The Cycle of Subterranean Drainage as Illustrated in the Bloomington, Indiana, Quadrangle[1].

By J. W. Beede.

The Bloomington, Indiana, quadrangle[2] is the first topographic map to be completed in the cave region of Indiana. It is fifteen minutes square with contour interval of twenty feet and scale of 1/62,500, or about a mile to the inch. Careful inspection of the field shows it to be remarkably full and accurate in detail.

While the cycle of subterranean drainage, as here presented, had not been discussed between us, yet all the various phases of it have been discussed and similar conclusions independently reached by both Professor Cumings and the writer as the result of tramps and class excursions over the cave regions of Indiana. The cycle has also been given as lectures, illustrated with lantern slides, in our classes. This paper has also had the benefit of Professor Cumings' criticism.

The physiographic history of the Bloomington region is such as to make this map very interesting, both for the remarkable preservation of the older geographic features and for the recent modification of them. Not the least interesting, nor the least important of these, is the subterranean drainage. Indeed the fine preservation of the older features is due to the fact that the water has, figuratively speaking, soaked into the old peneplain much as it would into a sponge, confining its work to the solution and honeycombing of the rocks beneath the surface instead of concentrating its energies cutting it into ridges and valleys.

The whole of the quadrangle, excepting, perhaps, the northwest corner, lies in the driftless area of Southern Indiana. The larger streams, except

[1] The title of the paper as shown in the program was "Features of Subterranean Drainage in the Bloomington Quadrangle." After the title had been sent in it was realized that it would be impossible to treat the subjects in mind intelligently without outlining the cycle of subterranean erosion. This outline, of course, overshadows the minor details intended to be covered in the paper, and hence the change in the wording of the title.

[2] Price five cents. Apply to The Director, U. S. Geological Survey, Washington, D. C.

Clear creek, were effected by glacial waters which were one of the potent factors in producing the beautiful terraces of Beanblossom, Salt, Richland and Coon creeks. However, it is with the subterranean drainage that we wish to deal at this time.

GENERAL CONSIDERATIONS.

Before discussing the details of the underground drainage of the Bloomington region it is necessary to discuss some of the general features of the development of subterranean drainage under various conditions. Underground drainage is developed in two ways:

1. In a region of very soft, porous rocks, where jointing and bedding may play a somewhat minor role, the channels are determined to some extent by the varying degree of porosity of the rocks through which the water percolates. Under such conditions the caves are apt to be less regular in their forms and their courses less angular than would otherwise be the case. This also has a marked effect upon the origin of the sink-holes and cave openings. Under these conditions the sinks may be formed where the rock is somewhat more porous or where there was a slight depression originally. These factors are modified by the proximity of channels beneath the surface. In such cases, as has been pointed out by Sellards[3], the sinks first appear as "cave-ins" of the soil and rock structure, the sink being first a hole of greater or less size, sometimes being larger below than at the surface. That is, the hole may be conical or "jug-shaped," as suggested by Eigenmann[4]. The caves of Cañas, Cuba, are of this type. Sinks of this kind are formed most abundantly where the surface of the region is but little elevated above tide or general drainage level and the caves or channels are close to the rock surface so that it is easily undermined. In cases where the caves are far beneath the surface the sinks will be determined—in the absence of surface irregularities—by the location of the more porous spots in the rocks near the subterranean channels and will be developed by solution from the top downward. It may be remarked here that the joints in some of the Cuban caves are inconspicuous.

2. The other condition under which caves are formed and free underground drainage developed is in the firmer limestones, usually well above sea level and the major drainage lines. The denser the limestone the

[3] Science, XXVI, p. 417, 1907. More fully, Bull. 1, Fla. Geol. Surv., pp. 49-57, 1908.

[4] Bull. U. S. Fish Comm., 1902, pp. 211-236.

smaller the percentage of pore space, and the thinner the beds the greater is the tendency to form sinks and caves and the more sharply angular are the subterranean drainage courses. This is excellently illustrated in the cave region of Indiana. The Mitchell limestone is very dense, thin bedded and impervious for a limestone and is broken into small joint blocks. Here the subterranean flow is largely confined to the joints and bedding planes, thus concentrating the solution effected by the water to the immediate channels through which it flows. In this way channels are produced and enlarged with maximum rapidity.

On the other hand we may contrast this condition with that of the Salem limestone lying immediately beneath the Mitchell limestone. The Salem is nearly devoid of bedding planes, a rather soft and quite porous limestone, through which the water percolates with relative ease. The result is that caves in the Salem limestone are very rare. When they occur,

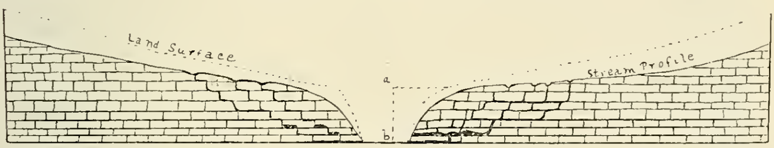

Fig. 1. Diagrammatic illustration of incipient subterranean drainage. The main stream is entrenched and the tributaries out of adjustment pitch over rapids to join it. Underground drainage has started through the joints. The vertical dotted line a b represents the original unbalanced static water head which started the circulation.

as at Mays cave, they may be formed by a cave passing down from the Mitchell limestone into it to reach the surface nearer the drainage level. The lack of frequent bedding planes is a strong contributory factor to this condition. Aside from its structure the opportunities for the formation of subterranean channels are as good as in the Mitchell limestone.

