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The Development of Karst Features

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ABSTRACT——Karst landforms may be considered to be largely composed of three features: cutters, sinks, and caves. These are interrelated and transitional between each other.

Cutters are solutionally enlarged joints. They are normally filled with a residual terra rosa, and form beneath such a soil cover. Cutters are a distinct karst landform, although they are often difficult to recognize because they may be obscured by the soil material. Cutters generally are not remnants of former caves. Where cutters are the dominant karst landform, joint solution generally decreases uniformly downwards. This solution is directly related to present topography in depth, intensity, and directional development. Cutters are normally developed into a crude, dendritic network similar in directional development to the overlying topography. Cutters originate through solution by ground water flowing laterally within the enlarged joints. This is a gravity flow under a gradient. The amount of development of cutters depends upon the climate, the rock properties, such as solubility and grain size, and the geologic-topographic situation.

Cutters are the only karst form present in completely homogeneous soluble rock. Under such conditions they are an equilibrium feature of the landscape, and they have a simple form that changes little with time. Where the rocks are heterogeneous, such as in area of associated soluble and non-soluble rocks, the greater will be the extent of development of sinks and caverns, and the cutter will be less prominent.

Cavernous passages result from solution of the bedrock by through-flowing ground water. Because of the necessity for continuous addition and removal of ground water in order for cavernous channels to form, caves are continuous conduits leading from a source of ground water to a ground water exit. No one theory of cave development or sequence of cave-forming events can be common to all caves. Every cave has a unique history, but nevertheless there are certain broad principles which are true of the development of all caves. Caves appear to fall into two classes, those that arise through solution and abrasion by free-surface ground water or ground water streams flowing with a definite gradient, and those that result by solution by ground water flowing under artesian pressure. Some caves have records of both processes having acted at different times.

Caves result from the presence of a favorable geologic situation (stratigraphy and structure). Both the geology and the geologic effects upon topography are factors which control the development of caverns. In order to completely describe the origin of a cave, the specific geologic-topographic relationship which promoted its development must be specified.

Sinks are enclosed topographic depressions which are collection areas for the diversion of surface water underground. Sinks presuppose caverns, but the reverse is not necessarily true. Most sinks derive their topographic form from the continuous removal of soil material underground, and the sink landform is usually a structure of the soil mantle only, for the bedrock surface does not usually have an associated funnel shape. Only a few sinks originate from the collapse of cavern roofs, and even these are perpetuated by continuous downward removal of increeping soil material.

Caves and sinks are most common in areas of great inhomogeneities of geology. In contrast to the rather static and monotonous topographic forms prevailing in areas of homogeneous rock, the topography in areas of great diversity of geology is generally varied and typically in a state of flux. Such conditions, which are the result of the influences of various lithologies and structures upon the topography, are often conducive to the development of caves and sinks when soluble rocks are present.

Because caves result from the effects of stratigraphy and structure upon topography, neither uplift nor peneplanation is called upon as a direct causal agent for the development of caves.

Cutters are also found in areas of diverse geology, but are present in inverse proportion to the degree of diversity. In such areas cutters will have various forms, and these may approach that of caves.

Karst in this paper includes all landforms on or above soluble rocks which are attributable to solution by ground and surface water. Most landforms on soluble rock are a hybrid of solutional processes and other erosional processes, and landforms on rocks not ordinarily considered soluble (pseudokarst) may resemble those of the true karst type.

Karst landscapes may be considered composed mainly of three forms: cutters (karren), sinks, and caves. These are interrelated and transitional between each other. Of these features, cutters have not previously been thought to be a major karst form, largely because of the lack of expression of these bedrock solutional forms on the surface topography and the general lack of exposure of cutters.

Cutters—In many places on limestone a peculiar bedrock topography is found where the soil overburden has been removed through erosional processes or by man. This topography is typified by an exaggerated valley and ridge appearance, the positive features termed *pinnacles* (karren) and the negative features called *cutters* (Smith and Whitlatch, 1940, pp. 46-47).

An easily accessible example of this solutional form is located just south of Bedford, Indiana on Highway U. S. 50. Limestone is exposed in the roadcut and on the surface adjacent to the cut where overburden has washed away from the limestone exposing an area of well-developed cutters (fig. 1). The negative areas of the surface are greatly enlarged joints, and the positive areas are intervening bedrock blocks. Because the joints are vertical, the cutters are also vertical. The greatest enlargement is along a set of joints that are spaced about 5 to 10 feet apart and strike at approximately right angles to the road. The cutters on the main joints extend downwards below the level of the road cut and are filled with clay. One or more secondary series of joints, closer together and less prominent, are hosts to secondary furrows which lead at a steep gradient from the higher blocks into the main cutters. They appear to be tributaries to the main channels. It is apparent that the main cutters are not funnel-shaped forms attributed to sinks in limestone terrain, for, although they have a steep funnel form in cross section, they extend linearly in the direction of the joints, and are of a smaller scale than sink features. These solution channels are normally filled with red clay, the usual residual *terra rosa.*

The surfaces of the limestone protuberances are characteristically rounded and streamlined, with conical peaks; their surface features are characteristic of solutional origin, with sharp projections and bowl-shaped depressions. Where only the pinnacles protrude above the soil cover and the trenches are filled with clay, the isolated and usually numerous bedrock exposures are termed *karren.*

In a number of limestone quarries near Bloomington, Indiana, quarrying of the Salem limestone exposes excellent sections across the limestone. These sections are well defined because the quarrying is by sawing rather than by blasting. Here enlarged joints similar to the ones at the roadcut were observed (fig. 2). The top parts of the pinnacles were not exposed but the section continued down enough to expose the lowest part of the enlarged joints. The cutters extended to variable depths beneath the top of the quarry and almost all decreased in

Figure 1
Pinnacle and cutter bedrock topography, southern Indiana

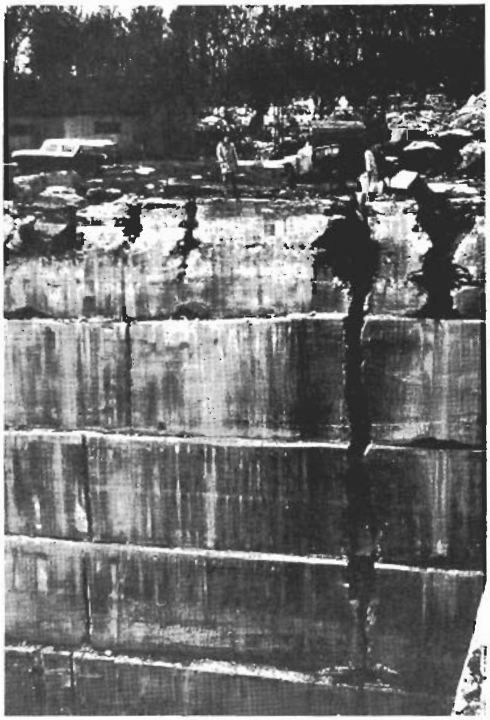

Figure 2
Joints enlarged by solution (cutters) in a quarry face in southern Indiana.

width rather uniformly downwards: all disappeared by pinching-out before reaching the bottoms of the quarries about 60 feet below. Almost all openings extended to the top of the cut, and expanded upwards. Only a few, small roofed cavities were noted, and these were usually beneath normal cutters, along the same joint. The cutters were filled with clay as in the roadcut. The Salem limestone in this area contains few sinks and the cutters in the quarry were not funnel-shaped bedrock depressions ascribed to limestone sinks.

Cutters when cleared of clay closely resemble cavern passages because of their development along joints and the solutional features they display. The possibility that they are cavern remnants which have lost their roofs by collapse should be considered. However, several factors make this unlikely:

1. In these localities and at others, there is no evidence that extensive roof collapse has occurred in pre-existing cavities. There are no buried flowstone deposits, no relics of speleothems, no blocks of roof limestone in cave fill, and no coarse clastics within the fills as one might expect from stream deposits within caverns.

