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The Lower Reaches of Long Creek, Kentucky: A Karst Anomaly in Allen County

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THE LOWER REACHES OF LONG CREEK, KENTUCKY:
A KARST ANOMALY IN ALLEN COUNTY

A Thesis
Presented to
the Faculty of the Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Doral Glen Conner
June, 1976

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THE LOWER REACHES OF LONG CREEK, KENTUCKY:
A KARST ANOMALY IN ALLEN COUNTY

Recommended July 2, 1976
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Dean of Graduate College

PREFACE

In a history of the settlement of Kentucky (Collins,1874), the following comment of Long Creek appears:

> ... On Long creek, half a mile from where it empties into Barren River, about 8 miles E. (east) of Scottville [sic], on the lands of Col. S.E. Carpenter, near where his mill stands, the following is inscribed on a large beech tree: "Ichabod Clark, mill site, 1779." On the opposite side of the tree, this inscription is found: "Too sick to get over," date and name not mentioned (p. 34).

One wonders if the carver of the latter inscription subsequently discovered that the Long Creek channel less than one half mile upstream is usually dry because of stream piracy. If he had prayed for a "parting of the waters," perhaps he was surprised to find his prayers so literally answered.

It is to be hoped that this study of the lower reaches of Long Creek will provide knowledge which will enable others in the future "to get over."

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THE LOWER REACHES OF LONG CREEK, KENTUCKY: A KARST ANOMALY IN ALLEN COUNTY

Doral Glen Conner 146 pages

Directed by: W. Willard Cockrill, Ronald R. Dilamarter, Noland E. Fields

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A field survey of the lower reaches of the Long Creek drainage area in southeastern Allen County, Kentucky, established the karst character of that area. The area heretofore had been described as a non-karst area. Four swallow holes, which individually or collectively totally pirate Long Creek, were identified. Two major resurgences of the pirated flow were located and described. A detailed study of a portion of the Long Creek drainage area revealed thirty-four springs, all of which were pirated at least once, and no flow from these springs reached Long Creek by surficial routes. The field survey also revealed dolines and a major cavern, Carpenter's Cave. The geologic formation responsible for the karst features within the Long Creek drainage area is the Louisville limestone of Silurian age. These strata are characteristically karstic wherever exposed. The impermeability of the Chattanooga shale which overlies the Louisville limestone was established by the analysis of spring piracy and resurgence. The phreatic character of the Carpenter's Cave and other karst features led to the conclusion that these karst features were developed prior to the deposition of the impermeable Chattanooga shale during Devonian time.

CHAPTER I

INTRODUCTION

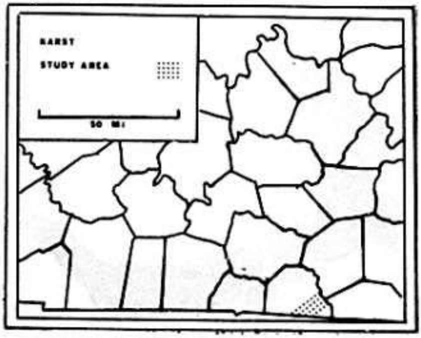
From the first recognition of a karst landscape, man has attempted to explain the origin, processes, controls, and stages of its development. As in other conceptual evolution, a constant re-evaluation of accepted concepts has occurred as new facts were verified.

Scientific study of karst did not really become active until the middle to late nineteenth century. One must wonder why this is so, particularly in the case of caves which offer satisfaction of the urge to explore. Once started, the study has been persistent through the years but may not have kept pace with some other areas of geomorphic thought.

In recent years, karst topography and its geomorphic features have been the objects of intensified scientific investigation. In particular, the Central Kentucky Karst has received much attention and study. These studies have contributed significantly to an understanding of this karst region. The development of some karst concepts was even based upon such area studies. The areal extent and quantity of karst features within the area make it an ideal laboratory for concept formulation.

Studies of the Central Kentucky Karst have assigned boundaries to the area (see Plate 1), it has become a frequent illustration in textbooks of a typical karst area.

PLATE 1. CENTRAL KENTUCKY KARST



SOURCE: S.N. Dicken, Journal of Geology, Vol. 43, p. 719.

This region consists of a landscape of dolines and an underground drainage system. Caves abound, stream piracy is common, and surface streams are rare.

The northwestern extremities of Allen County, Kentucky, are included within the Central Kentucky Karst as defined by Dicken (1935). The southeastern two-thirds of the county is excluded (see Plate 1). The latter portion is, by exclusion, non-karst. One would not expect to find karst features in abundance within the southeastern two-thirds of Allen County.

