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THE ORIGIN OF ASYMMETRY OF POSITION OF LONGITUDINAL SUBSEQUENT STREAMS IN THE FOLDED APPALACHIANS

By
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B.S., Mount Union College, 1949

A thesis submitted to the Faculty of Oberlin College
in partial fulfillment of the requirements
for the Degree of Master of Arts
in the Department of Geography

1951

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INTRODUCTION

In the early spring of 1950, the writer began a detailed study of the drainage patterns of the folded Appalachian mountains in Pennsylvania and Virginia. The study was undertaken in order to find if the nature of the folds (anticlinal or synclinal) could be determined by the drainage patterns alone.

During this study, the writer noticed several drainage basins wherein the longitudinal subsequent stream flowed markedly closer to one of the flanking ridges than to the other. It was noticed that the ridge nearer the stream was lower than the opposite ridge. This phenomenon was well developed in anticlinal valleys. Further investigation showed that, in each anticline, the higher ridge was underlain by rocks dipping more gently than those underlying the lower ridge.

The writer has undertaken a statistical study of a number of drainage basins in Pennsylvania and Virginia to determine the answers to the following questions:

1. Is this asymmetrical location of streams actually related to the difference in ridge heights? In other words, does statistical study bear out visual inspection?
2. Is the relationship sometimes absent? If so, what causes its absence?

3. Does increasing difference in ridge heights cause a corresponding increase in asymmetry of position of the longitudinal stream; that is, is the longitudinal stream deflected progressively closer to the lower ridge with increasing difference in heights of the ridges flanking the stream?
4. If in #3 there is a correlation, then can the difference in elevation be used to predict the degree of asymmetry of the position of the stream in the valley, and, conversely, can the degree of asymmetry be used to predict the difference between ridge heights? This point was thought to have a possible practical bearing on the interpretation of aerial photographs.

Description of Areas Studied

Geographical location-- The choice of areas for study was governed by the location of areas within the folded Appalachian Mountains of Virginia and Pennsylvania covered both by recent, accurate, topographic maps and by large scale geologic maps.

The study in the Pennsylvania area (Fig. 1) was done on the Mercersburg, McConnellsburg, and St. Thomas quadrangles of the U. S. Army Map Service, Series V 831, with contour interval 20 feet, on the scale 1/25,000. These maps were prepared by photogrammetric methods and meet national map accuracy standards. According to these standards, 90% of the well-defined planimetric features are plotted in correct position on the published map within a tolerance of 1/50 of an inch, and 90% of the elevations interpolated from the contours are correct within a tolerance of one-half contour interval.

The Pennsylvania area is characterized by long, straight streams which flow in a northeast-southwest direction parallel to the ridge crests in the valleys of synclines and breached anticlines. Such streams are subsequent in origin, having developed their courses on the weaker Ordovician and Silurian shales. Tributary to the longitudinal subsequents are much shorter streams which flow down from the flanking ridges.

Five drainage basins were studied in the Pennsylvania area; the valleys of: Little Cove Creek, Broad Run, Wilson Run (South Branch in McCasslin Valley), the headwaters of Conodoguinet Creek, and the South Branch of Little Aughwick Creek. The first three drain into the Potomac River, Little Cove Creek via Cove Creek, and Broad Run and Wilson Run via Conococheague Creek. Conodoguinet Creek is a tributary of the Susquehanna River. The South Branch of Little Aughwick Creek flows via Great Aughwick Creek to the Susquehanna.

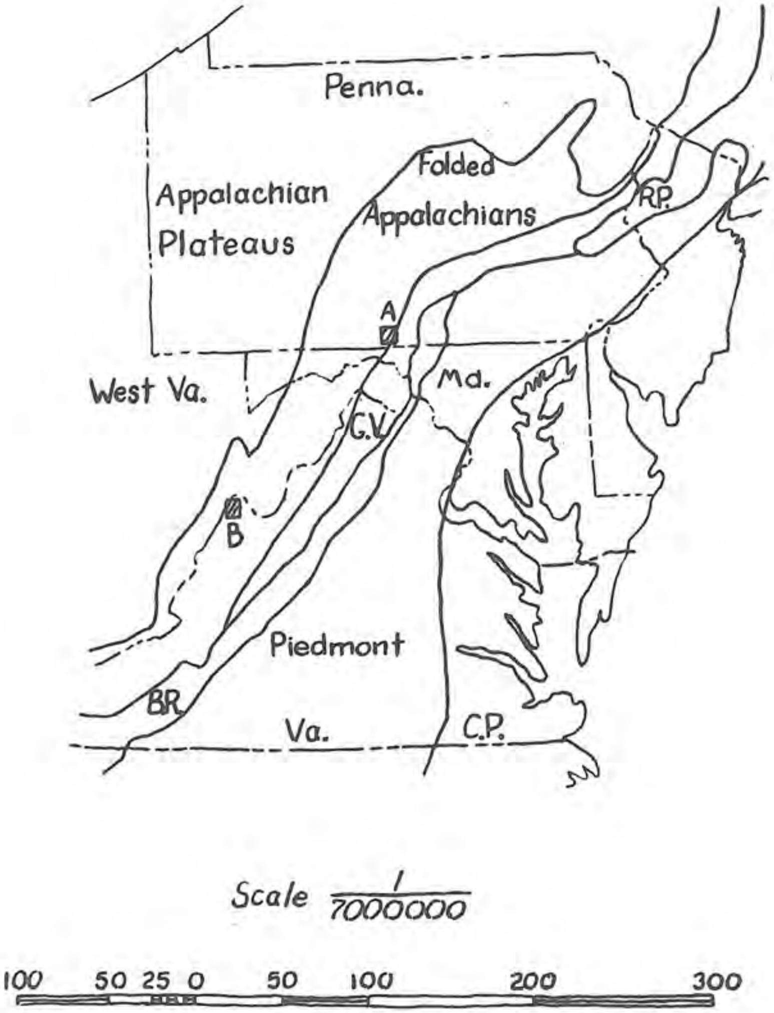
The Virginia area (Fig. 1) was studied on the Monterey quadrangle of the U.S.G.S., on the scale 1/62,500, with a contour interval of 40 feet. The writer checked this map in the field for a period of two weeks in the summer of 1950 and found it very accurate within the limits of the 40-foot contour interval and the scale of the map. In order to make errors introduced from the maps the same for the two areas studied, it would have been desirable to perform the study on maps of the same scale, but the only accurate topographic maps available for the two areas did not meet this requirement. The data taken from the Pennsylvania area, with its maps of a larger scale and smaller contour interval, would be more accurate than the data taken from the Virginia area.

The streams in the Virginia area are quite similar in pattern to those in the Pennsylvania area; long, straight subsequents flowing parallel to the ridges, and fed by streams rising on the ridge-crests and joining the main streams at angles of approximately 90 degrees.

Three drainage basins were studied in the Virginia area. The streams in all three basins are tributaries of the James River. The basins are: Back Creek Valley at its head and Monterey and Hightown Valleys where they are drained by the headwaters of the Jackson River.