Again, the Harrodsburg limestone, lying immediately below the Salem limestone, is harder, less porous, more highly jointed and thinner bedded than the Salem and shows a correspondingly greater tendency to develop underground water channels. The Mitchell limestone possesses the extreme of these conditions and the extreme development of underground channels.

THE SUBTERRANEAN DRAINAGE CYCLE.

In either a coastal plain or an interior region which has been thoroughly baseleveled and reëlevated, what drainage there is to begin with is surface drainage. It remains surface drainage until the rapids of the larger streams have deepened their valleys well across the plain, leaving their tributaries out of adjustment with them. At this stage underground drainage first takes place to a considerable degree. The rocks are saturated with ground-water and at the level of the larger streams is under an unbalanced static head equal to the difference in elevation of the surface of the tributary, and of the water table between the tributaries, and the

Fig. 2. Section of a funnel-shaped solution hole (enlarged joint) in limestone, illustrating the origin of solution sinks.

main stream. As this is slowly drawn off more is supplied from above and a subterranean circulation is begun. The development of sinks goes along with the development of the subterranean drainage channels. The cross-joints most favorably situated with respect to free circulation below and supply from above, soon begin to be enlarged by solution. This solution is most active where the water first comes into contact with the limestone and the upper part of the opening will be dissolved most rapidly, resulting in a funnel-shaped hole. The larger this funnel becomes the more water it collects and the more rapidly it widens at the top and the larger the sink becomes. In this way the sinks develop at the same time that the subterranean channels do and in a region of mature sink topography where the channels are well below the surface, as in the Indiana

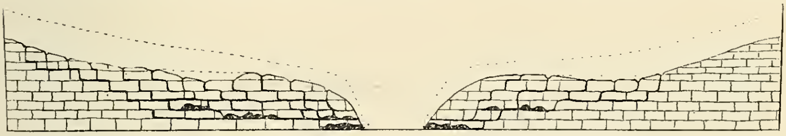

Fig. 3. A more advanced stage of subterranean drainage than No. 1. Sinks have developed and all the water of the stream passes beneath the surface and enters the larger stream as a great spring. It may be considered a sort of vertical self capture, a common occurrence. The underground channels have become enlarged and subterranean drainage has worked headward along the stream. At this stage the sinks will be developed over considerable of the surrounding land surface. It may be regarded as approaching maturity.

region, probably ninety-five per cent. of the sinks are formed this way.[5] It is certainly true of the Bloomington region and all the Indiana region as far south as Wyandotte that has come under the writer's notice. In some cases a sink may cover many acres and be as much as a hundred feet deep.[6] The first surface indication of the sink is frequently the collapse of the soil into the funnel which has been dissolved in the surface of the underlying rock. This has probably given rise to the popular notion that sinks are usually formed by the collapse of the roofs of caverns.[7] Incipient

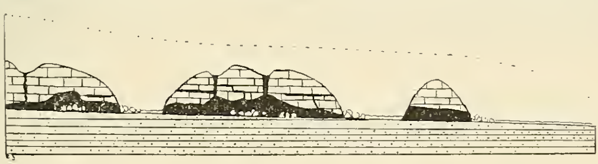

Fig. 4. An ideal section, similar to Nos. 1 and 2, in old age. Natural bridges are developed, much of the roof of the subterranean channel has collapsed, revealing the underground stream, and the mouth of the cavern has retreated by collapse and erosion. Dotted line indicates the old land surface.

[5] See Blatchley, 21 Ann. Rep. Ind. Dept. Geol. Nat. Res., p. 133, 1896.

[6] For a discussion of the solution of the Indiana limestones, see Cumings, Proc. this Acad., 1905, pp. 85-102, 1906. Caves, F. C. Greene, idem, for 1908, pp. 175-183, 1909.

[7] This does not seem to apply to the caves of Florida and some regions of Cuba where the channels are very near the surface and the roof soon becomes so weakened that it gives way, and the extreme porosity of the rocks does not concentrate the solution to the joints to produce solution sinks.

sinks and slightly developed underground drainage may be considered as characteristic of the youth of subterranean drainage. There will be no collapse sinks at this stage.

In the course of time the water of some of the streams may all pass below the surface and issue as great springs or subterranean streams in the channels of larger streams or in their own channels below where there may have been rapids or considerable fall in the beds. As time goes on this sinking of the water progresses headward along the stream, reducing

Fig. 5. Abandoned bed of Lost River, near Lost River station, north of Paoli, Ind. During floods this channel contains water. It is twelve miles long. The valley is very broad, with indistinct bluffs.

more and more of its course to underground drainage. The distance which streams may flow underground before reappearing at the surface depends upon the physical conditions in which they are placed. The distance that they are now observed to flow beneath the surface depends also upon the stage in the cycle of erosion in which they happen to be. Thus, in the Bristol-Standingstone region of Tennessee and neighboring country the distance seems to be about a mile. Lost river, in Indiana, flows about six miles in a direct line, or about double that distance by the old channel, before reappearing. Perhaps Lost river should be regarded as being in a somewhat later stage in its cycle than those of the region just mentioned, since there is evidence that collapse has brought the present stream to the surface for some distance below the "Gulf" where it now escapes.