2. Pinnacles and enlarged joints appear to be too numerous to be ascribed to former caves.

3. The tops of the pinnacles have been greatly affected by solution and are not fresh bedrock that one might expect to find as part of an earlier cavern roof.

4. Usually the joint openings expand upwards, showing no tendency to close over the cutter.

5. No caverns of significent size or numbers were noted below the cutters, which, in contrast, were very numerous near the surface.

All the cutters and pinnacles that I have seen have been formed under a soil cover. *Lapies,* a solution form which develops on subaerially exposed limestone and which generally occurs as small scale ridges and hollows, has often been mistakenly equated with cutters (Thornbury, 1954, p. 319-320) but it is a distinct form and is often developed on pinnacles that have been bared by removal of the soil mantle.

Different solubility of bedrock gives rise to secondary features on cutters and pinnacles. Chemically resistant beds generally form protuberances into the cutters, and weak beds are cut back. Figure 3 shows the effects of resistant beds at various positions within a cutter. The last form (c) appears to be the most abundant where there is a prominent resistant bed, for, being most resistant to chemical weathering, it persists longer at the surface of the bedrock than less resistant beds. Figure 4 shows a commonly-observed profile through cutters. It should be noted that such cutters are pene-caves, that is, they are nearly roofed over. In fact, it is observed that a resistant bed may entirely roof over a cutter for short stretches forming natural bridges or short caves. Also it was noted that solution is somewhat restricted beneath such a resistant cap, allowing only stunted cutters to form, because the downward movement of solvents in such cases is hindered. Similarly solution increased correspondingly above such a resistant layer, and short caves may also form by abnormal solution above the resistant layer. The number of these, however, is probably smaller than the number found beneath resistant beds.

An example of solution retardation by resistant beds is on Highway 31 north of Columbia, Tennessee. On the east side of this roadcut, cutters, being nearly perpendicular to the roadcut, are exposed in cross section (fig. 5). On the north end of the section are a number of apparently normal cutters, with bottoms not visible. On the extreme south end of the cut a relatively insoluble layer is present above the soluble, cutter-forming unit, and therefore no cutters have developed in this zone and the contact between bedrock and the mantle is essentially flat. Intermediate conditions are present in the center of the section where one cutter has a significant pinching in of its upper parts as compared to the usual widening. Where the resistant unit is thicker, the top is closed over to form a clay filled, cave-like opening of indeterminable extension into the hill. Taking the section as a whole, where the upper resistant unit is present, little vertical solution along the joints has occurred, and where absent the joints have widened into cutters.

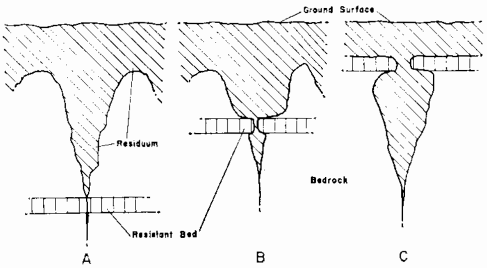

Figure 3
Cutters, showing the effect of a relatively resistant bed at three positions within the cutters.

The phosphate district of central Tennessee affords many excellent exposures of cutter topography because the phosphate-rich mantle has been removed from the limestone bedrock.

Cutters and pinnacles were also observed in tilted and deformed rocks, even where the dips of the rocks approximated 45 degrees. Despite the angle of the bedding, where the rock is essentially homogeneous, the dominant lineaments of the upper parts of the cutters are vertical, as opposed to the possibility of control by bedding or oblique joints (Watson, 1905). In the lower extensions of cutters, control by bedding and inclined fractures becomes more noticeable (e.g., in the marble quarries of eastern Tennessee).

The *pepino hills* of Puerto Rico, the *mogotes* in Cuba, and similar karst forms in other areas have almost universally been interpreted as being old age remnants of a former karst plain (Thornbury, 1954, p. 334). These features are steep-sided towers of limestone which protrude out of flat-floored valleys underlain by unconsolidated residual material. I disagree with the above conventional interpretation, for these towers seem to be more closely related to cutters in origin. They are essentially greatly enlarged joints, and the tops of the pinnacles have been exposed by concomitant removal of the residuum as the joints are deepened by solution. They are very close in origin to the *karren* terrains in the United States, but

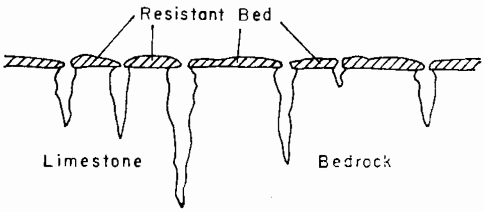

Figure 4
Section through cutters developed under resistant "cap rock".

the wider spacing of the joints and the different climatic conditions of the tropics have resulted in the difference in scale. Monroe (1960) notes that in Puerto Rico the tower forms are present in homogeneous limestone, while sink topography is present where the strata are alternately hard and soft.

It appears unquestionable that solution from which cutters are derived occurs while the cutters are filled with clay. A few interesting studies have been made of the depth of such solution, and the vertical distribution of solution in areas of enlarged joints. D. K. Hamilton (1948) has given a comprehensive treatment of the ground water occurrence in a carbonate rock area near Lexington, Kentucky. He notes that solution occurs along joints and bedding planes, and is directly related to present topography. Beneath both uplands and topographic lows, solutional enlargement was present to a depth not exceeding about 80 feet (fig. 6) and the amount of solution decreased downwards fairly uniformly. He notes that insoluble and impermeable beds inhibit solution beneath them and concentrate solutional effects just above them. Joints which are located beneath topographic lows are enlarged the greatest amount, and least enlargment of joints occurs beneath topographic highs. The solution pattern cannot be correlated with a nearly horizontal, well defined water table and solution development of enlarged joints and bedding planes seems to be patterned into a crude, three dimension connected network, similar in directional development to the overlying topography (fig. 7). Such considerations point to the conclusion that extensive lateral flow of ground water exists within the joints and bedding channels, and that cutters are, in effect, a sub-soil drainage network. The flow of water in cutters would be gravity flow with an assignable gradient. Solution would decrease with depth because of the limited vertical mixing of the ground-water solutions. Walker (1956, figs. 7 and 16) gives similar evidence of the depth of solution. In some localities solution openings have been found at great depth, up to 400 feet or more (Foose, 1953; Moneymaker, 1941). The anomalous openings at depth are probably the result of unusual lithologies and structures promoting deep flow of ground water.

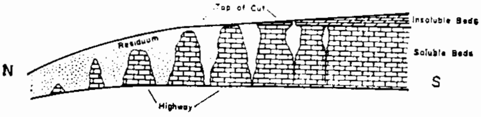

Figure 5
Generalized section of a roadcut north of Columbia, Tennessee, on highway U. S. 31.

Generally the soil-bedrock contact is quite sharp. This would indicate that solution is by surface attack only. The general homogeneity of limestone, its intergranular impermeability, the great volume reduction upon solution, and the rate of solution are probably factors that contribute to the sharp interface. More transitional soil-bedrock contacts are noted in impure limestones and dolomites (Rodgers, 1953, p. 116). Probable reasons for this are the more porous nature of these rocks, allowing more intergranular solution, and the slower rate of reaction, which makes intergranular solution more prominent.

Cutters are best developed in dense, pure limestone with an even, well-developed joint system, and in warm, damp climates. As limestone becomes more impure and more resistant, and the climate becomes less moist, the bedrock-mantle contact is flatter and the soil mantle thinner.