The area studied in southern Pennsylvania has a humid continental climate. At Chambersburg, Pennsylvania, 4½ miles east of the area studied, the average total annual rainfall is 39.09 inches. The greatest precipitation, 3.95 inches, falls in the month of June. The least precipitation, 2.64 inches, occurs in the month of February. The average annual

Figure 1. Location Map



Legend

A = Area studied in Pennsylvania
B = Area studied in Virginia
B.R. = Blue Ridge
C.P. = Coastal Plain
G.V. = Great Valley
R.P. = Reading Prong

temperature for Chambersburg is 52.2 degrees F. The annual average range in temperature is from 29.8 degrees in January to 74.8 degrees in July. The vegetation in the area consists predominantly of chestnut, chestnut-oak, and yellow poplar in the valley bottoms, and of birch, beech, maple, and hemlock on the ridge tops. The virgin forest of the area originally extended across the valley bottoms, but the valleys are now cultivated.

The area studied in northwestern Virginia has a humid continental climate. At Monterey, Virginia, which is located in one of the drainage basins studied, the average total yearly rainfall is 41.83 inches. The greatest total monthly precipitation, 5.02 inches, occurs in August, and the least total monthly precipitation, 2.39 inches, in November. The average annual range of temperatures is from a minimum of 22.5 degrees in January to a maximum of 66.8 degrees in July. It can be seen from these data that the climates of the two areas studied in Pennsylvania and Virginia are very much alike. This similarity in climate is reflected in a similarity in vegetation. The ridge crests in the Virginia area are covered by forests consisting predominantly of birch, beech, maple, and hemlock. The forest formerly extended across the valley, where it was made up predominantly of chestnut, chestnut-oak, and yellow poplar. The valleys are now cultivated.

Geology and Geomorphology-- The area studied in Pennsylvania is covered by the U.S.G.S. Mercersburg-Chambersburg Folio by G. W. Stose (1909). According to Stose, the geologic section for the rocks exposed in the drainage basins which the writer studied is as shown in Table 1.

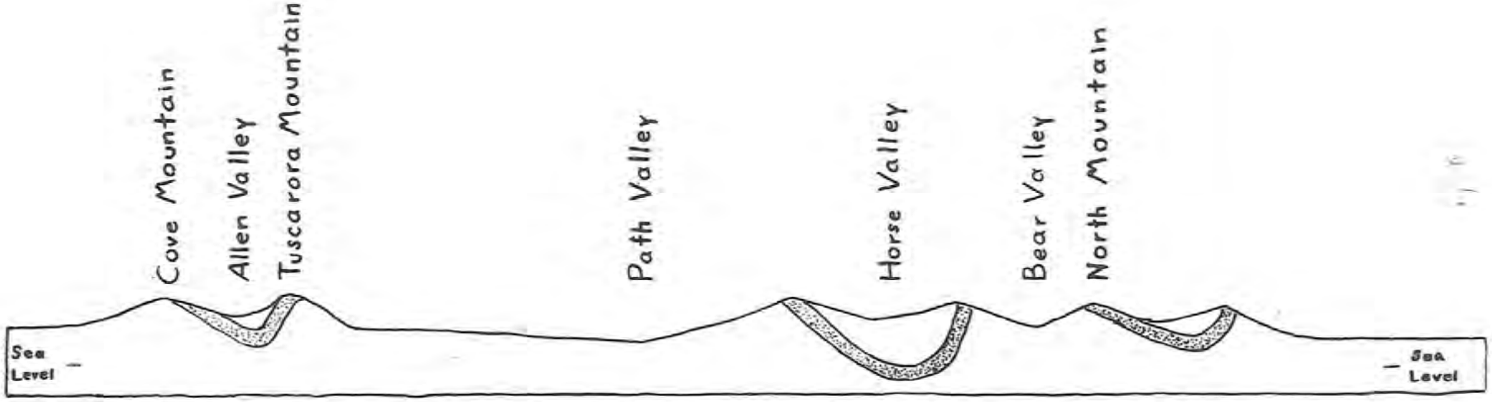
The formations described in Table 1 have been compressed into folds trending about north-northeast. A typical cross-section showing the nature of folding of the Tuscarora sandstone in the Pennsylvania area is shown in Figure 2A. It will be noted that the axial planes of these folds dip to the east, with the dips of the western limbs of the anticlines and the eastern limbs of the synclines having steeper dips than the eastern limbs of the anticlines and the western limbs of the synclines. Overthrust or reverse faulting is present but its effect on the ridgemakers is of minor importance in the area studied.

The ridges in the Pennsylvania area are remarkably even-crested and essentially horizontal. They are also remarkably concordant in elevation from ridge-crest to ridge-crest. The average range in elevation of ridge crests between water gaps in the Pennsylvania area is only about 200 feet, although the extreme difference is 960 feet. The concordant and even crests of the ridges preserve the level of the Schooley cycle of peneplanation of early Cenozoic Age. The Martinsburg shale preserves the level of the later, less complete cycle of peneplanation, the Harrisburg cycle. On the still lower

Table 1

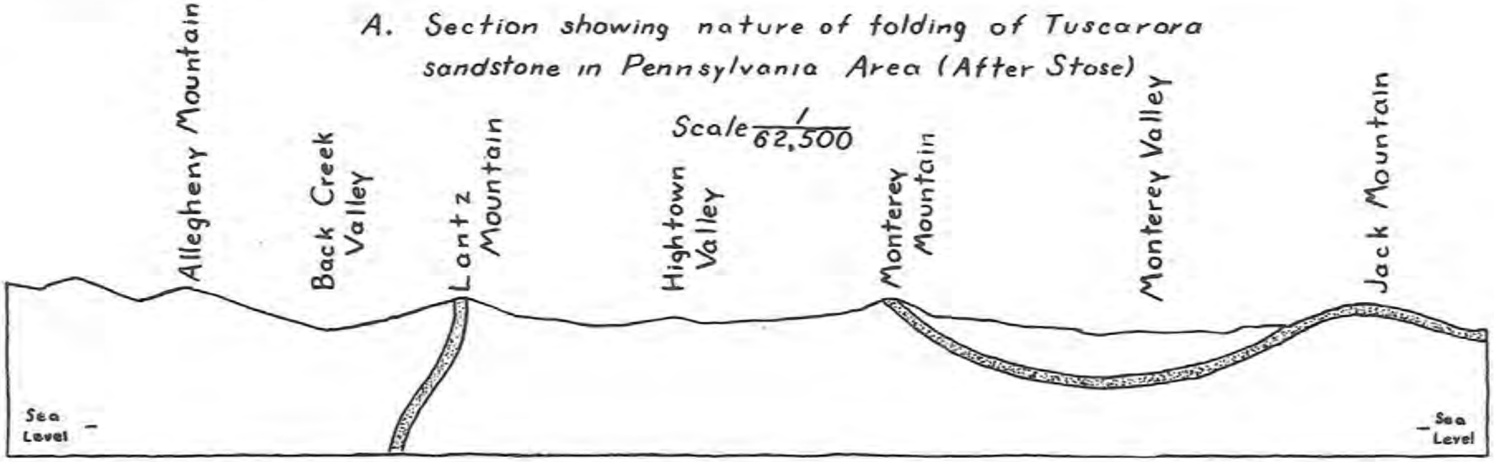
Summary of the Rocks Exposed in the Mercersburg Chambersburg Quad.
(After Stose)