The collapse of the mouth of the cavern is brought about by the increased width and height due to solution and abrasion, the fall of slabs

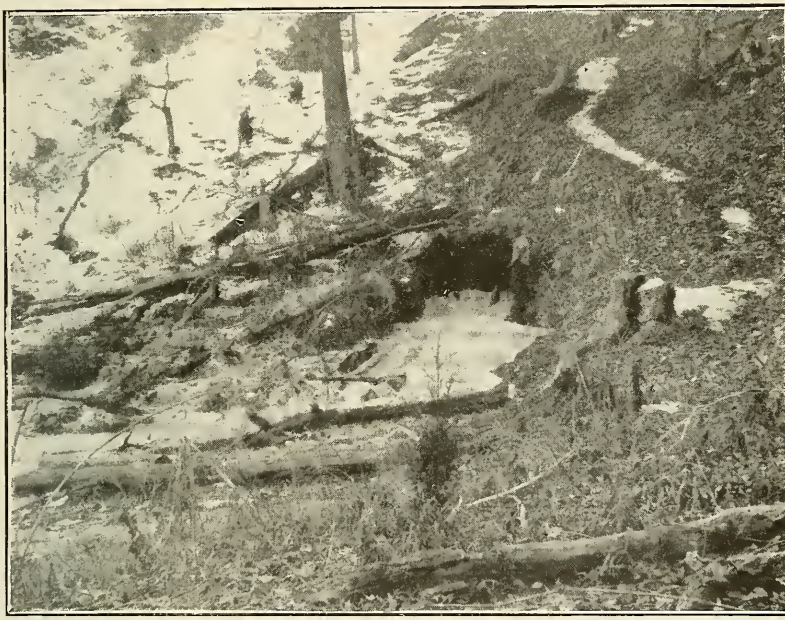

Fig. 6. Stony Spring, Bloomington waterworks. During freshets the water flows out all around the foot of the hill shown in the picture and even farther to the left. The cavern containing the stream is here collapsed, blocking the outlet. When the cave fills with water it breaks out wherever it can find an opening. The water comes from the former drainage basin of Indian Creek and now enters the head of Clear Creek.

from the roof and by the lowering of the channel until the roof, unable to support itself, finally falls. This collapse of the lower portions of caverns bringing more and more of the subterranean stream to light may be, and frequently is, going on at the same time that the upper reaches of the stream are being converted from surface into subterranean drainage. This is true of nearly all the largest outlets of subterranean drainage in the Bloomington region. Stone spring at the Water Works, Shirley spring and Leonards spring, southwest of the Water Works, and Blairs spring, just northwest of Stanford Station, all show this phenomenon, while the upper parts of the streams feeding them are still being more thoroughly taken under ground. A good example of this is seen in the sinks just east of the County Farm. The old sink is located in the angle of the road, while the stream now passes beneath the surface fully a quarter of a mile upstream to the northwest. Only the flood water now finds its way into the deeper sink below. The collapse of the mouths of caverns is excellently exhibited

Fig. 7. Shirley Spring (East Spring), S. E. of Leonard Schoolhouse. The outlet of the stream entering the sinks east of the Poor Farm and the intervening sinks. For abandoned, higher cave, see Fig. 30. The condition of collapse is similar to that shown in Fig. 6.

in the Shawnee caves east of Mitchell, Indiana, while Lost river shows it still better. In both cases the roof has collapsed back for considerable distances and in each there are cases of collapse above the mouths of the caverns where either the cave or the stream is brought to light.

When this stage of the drainage has been reached sinks have developed over most of the region on the interstream spaces as well as near the streams and most of the drainage is subterranean in the stricter sense of the word. This stage shows the large sinks near the larger drainage lines, surface or subterranean, and the smaller ones farther from them, as is illustrated in the plain southwest of Bloomington. When this stage has been reached—with sinks well developed over most of the region and collapse has begun at the exits of the cave streams—a region may be regarded as in its maturity. It is only after the mature stage of the cycle has been reached that sinks, due to the collapse of cave roofs, begin to appear in considerable numbers, and natural bridges, due to collapse of the cave roofs above and below a given point, begin to be developed. Solution

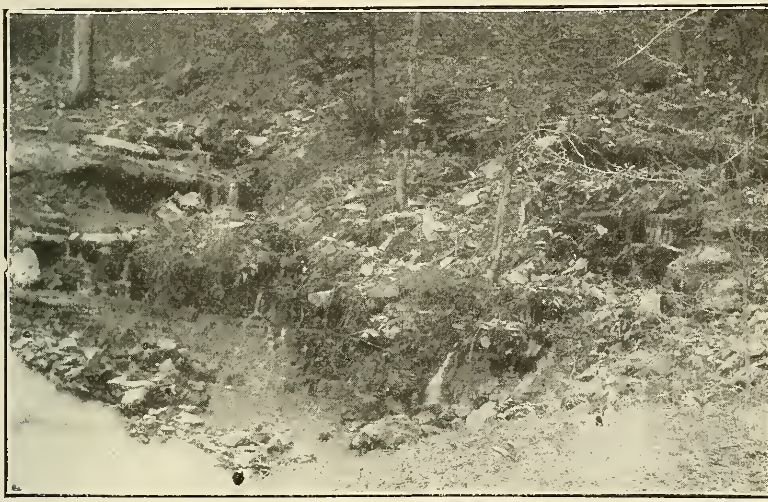

Fig. 8. Spring at Leonards Mill (house in deep gulch south of Leonards school), showing similar features as preceding. Note water escaping all around the foreground. A portion of the water from the main spring is shown in the extreme lower left corner of the picture. The outlet for the sinks south and northwest of Leonards school.

sinks that happen to be located above caverns may be, and frequently are, transformed into collapse sinks in the latest stages of subterranean erosion.

When these features of collapse become prominent and much of the drainage has been brought to the surface again and collapse sinks are numerous, old age has been reached.

