SOME SPECIAL PHYSIOGRAPHIC FEATURES OF THE KNOBSTONE CUESTA REGION OF SOUTHERN INDIANA: AN EXAMPLE OF EXPLANATORY PHYSIOGRAPHY.

By

Clyde A. Malott

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INTRODUCTION AND STATEMENT OF PROBLEM.

Physiography is a study which deals largely with the development of land forms. It attempts to explain the landscape by the action of certain processes on earth materials under particular conditions, and is perhaps less descriptive than it is explanatory. Probably no other phase of physiography presents so many problems as the results of the action of running water on the many kinds of rock material under various geologic and topographic conditions. The intricacies of drainage development and adjustment, traced by means of topographic forms, often present a history by no means simple.

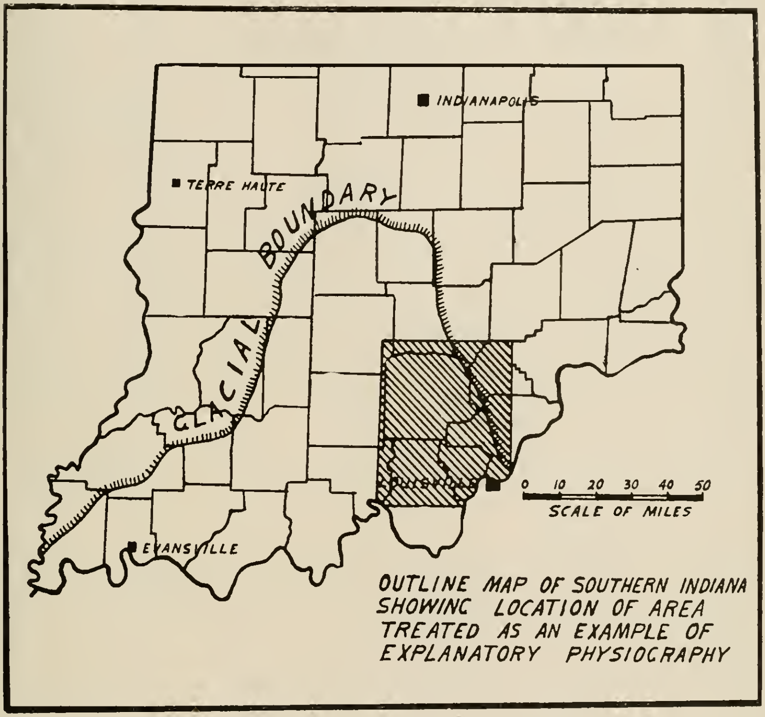
The more intricate and complex an individual history, the more fascinating it is to the student of physiography.

Problems pertaining to drainage are by no means few in southern Indiana. The division of the Illinois glacial lobe, or rather the projection of two lobes into southern Indiana, left a large triangular area of about 5,000 square miles in extent, untouched by the ice. Where the pre-glacial streams came against the eastern margin of the western lobe there was much derangement of the pre-existing drainage, especially the smaller streams. But it is in the unglaciated area that stream development and adjustment have gone on unhampered. It is here that we find some of the finest examples of adaptation of the drainage direction to the geologic structure and the topographic conditions. The details of drainage development involve intricate cases of underground drainage with diversion of the waters from original surface streams to other streams by subterranean piracy. Such a condition would result only in a special limestone region where both geologic and topographic conditions are favorable. But the subject matter of this paper is a presentation of the broader features which permit certain stream adjustments to take place rather than a consideration of the full details of drainage phenomena and topographic form. A part of the subject matter, however, is concerned with the general considerations of a rather odd case of stream gradient and also with the details of a notable case of stream piracy, but the cases are presented as illustrative of stream adjustments to the geologic and topographic conditions which characterize the particular region here chosen.

The area from the Muscatatook River along the southern boundary of Jackson County to the Ohio River on the south presents a number of rather striking physiographic features. The chief one of these is the southern and best developed portion of the Knobstone escarpment, the most prominent relief feature in Indiana. The area embraces western Scott, western Clark, Washington, Floyd, and Harrison counties. This is the area shown by the general map accompanying this paper. It is essentially the Knobstone cuesta and contiguous territory near the eastern margin of the unglaciated portion of southern Indiana. The topographic map is a bit of detail within the larger area shown by the general map. The area is chosen here to illustrate the importance of geologic structure in the development of topographic forms, and also to present one or two illustrations of adaptation of drainage to geologic structure and topographic condition. The special factors concerned in these phases of physiography will be presented in some detail.

DEFINITION OF GEOLOGIC STRUCTURE AND TOPOGRAPHIC CONDITION.

Frequent mention is made in this paper of geologic structure and topographic condition. There is no intention of using these terms in any other than the ordinary sense, yet it is well to give an exact statement of the meanings of the terms as used in the present discussion. The definition here given of geologic structure as a physiographic term is intended to be applied to a plains region. Under the term geologic structure are included the types of regional rock and the lithologic succession, as well as the inclination of the strata. Essentially this is the descriptive stratigraphy and the regional dip of the rock. It is lithology and structure. A physiographic paper need have no more of this phase of geology given than is necessary to show the responsibility of the inclination of the strata, the type of rock, and the relationship of the rock layers as conditioning factors in the devel-



OUTLINE MAP OF SOUTHERN INDIANA SHOWINC LOCATION OF AREA TREATED AS AN EXAMPLE OF EXPLANATORY PHYSIOCRAPHY

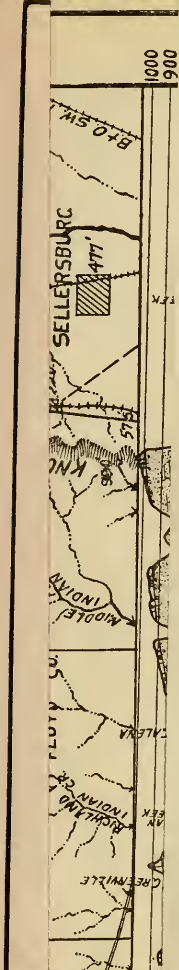
opment of topographic forms. It is the intention of the writer in this paper, however, to show specifically that the topographic forms present in the stages of youth and maturity are dependent very largely upon lithology and structure.

Topographic condition is the state of a region with respect to the form, size, and relationship of the relief features. The simplest topographic condition is that of a level plain. The coastal plain is an example. The topographic condition becomes more complex as relief or difference in elevation from place to place is produced by the physiographic processes, chief of which is running water. Essentially, topographic condition is expressed generally by stating the stage of topographic development in terms of the erosion cycle. But to say that a region is in youth, maturity, or old age is usually insufficient, since most regions with any but the softest rocks have more than one erosion cycle represented. If the region is limited in area, its topographic condition may be signified by the statement of the particular stage represented in the erosion cycle. But the terms youth, maturity, and old age are really only first glance terms when applied to any region of considerable areal extent. It will be seen that the form, size and relationships of the relief features are largely dependent upon rock structure and the denudational agency which actively produced them. The broader details included under the term topographic condition (details embraced in the statement of the stage of the erosion cycle, but never specifically stated) are such as the local base level, the elevation of areas above base level, the size of the streams, proximity to major streams, presence of major and minor divides or watersheds, and the regional topographic forms present which are dependent upon the type of rock and which may involve special physiographic processes. The meaning of the last mentioned detail of topographic condition may be clarified by an illustration. A region of limestone rock whose surface is well above the potential base level and in which subterranean drainage is well developed, is characterized by specific topographic forms. The outcrop of the Mitchell limestone, the so-called Mitchell plain with its disappearing streams and its sink-hole topography, illustrates the condition. Solution by descending meteoric waters concentrated along the joints and bedding planes of the limestone rock largely gave rise to the particular topographic forms present, and these forms are dependent upon the type of rock.

GEOLOGIC STRUCTURE OF THE KNOBSTONE CUESTA REGION.