Age	Formation Name	Character of Rocks	Thickness in feet	Usual Physiographic Expression
Silurian	Cayuga formation	Finely laminated limestone and shale in upper part; shale with hard white sandstone in lower part. Tough red sandstone at base	750	Valley bottoms and lower mountain slopes
	Clinton shale	Fissile shale with massive and thin-bedded sandstone in upper portion, and white quartzite at top. Soft calcareous sandstone in lower portion	750	Steep slopes and foothills of high mountains
	Tuscarora sandstone	Massive, granular, white quartz sandstone	270	Crests of mountains (chief ridgemaker)
Ordovician	Juniata formation	Soft red sandstone and shale with some hard quartz sandstone and conglomerate	400-450	Steep upper slopes of mountains
	Martinsburg shale	Soft green arkosic sandstone at top. Black to dark gray, fissile to crumbly shale	2000	Elevated level plateau, deeply cut by steep-sided ravines; lower mountain slopes
	Chambersburg limestone	Thin-bedded, tough dark limestone	100-750	Gentle to steep slopes of shale ridges
	Stones River limestone	Very pure fine grained limestone with some dolomite layers. Lime stone at top and bottom. Cherty, gray, coarse grained limestone in middle	675-1050	Gently rolling lowland
	Beekmantown limestone	Thick-bedded rather pure limestone, interbedded with dolomite and cherty beds	2300	Low, gently rolling plains and chert covered ridges



A. Section showing nature of folding of Tuscarora sandstone in Pennsylvania Area (After Stose)

Scale $\frac{1}{62,500}$



B. Section showing nature of folding of Clinch sandstone in Virginia area (After Butts, modified)

Scale $\frac{1}{62,500}$

Figure 2. Structure sections of the Tuscarora sandstone in Pennsylvania and Virginia

surfaces of the limestone is found the level of the Somerville cycle of erosion which lasted long enough to reduce the limestones to a surface of low relief.

The area studied in Virginia has been described by several authors. Nelson H. Darton (1899) published a U.S.G.S. Folio on the Monterey quadrangle on the scale 1/125,000. Frank J. Wright (1925) described the physiography of the upper James River Basin. Charles Butts published a geologic map of the Appalachian Valley in Virginia (1930) and a description of the stratigraphy of the same area (1940).

The geologic section of the rocks exposed in the drainage basins studied, according to Butts and Darton, and as checked in the field by the writer, is shown in Table 2.

The formations sketched in Figure 2 have been compressed into folds trending, like the folds in Pennsylvania, about north-northeast. Figure 2B shows the nature of the folding of the Clinch sandstone in the Virginia area. The overturned or asymmetric folding has caused the ridgemakers in the area to have dips steeper on the western limbs of anticlines than on the eastern limbs and steeper on the eastern limbs of synclines than on the western limbs. No faulting is known in the drainage basins studied.

In Virginia the principal ridgemaker is the Silurian Clinch sandstone, which is the same formation as the Tuscarora of Pennsylvania. The ridges held up by the Clinch in Vir-

Table 2

Summary of the Rocks Exposed in the Area of the Monterey Quadrangle

Age	Formation Name	Character of Rocks	Thickness in feet	Usual Physiographic Expression
Devonian	Catskill formation	Sandstone and shale, mainly red	1500-1800	Steep mountain slopes
	Chemung formation	Gray and buff sandstone. Olive and gray shale	3000-3800	Mountain slopes
	Romney shale (Hamilton)	Shale, black and fissile below, lighter colored and more sandy above	1000-1300	Wide valleys
	Oriskany sandstone	Calcareous sandstone; weathers to buff, porous sandstone	50-200	Low knobs to gentle slopes
	Helderburg limestone	Cherty, massive to flaggy limestone	550-1000	Knobby minor ridges and steep mountain slopes
Silurian	Tonoloway limestone	Finely laminated limestone with bed of quartzite at middle	200	Steep mountain slopes
	Clinton formation	Shale with thin sandstone and limestone beds	900	Rocky upper mountain slopes
		Red sandstone (Cacapon) at base	200	
	Tuscarora quartzite	Gray and white quartzite	50-300	Rocky mountain summits
Ordovician	Juniata formation	Interbedded brownish red sandstone and red shale	200-1250	Steep upper mountain slopes
	Martinsburg shale	Gray shale with soft red sandstone at top. Calcareous at bottom	800-1800	Lower mountain slopes
	Black River Group (Lowville limestone) Stones River Group (Lenoir Mosheim limestones) Beekmantown dolomite	Light to dark, cherty, siliceous, to pure limestones and dolomites	2400	Valleys with undulating slopes

ginia do not show the remarkably even crest lines and accordance of level from ridge crest to ridge crest which is notably present in the Pennsylvania area. The crests of the ridges in Virginia generally present a somewhat scalloped appearance due to streams working headward on opposite slopes of ridges and locally reducing the height of the ridge crest between their heads. The crests of adjacent ridges are only generally accordant. There are two possible explanations for the contrast in character of ridge crests between the Virginia area and the Pennsylvania area. First, the Virginia area was farther from baselevel than the Pennsylvania area during the Schooley cycle of erosion and, therefore, may not have been eroded to such low relief as the Pennsylvania area. Second, the Clinch sandstone is considerably thinner in the Virginia area than in the Pennsylvania area (see Tables 1 and 2). Thus, even if the Virginia area were eroded to a true peneplane in the Schooley cycle, post-Schooley erosion of the thinner Clinch in the Virginia ridges would have largely destroyed the trace of the peneplane on the ridge crests. Whatever may be the cause, the result is a considerably greater variation in ridge height in Virginia.

Two erosion surfaces are generally recognized in Virginia. An upland surface is now represented only by remnants of that surface on a few ridges. This surface has been correlated with the Schooley peneplane in Pennsylvania, and is therefore of early Cenozoic age. A lower or valley surface can be recognized in the remarkable, concordant summit levels of the gently rolling hills of the Great Valley, 40 miles east of Monterey.

Previous Studies

J. P. Lesley (1892, p. 674) noticed this difference in the height of the pairs of ridges formed by the two limbs of breached anticlines in several instances in Pennsylvania. He thought that beds of medium resistance to erosion, which outcropped on the flanks of the ridge, protected the ridgemaker against undermining. Lesley also thought that the protection afforded the ridgemaker by gently dipping rocks was greater than that provided by more steeply dipping beds. On the basis of this statement, he formulated the rule: "The flatter the rocks the higher the mountain, the steeper the dip the lower the mountain, the steepest dip (90°) makes the steepest mountain." (1892, p. 676)

Frank J. Wright (1925, p. 49) in a description of anticlinal valleys in the vicinity of Monterey, Virginia, noted that the western limbs of the anticlines, which have steep dips, are lower than the eastern limbs which have gentler dips. He attributed the difference in elevation to the wider outcrop of the ridgemaker on the limb with the lower dip. The wider outcrop of the ridgemaker would resist erosion more effectively than the narrower outcrop on the steeper limb. Wright also noted the effect of the differences in ridge height on the position of the longitudinal subsequent streams. He attributed the location of the watergaps, which are almost exclusively on the west limb of the anticlines, to the lower resistance to erosion of the steeper-dipping western limbs.