The valleys produced by the collapse of caverns and the transformation of subterranean drainage to surface drainage have a characteristic form that at once distinguishes them from ordinary drainage valleys. They are rather sharply U-shaped, with steep sides like a young valley but with a fairly wide bottom and a blunt, steep termination at their heads. In these respects they resemble miniature glaciated valleys. When well developed they may be shown on accurate topographic maps. Surface erosion begins modifying them at once and finally obliterates the evidence pointing to their origin. The final result of the subterranean drainage cycle is thus a surface drained peneplain.

There is a lack of subterranean drainage in the old age stage of the cycle in the Bloomington region. The whole sink hole plain of Indiana

Fig. 9. More distant view of Leonard's Spring. The main spring is seen back of the stone dam. The water is issuing from a hole in the dam in the middle foreground. Note the steep, blunt end of this collapsed-cave valley.

may be considered as in its maturity. However, there are exposed in the sides of the monadnocks west of Harrodsburg certain old solution channels which probably represent the very heads of the subterranean channels of the preceding cycles of erosion. Indeed it is not improbable that the streams tributary to Clear creek on the west and north of Harrodsburg owe their present position in some degree to the location of former subterranean creeks. These in turn were profoundly influenced by the position of the previous Tertiary(?) surface streams.

In a coastal plain the details of the cycle will be somewhat different, but the essential features will be similar. The differences will be due to the physical characters and structure of the rock, the lack of previously established drainage lines and the relatively low elevation above sea level.

Fig. 10. Leonard's Spring, S. W. of Bloomington, showing valley with spring in distance.

PIRACY.

At the time when the subterranean drainage is at the maximum it is subject to the same accidents as surface drainage, except that the *modus operandi* is different. Subterranean piracy falls under two distinct heads, the capture of one surface stream by another through subterranean drainage, the easiest form to observe, and the capture of one subterranean stream by another. In each case there are minor varieties of capture such as one tributary by another, and self capture. Indeed these are probably much more common than the capture of one surface stream by another.

If a surface stream flows a long distance over a rather gentle grade to reach a certain level while a competitor flows a short distance to reach a similar level it may capture the headwaters of the former through subterranean drainage, leaving the divide between the valleys intact. This

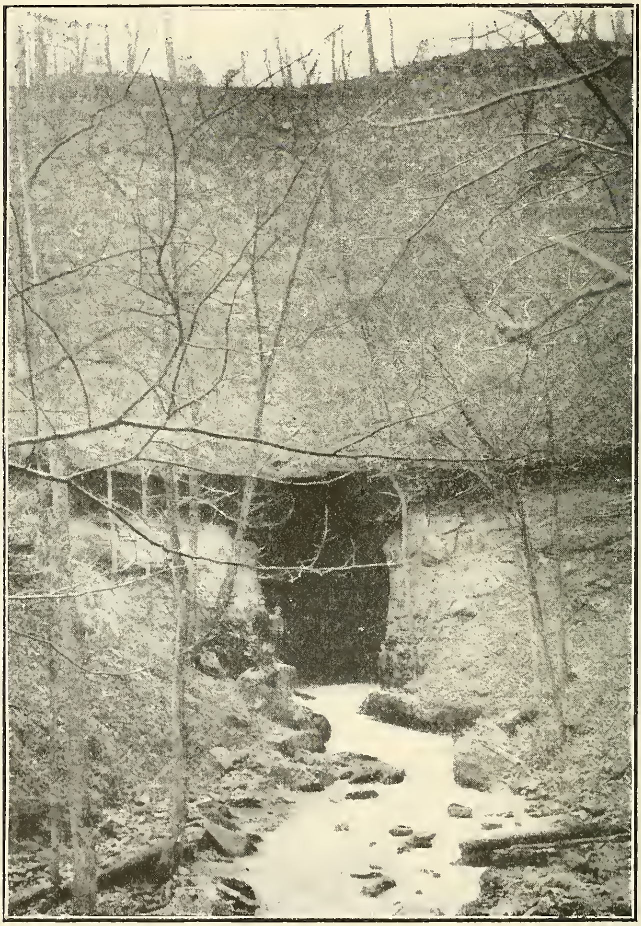

Fig. 11. Emergence of cave stream, mouth of Shawnee cave east of Mitchell, Indiana. The roof of the cave at its mouth is well supported. Just back of this there are two large rooms connecting with the main cave, leaving a large area of roof unsupported. It has faulted down about six inches. The completion of this collapse might, in time, leave a natural bridge at the present mouth of the cave. The valley is a typical collapse valley.

tendency is accentuated when the pirate is favored by the dip of the rocks, but frequently occurs in spite of the dip in cases where the dip is gentle. It is probably true that the only essential of such capture is that two streams lie one higher than the other in a region of soluble rocks sufficiently close to each other to permit the final entrance of some of the water of the one to the other. Examples of such piracy are by no means wanting in the Bloomington region.