General Stratigraphy.

The general geologic structure and topographic condition of the area here under discussion are shown on the general map. The map shows the Knobstone cuesta south of the Muscatatuck River. The general lithologic succession of rocks is shown by the geologic cross-section inserted in the map in proper position. This section extends from just north of Jeffersonville west to Marengo. Something like 100 feet of New Albany shale overlie the Devonian limestones which outcrop mainly east of the mapped area, and are present in the region mainly below drainage level. Succeeding the Devonian New Albany shale comes the Knobstone group of sandy blue-gray shales and muddy sandstones, the latter coming into prominence towards the top. The Knobstone group has a thickness of approximately 500 feet. The Knobstone and succeding formations discussed in this paper belong to the Mississippian period. The Harrodsburg, Salem and Mitchell limestones follow in order. The Harrodsburg limestone is rather silicious, and is usually more crystalline than the other limestones. It consists of thin to massive layers characteristically unevenly bedded, having a total thickness of about 90 feet. The Salem limestone is quite massive, and is typically a calcareous freestone. In the region under discussion it has



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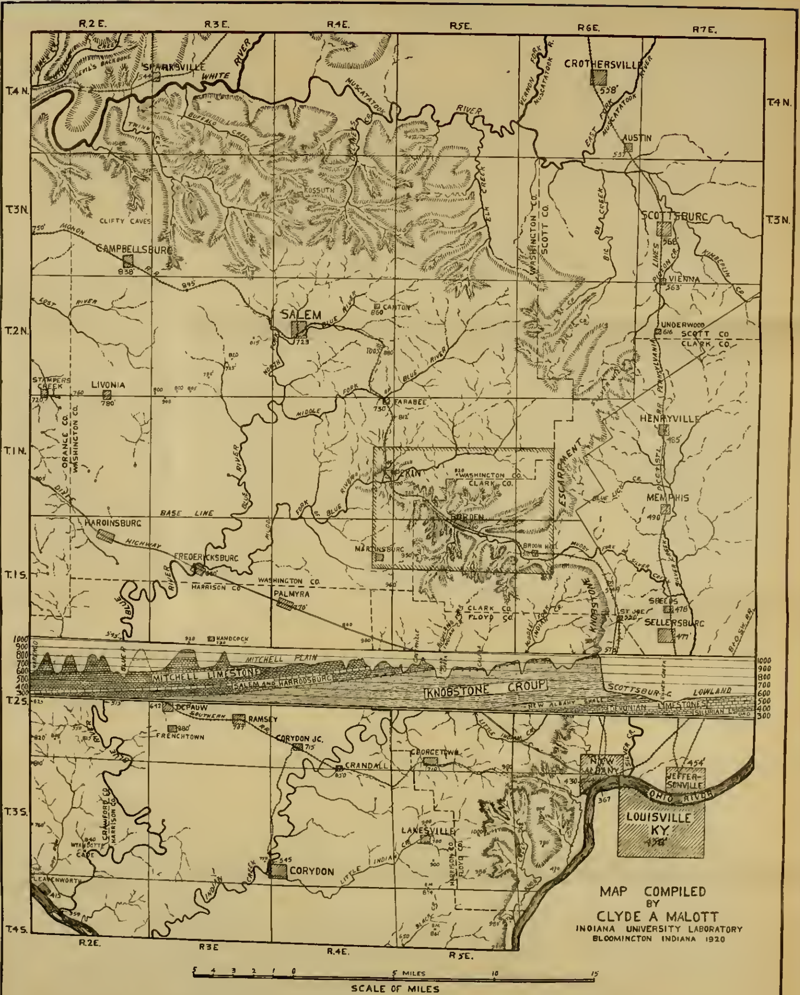

GENERAL MAP OF THE KNOBSTONE CUESTA REGION SHOWING THE GEOLOGIC STRUCTURE AND TOPOGRAPHIC CONDITION an average thickness of perhaps less than 40 feet. The Mitchell limestone is a group of limestones totaling some 350 feet in thickness in the region. It consists of about 220 feet of St. Louis limestone at the bottom, about 90 feet of Fredonia Oölite (representing the St. Genievieve), and about 40 feet of Gasper Oölite (distinctly of Chester age) at the top. The Mitchell limestone, though composed of several geologic units, is really a great lithologic unit of compact, thin-bedded, highly jointed limestone layers with occasional thin bands of shale and impure limestone horizons. The limestone in places contains considerable chert. Near the top of the St. Louis chert is quite conspicuous and bears numerous colonies of the coral *Lithostrotion canadense.* The uppermost strata outcropping in the region are the clastic members of the Chester series above the Mitchell limestone. The sandstones and shales, however, contain one or more members of limestone. The total thickness in the region is approximately 200 feet.

Regional Dip.

The above lithologic series dip to the west or probably a little south of west at the north of the area, at the rate of about 30 feet to the mile. Local dips may be much more or less than this amount, due to anticlinal or terrace flexures, such as the geologic cross-section shows. This regional dip causes each lithological unit to outcrop along its strike extending almost north and south. The lowest unit outcrops farthest east and the others follow in order to the west. No particular unit has an areal outcrop proportional in width to its thickness with respect to any other unit. This is because of the difference in resistance of the units and the topographic condition. The topographic condition of the area occasionally allows a thinner unit to occupy a wide area while a thicker unit may have a relatively narrow outcrop.

Areal Outcrop of Lithologic Units.

For the details of the areal outcrop of the above geologic or lithologic units, reference must be made to a geologic map. It may be stated here parenthetically that the writer is firmly convinced that no detailed physiographic study of the driftless area of southern Indiana can be adequately made without the aid of detailed lithologic knowledge of the region. This is essentially a geologic study, and its expression is found in the geologic map and the stratigraphic column. A general idea of the representative outcrop may be gained by reference to the geologic and topographic cross-section on the general map. This map also shows the position of Knobstone escarpment by means of hachure lines, following Newsom's map.[1] This escarpment is composed of the Knobstone strata. The lowland area to the east consists of both the lower softer portion of the Knobstone strata and the unresistant New Albany shale. At the south the Mississippian limestone belt begins at the very top of the escarpment and extends westward. In the middle portion of the area only the Harrodsburg limestone extends as far east as the

[1] J. F. Newsom, A Geologic and Topographic Section Across Southern Indiana. 26th Annual Report, Ind. Dept. of Geol. and Natural Res. 1901.

top of the escarpment. Farther north we have a true cuesta formed of the Knobstone, as the vale or back-slope is composed of the upper part of the Knobstone rock and this back-slope has a dip comparable to that of the strata of which it is composed. At the extreme north this cuesta is much dissected and destroyed by the short streams flowing north into the Muscatatuck River. Probably more than half of the mapped area has the Mitchell limestone as the surface rock. The great thickness of this limestone and the development of subterranean drainage have allowed a plain of considerable width to extend along the strike of the outcrop. This plain in places attains a width of 25 miles. To the west of the Mitchell limestone area and mainly at the south, the Mitchell limestone is partially covered by the clastic Chester members. The Chester in the area overlying the Mitchell limestone is mainly in the form of ridges and outliers..

The lower geologic units extend farther west along the east and west streams than their general upland outcrop, and often extend along the streams into the general outcrop region of the succeeding units. Thus, along Muddy Fork of Blue River the Knobstone strata extend several miles west of Pekin, whereas in the upland area adjacent the succeeding limestones form the surface rocks.

TOPOGRAPHIC CONDITION OF THE KNOBSTONE CUESTA REGION.

Factors Involved in the Development of Topographic Condition.