Robert E. Horton (1945) undertook the first quantitative study of drainage basins. Several of Horton's concepts were found helpful in this study. The first is the concept of stream order. Horton defines unbranched fingertip tributaries as being of the first order. Second order streams are formed by the junction of two first order streams. Third order streams are formed by the junction of two second order streams. The order of a stream is not affected by the junction with a stream of lower order. To distinguish the parent stream from a tributary stream upstream from a junction, Horton defined the stream course above the junction trending more nearly in the direction of the stream course below the junction as the parent. In cases where the two stream courses deviated to the same degree from the course below the junction, he defined the longer stream as the parent. By this process, some unbranched fingertip streams are assigned orders higher than one (1945, pp. 282-283).

The second of Horton's concepts of use in this study is that of drainage density, D_d, and stream frequency, F_s.

Horton defined stream frequency as the total number of streams, N, in a given drainage basin divided by the area, A, of that basin, or

$$F_s = \frac{N}{A} \quad (1945, p. 285).$$

Similarly, he defined drainage density as the total length, ΣL, of streams in a drainage basin divided by the area, A, of that basin, or

$$D_d = \frac{\Sigma L}{A} \quad (1945, p. 283).$$

The system actually used to determine the order, and thereby the number of the streams, is similar to Horton's, but follows Arthur N. Strahler's modification* of Horton's method. In Strahler's system, all unbranching streams are considered first order streams; all streams formed by the junction of first order streams are second order streams; all streams formed by the junction of two second order streams are third order streams, etc. However, if a first or second order stream enters a third order stream, the rank of the third order stream is not changed. In more general terms, a stream formed by the junction of two streams of equal rank is of an order higher than the order of its two tributaries, but the order of a stream joined by a lower-ranking tributary is not changed. In this system, a river mapped as one stream may be broken up into several streams,

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*A. N. Strahler: personal communication.

because it is met by tributaries of the same order as the "main stream." This subdivision of streams has proven to be no detriment in this study, and the system is easy to use.

METHODS OF STUDY

Even on the most accurate maps available, all of the streams are not mapped but only indicated by crenulations in the contour lines. Therefore, the first step in the investigation was to trace the mapped streams and then draw in on the tracing the position of those streams indicated only by crenulations in the contour lines. The outlines of the drainage basins were also entered on the tracing.

In order to determine the relationship between the relative heights of ridges and the position of the stream on the valley floor between them, elevations of ridges and valley floor were then obtained. At intervals of 0.2 mile along the stream valley, altitudes of the valley floor and the flanking ridges were obtained. The altitude above sea level of the ridges had no direct bearing on the problem, so the altitude of the valley floor was subtracted from the altitudes of the two ridges to give the true heights of the ridges above the valley floor. The actual difference in elevation between the two ridges is, however, of little importance since a small number of feet of difference in height between two low ridges is much more significant than the same number of feet of difference between two high ridges.

For example, let us say that ridge A is 1800 feet above the valley floor, and ridge B, to the west of ridge A, is only 1500 feet above the valley floor. The difference between the heights of A and B is 300 feet, and the <u>ratio</u> of the heights of A to the height of B is 6/5 or 1.20. On the other hand, if A is 600 feet above the valley floor and B only 300 feet, then the difference is still 300 feet, but the ratio of the two heights is 2.00. For this reason, the writer used the "height ratio" in preference to simple difference in elevation in the study. Height ratio is defined as the ratio of the height, H_h, of the higher ridge above the valley floor to the height, H_l, of the lower ridge above the valley floor. If the altitude above sea level of the higher of the two ridges flanking a stream basin is designated as A_h, the altitude of the lower of the ridges is designated as A_l, and A_v is the altitude of the valley floor, then the height ratio, R_h, may be defined as:

$$R_h = \frac{A_h - A_v}{A_l - A_v} . \tag{1}$$

The writer found it convenient in gathering his data to have columns H_h and H_l in his data sheets, where

$$H_h = A_h - A_v, \tag{2}$$

or the height of the higher ridge above the valley floor, and

$$H_l = A_l - A_v, \tag{3}$$

or the height of the lower ridge above the valley floor.

From the manner in which R_h is defined, R_h can never be less than one.

The asymmetry of the position of the stream in the valley was determined in a manner very similar to that used to determine R_h. A given difference in the distance between the stream and the higher ridge and the distance between the stream and the lower ridge would have greater significance in a narrow valley than in a wide one. Thus, if a stream flowing in a valley 3 miles wide has its position one-eighth mile from the center of the valley towards the lower ridge, the difference in the distances between ridges will amount to one-fourth mile, and the ratio of the two distances will be thirteen to eleven or 1.18. If the stream is flowing in a valley only one mile wide, however, and is offset one-eighth mile from the center towards the lower ridge, the ratio of the two distances will be five to three or 1.67. The ratio can be seen to give a better indication of the asymmetry, and was used for that reason in this study. The "distance ratio," as used here, is defined as the ratio of the distance from the stream to the higher ridge to the distance from the stream to the lower ridge. If S_h is taken as the distance from the stream to the higher ridge, and S_l the distance from the stream to the lower ridge, then the distance ratio, R_s, may also be defined

$$R_s = \frac{S_h}{S_l} . \qquad (4)$$

From the way R_s is defined, R_s may range from zero to positive infinity, but could never be negative. The distances S_h and S_1 were measured along a line between the two ridges perpendicular to the trend of the stream course. This does not mean perpendicular to the stream course where that course deviated from the trend of the stream as might happen along a short reach where the stream is meandering.

DATA

The data were taken at intervals of 0.2 mile along the valley bottom. Such rigid spacing reduced to a minimum the possibility of subjective choice of points. The method of spacing also makes the data reproducible, as the writer determined from data obtained on one of the drainage basins in Pennsylvania. Very little difference existed between the readings of two different sets of data obtained from the same valley.

The data were recorded in tables like those shown in Tables 3 to 11. The symbols in the charts are the same as those used in the previous section. The numbers in the first column correspond to the number of intervals of 0.2 mile at which the reading was taken along the stream.

Pennsylvania Area

Table 3

Little Cove Creek
A synclinal valley floored with Clinton shales and sandstone

	S_h	S_l	A_h	A_l	A_v	H_h	H_l	R_h	R_s
1	.94	.63	1960	1500	1320	640	180	3.55	1.47
2	1.00	.63	1940	1480	1200	740	280	2.64	1.59
3	.99	.76	1940	1560	1020	920	540	1.70	1.30
4	.97	.85	1940	1580	960	1980	620	1.58	1.14
5	1.09	.81	1920	1540	900	1020	640	1.59	1.34
6	1.12	.78	1880	1560	860	1020	700	1.46	1.43
7	1.16	.77	1880	1540	840	1040	700	1.48	1.51
8	1.22	.87	1940	1620	820	1120	800	1.40	1.40
9	1.07	.88	1900	1760	780	1120	980	1.14	1.22
10	1.13	.88	1900	1780	760	1140	1020	1.12	1.28