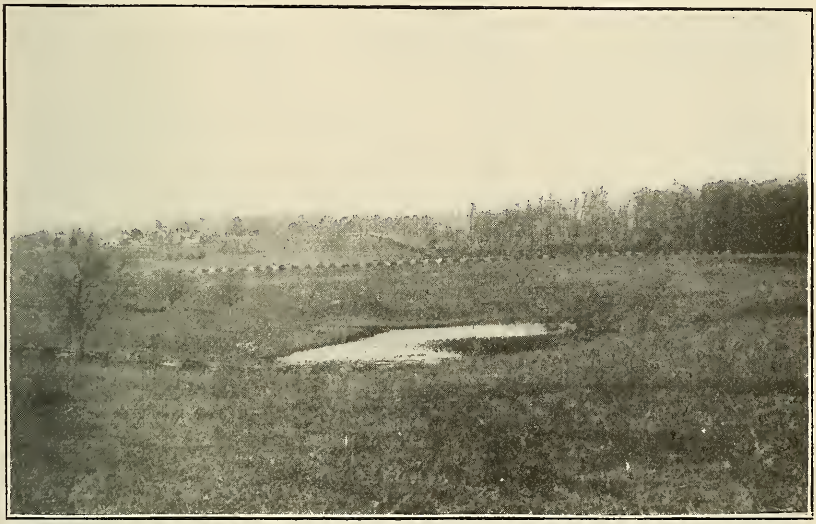

Fig. 12. A distant view of the Leonards Mill locality (Figs. 8 and 9), showing the form of the valley. The water from the Shirley Spring (Fig. 7) crosses the foreground.

In order to make these specific cases fully intelligible it is necessary to refer to some length to the physiographic history and conditions of the region. The well preserved plain west of Bloomington appears to be a very early Pleistocene peneplain. This plain extends at about the same altitude throughout the extent of the map, except that it is visibly beveled toward the major drainage lines, as will appear later. The peneplain is much dissected in the northeastern, southeastern, and western parts of the quadrangle. There are many monadnocks to be found along the old divides or near the headwaters of some of the minor streams, rising from a little over a hundred feet to two hundred feet or more above this old plain and reaching elevations of from a little under 900 feet to 1,000 feet A. T. The ones south of Kirksville are the best preserved and appear to be remnants of the very old Tertiary peneplain or, perhaps, base level. It seems probable that the whole region covered by the map and the higher, rougher parts of southern Indiana are a part of the Lexington plain of Campbell, reaching from the Cumberland Plateau westward to the Tennessee river,

Fig. 13. A monadnock southwest of Bloomington. It rises 115 feet above the surrounding plain. It is surrounded by sinks, especially on the north, west and south.

the Indiana portion being a spur extending northwest from the type region at Lexington. It will be noticed that the elevation of the old plain and monadnocks (catoctins) is materially lowered as the western edge of the map is approached. This is due to the surface dip into the West Fork of White river basin. A similar beveling will be noted on approaching Salt creek in the southeast corner of the map, and Beanblossom in the northeastern corner. Even in an extremely old peneplain this bevelling toward the main stream of the basin is the normal condition and should be expected to be found on a rejuvenated plain.

The physiographic history of the region may be briefly summarized as follows: When the Pleistocene peneplain had been developed the general level of the land was but slightly above the present level of the bottom lands of the larger streams. The streams flowed at about the level of the present larger streams, while the divides between them looked much as they do at present when viewed from the old peneplain west of Blooming-

Fig. 14. The Mitchell peneplain[9], about 4½ miles west of Bloomington. A part of the Indian Creek basin. The plain is here 160 feet above drainage level. Entire drainage subterranean.

ton. The valleys of even the small streams were wide and their bluffs indistinct. The landscape was wanting in angularity and was one characterized by gently flowing curves. All the streams seem to have meandered considerably upon their valley floors, the larger ones to a very great extent. Most of these features are well shown by the little streams in which

[9] The Sink-hole plain of Newsom. It is called the Mitchell peneplain since the country rock is the Mitchell limestone and it is typically developed at Mitchell, Ind., and southward.

the rapids have not yet reached the very headwaters and those which happen to be preserved just as they were upon the sink-hole plain.

The drainage was confined to the surface, since the streams and the water table were very near the general surface level. After this condition had been thoroughly established the whole region was uplifted without considerable tilting, to an elevation somewhat above that which it now possesses, an elevation amounting to upwards of 200 feet. Following this the

Fig. 15. View looking northwest from side of monadnock shown in Fig. 13. Closed sink in middle ground. Beyond is the plain of Indian Creek valley. Present drainage subterranean. The remnant of a monadnock (catoctin) interrupts the even sky line just at the right of the center of the background.

larger streams etched their channels to temporary base level, but soon afterward the region sank a little. As a result the streams flow at a level somewhat above the rock floors of their valleys. Other minor incidents occurred which have left their impress upon the region but which need not be discussed here. After the first elevation took place, rapids passed up the main streams cutting gorges in the valleys. As these rapids passed the mouths of the tributaries the latter were left out of adjustment with the master streams and reached them by rushing over high rapids and falls. Some of the larger tributaries reduced the lower parts of their courses with sufficient rapidity to prevent the development of extensive subterranean drainage beneath them, but this was not true of the smaller ones lying on the limestone plain. When the larger streams left the smaller ones hanging high in the air, subterranean drainage began in earnest. The

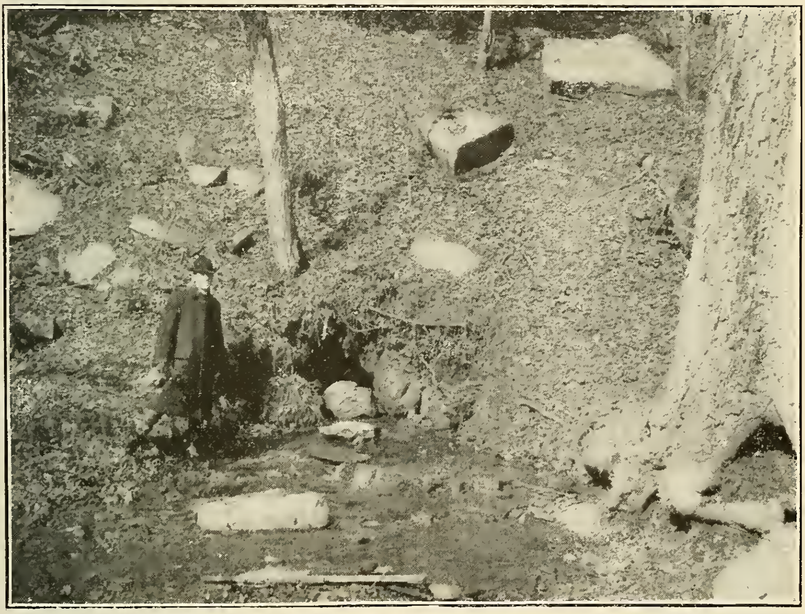

Fig. 16. Weimer Spring, Bloomington Waterworks.