The explanation of the topographic condition of a region brings in an inventory of the responsible active and conditioning factors. The active factors are simply the physiographic processes, viz., weathering and erosion. The conditioning factors consist of both material and time elements. The material elements are the various lithologic units exposed to the physiographic processes. The expression "time elements" as used here needs brief explanation. The physiographic development of any region involves certain changes in the lay of the land with respect to the sea. These changes may be due to regional elevation or depression, or warping and tilting. These things may take place in the region itself or in an adjacent region which is intimately related to it. Thus, a slight regional depression or a tilting in the lower Mississippi valley would allow the sea to come much nearer the southern Indiana region, and certain important changes in stream regimen would result. In addition to land movements, glaciation has been an important factor in the physiographic development of many regions. Climatic changes may give rise to important changes in stream regimen, and should be included here. Regional elevation, regional depression, warping and tilting, glaciation, and climatic changes are influential conditioning factors, and are here called time factors, since they are occurrences which may belong to any period of time without regard to any other factors concerned in topographic development.

A full explanation of the topographic condition of a region may involve all of the above factors. A detailed physiographic analysis of the area here under discussion would certainly involve all of them. A full discussion of them is not intended here. Such would call for a detailed topographic map of the entire region. The topographic condition is very inadequately presented on the general map. The elevations given here and there, the presence and position of the Knobstone escarpment, the drainage lines, and the inserted geologic and topographic cross-section show the main elements. Where some considerable detail is given, a topographic map has been prepared. This small bit of the larger area is presented in detail to reveal a particular condition. The explanation of the present topographic condition of the area emphasizes lithology, since the lithologic units largely control the topography. The time factors or elements will be little more than mentioned, except where the explanation offered is one which has never been brought to the attention of physiographers previous to this presentation.

Influence of Lithology.

The New Albany black shale and the sandy shale and muddy sandstones of the Knobstone group belong to the class of non-resistant rocks. They weather very rapidly by alternate freezing and thawing. The fragments given up by the freezing and thawing method of weathering are readily carried away by the streams of running water. These rocks also are easily corroded by running water. Streams even of small size in these rocks have reached grade close up to their sources. As a result of this, streams heading in a region where these rocks are relatively high above local base level have a very precipitous descent at their very headwaters, but soon take on a relatively flattened gradient within a short distance from their over-steepened heads. The upper part of the knobstone, however, consists of a relatively large amount of massive impure sandstone. It is much more resistant than the lower Knobstone rocks. Only very locally, however, does this upper portion resist weathering sufficiently to stand as vertical cliffs. It may be said that the great thickness of Knobstone rocks with the corresponding rather wide areal outcrop does not result in the formation of cliffs. But the outcrop consists of quite steep slopes, often attaining 30 degrees or more from the horizontal.[2]

The Harrodsburg limestone immediately over-lying the Knobstone is much more resistant to mechanical denudation, and the interstream spaces are often gently rolling tracts. Where the streams have cut through the Harrodsburg capping of the Knobstone, tongue-like upland tracts are bordered by the steep slopes leading abruptly to the Knobstone valleys. The limestone is soluble in meteoric waters and since it is bedded and jointed, sink-holes are quite common. The Knobstone-Harrodsburg contact is consequently a spring horizon of some importance. The Harrodsburg is

[2]For weathering and erosion of Knobstone rocks, see the following references: J. F. Newsom, A Geologic and Topographic Section Across Southern Indiana, 26th Annual Report, Ind. Dept. of Geol. and Natural Res. 1901, pp. 265-273. G. H. Ashley, Geology of the Lower Carboniferous Area of Southern Indiana, Ind. Dept. of Geol. and Natural Res. 1902, pp. 54-58. E. R. Cummings, The Geological Conditions of Municipal Water Supply in the Driftless Area of Southern Indiana, Proceedings of the Ind. Acad. of Science, 1911, p. 114-124.

frequently the regional rock back from the Knobstone escarpment for miles, and forms an excellent example of a structural plain. Newsom[3] makes it clear that the Harrodsburg has been stripped by erosion from the underlying Knobstone to the north of the area under discussion, and that this removal has permitted in later times the more rapid dissection of this portion of the area.

The Salem limestone where typically developed is a calcareous freestone. It is very massive and unbedded, and is not a well-jointed limestone. These structural characteristics prevent it from having many sink-holes formed in it directly. Topographically it is characterized by long gentle slopes and fairly broad valleys. It is somewhat less resistant to denudational agents than the underlying Harrodsburg, but frequently the topography of one merges into that of the other rather indistinctly.

The Mitchell limestone is fairly resistant to mechanical denudational agents. It is structurally characterized by its great number of thin beds of very close and compact nature and its highly jointed condition. These structural characteristics combined with its position above the base level of the region of its outcrop have been responsible for a wide area of subterranean drainage whose perfection of development is probably not excelled anywhere. It is pitted with numerous sink-holes of all sizes and combinations. Only the larger streams in this limestone belt are surface streams. The outcrop of this limestone belt almost everywhere possesses a typical karst topography. Its presence as a fairly resistant stone mechanically and its disposition to drink up the waters which fall upon it by subterranean drainage have caused to come into existence a wide structural plain which has a westward dip somewhat less than the dip of the strata which make up the lithologic unit. A structural plain of this kind is expected to have an inclination less than the dip of the rocks where their thickness is considerable and their resistance not extraordinary. The removal of the overlying material took place rather progressively from the east to the west. The eastern portion was exposed first and is therefore older. While the western part was still protected by overlying strata, the eastern portion was being reduced. The presence of outliers of the overlying clastic Chester several miles to the east of the general Chester scarp is indicative of the method of the formation of the Mitchell plain.[4]

The clastic Chester members over-lying the Mitchell limestone are made up of unresistant shales and rather resistant sandstones with one or more intercalated limestones. Sandstones predominate in the region here mapped. The limestones are inconstant. The Chester of the region is found rather

[3]Loc. Cit., p. 268.

[4]Probably no clearer presentation of the principles underlying the development of sinkholes and underground drainage has been written than the article by J. W. Beede entitled, "The Cycle of Subterranean Drainage as Illustrated in the Bloomington, Indiana, Quadrangle". Proceedings of the Indiana Academy of Science for 1910, pp. 89-111. This article is a classic of its kind. Beede regards the Mitchell plain (which he names such) as a peneplain. This idea is not emphasized by the writer, yet some evidence appears to show that the Mitchell plain part coincides with local peneplains, representing one or more halts in regional uplift, but as a whole it is probably structural. See pp. 24-26. "The 'American Bottoms' region of Eastern Greene County, Indiana—A Type Unit in Southern Indiana Physiography", C. A. Malott, Indiana Univ. Studies No. 40, March 1919.

as outliers on the Mitchell. As indicated above, the Mitchell has been revealed by the stripping away of the over-lying clastic Chester materials by mechanical denudation. Outliers occur as much as ten miles east of the much dissected Chester scarp. The cross-section on the general map shows the topographic position and nature of the outliers. They are often ridge-like on the interstream tracts.

Influence of Physiographic Development.

Further explanation of the present topographic condition of the area may be gained from the interpretation of the topographic forms present in the region itself and in the adjacent regions. It appears that sometime about the middle of the Tertiary the entire region was reduced to a peneplain, all parts having been reduced to their respective base-levels.[5] The region was then rejuvenated by uplift. Dissection of the uplifted peneplain followed. Dissection was fairly complete near the major streams, and in the regions of soft rocks local areas were reduced to base-level. These locally reduced plains indicate that the uplift amounted to something like 175 feet. The region was again rejuvenated and dissection was renewed or continued. The Tertiary uplifted peneplain is now represented by remnants which are as much as 300 to 500 feet above the present base-level.