West Half of Valley

$F'_s = 14.4 \qquad D'_d = 3.58$

East Half of Valley

$F'_s = 14.8 \qquad D'_d = 3.42$

S_h = distance from higher ridge to stream
S_l = distance from lower ridge to stream
A_h = altitude of higher ridge
A_l = altitude of lower ridge
A_v = altitude of valley bottom
$H_h = A_h - A_v$
$H_l = A_l - A_v$

$$R_h = \frac{H_h}{H_l}$$

$$R_s = \frac{S_h}{S_l}$$

Table 4

South Branch of Little Aughwick Creek
A synclinal valley floored by Clinton shale and with Tuscarora sandstone on limbs of syncline

	S_h	S_1	A_h	A_1	A_v	H_h	H_1	R_h	R_s
1	.53	.42	1920	1860	1240	680	620	1.20	1.26
2	.55	.38	1940	1860	1240	700	620	1.13	1.47
3	.53	.44	2020	1920	1240	780	680	1.15	1.20
4	.57	.43	1980	1960	1260	720	700	1.03	1.33
5	.58	.42	2040	1940	1280	760	660	1.15	1.38
6	.60	.40	2040	1940	1280	760	660	1.15	1.50
7	.55	.40	2000	1900	1320	680	580	1.17	1.38
8	.57	.44	1960	1940	1320	640	620	1.03	1.29
9	.46	.58	2020	1980	1340	680	640	1.06	0.79
10	.68	.44	2020	2000	1360	660	640	1.03	1.54
11	.68	.50	2060	2000	1380	680	620	1.10	1.36
12	.73	.54	2100	2000	1400	700	600	1.17	1.35
13	.71	.63	2200	2000	1400	800	600	1.33	1.13
14	.90	.53	2420	1940	1440	980	500	1.96	1.64
15	.93	.46	2440	1960	1480	960	480	2.00	2.02
16	.85	.42	2420	2040	1520	900	520	1.73	2.02
17	.78	.36	2400	2100	1580	820	520	1.60	2.17
18	.68	.30	2360	2100	1620	740	480	1.54	2.27
19	.66	.43	2340	2000	1680	660	320	2.06	1.54
20	.65	.22	2300	2060	1780	520	280	2.00	2.95
21	.56	.17	2300	2140	1860	440	280	1.57	3.29
22	.35	.13	2320	2160	1960	360	200	1.80	2.69
23	.21	.11	2280	2200	2140	140	60	2.33	1.91

West Half of Valley
$F_s' = 6.06 \quad D_d' = 0.97$

East Half of Valley
$F_s' = 4.28 \quad D_d' = 1.26$

Table 5

Broad Run
An anticlinal valley in the Juniata formation

	S_h	S_1	A_h	A_1	A_v	H_h	H_1	R_h	R_s
1	.22	.37	1940	1860	1400	540	460	1.13	0.59
2	.37	.22	1980	1960	1460	520	500	1.04	1.68
3	.22	.38	2000	1860	1480	520	380	1.53	0.58
4	.23	.38	1960	1940	1500	460	440	1.14	0.61
5	.19	.42	1940	1920	1520	420	400	1.05	0.45
6	.43	.21	2020	1960	1540	480	420	1.14	2.05
7	.40	.23	2020	1960	1580	440	380	1.16	1.74
8	.37	.25	2020	1940	1600	420	340	1.24	1.48
9	.38	.24	2020	1900	1620	400	280	1.43	1.58
10	.37	.24	2020	1940	1660	360	280	1.26	1.54

West Half of Valley
$F'_s = 8.16$ $D'_d = 1.12$

East Half of Valley
$F'_s = 7.14$ $D'_d = 1.60$

Table 6

Conodoguinet Creek (headwaters)
A synclinal valley floored by Clinton and Cayuga shales

	S_h	S_l	A_h	A_l	A_v	H_h	H_l	R_h	R_s
1	.83	1.05	1960	1820	1120	840	700	1.20	.79
2	.82	1.03	2000	1820	1140	860	680	1.24	.80
3	.77	1.09	1980	1920	1160	800	760	1.05	.71
4	1.09	.67	1960	1920	1160	800	760	1.05	.61
5	1.03	.64	1980	1960	1200	780	760	1.03	1.63
6	.88	.72	2020	1900	1200	820	700	1.17	1.22
7	.80	.66	2020	1920	1220	800	700	1.14	1.21
8	.70	.63	1940	1920	1240	700	680	1.03	1.11
9	.65	.64	1940	1920	1280	660	640	1.03	1.02
10	.55	.63	1960	1900	1320	640	580	1.10	.87
11	.58	.62	1980	1840	1340	640	500	1.28	.94
12	.52	.52	1960	1820	1400	560	420	1.33	1.00
13	.48	.52	1960	1880	1420	540	360	1.50	0.92
14	.45	.41	1940	1860	1440	500	420	1.19	1.10
15	.46	.33	1940	1820	1480	460	340	1.44	1.39
16	.37	.31	1960	1860	1620	340	240	1.42	1.19
17	.28	.20	1920	1880	1740	180	140	1.28	1.40

West Half of Valley

$F'_s = 38.8 \quad D'_d = 5.51$

East Half of Valley

$F'_s = 35.4 \quad D'_d = 6.91$

Table 7
McCasslin Valley
A synclinal valley on Clinton shales

	S_h	S_l	A_h	A_l	A_v	H_h	H_l	R_h	R_s
1	.44	.36	1820	1640	1100	700	540	1.30	1.22
2	.45	.36	1240	1690	1140	700	550	1.27	1.25
3	.40	.39	1890	1760	1200	640	560	1.14	1.02
4	.36	.42	1840	1780	1260	780	520	1.50	0.86
5	.42	.29	1820	1860	1300	520	460	1.13	1.45
6	.34	.42	1820	1800	1360	460	440	1.04	.89
7	.38	.34	1820	1800	1420	400	380	1.05	1.12
8	.34	.29	1780	1740	1480	300	260	1.15	1.17
9	.28	.17	1880	1720	1600	280	120	2.33	1.64
10	.29	.11	1880	1780	1700	180	80	2.25	2.64
11	.16	.17	1880	1840	1820	60	20	3.0	0.94