rocks were saturated with ground-water and near the mouths of these streams was under an unbalanced static head of about a hundred feet. This water gradually flowed into the deeper valleys and was in turn replenished by more from above, and active underground drainage began and continued in the manner already indicated.

Fig. 17. View from side of monadnock, showing great terrace deposits on about the level of the Mitchell plain a mile south and 4 miles west of Elletsville. A somewhat interrupted monadnock divide forms the sky line in the distance.

Fig. 18. Gorge of the Cascade tributary to Rocky Branch north of Bloomington. This is a very small stream which has not reduced its whole valley to grade since the uplift. The valley profile is shown; the right side is clearest on account of the removal of the vegetation.

On turning to the Bloomington quadrangle some very peculiar drainage features will be seen. It will be noted that the headwaters of the western branches of Clear creek southwest of Bloomington and the eastern tributaries of Richland creek nearly west of Bloomington and north of Stan-

Fig. 19. View of the same valley, as shown in Fig. 18, looking in the same direction above the cascade, showing the old, wide valley with indistinct retreating sides. Were this valley developed in soluble limestones it is easy to see how the water might enter the ground above the cascade and appear as springs below it.

ford Station frequently lie in deep valleys with steep heads. On the plain between these two creeks is a region which is drained by great sinks opposite the heads of these streams. A little farther south Indian creek heads on this plain and continues a little west of south with gentle grade in its headwaters compared with the ones before mentioned. By following the valley at the head of Indian creek northward it will be discovered that the valley extends as far north as the race track west of the northern part of Bloomington, and that the water entering the large sinks just mentioned is really the water of the head of Indian creek. The same will be noted of the great sinks northeast and south of Blanche. The water, after entering these sinks, appears in the deeply incised heads of Clear creek and Richland creek instead of continuing down Indian creek. In other words, Richland creek and Clear creek have captured the waters of Indian creek by subterranean piracy.

This diversion of water was brought about by the location of the streams in question with respect to the rock structure of the region.[8] The strike of the rocks is nearly north and south. The lower rocks in the northeast and southeast part of the region are the soft, easily eroded "Knobstones." Salt creek, on account of its very large size, readily etched its lower course to grade and when the soft knobstone underneath the Mississippian limestone was reached it probably formed falls which rapidly retreated headward and permitted proportionally early deepening of many of its tributaries. Throughout the central part of the region the heavy, resistant, Mississippian limestones form the country rock, dipping westward, through which no drainage channels completely penetrated. The headwaters of Indian creek lie upon these rocks and nowhere do they cut through them. In a large part of its course the soft shales, sandstones and thin limestones of the Mississippian formations form the upland rocks. The result is that Indian creek with long and gentle grade could not compete with Clear creek, a branch of Salt creek, in deepening the channels of its headwaters. In the west part of the region the soft formations of the upper Mississippian and the basal soft sandstone and soft shales of the Coal Measures or Pennsylvanian rocks form the upland. The Mitchell limestone forms the beds and basal part of the bluffs of the streams in this part of the quadrangle. Richland creek for the most part lies in these soft formations and flows a short distance to the west fork of White river at Bloomfield, reaching about the same elevation as Indian creek flowing twice the distance to the east fork of White river north of Shoals, in Martin County. Richland creek being thus favored soon reduced the valleys of its headwaters below the level of Indian creek. This left the head of Indian creek 100 to 150 feet above the creeks on either side and its bed resting on soluble rocks. That is, Indian creek lay upon a table land of soluble rocks with lower streams on either side of it. The divide between Indian creek and Clear creek has been cut through and removed much of the way just southwest of Bloomington. Thus the headwaters of Richland creek northeast of Stanford Station are at a level of 680 to 700 feet above tide and were cut into the top of the Mitchell limestone which dips west from the Indian creek plain into Richland creek valley, while a west branch of Indian creek lay at an elevation of 800 feet but a half-mile or a little more to the eastward. The divide between the two is formed of the shales

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[8] See geologic map accompanying 28th Ann. Rep. Ind. Dept. Geol. Nat. Res. 1904

and sandstones of the Upper Mississippian. The result of this condition was that the water in the western branch of Indian creek, a mile or more south of Blanche, sank and reappeared in a great spring in the head of Blair Hollow a half-mile farther west. A similar thing occurred less than a mile northeast of Blanche and again about a mile and a half farther northeast. These sinks are the largest, or most extensive, on the quadrangle. As we approach the heart of the plain farther east the sinks become smaller and less conspicuous, the smaller ones not being shown upon the map.