The New Albany shale and the lower part of the Knobstone areas were reduced to a lowland in contrast to the region to the west of the Knobstone escarpment. The lowland plain consists of an undulating strip of country varying from slightly above 400 feet in the lowlands adjacent the Ohio River to something like 600 feet in the low divide between Silver Creek and the tributaries of the Muscatatuck River. Since there are a large number of hills and rather flat interstream tracts at an elevation of 500 feet or more at the south and coming up to 600 feet near the above mentioned divide farther to the north, it has been stated that a base-level plain or local peneplain was formed at that level.[6] The writer concurs in the belief in a base-leveled plain of local area, and believes that its further development at the south was terminated by rejuvenation. The rejuvenation, however, was not necessarily brought about by uplift, as stated by Butts. The dissection of the plain was just as likely brought about by drainage changes made near the beginning of the Pleistocene. The present Ohio River is a large stream made up of a number of former drainage basins which were more or less individually destroyed or deranged by combination into a large major stream approximately skirting the outer limits of glacial advance. This drainage derangement took place largely near the beginning and during the earlier part of the Pleistocene. A very much

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[5]For the physiographic development of southern Indiana and associated regions see the following: C. A. Malott, the "American Bottoms Region of Eastern Greene County, Indiana—A Type Unit in Southern Indiana Physiography, Ind. Univ. Studies No. 40, 1919, pp. 3-4, 21-36. Chas. Butts, Geology of Jefferson County, Kentucky, Kentucky Geological Survey, 1915, pp. 201-203. It may be stated here that valley filling is not a problem of the region considered in this paper. Such valley filling as occurs may be definitely referred to outwash and valley-train material from the Illinoian and Wisconsin glacial borders.

[6]Chas. Butts, Geology of Jefferson County, Ky., Ky. Geological Survey, 1915, pp. 201-203.

smaller stream than the present Ohio occupied this territory near Louisville. It was able to reduce the area of the soft rocks nearly to base-level, but it had a much steeper gradient in its graded condition than the much larger present Ohio. When the present Ohio invaded the basin of the much smaller pre-glacial stream the local peneplain was STATICALLY REJUVENATED, due to the sinking of the larger stream into the plain on account of its ability to reach a much lower gradient in its graded condition. It may be further noted that the region of the Muscatatuck River to the north still possesses such a local base-leveled plain as existed in the New Albany locality. It is inferred that the stream which the present Ohio dispossessed was somewhat near the size of the Muscatatuck or the White river. These streams possess a gradient in their graded condition of slightly less than one foot to the mile, while the Ohio below New Albany has a gradient slightly less than three inches per mile. It would appear that such a change in gradient initiated by the invading Ohio would allow a trenching of something like 90 feet.[7] This corresponds to the amount of the trenching of the local peneplain in the vicinity of New Albany.

Thus the region of soft rocks, the region occupied by the New Albany shale and the lower part of the Knobstone group, has been greatly reduced as a whole. In this region no remnant of the uplifted Tertiary peneplain is preserved. It is low compared to the region on the west where considerable tracts of the uplifted Tertiary peneplain remain at an elevation of 900 to 1000 feet above sea level. The broad valley of the Muscatatuck on the north is at an elevation of 525 to 550 feet. The Ohio on the south has a narrow alluvial plain of about 430 feet in elevation. Low water is 60 feet lower. Silver creek flowing directly to the Ohio along the strike of the outcrop of the non-resistant lower Knobstone shales and the New Albany shale has reduced much of its drainage area to a low plain. The Muscatatuck and its tributaries in the same soft rocks have developed a notably wide plain. The continuous lowland developed in these soft rocks has been designated the Eastern Lowland by Newsom.[8] It will here be referred to as the Scottsburg Lowland, from its typical development in the vicinity of Scottsburg in Scott County.

Immediately to the west of this lowland comes the Knobstone escarpment, which from a distant view loses its ragged, dissected aspect, and appears wall-like to the observer. It rises abruptly 300 to 500 feet above the lowland. The short streams which descend the escarpment against the dip of the rock have cut down to a fairly low gradient, almost back to their very sources. Back of the escarpment the streams often head at the very crest and flow west and south down the long back-slope of the cuesta. These streams have a relatively long distance to go before reaching the Ohio,

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[7]This figure is derived by taking the difference between the gradients of the Ohio and its assumed predecessor from New Albany to Cannelton, a distance of approximately 120 miles. In the latitude of Cannelton valley filling begins to be rather conspicuous, and nullifies any difference in the gradients of the former and the present stream, assuming that the valley filling of southwestern Indiana and associated regions belongs to the Pleistocene. (See C. A. Malott, The "American Bottoms Region", Ind. Univ. Studies, No. 40, 1919, pp. 26-34.)

[8]J. F. Newsom, A Geological Section Across Southern Indiana from Hanover to Vincennes, Proceedings of the Indiana Academy of Science, 1897, p. 251.

and consequently must have a much lower average gradient. These latter streams flow over fairly resistant rock. They are rather peculiar in that they possess gradients about equal in all portions of their courses. The gradient of Blue River will be discussed in some detail below.

The general topography of the back-slope portion of the cuesta is largely dependent upon the rock in which it is developed. These regional features dependent upon the rock have already been briefly described. For some miles back from the escarpment crest, the interstream tracts reach up to the preserved portions of the uplifted Tertiary peneplain. The main streams have broadly trenched this uplifted plain, and are from 100 to 250 feet lower. The interstream areas are somewhat beveled toward the main streams, and fairly gentle slopes are the rule. Even in the Knobstone rocks (these are the rocks on which the slopes are developed for several miles back from the scarp), the valley slopes are fairly gentle. The exception is along the line of Muddy Fork of Silver Creek, which is a special exception, and will be discussed below. Where the regional rock is composed of the Harrodsburg and Salem limestones, the slopes are long and gentle, and a late maturity type of topography is generally prevalent. This sort of topography is excellently shown on the detailed topographic map in the vicinity of Martinsburg.

Farther west, in the region of the outcrop of the Mitchell limestone, the topography has the appearance of an uplifted sinkhole plain, which it probably is in part. This plain has a westward slope of about 20 feet to the mile. The uplift following the development of the Tertiary peneplain permitted removal of waste material down to about the top of the St. Louis limestone horizon. Drainage upon this rock is typically subterranean. But it is probable that a portion of this plain is of base-level origin, as it in part corresponds to locally developed plains elsewhere about 175 to 200 feet below the older and higher peneplain. Further uplift of the region permitted the trenching of the plain by the main streams. Blue River and Indian Creek receive few surface tributaries in their intrenched condition in the sinkhole plain, or Mitchell plain. Lost River in its headwater area flows over this broad fairly level plain in a valley scarcely below the plain itself. Farther west this stream sinks into the limestone and is lost to view for some 10 miles. From the place where it sinks to where it appears again at the surface it makes a descent of about 125 feet. The old surface channel is present. There is little doubt but that uplift was a factor in bringing about this subterranean condition. Distinct evidence is at hand showing that this subterranean space of Lost River has been progressively made longer and longer, and it is probable that sinks will continue to develop in the stream farther up than the present sink with a resultant abandonment of the present one.

Approximately one-half of the Mitchell limestone area above the general ground-water table is partly covered by clastic Chester strata. The Chester occurs as ridges and isolated hills which rise high above the flat spaces of the Mitchell limestone areas. These hills reach approximately to the elevation of the uplifted Tertiary peneplain, attaining heights of

900 feet or more. The region of their occurrence is quite rugged. Blue River from the vicinity of Fredericksburg to the Ohio River is intrenched deeply in the Mitchell limestone group, and the adjacent hills are developed in the clastic Chester Series. The tributary streams upon approaching Blue River become subterranean. The intrenched condition of the main stream is responsible for this condition of the tributaries. The streams are surface streams in the clastic rocks of the Chester Series, but on coming down to the limestone below, the water disappears in the enlarged joints. The development of these streamless tributary valleys has been progressive. As the tributaries have grown and cut downward, they have progressively reached the limestone. The water then has developed a sink near the margin of the uncovered limestone. Later, when more of the limestone became exposed by the removal of the clastic material, a new sink would appear farther upstream, and the old one would be abandoned. In this way, too, the flat valleys in the Mitchell limestone have been developed. Probably much of the Mitchell plain itself has been developed in this manner.