Some granites in arid climates develop a pinnacle topography that is probably closely related in origin to cutters in limestone. Such topography is found in homogeneous granite with even, well developed, coarse

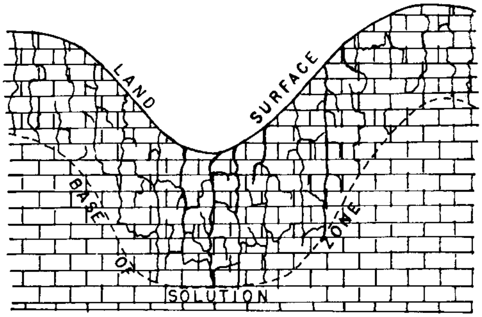

Figure 6
Zone of solution in a valley developed in essentially homogeneous rocks, (Hamilton, 1948, figure 4).

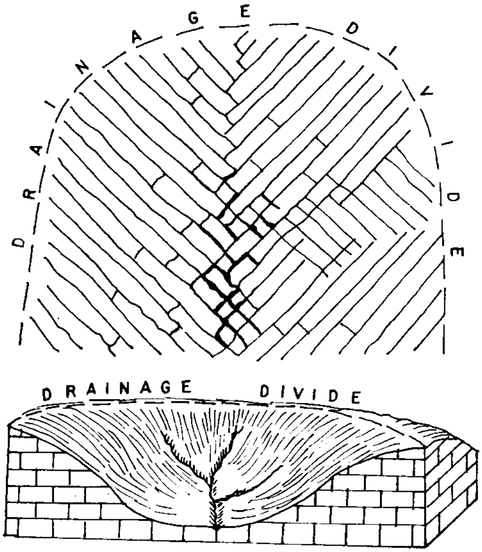

Figure 7
Directional solution along joint planes discordant with drainage, (Hamilton, 1948).

textured joints of vertical orientation. The arid climate that seems necessary for the development of this topography probably results in weathering of the granite by surface attack only, and not by intergranular disintegration.

KARST FORMS OF AREAS OF HOMOGENEOUS SOLUBLE ROCK

Cutters are best developed in areas of essentially dense, homogeneous limestone. The Salem limsetone and Tennessee marble, which have well-developed cutters, are both essentially homogeneous. The Puerto Rico *pepino hills* are in homogeneous limestone and many of the areas in which cutters have been observed in central and western Tennessee are in monotonous topography developed on thick, nearly homogeneous limestones and dolomites.

The form of cutters in homogeneous rock is that of trenches along the joints narrowing downwards rather uniformly. These cutters have sizes and depths of varying orders of magnitude and are so arranged to form a crude sub-soil drainage network. Cutters are also found in areas of variable geology and this will be considered in a later part of this paper.

A critical point to be determined is the topographic elements that might be expected to develop in an area of homogeneous rock. Classical theory assumes that the topography depends mainly upon the stage of landform evolution, and that whether one should expect surface drainage or subterranean drainage through caverns depends also upon the stage of the karst cycle in soluble rocks. Recently, however, the importance of *equilibrium topography* has become apparent as quantitative studies have been made. For example, Strahler (1950) points out that in the mature and later stages of landform evolution the topography of areas of homogeneous rock is typified by a monotonous topography of similarly shaped hills with similar relief, and that all areas have equally well-developed drainage. This equilibrium hill profile would be determined by the physical properties of the rock (solubility, grain size, fracture pattern, etc.), the local rate of erosion, and climate. All parts of the topography (streambeds, hillslopes, and hilltops) would be downwasting at essentially the same rate. This topography is essentially *static* in that there is little shifting of drainage, migration of divides, or changes of hillform during erosion, although relief may decrease or increase as erosion continues.

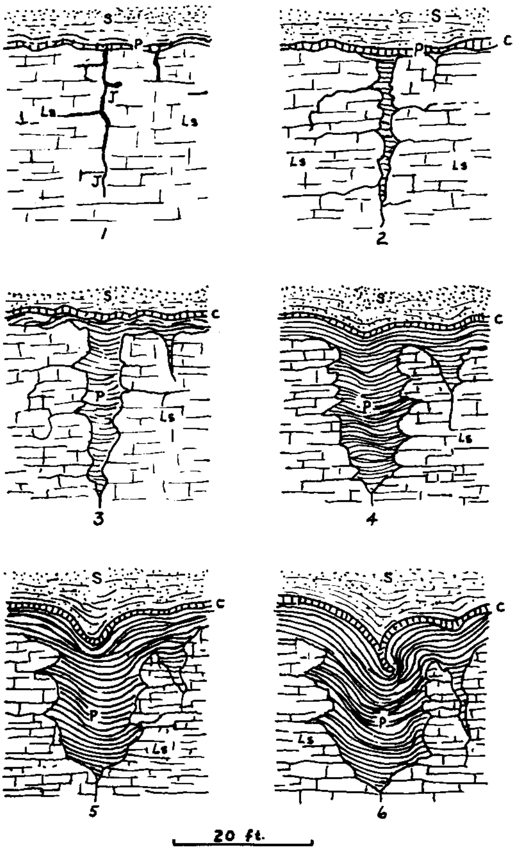

Figure 8

The development of cutters, (Hook, 1915).

S = Soil
Ls = Limestone
C = Clay seam
J = Jointing
P = Phosphate

Because it is an equilibrium topography all disturbances in the topography caused by rapid increase or decrease of rates of erosion should be short-lived and should rapidly reach equilibrium. It also means the direct effects of any initial conditions impressed upon the topography (for example an initial peneplaned surface) would be rapidly eliminated from the topography.

The stage of youth occupies only a short period in even an ideal cycle (less than 5% according to Johnson, 1932), and we should expect that most of the present topography on homogeneous rocks should approximate a static equilibrium topography. Hack (1960) maintains that very little or none of the topography of the eastern United States bears any imprint of cyclical tectonics and, correspondingly, is an equilibrium topography. Equilibrium topography would be continuously present under condtions of constant or slowly varying rates of uplift.

Let us now consider cutters in the framework of the concept that in areas of homogeneous rock the landforms are not changing in form or quality during erosion of the land, and the topographic elements are essentially time-independent. An early concept

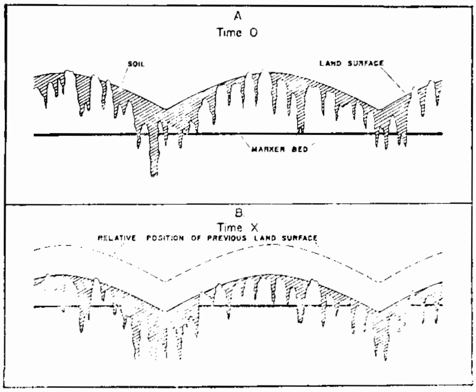

Figure 9
Vertical migration of cutters by erosion.

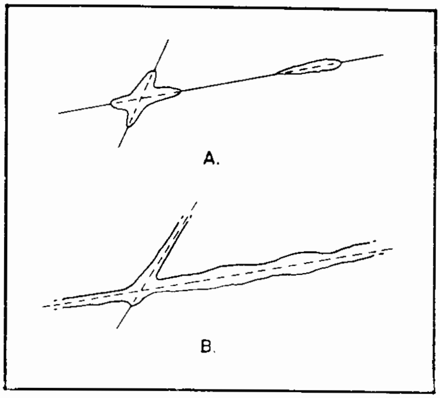

Figure 10
Types of solution along joints; A). Random, non-integrated pockets, B). Continuous channels.

of the development of cutters given by Hook (1915) (fig. 8) is notable in that a cyclical or unidirectional development of cutters was imagined. However, it is the present opinion that such a waxing and waning of cutters is not to be expected in homogeneous rocks, but rather, the amount of solution should remain essentially constant during erosion (fig. 9).

Caves and sinks are not to be expected in extensive areas of homogeneous rocks, but rather are confined to areas of changing topography caused by inhomogeneities of geology. Cutters, on the other hand, are the only karst landform present in areas of homogeneous soluble rock, although they are also present in areas of diverse geology.