On the eastern side of Indian creek valley we have large sinks. One of these is just north of the Water Works pond. Here the drainage entering the sink flows into the pond through Stone spring a few hundred yards farther south, entering the Clear creek valley, being diverted from Indian creek into which the surface drainage once flowed. Southeast of this there is a large sink east of the County Farm which receives the drainage of a large region to the north which normally belongs to Indian creek drainage but appears at the surface as a large spring in the north side of the branch of Clear creek valley in the N. W. ¼ of Sec. 24, nearly two miles south of the sink. The large sinks south and northwest of Leonards Schoolhouse have their outlet at Leonards Mill by the house in the head of the deep valley a half-mile south of the schoolhouse. Rags put in the upper sink are said to reappear at Leonards Mill.

From the foregoing it will be seen that the headwaters of Indian creek have been diverted into Richland creek and Clear creek by subterranean

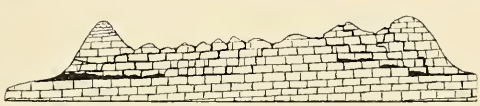

Fig. 20. A somewhat diagrammatic profile of a section across the valley of Indian creek into a tributary of Clear creek on the right and tributary of Richland creek on the left. The high points on either side of the figure are the old divides between the three drainage basins. It illustrates the manner in which Indian creek has been robbed of its waters southwest of Bloomington. The dip of the strata has favored Richland creek.

piracy. On the west this piracy is favored by the dip of the limestone and on the east it has taken place against the dip, which is very gentle. The sinks near the outlets of the underground streams are large, while those more remote and younger are smaller. The smallest are not represented on the map. There is another case of piracy in the sinks near Kirksville which is of the same type as that just described.

Other forms of piracy are probably much more common than the type described. That piracy occurs between adjacent subterranean streams seems very probable on account of the greatly varying levels occupied by them at different times and different parts of the same stream at the same time. This is facilitated by the fact that cave streams are below the level of the general water table and also because the falling of slabs from the roofs frequently clog the channels and temporarily fill the caves with water until further underground passages may be discovered and enlarged. It is impossible to cite specific cases at present because caves have not been explored with this object in view and because such cases will probably be difficult to recognize even under the most favorable circumstances.

Cases of subterranean self-capture, capture of one tributary by another, or by the main stream or the capture of the main stream by a tributary finding a short cut through a new channel are too common to be discussed at length here. A glance at Hovey's map of Mammoth cave is sufficient to suggest a most complex and interesting set of captures and changes of level for some one to work out.

RÉSUMÉ.

1. Extensive subterranean drainage is developed in interior regions only when they have been sufficiently elevated to allow rapid downward movement of the ground water and its easy access to drainage lines considerably below the general level of the land surface.

2. The conditions best facilitating subterranean drainage are regions well elevated with relatively impervious soluble rocks, well jointed and thinly bedded.

3. In regions of low elevation the sinks may be largely collapse sinks, and, in soft, porous rocks, the channels rather irregular.

4. The cycle of underground drainage may be stated as follows: It begins with surface drainage and in its youth develops subterranean drainage near the points of easy escape for the water. In its maturity there is the maximum of subterranean drainage and the lower parts of the caverns have begun to retreat by collapse while in the uppermost reaches of the stream the transformation from surface to subsurface drainage may still be in progress. Old age is shown by the more general condition of col-

lapse and the return to surface drainage. Briefly, it may be stated that the cycle is: surface drainage, partial subterranean drainage, and a return to surface drainage. The final state is peneplanation or base leveling.

5. In youth and maturity nearly all the sinks are solution sinks.

6. In old age many of the sinks are formed by collapse. Solution sinks may finally be transformed into sinks of collapse.

7. Surface streams resting on a plain of soluble rocks with streams at lower levels bordering them may have their waters diverted by subterranean capture.

8. Piracy probably takes place between subterranean streams and between parts of the same stream.

Bloomington, Indiana.

References to the "early pleistocene" peneplain in this paper should read "late tertiary (?)," since the cycle was interrupted at about the close of the tertiary or beginning of the pleistocene period.

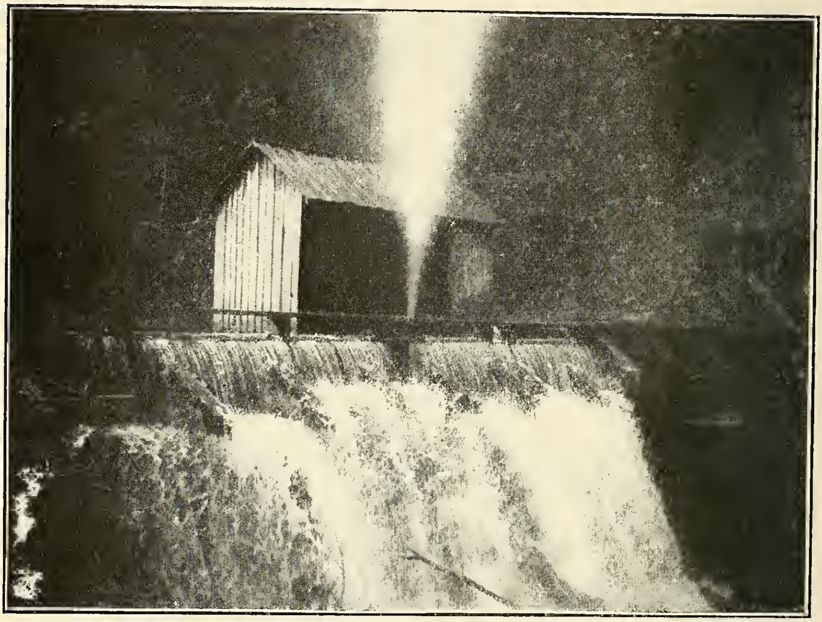

Fig. 21. Hamers Cave east of Mitchell, Ind. The water from this cave furnishes the supply for the two Lehigh cement plants at Mitchell. The picture shows the overflow from the dam. Water higher than usual.