THE PECULIAR GRADIENT OF BLUE RIVER.

Blue River with its several head streams each beginning at the crest of the escarpment, offers an excellent example of the southwestwardly flowing streams. The several sources of Blue River are well above 900 feet above sea level on the remnantal portion of the Tertiary peneplain at the crest of the escarpment. The three main branches are down to 715 feet at Salem, 730 feet at Farabee, and 700 feet at Pekin, respectively. From these places to the Ohio River the fall is a little better than five feet to the mile. This gradient is continued practically to the very Ohio itself. This condition is rather unusual. Normally a stream is well graded in its lower course, and possesses a much lower gradient in this portion of its course. Blue River is not in a graded condition in its lower reaches, nor does it have a lower gradient in its lower reaches than it has much farther up stream. It is in a graded condition, however, in its middle portion, as for instance, Muddy Fork in the vicinity of Pekin. Here, in one of the three branches of Blue River, the gradient is as low as in the many times larger lower portion of the stream. Ashley noted this peculiarity of Blue River, and offered rejuvenation by uplift or tilting as an explanation.[9]

There are three different explanations which may be offered in interpretation of this rather unusual gradient of Blue River and other similar streams of the region. First, the condition may be the result of the difference in the hardness of the rock in different reaches of the stream. In the region of Pekin, Muddy Fork of Blue River is at grade in a wide valley which it has developed in Knobstone strata. The Salem and Farabee forks are in a similar condition where they are developed in the Knobstone. Farther down in the course the stream is intrenched in the mechanically

[9]G. H. Ashley, Geology of the Lower Carboniferous Area of Southern Indiana, 27th Annual Report, Indiana Department of Geology and Natural Resources, 1902, pp. 58-61.

resistant Mitchell limestone with its capping of Chester sandstones. The hard rock below has acted as a barrier permitting the stream to reach a graded condition where it passes over the non-resistant strata, while in the hard rocks time enough has not yet elapsed to permit a graded condition to come into existence. Second, the condition may be the result of rejuvenation by uplift, as explained by Ashley. Under this explanation the effects of the rejuvenation have not yet been transferred to the middle and upper reaches of the stream, and these upper reaches still possess the old graded condition while the lower reaches are steepened as a result of rejuvenation. The third explanation offered is the same as that given above as an explanation of the partial or local peneplain stretching north from New Albany. Under this explanation rejuvenation took place on account of a major drainage line, the present Ohio River, taking the place of a small pre-glacial stream.

It is likely that the peculiar gradient of Blue River is a combination of the three conditions offered in explanation. The effect of rejuvenation by uplift would ordinarily be transferred gradually up stream. The hardness of the rock of the lower reaches of the stream has much delayed the transference of the rejuvenated condition of the stream gradient, permitting the retention of the graded condition in the mechanically unresistant rocks above. The later rejuvenation caused by the replacing of the minor local stream by an important major stream since the beginning of the Pleistocene has given an additional steepness of gradient to the lowest reaches of the stream. The transference of this steepened gradient beyond the lowest part of the stream has not yet taken place, because of insufficient time since the last change in stream regimen. It is not thought that subterranean drainage of much of the tributary space should influence the gradient of Blue River, unless it can be shown that much water which formerly went into it is now diverted to another stream by an underground channel. Blue River probably receives as much of this sort of drainage as it loses. Should considerable tributary space, however, have its waters diverted much farther down stream than these waters formerly entered, there would be some change in the gradient locally. It may be mentioned further that the graded condition of Muddy Fork of Blue River may have been partly brought about by the loss of a large tributary in the vicinity of Pekin by surface piracy.

A NOTABLE CASE OF SUCCESSIVE STREAM PIRACY.

The Development of Muddy Fork of Silver Creek.

The factors as above outlined in the topographic development of the Knobstone cuesta region have permitted considerable areas of the old uplifted Tertiary peneplain to exist near the crest of the escarpment. But such a topographic condition as exists in the region of the escarpment with the present drainage systems is rather unstable. There is such an unequal amount of work being done by the set of streams that flow from the scarp eastward and northward and the set of streams which flow westward and southward, that the divide is being shifted down the dip of the rock westward and southward. This condition of instability of the position of the crest of the escarpment has been continued from the past. From early topographic maturity until the beginning of old age is a period of drainage adjustment. When adjustment has been completed, old age of the stream system has already begun. In the region in question stream adjustment began a long time ago, but the adjustment is far from complete.

Since the short, steep-headed streams coming down from the Knobstone escarpment have a decided advantage over the back-slope streams, they have a tendency to develop their drainage area by headward erosion into the territory drained by the back-slope streams. The headwaters of the backslope streams may be expected to be captured by the eastward and northward flowing streams. Search along the escarpment shows that this drainage adjustment as a whole has not taken place, but in a number of places appears imminent. There is one place, however, where such piracy has notably taken place. This is along the line of Muddy Fork of Silver Creek, from near Pekin in southeastern Washington County to near Broom Hill in Clark County. Here, much reversal of drainage has already taken place, and a great break occurs in the escarpment along the line of this stream. Newsom[10] repeatedly calls attention to this rather unusual opening in the Knobstone escarpment. His maps show a beautiful example of barbed drainage pattern and the broad col at Pekin where the formerly westwardly flowing stream entered Muddy Fork of Blue River But it does not appear that Newsom realized the significance of these tell-tale features. Ashley[11] calls attention to the area and the causes of the condition in the following words: "- the soft and easily eroded nature of the Knobstone has allowed the erosion to proceed more rapidly so that the gorge has in many cases sunk its bottom down to drainage level, and the point of rapid descent has advanced from the mouth to the headwaters on account of the shortness of the stream. Indeed, in many cases it is evident that, due to their shortness, these northward and eastward flowing streams are cutting down the divides at the expense of the streams flowing the other way. A good illustration of this 'river stealing', as it is called, is seen about Borden. The valley in which Borden lies originally drained to the northwest, the divide being nearly as far east as Broom Hill. But the Muddy Fork of Silver Creek, having cut down its side of the divide faster than the stream draining to the northwest, has captured all the drainage about Borden and it is only a question of time when it will extend up so far as to tap the Mutton (Muddy) Fork of Blue River at Pekin and divert all the drainage above that point to Silver Creek".

The topographic map accompanying this paper shows the topographic conditions of a small area in the region of Pekin and Borden. This somewhat restricted region offers details of much interest in the drainage

[10] J. F. Newsom, Geologic and Topographic Section Across Southern Indiana, 26th Ann. Rept. Ind. Dept. Geol. & Natural Resources, 1901.

[11] Geology of the Lower Carboniferous Area of Southern Indiana, 27th Annual Report of the Dept. of Geology and Natural Resources, 1902, p. 61.

adjustment of the region. It lies between five and ten miles back from the general scarp. Muddy Fork of Blue River flows west-southwest past Pekin, and as a graded stream is entirely in the Knobstone rocks. Muddy Fork of Silver Creek flows southeast, and is characterized by a barbed drainage pattern. This drainage is almost wholly in the Knobstone rocks. Only the long, tongue-like, inter-stream tracts 800 feet or more in elevation are capped by the Harrodsburg. The slopes are steep and wooded, and are quite characteristic of Knobstone topography where it is in a much dissected condition due to minor stream development. The uplands between Pekin and Martinsburg have a typical surface expression of the overlying Harrodsburg. The inter-stream tract east of Martinsburg reaches an elevation of about 950 feet, and is expressive of a remnant of the uplifted Tertiary peneplain, being capped by Tertiary gravels and sand.