In equilibrium topography on homogeneous rocks essentially no drainage gradients exist between a topographic point and any lower topographic point passing through bedrock which are greater than a gradient between the same upper elevation and an equal lower elevation by following a surface route only. Hence subterranean drainage capture cannot be expected. It has already been shown from studies of limestone terrains that are nearly homogeneous that solution decreases regularly with depth, and cutters are not roofed over in homogeneous strata. Even at greater depths there does not appear any reason that one should encounter abnormal cavities or caverns in homogeneous soluble rock.

Significant thicknesses of limestone strata that are homogeneous, or nearly so, are probably the exception rather than the rule. Even in the most nearly homogeneous strata, for example the Salem limestone and Tennessee marble, lithologic variations occur that permit small cavernous openings to form. To the degree to which soluble rocks approach homogeneity they will exhibit few or no cavernous openings (as opposed to cutters along joints, which will become more common). To the degree to which soluble rocks, or combinations of soluble rocks and non-soluble rocks, approach greater inhomogeneity caverns and sinks will form.

Caverns

Caves (caverns) are here defined as enclosed bedrock channels, generally of horizontal extension. All linear openings, from anastomoses to large cavern chambers, are therefore considered to be one continuum.

Cavernous passages result from solution of the bedrock by through-flowing ground water. Some authors have maintained that unintegrated, pocket-like openings often form in limestone by solution, especially in the saturated zone (Davies, 1958, p. 27). Figure 10 demonstrates the difference between an integrated passage and non-integrated pockets. An integrated passage is continuous, although it may enlarge or contract in dimensions. A non-integrated passage is fragmentary, or discontinuous.

Any continued solution of limestone must be accompanied by a relatively continuous addition of fresh solutions and removal of saturated solutions. Ground water with no appreciable flow cannot, therefore, create openings underground, for saturation is soon achieved, and, even if we postulate production of acid by bacteria after ground water is introduced into the rock, oxygen and food must still be supplied. Therefore, to dissolve limestone, a continued flow must be maintained, and, correspondingly, the openings through which the ground water flows must be continuous.

Evidence for the above conclusion may be cited from observation. Reference is made to a quarry near Hershey, Pennsylvania which encountered a 6-inch opening in limestone at a depth of 400 feet (Foose, 1953). This opening yielded 8,000-10,000 gallons of water per minute, but is well within the ground water zone which would be characterized by some as containing only primitive, nonintegrated openings. These, by definition, could not yield more than their capacity of water. The opening encountered must be part of an integrated cavern system, although it probably consists of generally very small openings. This system of openings was able to produce a cone of depression in the water table when water was pumped from the opening. The openings found in the limestone in Pennsylvania are not large when compared to a enterable cave, but are as integrated as their larger brethren.

Because caves must have, or have had, a circulation of ground water through them in order to be formed, they must have or have had a point or points connecting the cave to the surface from which the ground water entering the cave originated, and a corresponding discharge point or points through which the ground water exited from the cave to the surface. One possible exception to this rule are caves in porous limestone. In such a situation, dispersed flow of water through the rock might concentrate in discrete openings, giving no original connection between the cave and the surface. The determination of the entrance and exit points for ground water, and the determination of the general pattern of cir-

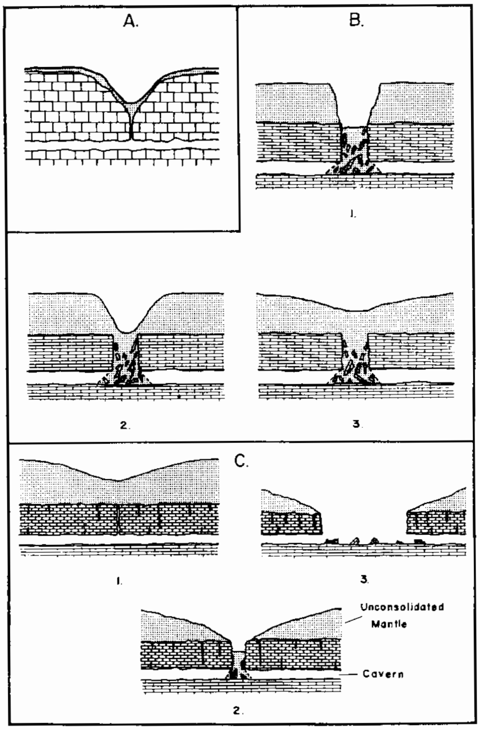

Figure 11

Sink morphology in horizontol rocks: A). Surface topography mirrored on the bedrock surface, B). Sinks resulting from cavern collapse, passing from stages 1 to 3 as surface mantle creep tends to obliterate surface expression of the collapse, and C). Concept advanced in this paper, that surface expression of a sink is not necessarily mirrored in the bedrock. Sink passes through a series of stages 1 to 3, with a much greater length of time in the first stage than in later stages.

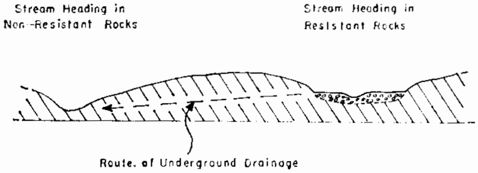

Figure 12

Capture by solution piracy of a stream heading in resistant rocks by a lower stream heading in weakly resistant rocks.

culation within a cave is as important as the determination of the history of the cave, the determination of the ground water zone in which the cave was formed, and the deciphering of the other critical elements of cavern form and history.

A person visiting both Carlsbad Caverns, New Mexico, and Eldon's Cave, Massachusetts, could not help but be impressed by the differences between them. Eldon's Cave is essentially an underground stream through a single, small passage, while Carlsbad is essentially dry and capacious. Some caves, like Carlsbad, are somewhat comparable to the interconnecting chambers of a sponge, while other caves, such as Carrol Cave, Missouri, consist of a few major passages which extend for miles. Some caves have streams which occupy almost all major passages, while others are almost dry. Some caves, even in folded rock, are predominantly horizontal in extension, while others, such as Breathing Cave, Virginia have prominent down-dip extensions, resulting in an inclined cavern.

Even when confronted with the extreme diversity of caverns, most speleologists would like to think of all caves as originating in essentially the same manner (Davies, 1960, p. 29; Bretz, 1956; and Woodward, 1961). I do not believe that it is possible to discover one universally applicable origin of caves unless one speaks in vaguest and most inconsequential terms. Variations in the features and histories of caves must, to a large extent, reflect corresponding variations in the processes operating to form the caves. This approach has been anticipated by Halliday (1960, p. 28) and Lange (1960, p. 29). However, this does not mean that we are forced into an alternative that each cave originates under *completely* unique situations. Many caves are very similar in features and history to other caves, and must have originated under similar, but not identical circumstances. Therefore the problem becomes one of discovering the various classes of situations which lead to the development of caverns.

Because of this viewpoint, the reader will not find in the following pages a complete description of all circumstances leading to the development of caves, but only those situations which the author believes at present to be responsible for the developmnet of some types of caverns. There are, of course, other types of caverns which have not been studied sufficiently to be encompassed within this paper. Although all caverns develop under at least partially unique circumstances, there are a number of principles that are true of all caves. One of these has already been discussed, that no caves can be expected in large areas of homogeneous rock.

The type of ground water flow through discrete bedrock channels which leads to the development of cavernous passages has already been noted as lacking in topography on homogeneous rock. It is my opinion that two types of geologic-topographic situations may lead to the development of caves. The first is the situation where a drainage gradient through soluble rock exists between an upper topographic point at a source of drainage to a lower topographic point which is greater than the topographic gradient. The other situation is where artesian circulation is promoted through soluble rock.

SINKS

Sinks, or sinkholes, may be defined as enclosed topographic depressions resulting directly or indirectly from solution by ground water. Sinks are generally found on otherwise gentle to flat topography, for on significant topographic slopes they are highly unstable. Sinks are collection areas for the diversion of surface water underground. They may have formed primarily from this function, or, like some sinks formed by collapse of cavern roofs, this may be a secondary attribute.

