Pottsville quartzite-conglomerate which he attributes to relief from pressures superinduced by folding.[36] Certainly it would be well, in any survey of relations of streams to structures, to keep in mind the possibility that relief of stress due to cutting of transverse valleys might lead to the formation of joints.

Meyerhoff and Olmsted do not state whether these essential considerations were taken into account in their interpretation of the bearing of Ashley's observations on the theory of regional superposition. In the absence of such a statement the facts presented by them as to the degree of correlation between transverse zones of weakness and stream gaps certainly do not justify their conclusion that regional superposition of Appalachian streams is "incredible."

Space does not permit discussion of each of Ashley's cases; it may be stated in general that study of the Kittatinny gaps in the field generally bears out his observations as to the presence of minor faults and structural complexities, but leads to an interpretation which is diametrically opposed to the theory that the streams gained their transverse courses by capture

[35] Gilbert, G. K.: Domes and dome structures of the high Sierra, Geol. Soc. Am., Bull., Vol. 15, pp. 29-36, 1904.

[36] Douglas Johnson: personal communication.

controlled by these structural features. The channel of the Susquehanna, in the water gaps north of Harrisburg, is a most impressive example of very great and uniform rock resistance to stream cutting. It is nearly a mile wide, and is everywhere shallow; notably resistant beds in the Medina quartzite form lines of ledges, standing above the rushing waters, that can be followed with the eye from one bank to the other. Many of the resistant beds cause minor breaks in the longitudinal profile of the stream, and some can be traced up the steep valley sides to the ridge crest that stands from 500 to 700 feet above the valley floor. If the Susquehanna, which is the largest stream in eastern Pennsylvania, has difficulty in cutting downward to *maintain* its course across this quartzite barrier, it seems highly improbable that a small stream could have extended itself headward across the same barrier, at the same place. That the same small stream could have extended itself headward across three such barriers (as it must have done, according to the capture theory, in the five-mile stretch north of Harrisburg) is of a probability infinitely more remote (Fig. 2). The final, and, in the opinion of the writer, fatal objection to the capture theory is the fact that the small stream could have avoided the doubled outcrop of the Pocono quartzite by working headward in the weak rocks that encircle the synclinal nose of the Pocono. Scores of captures by subsequents working in such weak rock belts have been described in the Appalachians; not one case of capture across hard rock belts, in a situation comparable with that described above, has ever been found.

The same reasoning, and essentially the same conclusions, apply with greater or less force to every water gap in the Pennsylvania Appalachians. Difficulty of capture across one barrier is great; difficulty of capture by the same stream across two barriers is far greater; most of the larger transverse streams cross many barriers. Many of the crossings are unnecessary and wholly inexplicable if the streams gained their courses by selective headward erosion.

CONCLUSIONS.

The crux of the problem of evolution of Appalachian drainage lies in the explanation of the origin of the transverse streams. The major thesis of the Meyerhoff-Olmsted article is that these streams inherited their courses from southeastward flowing Permian consequents.

Too little is known about the conformation of the Permian surface in the Piedmont district to permit any definite judgment as to the degree of probability or improbability of their basic postulate that the Permian drainage of the Appalachian region as a whole was directed southeast; there is no tangible evidence that such was the case. The lack of correspondence between the positions of Triassic streams, as indicated by distribution of conglomerates near the western boundary faults of the Newark area, and the positions of present streams, is not fatal to the theory, for there is good reason to believe that Triassic streams may have shifted markedly, during some stages of sedimentation, on alluvial plains that extended west of the present western boundary of the Triassic Lowland. The theory of preserved Permian consequent drainage fails in part because it offers no satisfactory explanation for the greatly extended southeast courses of streams across highly variable structures; and in part because two of the three major transverse streams of the Ridge and Valley Province occupy courses that could not have been assumed by Permian consequents, *if there had been even the most general correspondence between the form of the Permian surface and structures at the present erosion.*

The italicized words above express the assumption on which any discussion of *consequent* drainage in the fold mountain belt must be based. If major Appalachian structures were not reflected in the Permian surface, the present master streams of the Atlantic slope might have inherited their courses from Permian streams which, for some unknown reason, happened to flow southeastward in the positions of the present streams. A postulate of this nature is not open to discussion. It is exactly equivalent to the statement that the present streams happened to assume their transverse courses for some unknown reason.

Generally accepted principles relating to causes and mechanism of stream capture in a folded mountain belt are based on study of many actual cases of capture in the Appalachians and in other similar regions. If our understanding of these principles is correct, it is in the highest degree improbable that such master streams as the Susquehanna could have gained their transverse courses by headward erosion.

The absence of any evident relationship between transverse streams and structure, and the parallel southeast trending courses of the streams, suggests that they were superposed. Various possibilities as to manner of superposition: as (1) from an overthrust sheet, or (2) from a weathered soil mantle, immediately present themselves. Analysis demonstrates that they are, for the most part, either inherently improbable (1, above) or wholly inadequate (2, above). Marine Cretaceous strata underlie the Atlantic coastal plain. Since these strata form a cuesta at its inner margin, it is certain that they formerly extended farther inland. In view of the fact that Cretaceous seas submerged a very large percentage of continental areas, over the earth as a whole, it seems probable that they may have extended some considerable distance inland across beveled Appalachian structures, and that the problematic southeast flowing streams may have been formed on the Cretaceous sedimentary cover when the seas withdrew.

The theory of regional superposition of Appalachian drainage, developed by Johnson on the basis of this postulate, provides a complete and simple explanation of the courses of the transverse streams, and for other long recognized problems of Appalachian geomorphology. Deduction of the consequences of the theory has led to the discovery of past changes, as in the Hudson-Watchung area, not known at the time the theory was formulated.[37] The logical character of the sequence of modifications by which Johnson derives the present drainage pattern of the Northern Appalachians from the southeastward flowing consequents of the Cretaceous mantle has not been questioned.

Johnson presented his view as a "working hypothesis," to be tested, in use, by other workers. The two points in the Meyerhoff-Olmsted article which bear directly on Johnson's theory, and might be considered tests, are the supposed correlation in position of Triassic and present streams, and the supposed correspondence of zones of weakness in Appalachian ridge-formers with stream gaps. The writer has endeavored to set forth evidence bearing on these points that is not included in Meyerhoff and Olmsted's statements. Whatever the judgment of the reader on these specific points, the many and serious difficulties faced by the alternative theory (or theories) proposed by Meyerhoff and Olmsted seem to strengthen the claim of the theory of regional superposition to careful consideration by students of Appalachian history.

[37] Johnson, Douglas: op. cit., pp. 103-130.

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