West Half of Valley

$F'_s = 22.78$ $D'_d = 17.11$

East Half of Valley

$F'_s = 20.27$ $D'_d = 3.64$

Virginia Area

Table 8
Back Creek Valley
A homoclinal valley floored with Romney shale

	S_h	S_1	A_h	A_1	A_v	H_h	H_1	R_h	R_s
1	1.81	.45	4400	3600	2720	1680	880	1.91	4.02
2	1.88	.47	4200	3680	2720	1480	960	1.54	4.00
3	1.91	.44	4120	3680	2760	1360	920	1.48	4.34
4	1.95	.35	4320	3600	2760	1560	840	1.85	5.57
5	1.73	.45	4480	3640	2800	1680	840	2.00	3.84
6	1.72	.44	4440	3640	2800	1640	890	2.00	3.91
7	1.55	.50	4480	3720	2800	1680	920	1.83	3.50
8	1.69	.42	4480	3720	2840	1640	880	1.86	4.02
9	1.62	.47	4360	3720	2840	1520	880	1.73	3.45
10	1.59	.43	4280	3680	2880	1400	800	1.75	3.69
11	1.64	.45	4280	3800	2880	1400	920	1.52	3.64
12	1.62	.64	4000	3720	2920	1080	800	1.35	2.53
13	1.00	.65	3960	3720	2920	1040	800	1.30	1.54
14	1.06	.56	4000	3720	2920	1080	800	1.35	1.89
15	1.05	.54	4020	3720	2960	1080	760	1.42	1.94
16	1.00	.52	4020	3720	2960	1080	760	1.42	1.92
17	1.06	.53	4080	3840	3000	1080	840	1.28	2.00
18	1.07	.60	4040	3760	3000	1040	760	1.37	1.78
19	1.04	.65	3960	3800	3040	920	760	1.21	1.60
20	1.12	.56	3880	3800	3080	800	720	1.11	2.00
21	.51	1.11	3800	3760	3080	720	680	1.06	0.46
22	1.12	.61	3960	3760	3100	760	560	1.36	1.83
23	1.09	.55	4040	3720	3080	960	640	1.50	1.98
24	1.12	.52	4200	3840	3080	1120	760	1.47	2.15
25	1.00	.52	4120	3800	3120	1000	680	1.47	1.92
26	1.05	.53	4020	3800	3120	900	680	1.32	1.98
27	1.07	.53	4080	3840	3160	920	680	1.32	2.02
28	1.27	.54	3920	3880	3200	720	680	1.32	2.35

West Half of Valley

$F'_s = 23.86 \quad D'_d = 5.12$

East Half of Valley

$F'_s = 28.30 \quad D'_d = 5.67$

Table 9
Hightown Valley
An anticlinal valley floored with Martinsburg shale

	S_h	S_l	A_h	A_l	A_v	H_h	H_l	R_h	R_s
1	1.09	.72	3960	3720	2920	1240	800	1.55	1.51
2	1.00	.82	3930	3600	2880	1040	720	1.44	1.22
3	1.11	.79	3880	3640	2840	1040	800	1.41	1.40
4	1.16	.88	3960	3720	2840	1140	880	1.29	1.31
5	1.13	.90	3880	3680	2800	1080	880	1.23	1.26
6	1.13	.97	3760	3640	2760	1000	880	1.14	1.16
7	1.08	1.04	3620	3620	2760	860	860	1.00	1.04
8	1.14	1.08	3940	3440	2720	720	720	1.00	1.06
9 10	opposite a water gap								
11	1.37	.92	3520	3320	2720	900	600	1.50	1.49
12	1.10	1.20	3680	3480	2760	920	720	1.29	0.92
13	1.23	1.04	3760	3680	2760	1000	920	1.09	1.18
14	1.26	1.04	3720	3720	2760	960	960	1.00	1.21
15	1.30	.97	3800	3520	2760	1040	760	1.37	1.34
16	1.36	1.02	3920	3680	2800	1120	880	1.28	1.33
17	1.42	.97	3920	3680	2800	1120	880	1.27	1.46
18	1.42	1.01	3880	3720	2840	1040	880	1.18	1.41
19	1.42	.99	3880	3720	2840	1090	880	1.18	1.54
20	1.52	.88	3800	3760	2840	960	920	1.04	1.73
21	1.56	.91	3840	3720	2880	960	840	1.14	1.71
22	1.60	.90	3840	3760	2920	920	840	1.09	1.78
23	1.57	.87	3920	3720	2920	1000	800	1.25	1.80
24	1.57	.87	3920	3720	2960	960	760	1.26	1.80
25	1.62	.81	4000	3720	3000	1000	720	1.39	2.00
26	1.65	.88	4000	3720	3000	1000	720	1.39	1.88
27	1.58	.97	3960	3800	3040	920	760	1.21	1.63

West Half of Valley
$F'_s = 21.81 \quad D'_d = 7.33$

East Half of Valley
$F'_s = 24.32 \quad D'_d = 6.47$

Table 10
Monterey Valley
A synclinal valley floored with Helderberg limestone, Oriskany sandstone, and Romney shale

	S_h	S_l	A_h	A_l	A_v	H_h	H_l	R_h	R_s
1	2.40	1.29	3880	3760	2600	1280	1160	1.10	1.86
2	2.34	1.35	3880	3800	2600	1280	1200	1.07	1.73
3	2.04	1.45	4000	3880	2640	1360	1240	1.10	1.41
4	2.06	1.43	4080	3920	2640	1440	1280	1.12	1.44
5	1.97	1.40	4200	3920	2680	1520	1240	1.22	1.41
6	1.90	1.33	4240	3880	2680	1560	1200	1.30	1.30
7	1.68	1.44	4160	3800	2680	1480	1120	1.32	1.17
8	1.58	1.44	4080	3840	2720	1360	1120	1.21	1.10
9	1.45	1.54	4040	3840	2720	1320	1120	1.18	0.94
10	1.29	1.64	4000	3880	2720	1280	1160	1.10	0.79
11	1.39	1.55	3960	3920	2760	1280	1120	1.14	0.90
12	1.41	1.55	3960	3960	2800	1160	1160	1.00	0.91
13	1.29	1.63	3920	4040	2800	1120	1240	1.11	1.26
14	1.19	1.91	3920	4000	2800	1120	1200	1.07	1.60
15	1.00	1.87	3920	4000	2840	1080	1160	1.07	1.87

West Half of Valley

$F'_s = 31.14$ $D'_d = 6.80$

East Half of Valley

$F'_s = 22.51$ $D'_d = 6.19$

DISCUSSION AND INTERPRETATION OF DATA

The pairs of values of R_h and R_s obtained for each of the two areas studied were plotted on two graphs, one for each area. The points were first plotted on rectangular coordinates. The distributions of the points from both areas showed no linear trends on these coordinates. However, when R_h was plotted on a logarithmic scale and R_s on a linear scale, a linear trend of the points became apparent, especially for the points from the Virginia area (see Fig. 3 and 4). Therefore, the correlation coefficients between log R_h and R_s were found from standard correlation tables following the procedure outlined by Mode (1945, pp. 292-293). The value of the correlation coefficient for the Virginia area was 0.64 and that for the Pennsylvania area was 0.427. Using the means and standard deviations of log R_h and R_s computed from the same tables, there was obtained the equations for the regression lines.

The regression line of R_s on log R_h is the line for which the sum of the squares of the vertical distance of the points from it is a minimum. It may be used to find an expected value of log R_h from an experimental value of R_s. Similarly, the regression line of log R_h on R_s is the line for which the sum of the squares of the horizontal distances of the point from it is a minimum. This line may be used to find an expected value of R_s from an experimental value of log R_h.