Sinks presuppose caverns, but the reverse is not necessarily true. In areas of almost complete drainage underground through sinks, they are the sole source of ground water responsible for the caverns. However, many caves receive ground water flow through sources other than sinks, and such sinks as may be above them result either from cavern passage collapse or a secondary diversion of drainage from the surface into the cavern.

The simplest and the most prevalent concept of the forms of sinks is that the bedrock surface essentially mimics the surface topography; the bedrock surface is assigned great funnel-shaped depressions (fig. 11A), which form by solution as ground water moves down into cavern passages. Although I have examined many sinks, and quarries in sink areas, I have not seen this type of bedrock depression. The quarries in sink areas , for example near Mitchell, Indiana, show the bedrock surface to be essentially planar. I have seen sinks with nearly vertical bedrock walls, obviously formed by collapse into underlying cavern passages, but these are not of a solution origin.

Coleman and Balchin (1959) conceive of sinks in a different way, envisioning cavern collapse to explain the surface depressions. Their reasoning appears to be as follows: solution depressions in limestone are admitted to exist. They correctly observe, however, that solution, acting downward but slowly, is much slower than the rate of mantle creep, and therefore bedrock solution depressions (such as cutters) have no surface expression, solutional lowering being counterbalanced by inward soil creep. Rather, cavern roof collapse acts to make an initial depression (fig. 11B). After initial collapse of the cavern roof, mantle creep gradually forms a shallower, broader depression, which is finally eradicated by further inward creep, at which time no further surface expression exists above the collapse. However, the quarries in karst areas, mentioned above, show no cave openings large enough to promote roof collapse, even though the quarries are in areas of abundant sinks. In such areas the subterranean drainage is through small joint and bedding openings. In addition, these quarries show no evidence of former collapse of bedrock. Also, passages in many caves pass shallowly beneath surface sinks, and show no collapse. Therefore, although collapse sinks most certainly exist, they do not account for most of the sinks of the sink plains.

The two hypotheses of sink morphology given above neglect process of removal of the unconsolidated mantle material through bedrock openings. Malott (1922, p. 197) points out that in solution valleys all weathered material must be transported underground to surface streams. Where streams disappear underground, they must also carry their suspended material and bed load underground. In caves it is possible at times to see sinks from the bottom up; debris is actively and continually entering caverns through these openings. In many cases it is also being removed from the cave by subterranean streams.

Soil material washed into underground passages is capable of producing funnel-shaped surface depressions of sinks. Several variables would affect the rate of soil material and the shape of the sinks: the type of overburden, the topographic position and nature of the bedrock channels, and climate. The surface forms of sinks might be expected to change throughout time as variations in the rate of erosion of soil material occur. At irregular intervals the mantle material might effectively plug drainage routes causing a lessening of the rate of removal. This would cause mantle creep to start filling the basin, and a perched lake might form. Alternately, these seals would break, and large quantities of material would suddenly wash underground, leaving fresh, steep sinks. Such sudden releases of material underground would be a sufficient cause for the rapid disappearance of lakes or appearance of sinks which are often attributed to cavern collapse. An instructive example of this occurred near Hershey, Pennsylvania (Foose, 1953) where the stone company (previously cited) artificially lowered the water table in a limestone terrain. The resulting cone of depression increased the efficiency of underground drainage. A surface stream was immediately diverted to a subterranean course and a large number of sinks appeared. The underground water correspondingly was muddied with suspended material. No mention of collapse was made, although these sinks were observed in formation.

Compared with quarries or limestone exposures in areas of cutters, those quarries in sink areas in flat lying rocks show contrasting morphology. No cutters were seen in these quarries, rather the mantle-bedrock contact is essentially planar. Surprisingly, perhaps, the total amount of bedrock solution in the sink areas appears to be much less than in the areas of cutters. The solution forms that were seen were stratigraphically determined cavernous channels, most of them rather small (3-4 inches wide and a few feet in height), but occasional larger cave passages are to be found.

My conception of the sink in essentially flat-lying rocks is shown in figure 11C. The flatness of the bedrock surface is caused by the differential resistance of the rock units. The unit immediately below the mantle and above the cavern passage is an especially resistant unit. The less resistant rock overlying this unit has been removed by erosion, and downward weathering has almost halted at the resistant unit. Because the resistant unit has persisted, it has assumed a position as an upland structural plain. Malott (1922, p. 194) points out that the great sink areas in Indiana are found on structural plains. It is assumed that more soluble layers are present beneath the resistant unit. Streams or other concentrations of water on such an upland must exist as perched water bodies by virtue of the very low stream gradients on such a structural plain and its position high above the lowest topographic points of surrounding areas. Hence water on the uplands, where possible, is diverted downwards into the more soluble layer; this results in the formation of an underground drainage network.

The openings through resistant bedrock are small compared to subterranean passageways, and generally become significantly large only at wide intervals, for ground water will concentrate upon enlarging a few larger openings rather than enlarging all joints equally. Hence removal of soil material will occur only at wide intervals, producing the pitted sink plain.

As solution continues, the bedrock channels enlarge, and collapse may occur above the largest cave passages. Such occurrences are relatively rare, for solution must effectively quarry out the collapse block, for rock spans can generally bridge large widths. Figure 11C-2, 3 shows later stages in the evolution of some sinks, where by collapse they become gulfs.

To this point I have discussed only sinks in heterogeneous, nearly flat-lying rocks where the sinks are the sole contribution of ground water to the caves, as is the case for the great sink plains of the eastern United States. The second set of conditions is where the sinks are secondary features dependent upon the presence of cave passages in which the main sources of ground water are from areas other than sink plains. In such cases sinks may form either by collapse of cavern roof or by diversion of surface drainage into the cavern system. Such sinks need not have lithologically determined morphology, and should be relatively rarer than those in the sink areas of flat-lying rocks. Such sinks may form above pre-existing caverns in both horizontal and tilted rocks.

KARST FORMS OF AREAS OF NONHOMOGENEOUS GEOLOGY

Caves and sinks seem to be most common in areas of great inhomogeneities of geology. Many large caves are found at or near the escarpment of the Cumberland Plateau, which is upheld by a resistant sandstone series, and the caves are formed in limestone layers underlying the sandstone. Wind Cave, South Dakota is found in a limestone member of a series of shales, sandstones, and limestone forming the flanks of the Black Hills Dome. The caves of southern Indiana are found in the areas of rough and varied topography developed on shales, sandstones, and limestones. The caves of the Mammoth Cave region are characteristically associated with the escarpment of the resistant Cypress sandstone, which contrasts greatly in geology with the soluble limestone beneath that contains the caves. Carlsbad Caverns are developed in a variable reef facies, and the effect of the variations on the topography of the area is quite noticeable. In the Appalachians caves of large size are found where the stratigraphy has the greatest variation. Such examples might be extended almost without limit.

In contrast to the rather static conditions prevailing in areas of homogeneous rock, the topography in areas of great diversity of geology is generally in a state of flux. Divides may be actively migrating; drainage conditions, topographic slopes and profiles, and stream gradients may vary greatly from one location to another; certain areas may have streams "perched" with respect to nearby areas, and stream capture may be common. Such conditions, which are the result of the influences of various lithologies and structures upon the topography, are often conducive to the development of caves and sinks where soluble rocks are present.

Hack (1960), and earlier Gilbert (1877), have shown that pediments are a common feature where drainage from resistant rocks passes onto less resistant rocks. Hack treats as an example an area in Virginia where streams from collection areas in resistant rocks flow onto the less resistant rocks of the Shenandoah Valley. The stream gradients in the resistant rocks are greater than those in the non-resistant rocks, for the non-resistant rocks are more easily eroded. Where the drainage from the resistant rocks enters the area of lower relief of the weaker rocks, a transitional phase of lateral planation, or terrace and flood plain development, is present, and is present only in such areas. Lateral planation occurs because bedload, composed of debris derived from resistant rocks, is more difficult to erode than the weak carbonates and shales. Streams which are developed entirely on less resistant rocks will tend to capture nearby streams which derive drainage from the resistant rocks by virtue of the lower altitude of the former. Such a capture would result in the abrupt lowering of the upper course of the stream heading in resistant rocks, and aggradation of the lower streams, the former resulting in the formation of dissected terraces.