The valley of Muddy Fork of Blue River at Pekin has an elevation of 700 feet, and seems to be in a graded condition. In the next fifteen miles the valley descends 100 feet, being approximately at an elevation of 600 feet at Fredericksburg. Drainage from approximately forty square miles flows past Pekin. Muddy Fork of Silver Creek heads in a number of steep ravines a short distance southeast of Pekin. These ravines are sharply trenched below the general level of the upland. Starting from an elevation of 730 feet in a broad, valley-like sag, a mere gravel and silt terrace above Blue River valley at Old Pekin, marking the lowest part of the divide between the two stream systems, one may make a rapid descent into Muddy Fork of Silver Creek. A descent of 100 feet is attained in the first mile, and within one and one-half miles the elevation is down to 600 feet. This is the elevation of Blue River fifteen miles below Pekin. At Borden the valley of Muddy Fork of Silver Creek is down to an elevation of 560 feet. The stream here has developed a fairly wide, flat valley and is in a graded condition.

The barbed drainage pattern of Muddy Fork of Silver Creek is a result of stream piracy. The parent stream of the present Muddy Fork of Silver Creek was a small stream flowing down the eastern face of the Knobstone scarp very similar to numerous others of the present time. Back-slope streams of the cuesta flowed westward from the crest of the escarpment. The position of the parent stream of Muddy Fork of Silver Creek does not appear to have been more favorably located for its development of headward erosion than many streams of the present along the escarpment. But for some reason it has succeeded in capturing practically the entire stream system of a large tributary that formerly flowed northwest and emptied into Blue River at Pekin. It would appear that after having once broken through the divide near the crest of the escarpment further capture of the lower tributaries followed in relatively quick succession.

The drainage direction of the tributaries of Muddy Fork of Silver Creek coming in from the south between Borden and Broom Hill suggest that a single stream flowed to the northwest one time through sections 13, 12 and into section 1, and that this unit of drainage has been broken up by the successive capture of parts of it by different branches of the invading Muddy Fork. Fairly distinct sags in the ridges between the small separate systems strengthen this suggestion. If such a drainage adjustment ever took place, it has been so long ago that only these slight evidences of it remain. Such an adjustment would be possible, and if it did actually take place, it is probable the only case of its kind described.

The first stream which still retains direct evidence of having once drained into the Blue River system is Dry Fork Branch. This stream now empties into Muddy Fork of Silver Creek, about a mile below Borden. It is the first of the series of barbed tributaries. In succession the tributaries of the old northwest drainage line were annexed to the Silver Creek system. A number of these, especially those coming in from the north, are decidedly barbed. The latest ones to be taken in were those in sections 29 and 32, between Pekin and Borden. Evidence of this successive capture of the tributaries of the northwest extending stream is not found alone in the barbed drainage pattern. The gradation plain formed by the northwesterly flowing stream has not been entirely destroyed. To the northwest of Borden, just above the town, is preserved the oldest recognized portion of the old gradation plain. Quite a large remnant is preserved here, and it still retains the silts and gravels of the old stream bed. This remnant is shown beautifully on the topographic map. Fig. 1 shows its even line as quite a distinct feature where it has been cut into by the reversed drainage. The elevation of this ancient valley remnant is about 755 feet, whereas the present reversed valley floor is 575 feet in elevation. This means that the drainage change permitted the old gradation plain to be trenched at this place something like 180 feet. At the mouth of Dry Fork Branch the en-

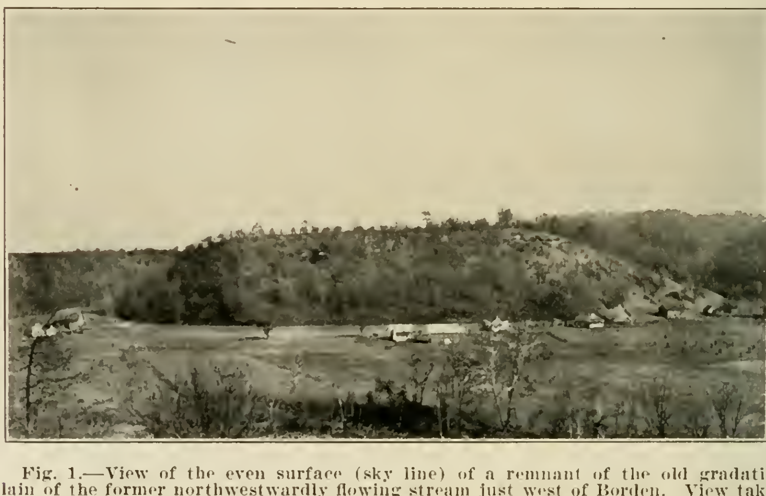

Fig. 1.—View of the even surface (sky line) of a remnant of the old gradation plain of the former northwestwardly flowing stream just west of Borden. View taken from the south side of the present reversed valley. The present reversed stream is entrenched at this place 180 feet below the old gradation plain. The gradation plain remnant here has preserved upon it old gravels and silts similar to those shown in Fig. 5.

trenchment is not less than 200 feet. Remnants of the gradation plain are perfectly preserved on both sides of the present intrenched valley to the northwest of Borden. The remnants are more extensive farther up the stream where the piracy occurred at successively later periods. Finally the whole of the old valley is seen for a stretch of about three-fourths mile in section 30 stretching southeast from old Pekin. Old Pekin is built on the Blue River margin of it. (See Figure 2, 3, and 4.) This portion of the old valley is more than one-half mile wide, as wide as the present valley of the Muddy Fork of Blue River. It was made by a stream comparable in size to this Fork of Blue River. It drained an area of approximately 35 square miles while that of Muddy Fork of Blue River drains approximately 40 square miles.

The few tributaries of the old drainage course yet remaining are shallow streams. The largest one comes in from the south. It is not discernably below the old valley flat in the northeast one-quarter of section 31, (See Fig. 4). On approaching Blue River it is trenched broadly into the old alluvial deposits, and enters Blue River accordantly. The small tributaries from the north have scarcely been able to transport their load across the old valley flat, and have the appearance of having slightly aggraded the old valley flat where they debouch upon it.

Fig. 2.—View of the old valley where it joins the valley of the Muddy Fork of Blue River near Pekin. View taken from the road on the hill in the northern half of Sec. 31. Old Pekin in the distance.

The divide between the present streams on the old valley flat southeast of Old Pekin is only 30 feet above the valley of Blue River. The old valley-flat projects above the valley or Blue River as a terrace. It appears that Blue River has cut its valley down something like 30 feet since the stream adjustment has taken place, but such is probably not the case. It is evident

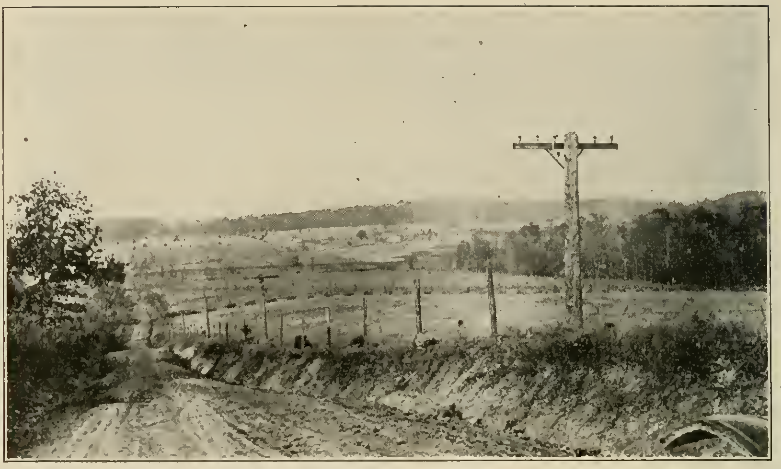

Fig. 3.—View taken from the same place as in Fig. 2, but looking more directly across the old col which formerly was occupied by a stream draining an area of 35 square miles in extent. This old abandoned valley is filled 30 feet or more with ancient alluvium, and stands 30 feet or more above Blue River valley.