Long Creek flows through the "non-karst" portion of Allen County and empties into Barren River. Nevertheless, the Long Creek drainage area exhibits many karst characteristics. Long Creek is pirated, takes an underground route under an interfluve, and makes a resurgence on the other side. This phenomenon does not occur elsewhere in Allen County, including the karst portion of the county. There are other karst features in the Long Creek drainage area. Springs, rising in the valleys which are contiguous to the Long Creek valley, seldom reach Long Creek because their flow is pirated enroute. The well developed Carpenter's Cave underlies a portion of the drainage area.

Karst features are common rather than rare in the Long Creek drainage area; therefore a geomorphic anomaly could be said to exist in this area which has been identified as non-karst. This paper describes the lower reaches of Long Creek and its associated drainage area. The confirmation of the existence of this anomaly and the determination of its areal extent and intensity are major objectives of this study.

The primary purpose of this study is to add to the body of knowledge from which concepts of karst development have evolved. Perhaps the addition of data about the Long Creek anomaly may promote a reconsideration of some of those concepts.

CHAPTER II

REVIEW OF LITERATURE

Early Observations of Karst

Although karst was not a subject of detailed scientific investigation until the middle nineteenth century, man's interest in springs and underground water was recorded much earlier. Early philosophers were among those who were interested. Thales (640-547 B.C.) believed that springs and rivers are generated by air condensed into water in the caverns of the earth by a cold which is always present there and which occurs by the same process as above the earth (Perrault, 1674). Lucretius (98-55 B.C.) described a circulation between the sea and the earth in which salt was removed from the water before being discharged as a spring (Herak and Stringfield, 1972). A more thoughtful view was presented by Vitruvius (circa 100 B.C.), who was an architect. He spoke of springs resulting from rain water and winter snow which sink into the earth and are stopped by solid and non-spongy layers (Perrault, 1674). His views were not accepted because there appeared to be too much water in the springs and rivers to be explained by rain alone. These and other theories were critically examined by Pierre Perrault (1674) in his book concerning the origin of springs. His experiments proved that rainfall was more than enough to account for the flow of springs and rivers. His findings were a landmark in what was to become the study of karst.

It was inevitable that Perrault's investigation of springs would lead him to a cave spring. He described such a cavern which he explored near the city of Vermenton, Burgundy. His description was most perceptive:

> . . . This grotto, from what I can judge, crosses under the earth under the hill. . . which the river surrounds with a semicircle. . . I am certain that if the river were made to enter this grotto, through the arcade through which we entered, it would come out at Arcy and return to its bed, leaving dry the one that makes this semicircle. I believe that the opening through which sometimes passes the torrent is a smaller channel which receives the water of this river when it is high, and which takes them to the river itself some place lower down, or which produces some spring and a flow of water in some part of this region which is unknown to me (p. 128).

His description of stream piracy, abandoned meanders, and cave invasion was remarkable considering the geomorphic knowledge existing at that time.

Perrault also observed and described stalactites, stalagmites, domes, and cave water flow. He speculated about the origin of the stalactites which he noted were hollow and contained growth rings. He concluded that "these congelations are produced only by the waters that pass through the earth from above, and which by distilling in this grotto have brought with them the stony salt with which it is filled" (p. 130). This observation was perceptive.

Summarizing his observations, Perrault arrived at a belief that ". . . there are channels in the earth which can preserve the waters that pass through them, with as much safety and ease as is needed to make them come out in various places, even far away" (p. 130). Unfortunately, he did not comment on the origin of the channels.

Nevertheless, Perrault's work stands as one of the first recorded observations of karst features and processes.

One of the first descriptions of karst landforms was provided by J.W. Valvasor in 1689, but its emphasis was on the folklore associated with karst (Herak and Stringfield, 1972). A scientific study of the karst in Yugoslavia did not begin until the middle of the nineteenth century. This study was based on theories by J. Virlet in 1834 that dolines were formed by collapsed caverns and by Charles Lyell in 1839 that the solution process by atmospheric water was a factor (Herak and Stringfield, 1972). American investigations into the karst features in Kentucky by D.D. Owen in 1856 and in Indiana by E.T. Cox in 1874, both favoring the solution process, were the basis for the intensified study of karst by the turn of the century (Herak and Stringfield, 1972). The succeeding paragraphs in this chapter will consider the evolution of concepts of karst processes, karst controls, karst stages, and cave development which were acting in the Long Creek drainage basin.