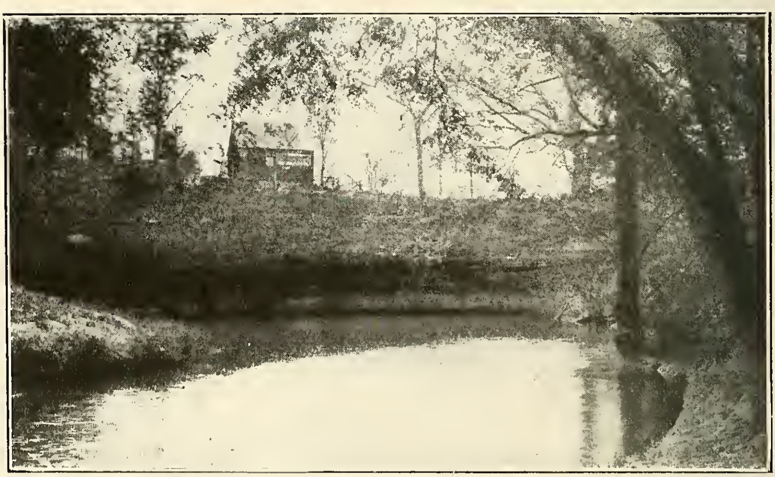

Fig. 22. The "Gulf" of Lost river at Orangeville, Ind. Here the roof of the cave in which the river flowed has collapsed and the stream comes to the surface.

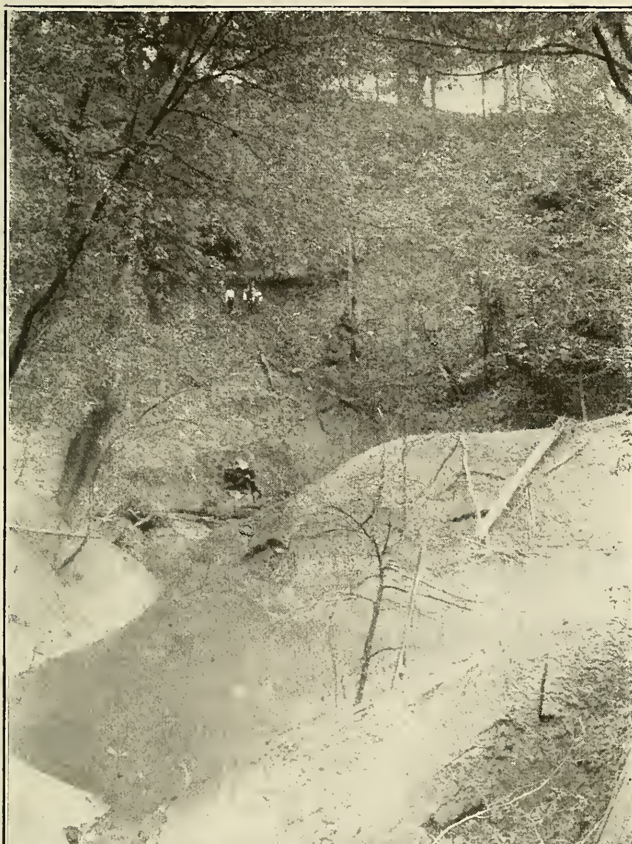

Fig. 23. A "Gulf" of Lost river above its outlet at Orangeville. The water rises to the surface at the right of the middleground of the picture and flows to the right and left, forming two streams, for a very short distance which sink and finally rejoin the subterranean channel. The little pond on the left side of the picture is one of the places where the water sinks. Just above the heads of the group in the middle background is a large cave, one of the abandoned subterranean channels of the river. The second, or present channel is considerably below the water shown in the foreground. Here a large area has collapsed blocking the lower channel and forcing the water to the surface, when it again finds new channels around or through the obstruction to its main channel again in which it continues.

Fig. 24. Abandoned channel of Lost river mentioned in explanation of previous figure.

Fig. 25. Phantom lake, near Toyah, Texas. A collapse sink where the subterranean stream is revealed. The roof, of Washita limestone, collapsed, filling the channel and forcing the stream to the surface—cave on the left—in a stream about six feet in diameter. It fills the depression formerly occupied by the roof with water and enters sinks in the immediate foreground to its channel below.

Fig. 26. A diagrammatic figure illustrating the origin of Phantom lake.

Fig. 27. Upper Dalton cave, part of Shawnee cave (Fig. 11) east of Mitchell, Ind. The location of cross caves and a sink at this point caused a collapse which brings the stream to the surface for several rods when it again continues in its subterranean channel.

Fig. 28. Lower Twin cave (part of Shawnee cave) looking north. Here the roof collapsed at a right-angled turn in its course where it appears to have been joined by another cave from the south. The location of a sink here caused a collapse similar to the preceding case. The water formerly flowed from the upper cave toward the east and then turned north into this opening—does at present during high water—but now occupies a cutoff between the two caves.

Fig. 29. Spring west of the large sinks north of Blanche. This is one of the sinks draining the western part of Indian creek valley.

Fig. 30. Old channel of Shirley spring, above present outlet, as shown in Fig. 7.

Fig. 31. Mouth of Wyandotte cave, a former location of an underground stream.

Fig. 32. Old opening to one of the large springs draining the Strongs cave sinks four miles west of Bloomington.

Figures 6, 7, 8, 10, 12, 13, 14, 17, 19, 21, 29, 30, 31, 32, from Professor Cuming's negatives.