Fig. 4.—View taken from the hill in N. E. quarter of Sec. 31, looking east up the old graded valley. The trees in the distance mark a deeply intrenched drainage line belonging to the Muddy Fork of Silver Creek. The newly diverted drainage is rapidly destroying the old graded valley plain.

that the old valley-flat is composed of alluvium to a considerable depth, probably as much or more than the entire 30 feet of its projection above Blue River valley. (See Fig. 5). This alluvium composed of gravels and silts over the old bed rock floor is much deeper than a normal stream of its size should have possessed. With the beheading of this ancient drainage in the earlier stages of successive piracy the drainage remaining would not be able to retain as low a gradient as the previous larger more vigorous drainage. The result would be aggradation of the valley. If this is a correct interpretation, the fact that the present valley of Blue River is 30 feet below the old valley flat is not altogether a result of erosion downward of its bed since the stream adjustments have been made. Again this aggradation of the lower part of the valley will aid in explaining the exceptionally low gradient of the old northwestwardly flowing stream as determined by the relative elevations of the remnants of the gradation plain. At Borden it is 755 feet and in the preserved lower portions it is 730 feet where it is lowest. This would be a gradient of less than five feet to the mile.

The Potential Future of Muddy Fork of Silver Creek.

When one realizes that the larger part of Muddy Fork of Silver Creek has been made at the expense of the Blue River drainage system, and that

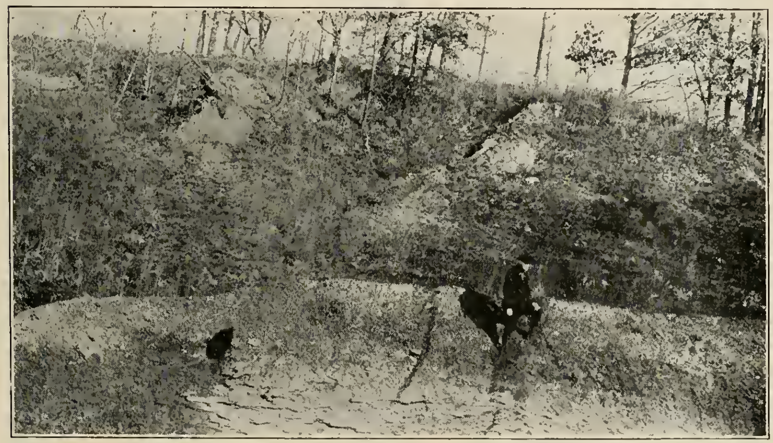

Fig. 5.—View showing gravel and silt overlying the bed-rock floor of the old abandoned valley southeast of Pekin. Monon R. R. cut in the southwest corner of Sec. 29, about 2 miles southeast of Pekin.

the last annexation was relatively recent, one must inquire whether the drainage adjustments are yet complete. It needs little more than casual observation to note that the piracy is far from complete in the Pekin-Borden region. The tiny stream shown on the topographic map in the southeast corner of section 30 was really the latest accession. This was a mere wash leading to the northwest before the Monon Railroad was built through the old col. The cut necessary for a more gradual descent into the Silver Creek system allowed the wash to send its waters into the

Silver Creek system. The small wash from the north now sends its water into both systems. The rapid headward erosion of the new system will soon cause all of it to be deflected to the southeast. Likewise, the remaining tributaries of the old system must be taken over into the new system. Muddy Fork of Blue River would normally remain at its present elevation for a long period. In the meantime, the new system will invade farther and farther to the northwest, and in a short time, geologically speaking, Muddy Fork of Blue River itself will be taken over into the Silver Creek system. The headward erosion of the invading system will be relatively rapid, since it has mainly alluvium to work upon in order to capture Blue River. One might go still further in anticipation of this successive piracy. The invading system will extend itself in the direction of the present flow of Muddy Fork of Blue River and capture tributary after tributary of the present stream, just as it has done in the past after capturing Dry Fork Branch of the old system. By following the line of a graded stream in this manner, the successive stream piracy must be relatively rapid. Such successive stream piracy will continue as long as the stream gradient in the reversed direction is more favorable for headward erosion than the normal present direction. Whenever these stream gradients reach a balanced condition the adjustment is complete and the drainage systems have arrived at the beginning of the old age condition.

Development of Special Bed-Rock Terraces.

Another result of the above described stream adjustments must be mentioned in this paper. The barbed tributaries of Muddy Fork of Silver Creek have been adjusting themselves to a direction of flow in accord with that of the main stream where they enter it. They have a tendency to adjust themselves in such a manner that the junction of the main stream and the tributary form an acute angle pointing in the down stream direction. Practically all of the barbed tributaries have been and are making this adjustment. Those on the north of the main stream have much more perceptibly oriented themselves in the down stream direction than those on the south. This is because the dip of the rock favors a migration of the main stream against the south bluff, especially in the non-graded portion of the valley. This has resulted in a shortening of the tributaries from the mouth and the consequent nullification of their orientation in the downstream direction of the mainstream. While this direction adjustment of the barbed tributaries has been taking place, the valleys have also been deepened by down cutting. The combination of this direction adjustment at the mouth of the tributaries and the down cutting has permitted bed-rock benches or terraces to come into existence on the upstream side near the mouths of the tributaries. (See Fig. 6.) Some of the tributaries have more than the one set of terraces. They range in height from 10 to 25 feet above the present valley flat or above one another. It is probable that new accession of drainage due to capture above has had something to do with the development of these bed-rock terraces, since the resulting more vigor-

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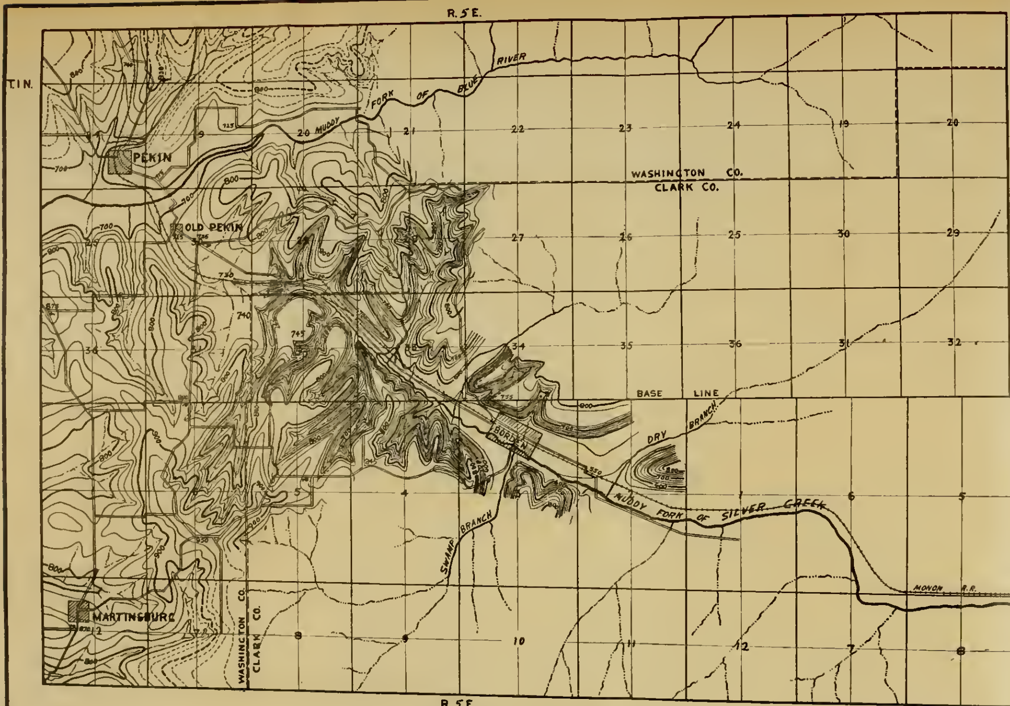

TOPOGRAPHIC MAP OF PEKIN-BORDEN REGION, WASHINGTON AND CLARK COUNTIES, INDIANA

SHOWING A NOTABLE CASE OF STREAM PIRACY, WHERE BY REVERSAL OF THE DRAINAGE A NEW CYCLE OF EROSION IS INTRENCHED WITHIN AN OLDER ONE. NOTE THE IMMINENCE OF THE DIVERSION OF MUDDY FORK OF BLUE RIVER AT OLD PEKIN.