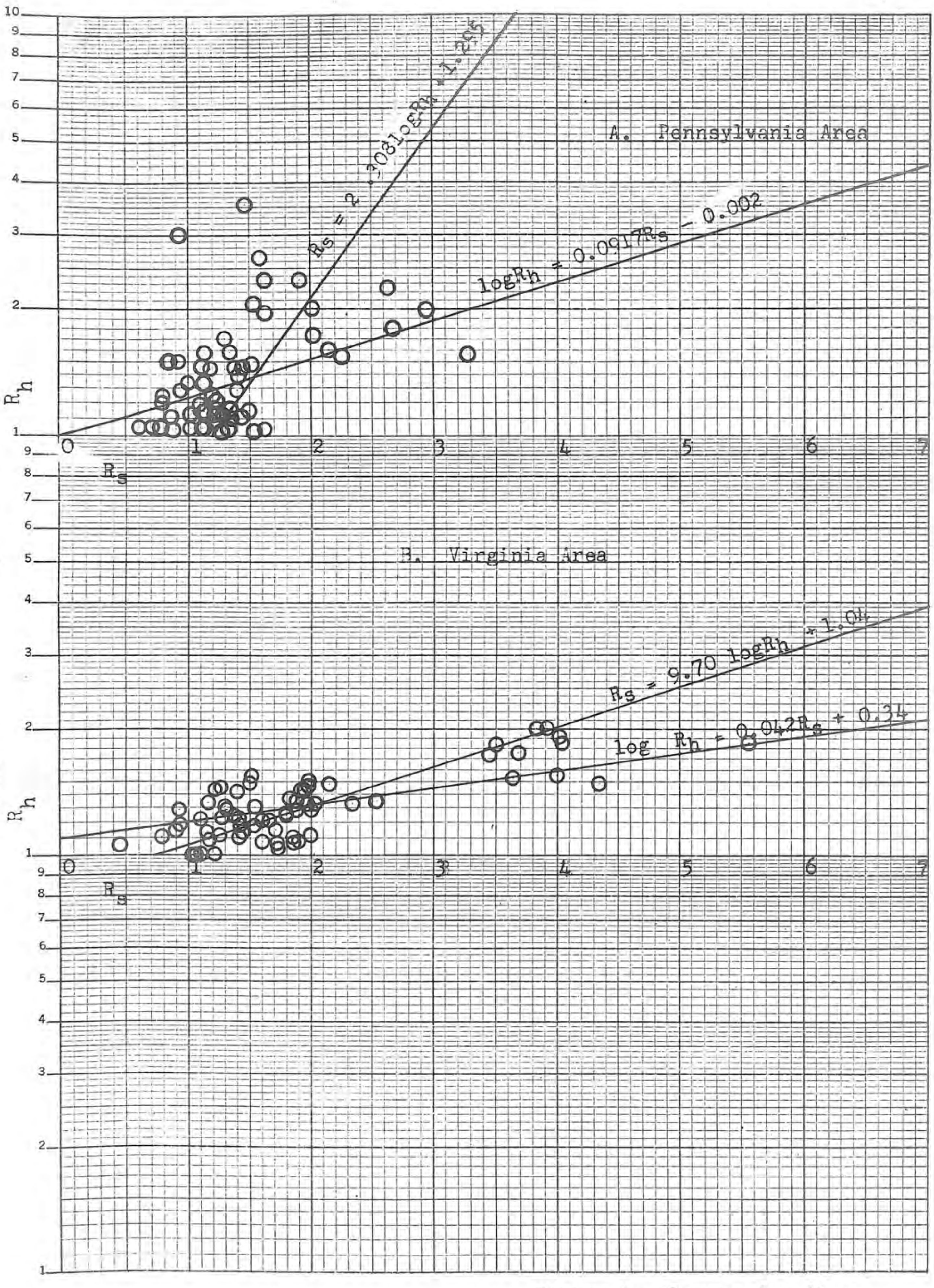

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Figure 3. Regression Lines

For the Virginia area, the equations are:

$$R_s = 9.70 \log R_h + 1.04; \log R_h = 0.042 R_s + 0.384. \quad (5)$$

For the Pennsylvania area, the equations are:

$$R_s = 2.31 \log R_h + 1.29; \log R_h = 0.92 R_s - 0.002. \quad (6)$$

The bearing of the data on the questions raised at the beginning of the paper may now be determined. First, does the supposed relationship between difference in ridge heights and position of the stream exist? The values of the correlation coefficients obtained are by no means near 1.00, which value would show a direct relationship between log R_h and R_s, nor are they low enough to show the relationship non-existent. One can say then, that the position of the stream in the valley is only in part a function of the difference between the heights of the ridges flanking the stream. The question then arises, what is the agent, or agents, related to this difference in ridge heights that is directly responsible for the asymmetry of position of the longitudinal streams? First, it may be the effect of more material moved from the higher ridge than from the lower ridge by the processes of mass-wasting. Second, it may be due to the greater amount of material brought down to the main stream by the tributaries rising on the higher ridge. Third, both of these processes may cause the asymmetry.

While the number of measurements made on each drainage basin were too small to make possible the determination of meaningful correlation coefficients and regression lines for each drainage basin, there is a simpler device for attacking this problem. By comparing the number of values of R_s equal to or less than 1.00 to the total number of values of R_s taken for a given basin, we can see that in only one basin, that of Broad Run in Pennsylvania, is there a high percentage of values of R_s less than or equal to 1.00, that is, where the stream is closer to the higher ridge. If we compare the lithology and drainage characteristics of this basin with those of the other basins studied, we notice some important differences. The drainage basin in question is underlain, in its upper reaches, by the Juniata formation. That the sandstone of this formation is quite permeable is shown by the almost complete lack of streams tributary to Broad Run. Farther downstream, where the Martinsburg shale floors the valley, the increase in streams on the side of the valley is quite striking, and the longitudinal stream can be observed to swing towards the lower ridge.

Determinations of the stream frequencies and drainage densities of the portions of each drainage basin on either side of the main streams were made, therefore, so that some basis for comparing first, the two sides of each basin, and second, the individual basins as units was available. Areal drainage density, D_d', is here defined as the ratio of the total length of streams in a given area to that area, A', or

$$D_d' = \frac{\Sigma L}{A'} .$$

A' is used for the area, since Horton (1945, p. 283) uses A as the area of an entire basin.

Areal stream frequency, F_s', is defined here as the ratio of the total number, N', of streams in a given area to that area, A', or

$$F_s' = \frac{N'}{A'} .$$

N' is used for the number of streams, since Horton (1945, p. 285) uses N for the number of streams in an entire basin.

By studying the values obtained for the drainage density and stream frequency on opposite sides of each longitudinal stream which was studied, no great differences were observed between such portions of each basin. The values of the areal drainage densities and areal stream frequencies from the valley of Broad Run, however, are only one-third to one-half as great as the basin with the next highest values of drainage densities and stream frequencies. From this it can be seen that the greatest number of values of R_g less than or equal to 1.00 exist in the stream basin where mass-wasting operates alone to deliver material to the stream. Furthermore, in all of the other basins, streams are quite abundant. For the latter basins, the areal drainage densities range from 7.33 to 17.11. This excludes the values for the synclinal valley of South Branch of Little Aughwick Creek, where the asymmetry appears to be the result of direct structural control by the Tuscarora sandstone. The sides of this valley are stripped surfaces on the Tuscarora. In general, the highest values of areal drainage density occur in the Virginia area. This may be due to the wider exposures of shale in the Virginia area. In all of the basins excepting that of Broad Run, there are no high percentages of values of R_s less than or equal to 1.00, which indicates that the asymmetry is produced by the action of streams bringing down greater loads from the higher ridges, and not by the effects of mass-wasting.