If these weakly resistant rocks are also soluble, the possibility of underground drainage capture is likely. A case of stream capture underground is shown in figure 12. In constructing this figure it is assumed that the two streams flow essentially perpendicular to the plane of the section at this point. The stream headed in resistant rocks, by virtue of being "perched" with respect to the stream headed in the weaker rocks, will tend to loose water to the adjacent lower stream, and the underground route, being more direct, will be favored. It is notable that, when discussing the above type of surface stream capture, Hack used as an example the incipient capture of North River by Mossy Creek. On the topographic map of this area (Parnassus, Virginia Quadrangle) a series of sinks connects the two streams near their closest approach, indicating that limited subsurface drainage capture beneath the gravel cover of North River has probably already occurred.

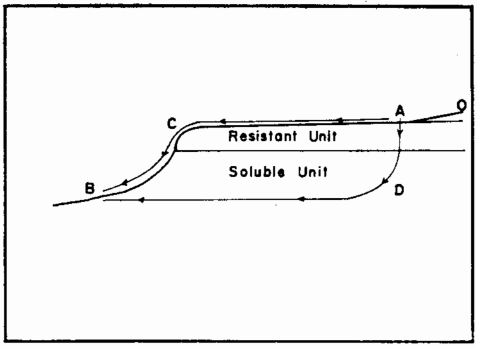

Figure 13
Two possible paths for drainage in a given geo-topographic situation. Path ADB is more stable than path ACB and will replace the surface path as suitable solution channels develop.

In the above case the geologic situation was the presence of adjacent areas of resistant and weak, soluble rock, and the resulting topographic situation was the presence of high gradient streams where the drainage heads in the resistant rocks, and lower gradient streams which are developed entirely on the less resistant rocks. This situation promotes underground capture of the higher gradient streams by the lower.

The above case illustrates some principles that can be extended to the study of many types of caves:

1. No regional uplift of the land, nor tectonically influenced rejuvenation of streams, is called upon as a direct causal agent for cave development. The lateral planation and corresponding sporatic stream

capture (and cave formation) will continue throughout the erosional history of the area, whether there is rejuvenation or not.

2. Caves, and such areas in general, will have time-dependent histories. Before surface capture of the upper stream by the lower, subterranean flow through the cave would be at a maximum, and the cave would be actively enlarging. After the upper stream has been captured by the lower stream by surface diversion, the ground water flow through the subterranean route would suddenly almost cease, and the cave would no longer be enlarging. This time-varying history is in direct contrast to the rather static conditions in homogeneous rock areas.

3. Residual landforms are present in the terraces left after surface stream capture, and the dry cave similarly created; both are remnants of processes no longer operating. In homogeneous rock areas there are no such remnants, and in the present case these remnant landforms are not the result of tectonic uplift.

4. Caves have a morphology that is a function of the situation which has caused their development: the gradient of the cave in the above example will be well defined, and would be from the upper to the lower stream (or, after subsequent surface capture, from an upper dissected terrace to a lower stream or filled stream); the levels within the bedrock at which the caves are found in the above case will correlate with terrace levels on the surface; such a cave may be expected to be a simple and linear underground stream passage that is nearly horizontal and structure-crossing; similarly, the cave should be expected to be of shallow phreatic origin; this type of cave might have wall flutings and cave deposits of a pebble conglomerate derived from the material of the upper stream bed load and terraces; one might expect a paucity of sinks above such a cave, for it does not derive its through-flowing water primarily from sinks, although secondary and collapse sinks may be found directly above cave passages; and, because of the sudden decrease in drainage through these caves if surface capture of the upper stream by the lower occurs, a partial aggradation of the cave stream and complementary filling of passages may be present.

Deike (1960) has treated a strikingly different type of cave (Breathing Cave, Virginia) in folded rock. Here a soluble limestone is sandwiched between two insoluble and impermeable units. The topography is developed with respect to the geology such that an upper collection area on the limestone is on the flank of Jack Mountain, which is supported by the resistant rocks above and below the limestone, and a lower ground water exit point is present at a lower altitude where the strata are bent up into a sharp anticline. At an earlier time when the surface of the land was higher, this situation promoted artesian flow through the limestone from the upper area to the lower. Deike demonstrates that such "deep phreatic" artesian flow has resulted in the development of Breathing, and perhaps Butler caves in Virginia (Deike, 1960).

Cavern characteristics apparently associated with this type of development by artesian flow are: passages which follow the dip downwards without diminution; two or more joint systems almost equally dissolved, and a wide zone of solution, thus giving a maze-like pattern to the cave; generally fine-grained cavern sediments; and subterranean streams that are clearly secondary. This type of cave most closely approaches Bretz's (1942) conception of cave morphology.

In this case there is also a time-dependent history of the cave, but in this instance there are two distinct epochs of conditions: the deep phreatic flow of ground water through the cave under artesian pressure, and a later period of subterranean stream invasion after erosion lowers the siphon level of the standing water below that of the cave.

Again, no rejuvenation or particular "stage" of landform development is required in order to account for the presence of the caves. Although Deike shows a previous, higher land surface of low relief, the type of flow leading to the development of the caves would have occured even if the previous relief at the time of artesian flow (when the land surface was at a higher level relative

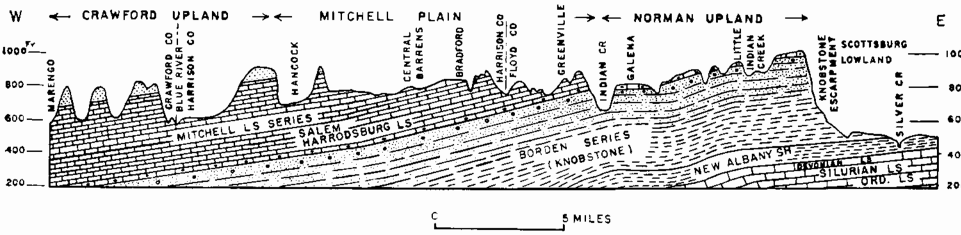

Figure 14
Geologic and topographic profile from about 5 miles north of Jeffersonville westward to Marengo, a distance of 33 miles (Malott, 1922.)

to the structure) was of similar relief as that at present.

Woodward (1961, p. 50) asserts that caves must come about as a relatively sudden event. This may be often true in the case treated previously, but clearly in this case the conditions for artesian flow may persist for millions of years. Thus, depending upon the geologic and topographic circumstances, caves may come about as the result of intensive processes acting for short periods, or as the result of lesser agencies acting for longer times.

Let us now consider the origin of some caves in nearly horizontal rocks. One of the most common situations conducive to the development is that shown in figure 13. The geological situation is that of a soluble unit overlain by a relatively resistant unit. The profile is constructed along a surface drainage route OACB. The stream profile clearly shows the effects of this contrast of geology. The sections of the stream to the right of point A and to the left of point B may be taken to be "normal" stream gradients on uniform rock. However, as the stream has cut down it has encountered the resistant unit which it is unable to erode by usual means at a rate equal to that of the erosion of the normal sections of the stream. Therefore the stream follows along essentially on the top of the resistant unit to the point C. Between point C and B is the nickpoint characteristic of such situations. This develops because it is the only effective way to remove the resistant unit at a rate equivalent to the rate of lowering of the downstream portions. This is accomplished by the intense forces of abrasion and undercutting acting to remove the resistant unit in such a steepening of slope. Therefore the resistant unit is effectively removed by upstream advance of the nickpoint, which is, incidently, not eradicated by further erosion as Davis (1930) imagined. Interstream areas are eroded by a very similar type of escarpment retreat.