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SCALE OF MILES

CLYDE A. MALOTT
INDIANA UNIVERSITY
1919

ous stream would permit a lowering of the gradient where previous to drainage accession the valley had become somewhat broadened in a comparatively graded condition. But in any case the adjustment of the barbed tributaries in the down stream direction of the main stream is the responsible factor determining the position of the terraces. These terraces have an origin unlike any others that have come under the observation of the writer. So far as he is aware such terraces have never been described before.

It may be mentioned here that the case of piracy here described is one of the same type as that of the famous Kaaterskill Creek of the eastern face of the Catskill mountains, New York.[12] The topographic conditions are essentially the same except for magnitude. Kaaterskill Creek has taken over about 12 square miles of the head-water drainage of Schoharie Creek, the back-slope stream of the Catskill mountains cuesta. On the same cuesta an adjacent scarp-stream, Plaaterskill Creek, has added some 5

Fig. 6.—Bed-rock terrace northwest of the mouth of the barbed stream one-half mile northwest of Borden. This terrace is an example of those being formed where the barbed streams come into the main stream. They are due to an adjustment of the barbed tributaries to the present reversed drainage line as downward erosion is taking place. These terraces have an origin unlike any others known to the writer.

square miles to its drainage by successive piracy. Farther south, Sawkill Creek has stolen some 10 square miles from a westward flowing stream, but this case is not a case of successive piracy. It was perhaps largely brought about by glacial action. It will be re-called that Muddy Fork of Silver Creek has added something like 35 square miles to its drainage by successive piracy.

[12]For a brief description of this piracy see: N. H. Darton, Bull. Geol. Soc. Amer., Vol. VII, 1896, pp. 505-507. Also, R. D. Salisbury and W. W. Atwood, U. S. Geol. Surv., Prof. Paper, 60, 1908, pp. 49-50.

SUMMARY AND CONCLUSION.

This paper conforms to the principle that physiography is explanatory rather than a mass of descriptive matter. The map, especially the topographic map, takes the place largely of the descriptive matter. The purpose of the paper is to show specifically the responsibility of the geological structure in the development of topographic form, especially in a regional way, and also to show the importance of the combined geologic structure and topographic condition in drainage adjustment. It deals with the knobstone cuesta region lying between the Muscatatuck and Ohio Rivers near the eastern margin of the driftless area of southern Indiana. The details defining, describing, and explaining the geologic structure and topographic condition take up a relatively large proportion of the paper. Details are given showing how the particular lihtologic units with their regional westward dip are important conditioning factors in giving rise to topographic forms, and that the topographic condition in the stages of youth and maturity are lagely dependent upon lithology and structure. Other conditioning factors scarcely less important are the so-called time factors, such as regional elevation and depression, warping and tilting, glaciation, and climatic changes. Active factors, weathering and erosion, are given no detail, but their activity is tacitly assumed and occasionally referred to directly. The development of the Scottsburg Lowland, or the Eastern Lowland of Newsom, is given an explanation somewhat different from any heretofore advanced. A local peneplain after having been normally developed is subjected to further erosion by a peculiar sort of rejuvenation brought about by glaciation. The Ohio River has been formed from a number of smaller streams which were near the margin of the glacial ice at its farthest advance. This stream dispossessed a minor stream in the vicinity of New Albany, and on account of its ability to reach a much lower gradient than the smaller stream, intrenched itself in the local peneplain developed in the area of soft rocks. Tributary streams have since partially destroyed the local peneplain rejuvenated in this manner. Such a rejuvenation is here called *static rejuvenation.*

The peculiarity of the streams flowing east and north from the Knobstone escarpment is described. Blue River is discussed in some detail, since it is representative of all the streams on the back-slope of the cuesta. Its peculiar, fairly uniform gradient demands explanation. It is shown that such a gradient is the result of a complex set of conditions, in which lithology, uplift, and static rejuvenation play their part.

Finally the details of the piracy of Muddy Fork of Silver Creek are given. It is shown that this piracy is a direct result of the geologic and topographic condition along the Knobstone escarpment. This piracy is not an instance of a single case, but consists of successive piracy wherein a large number of tributaries belonging to a single streato system are annexed to the drainage system of an invading stream. It is noted that the conditions are highly favorable for the piracy to continue, and that eventually the larger part of Muddy Fork of Blue River will be taken over by Muddy Fork of Silver Creek. Such piracy will continue until a balanced condition of the gradients of the two stream systems is reached. Such a condition will mark the beginnings of old age of the stream systems, when stream adjustments are practically complete. It is further noted that in the adjustment of the barbed tributaries to the reversed drainage, an unusual set of bed-rock terraces is being made where the barbed tributaries join the main stream. These terraces are due to conditions unlike any which have elsewhere come under the observation of the writer.

The special features in this paper to which the attention of physiographers is directed are as follows: definition of the terms "geologic structure" and "topographic condition" as physiographic terms; a grouping of the physiographic factors under two heads, active factors and conditioning factors; a division of the conditioning factors into the so-called "material" and "time elements", with definitions and illustrations of the new terms used; a declaration of the importance of geologic structure (lithology and structure) in the development of regional topographic forms in the stages of youth and maturity;[13] an extension of the use of the term "rejuvenation" in which the term "static rejuvenation" is proposed, and along with the term a regional example of it offered. These are phases of physiography which the writer attempts to make pertinent or which he wishes to present initially. Finally contributions to regional physiography are made in the treatment of a particular region as a whole and parts of it in detail.

The viewpoint of this paper is pre-eminently that of explanation of physiographic phenomena. A region is selected and discussed purposely for the presentation of this sort of physiographic treatment. The common physiographic forms and processes are given little space. It is held that the topographic map contributes such data as size, shape, and relationship of topographic forms, and that the text need not be filled with a mass of rather unnecessary and burdensome detail. The text should be concerned primarily with the general conditions which permit of the development of the particular array of topographic forms, and should be focused especially on the unusual forms and unusual relationships. When these latter things are considered the text may have in it then such additional descriptive matter as may be necessary in the explanation of the forms or relationships. Such a program is attempted in the presentation of the material in this paper. Attention is first centered upon the factors which have controlled the topographic development. Then follows a presentation of the unusual features with sufficient detail to show what the features are and why they exist.

[13]This idea is by no means new, but it appears to the writer that too little emphasis has been placed upon it in physiographic papers. English physiographers are more appreciative in this respect than their American neighbors. "These forms (land forms) never occur scattered haphazard over a region, but always in an orderly subordination depending on their mode of origin. . . . . The geological structure and the mineral composition of the rocks are often the chief causes determining the character of the land forms of a region. Thus the scenery of a limestone country depends on the solubility and permeability of the rocks, leading to the typical Karst-formations of caverns, swallow-holes and underground stream courses, with the contingent phenomena of dry valleys and natural bridges. A sandy beach or desert owes its character to the mobility of its constituent sand grains, which are readily drifted and piled up in the form of dunes. A region where volcanic activity has lead to the embedding of dikes or bosses of hard rock amongst softer strata produces a plain broken by abrupt and isolated eminences." Hugh Robert Mill, Encyclopaedia Britannica, Vol. XI, Eleventh Edition, P. 633.