Wright (1925, plate XB) noted gentler slopes leading down from higher ridges. If the longitudinal stream was once symmetrically located with respect to the ridges, the gradient of the streams from the higher ridge would be steeper than the gradient of the streams leading from the lower ridge. This would enable the streams rising on the higher ridge to transport a greater load to the longitudinal stream than would the streams rising on the lower ridge. The greater stream loads transported from the higher ridge to the valley below would shift the longitudinal stream toward the lower ridge. At least part of the load from the tributaries from the ridges is deposited as alluvial fans at the junction of the tributary and longitudinal streams. These fans can be observed forcing the stream toward the lower ridge in Back Creek Valley on the Monterey topographic sheet, and near Richmond Furnace on the west branch of Conococheague Creek on the McConnellsburg sheet.

As the longitudinal stream moved toward the lower ridge, the lengths of the streams rising on the high ridge would be lengthened, with the result that the gradients of those streams would decrease. The streams on the lower ridge, on the other hand, would have their courses shortened, and their gradients steepened. Under these conditions, the longitudinal stream would move toward the lower ridge until the gradients of the streams rising on the two ridges are such that the amount of material brought down from each ridge is the same, and a state of equilibrium is reached.

It may be noted here that since the valley of Broad Run is of a character not favorable for the development of the asymmetric type of stream pattern, the figures determined for this basin were not used in the computation of the correlation coefficient and the finding of the regression lines in the Pennsylvania area.

The possibility that asymmetry of stream position is due to the asymmetric location of the weak rock, due to the asymmetric nature of the fold itself, is eliminated by the extremely wide outcrop of shale flooring some of the valleys studied.

The third question raised in the introduction may now be examined. Is an increase in R_h, the height ratio, followed by a corresponding increase in R_s, the distance ratio? Inspection of the distribution of points, and the positive values obtained for the correlation coefficient, indicate that, on the average, R_s does increase with R_h.

The cause for this is related to the cause of the asymmetry of the position of the streams. If two ridges flanking a valley are only slightly different in height, that is, if R_h is low, the streams rising on the higher ridge will have an initial gradient only slightly steeper than the streams rising on the lower ridge. Therefore, equilibrium will be established after only a slight movement of the longitudinal stream toward the lower ridge. If, however, R_h is quite high, the gradient of the streams rising on the higher ridge will be much steeper than the gradient of the streams rising on the lower ridge. Considerable displacement of the stream will be necessary, therefore, before the amounts of material brought down from each ridge in a given time are equal, and equilibrium is established.

The last point raised in the introduction, the possibility of predicting the distance ratio from the height ratio, and conversely, the possibility of predicting the height ratio from the distance ratio has already been answered. The equations for the regression lines will make the prediction possible.

Two additional questions arise at this point. The first is, why do the equations for the two areas vary so widely? The cause for this variation may be quite complex, and the answers given here are only suggestions. The two areas differ in two important ways. First, the drainage basins in Virginia are underlain by greater thicknesses of shale than is the case in Pennsylvania. Second, the sandstones are thicker in Pennsylvania than in Virginia. The effect of the second factor on the preservation of peneplanes has already been discussed. The greater width of outcrop of shales in the Virginia area is reflected in the greater stream frequencies and drainage densities for that area. It has already been shown that the existence of asymmetry is directly dependent on the presence of streams on the flanks of the valley. The higher values of correlation coefficients might be interpreted as evidence that an increase in the number of streams produces greater obedience to structural controls. In general, the values of R_h, the height ratio, are much lower in the Pennsylvania area than in the Virginia area. This reflects the greater accordance of ridge crests in the Pennsylvania area, which is probably due to leveling by Schooley peneplanation. The greater values of R_h for the Virginia area reflect the less concordant and more serrate nature of the ridge crests for that area.

The physiographic history of a region thus appears to have a definite bearing on the perfection of development of stream asymmetry in that area. As the ridges become lower, and more accordant, the structural control decreases in effectiveness. During the well-developed Schooley cycle of peneplanation that occurred in the Pennsylvania area, the ridges were leveled and the streams were free to meander without effective interference from structural control. When the streams were rejuvenated, they started to erode the weaker rocks that occupied the present valleys. If the streams cut deeply enough to permit the undermining of the ridgemakers and lowering of the ridge crests, the difference in dip of the ridgemakers would have again caused a difference in elevation between the ridges flanking a given basin. As R_h, the height ratio, increased, it acted to produce the difference in gradient that causes the asymmetry of position of the longitudinal streams.

In the Virginia area, the original upland surface has been so much eroded that the values of R_h are now sufficient to produce a marked asymmetric stream pattern, whereas in the Pennsylvania area, the ridges are not yet sufficiently lowered differentially to produce a value of R_h sufficient to cause so great a mean value of R_s. The difference in value of the correlation coefficients may be due to the differences in stream frequencies and drainage densities, or to the incomplete reestablishment of structural control in causing asymmetry of longitudinal streams, or a combination of the two. There appears to be no means of deciding which of the three possible choices is the correct one. In the light of this discussion, the equations for the Virginia area would be more reliable than the equations for the Pennsylvania area. However, the differences in the equations for the two areas are so great that in working in only one area, more accurate results might be expected from the equation derived for that particular area.

The second question is the validity of the method used in this study. The matter of random choice of points has already been discussed. The values of the correlation coefficients were derived from standard correlation tables, with the table for the Virginia area having 13 rows and 16 columns, and the table for the Pennsylvania area having 10 rows and 21 columns. According to Mode (1945), the error introduced by grouping data for computation is less than four percent if the number of columns and the number of rows are each greater than ten. Also, Mode (1945) states that any corrections for errors in the standard deviation from grouping data with fewer than 1000 pairs of values are not worth while. The weakest point of the method is the number of pairs of values of R_h and R_s. When the number of pairs of values is less than 100, the possibility of sampling errors is high enough that the values of the correlation coefficient obtained cannot be regarded as completely trustworthy. As there were 67 pairs of values of R_h and R_s for the Virginia area, and 84 for the Pennsylvania area, the equations must be regarded as approximations. Any regression lines must be interpreted as representing the average, with values that deviate from that line. Thus, in interpreting the equations derived, one could say that given a value of R_h or R_s, in a given area, one could use the proper equation to find the value expected, <u>on the average</u>, for R_s or R_h, respectively.

The method by which the data were obtained has the great disadvantage of being a tedious and time-consuming process. The applicability of the results of the research is restricted to narrow areas and can be extended to other areas either with doubt as to the accuracy of the results of the extension or by a repetition of this type of study to the area to be studied. Furthermore, they are restricted to areas where at least a moderate number of streams are flowing. For areas of low drainage densities and stream frequencies, the results have been demonstrated to be invalid.

CONCLUSION

The results may be stated briefly as follows. (1) The asymmetric drainage pattern exists in areas of maturely eroded folded mountains, where the streams have not yet had time to open out wide flood plains. (2) It occurs only on impervious rocks, or where areal drainage density and areal stream frequency are above 3.00 and 7.00, respectively. (3) It occurs only in areas where the structure is such that the ridges flanking a valley are of sufficiently unequal height, that is, where R_h is greater than 1.10, on the average. (4) It may be used to interpret structure to the extent of determining relative steepness of dip, but not direction of dip in areas meeting the restrictions enumerated above.

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