Now consider the two points A and B. Point A is anywhere on the flat plain on the resistant unit, and B is a point on the lower area. Drainage will tend to move from A to B by either of two routes, the surface route ACB, and the subterranean route ADB. ADB is the more stable configuration, and will tend to replace ACB, for the subterranean gradient at point A is greater than the gradient of the surface route. Hence sinking creeks and a sinkhole plain, with a corresponding cavern system, will tend to form. Major streams along the upland plain will be diverted into one or more swallow holes, and the drainage system will be fragmented into enclosed sink basins. Sinking streams will form the largest subterranean channels, and lesser sinks, smaller channels, all of which would be organized into a crudely dendritic subterranean drainage system. In cases where the resistant unit over a soluble unit is very insoluble and impermeable, no significant solution can occur beneath such a cap except near the margins of the escarpment, and such features as domepits can be sculptured by vertically moving water from marginal sinks (Pohl, 1955).

Let us consider a number of cases where the above geologic situation is present. Malott (1922) described the karst plains of

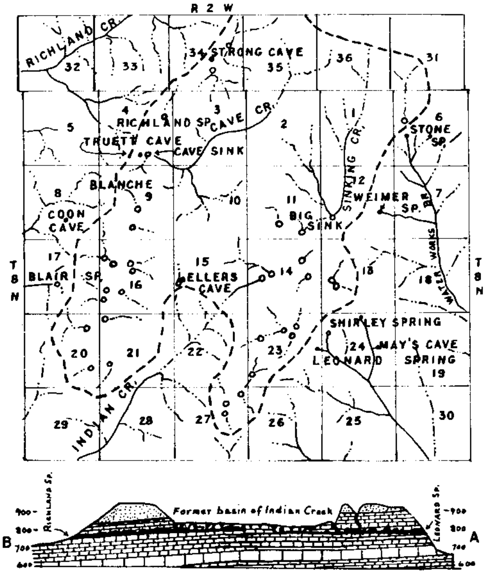

Figure 15

Present drainage conditions near the headwaters of Indian Creek southwest of Bloomington, Monroe County, Indiana. Note that the former Indian Creek basin is 100-150 feet higher that the surrounding streams, and also that this basin floor is developed at approximately the level of the resistant unit of the St. Louis limestone, (Malott, 1922). Dashed line bounds area of subterranean drainage.

Indiana, and figure 14 is a cross section through this karst area. Several correlations between geology and topography can be seen in this section. The upper portions of the Mitchell limestone series, the Gasper and Ste. Genevieve sub-units, are found only under cappings of resistant clastics; they are, therefore, apparently easily stripped away when this capping is removed. Probably because of their homogeneous and weakly resistant properties, correspondingly small outcrops and steep topographic expressions, these limestones, while very soluble, have little subterranean drainage developed in them. The middle of the Mitchell series, which is the top of the St. Louis sub-unit, is a resistant unit of cherty limestone. This unit forms extensive area of outcrop, in an upland structural plain closely following the dip of the strata. For example, the area around Central Barrens is such a structural plain developed upon the cherty unit. It is upon these chert-capped plains that the greatest development of sinks is found, with large areas drained only by sinks. A good portion of the subterranean channels lies just beneath the chert horizon, and most of the well-developed sink topography lies just above the same unit. Most of this underground drainage exits to the west, down-dip, in the deep valleys of the Crawford Upland as springs and resurgences. The western-most portions of some underground channels are apparently under artesian conditions, because the channels closely follow the dip of the strata downward to the west, and rise as vertical resurgences, or "negative sinks". The caves further to the east, under the karst plains, are well above the level of the main streams, and are free surface, graded, underground stream passages. The lower part of the St. Louis, the Salem, and the Harrodsburg limestones are of about equivalent resistance and solubility; in these nearly homogeneous but soluble rocks little underground drainage is present except that in cutters. It will be remembered that the Salem limestone is characterized by well-developed cutters. The surface-drained areas on these units extend from Bradford to Indian Creek (fig. 14), and the surface drainage from these areas often passes westward into underground streams where the capping of the cherty unit is present.

The subterranean capture of the headwaters of Indian Creek, near Bloomington, Indiana, affords a striking contrast between the conventional theories of karst interpretation and the present view. Figure 15 shows the present conditions at the former basin of the headwater portions of Indian Creek. This drainage basin is now drained entirely underground, and the subterranean waters exit into the lower 'intrenched" tributaries of Clear Creek and Richland Creek.

According to the conventional cyclical interpretation of the underground capture, at the time of the late Tertiary peneplanation the entire area was drained by surface streams, as illustrated in figure 16. After uplift of the area, Clear Creek, Richland Creek, and Indian Creek began to intrench their drainage. Clear Creek and Richland Creek, being larger than Indian Creek in its headwater portion, intrenched their stream channels by nickpoint advance before Indian Creek could do so. These creeks, by virtue of their lower topographic position, then began subterranean capture of the waters of Indian Creek. When this became virtually complete, downwasting of the Indian Creek basin was effectively halted, and it stands as such a structural sink plain today.

As can be noted in the geologic cross section of figure 15, however, the perched basin of Indian Creek is stratigraphically controlled at the horizon of the resistant cherty unit. This gives a basis for an alternative explanation in terms of the geologic effects of topography.

We can consider figure ~~15~~ 16 to represent the drainage conditions at some indeterminate point in the past when no subterranean drainage was present (before the exposure of significant portions of the middle of the Mitchell limestone). However, unlike the previous interpretation, we could assume the topography at this earlier time to be essentially as great in relief as it is at present, for an earlier peneplanation is not a prerequisite. As erosion continued the major streams reached the resistant cherty unit of the Mitchell, the larger creeks, Richland and Clear, reaching it first. Because of the resistance of the unit, erosion was effectively halted for some time beneath each stream, resulting in very low gradient stream segments and partially stripped plains on the cherty unit. In order to accomplish further erosion the streams had to establish a steeper gradient through the resistant unit. This was accomplished largely by the migration of a stratigraphically-determined nickpoint upstream. Richland and Clear Creeks, because of their greater size, accomplished this more rapidly and with a smaller flat transition zone on the resistant rock than did Indian Creek. The migration of the nickpoint upstream on these creeks left Indian Creek perched with respect to the lower creeks, subterranean capture of Indian Creek resulted, and an upland karst plain developed at the level of the resistant cherty unit.

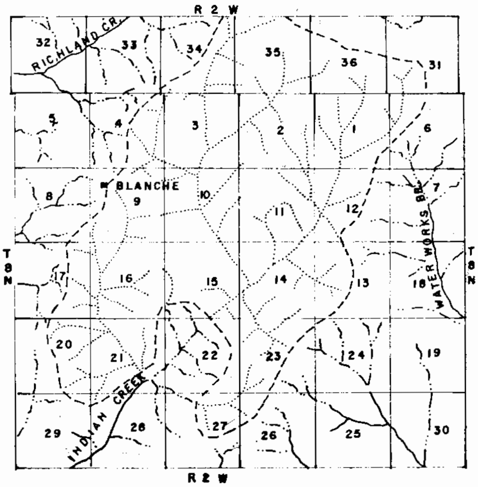

Figure 16

Restoration of surface drainage of the headwater portion of Indian Creek. Such a stage of development is assigned by Malott to the close of the late Tertiary peneplanation. Little underground drainage is assumed to exist at this stage, (Malott, 1922).

In the above interpretation no specific rejuvenation of drainage is called for as a casual agent for the development of underground drainage; the development and migration of the nickpoint is caused by the presence of the resistant unit.

One more case from the karst area of Indiana will be considered (fig. 17). A striking gradation of topographic forms may be seen along this strip of land. In the state park are the headwater portions of Mill Creek, which in this zone is deeply incised beneath the level of the surrounding upland karst plain. This stream ends abruptly at the entrances to caves and at springs, all of which discharge water from underground drainage channels to the surface stream. This underground drainage derives from the extensive karst plain above the incised stream. Progressively from Mill Stream the "intensity" of sink drainage decreases, until, near the far end of the section, surface drainage predominates. Once again this variation in karst forms may be explained by recourse to the geologic controls. Figure 18 is a schematic geologic cross section from

the incised stream to the farthest portions of the strip along an imaginary underground stream passage.

The resistant unit is the cherty part of the Mitchell limestone series, the soluble unit comprises the limestone under the cherty unit, and the weak rocks are the limestones of the upper Mitchell. The sink plain is on top of the cherty unit, the upper Mitchell is in the generally non-sink, low hills to the southwest, and the lower limestone is at the surface only where the incised stream is present. Mill Creek is incised or intrenched because of the presence of the resistant unit, and is slowly eroding headward by nickpoint advance. Because of the intrenchment and the presence of soluble rock underneath the resistant unit, sink drainage is more stable than surface drainage on the upper structural plain. The extent of underground drainage is greatest near the incised stream, where underground gradients are greatest and where sinks and caves have been present for the greatest time, and the amount of underground drainage is least in areas far from this stream, where the underground drainage gradient is much less, and which have had the shortest exposure from beneath the overlying, more homogeneous limestones which are not particularly subject to sink drainage. The areas of intense karst drainage have all the characteristics of what has been termed "old age" karst by the proponents of the karst cycle, for in these areas cave roof collapse and corresponding cave destruction is prominent. However, if the former is true, we must also recognize that the areas farther from Mill Creek must be merely "mature" or even "youthful." But if all stages exist concurrently in adjoining areas this karst cycle must be quite different from the classical conception of the same. It is true, however, that an area of poorly developed sink topography may advance to more well-developed stages as the advance of the intrenched stream steepens the underground gradients,

Figure 17

Topographic map, karst area, southern part of Lawrence County, Indiana (U. S. Geol. Surv. Mitchell Quadrangle).

and solutional enlargement of these caverns continues. But the main objection to the term *karst cycle* is the inherent inferences of cyclical landform evolution, a concept which is not necessary in order to describe the origin of caves, or other karst forms.

Although cutters are the only karst feature of areas of homogeneous soluble rock, they are also present in areas of inhomogeneous rock. To the extent that the rock is inhomogeneous, the form and distribution of cutters will depart from the simple, upward expanding cutters of uniform soluble rock. Because cutters are an equilibrium landform in homogeneous soluble rock, wherever a large area of soluble rock is or becomes exposed, cutters will tend to develop, and caves and sinks will be unstable. Transitional forms between cutters and caves may often be found; their closeness to caves or other cutters is dependent upon the degree of inhomogeneity. For only slight lithologic variations, cutters will be prominent, but will have reentrants or overhangs (fig. 4). All areas of predominantly cutter type bedrock surface have some sinks in the surface topography. Such sinks can often be demonstrated to result from collapse of soil material into cutter channels whose original filling has been removed by abnormal amounts of underground drainage because of heavy rainfall. E. H. Walker (1956, p. 24-25) notes that such sinks are most common where the cutters are characterized by having overhangs of more resistant bedrock. In such cases most soil material is held by the horizontal projections and soil removal into the lower openings occurs only at wider intervals, and sinks are the result. If the resistant layer were more prominent, a normal sink plain would have formed, and if less prominent, normal cutters would be found.

In areas of nonhomogeneous rock the development of cutters may approach the "cyclical" evolution of Hook (fig. 8). Where limestone is overlain by impermeable shale, no cutters form, but as the cover is removed from the limestone cutters will start to form.

As another example, let us consider the karst forms developed on Silurian limestone escarpments in northeastern Iowa (fig. 19). Here the karst forms, while still intermediate between cutters and normal sink plain caves, are closer to the latter. The Silurian dolomite, which overlies an impermeable shale, contains one prominent resistant bed, and the limestone beneath is nearly homogeneous. Where the resistant bed forms a cap over the solutionally enlarged joint in the underlying limestone, high, narrow caves are to be found, as in section B-B' (fig. 19). Above these caves are surface sinks where surface drainage passes vertically through isolated openings in the cap rock, carrying soil material with it, as at E. Some places where such openings through the cap are large and where the soil material brought in is continuously removed by underground streams, as at D, cave entrances will be found. Most often, however, where the resistant cap has been breached, as near cross-section A-A' and C-C', the underlying openings are clogged with soil and debris, and a cutter-like form will be found.

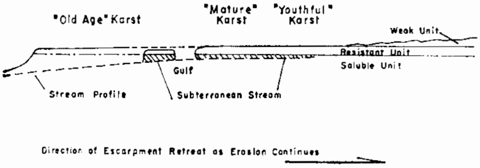

Figure 18
Elements of karst topography where a horizontal resistant unit overlies a soluble unit.

Because cutters are the equilibrium karst landform on homogeneous soluble rocks, where uniform limestones are exposed at the surface, cutters tend to form. As erosion strips away layers of rock such areas of uniform rock will shift. Thus cutters will wax and wane in response to the degree of homogeneity of limestone at the surface, and caves and sinks will be formed and eradicated in response to inhomogeneous geology. The effects of continuing erosion on the distribution of caves and cutters in Indiana is sketched in figure 14.

The rock units above the cherty unit of the Mitchell covered the areas to the east at one time, as shown in this figure, but have now been stripped off. Hence, at one time the type of topography now found in

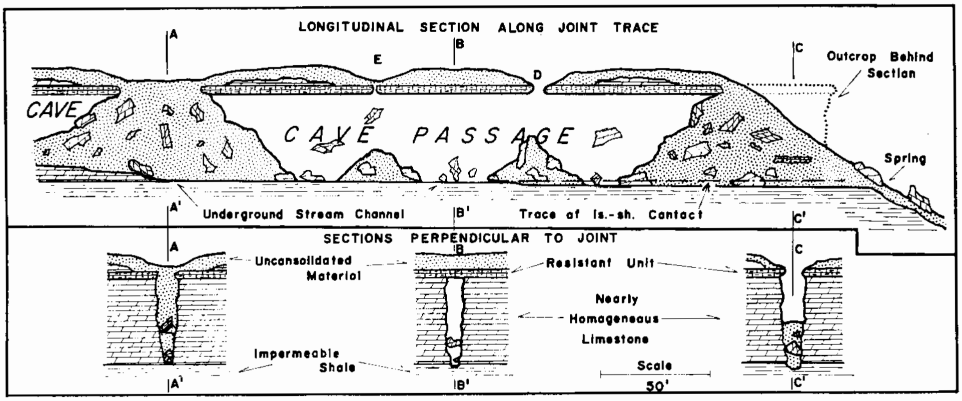

Figure 19
Karst landforms of the Silurian escarpment of northeastern Iowa.

the Crawford upland probably was present where the Mitchell plain is now. Specifically, the area of the present sink plain at one time had no sink and karst features. But when erosive processes had bared the cherty unit of the Mitchell, underground diversion of drainage became more stable than surface drainage which is the condition that now exists. Eventually the resistant layer supporting the sink plain will be removed and more homogeneous limestones underlying the cherty unit will be at the surface. Cutters will replace caves and sinks as the dominant karst form, and topography similar to that near Greenville, with surface drainage, will develop in the present areas of sink drainage. If we choose a point in the Crawford upland, say Marengo, the topographic changes as one progresses eastward from Marengo gives a preview of the successive changes of cave formation and destruction that will eventually prevail in the vicinity of Marengo. Thus by knowing the present relationships between geology and topography, and the resulting karst forms, it is often possible to extrapolate to future or past conditions.

ACKNOWLEDGMENTS—This paper is derived largely from a Senior Honors Essay completed at Yale University in May 1961. In addition to the referenced literature, my conclusions are based upon observations made during caving trips in the eastern United States throughout the past 3 years. In December, 1960, a 5-day trip was made through Indiana, Tennessee, and Virginia for observation of karst landforms.

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