Concepts of Karst Processes

The Solution Process

The processes which produce karst landforms were the subject of early investigations. Charles Lyell, who was subsequently to advocate the geomorphic theory of gradualism, published a paper in England in 1839 which described the solution process of atmospheric water (Herak and Stringfield, 1972). By 1886, when dolines in Lebanon were attributed to the solution process, carbon dioxide was already commonly taken into account. By 1927, it was understood that rain water absorbs carbon dioxide, which is present in small quantities in the air, and that these carbonated waters act upon the calcite in limestone to produce calcium bicarbonate (Weller, 1927). Various estimates have been made concerning the amount of limestone which a given quantity of carbonated water can dissolve. James Weller (1927) stated that "the amount of water which falls as rain upon one acre of land in Edmonson County, in the course of a single year, is capable under favorable conditions of dissolving some twenty-five cubic feet of rock." Adrian Scheidegger (1961) determined that one liter of water can dissolve 0.5 grams of limestone. Such calculations were made to show that Carlsbad Cavern could have been dissolved in one million years at a water flow of three liters per second. Another estimate is that a cubic foot of water exposed to limestone and air with ten percent carbon dioxide can dissolve one half ounce of limestone (Moore and Nicholas, 1964).

The amount of carbon dioxide in water is variable. It has been found that melt-water from snow in the spring is twenty times richer in carbon dioxide than ordinary water (Birot, 1960). This may explain karst features which occur in cold climates. In humid areas, carbonic acid is produced by plant decay and most of water's carbon dioxide content is obtained by flow through humus (Moore and Nicholas, 1964). In addition, water is enriched in carbon dioxide as a result of its passing through the crown of trees (Herak and Stringfield, 1972). However, one study (Smith, 1965) analyzed streams and springs for calcium content. The results were that ". . . calcium carbonate remains constant regardless of the season of the year or the discharge of the springs" (p. 45). This disagrees with the soil-carbon dioxide hypothesis which says that for a given soil at a given depth, carbon dioxide content reaches a maximum in the summer. It also disagrees with the seasonal variations in water chemistry found by Harmon et al.(1975). One can conclude that while the process of the solution of limestone is understood, the factors which affect the process have not yet been fully explained.

The Saturation Problem

If carbon dioxide in water is not replenished as the water percolates through limestone, the water would eventually become saturated, no longer able to dissolve limestone. This problem has led to several studies. One concluded that deep circulation must be rapid if the water is not to become saturated at shallow depths (Piper, 1932). This view generally agreed with that of A.C. Swinnerton (1929) who held that a large volume of solvent of low concentration flowing over a large area is probably more effective in producing solution that a more stagnant solvent of lesser volume and contact. William M. Davis did not agree. He believed that the greatest amount of solution took place where ground water moved very slowly (Kaye, 1957). Experiments with flow rate as a solution factor have been conducted with varying conclusions. One study concluded that the rate of solution varies with the relative movement of solvent to limestone (Kaye, 1957). Another found that the amount of limestone dissolved is solely determined by the amount of water coming in contact with it and by the prevailing conditions of pressure, temperature, etc. (Weyl, 1958). The latter study also found that the water inside rock is essentially in chemical equilibrium with its surroundings and that the solutionreaction process is short compared with the time during which the water remains in the rock. Still another view (Moore and Nicholas, 1964) is that water below the water table moves only ten feet per year. When a channel reaches a critical diameter of about one quarter inch, water flow becomes turbulent, increasing the solution process and robbing nearby fractures of their flow (Moore and Nicholas, 1964). A mathematical analysis (Scheidegger, 1961) concluded that "there is no danger that water will percolate through a cavern without becoming completely saturated while doing so." It has also been noted (Williams, 1968) that surface streams in limestone areas are almost saturated before they sink underground and do not substantively contribute to the solution process.

The question remains how water which is depositing calcium carbonate above the water table (stalactites for example) can dissolve calcium carbonate below it. It has been suggested (Thrailkill, 1968) that phreatic water can become undersaturated by the effects of temperature change, mixing of dissimilar waters, and floods in surface streams. The relative importance of these factors has not been assessed satisfactorily.

The Collapse Process

The collapse of caverns was considered to be a major karst process in early investigations. Dolines were thought to be collapse features in early writings (Herak and Stringfield, 1972). More recently, collapse dolines are considered to be less normal than solution dolines (Weller, 1927). Nevertheless, collapse is still recognized as a karst process (McFarlan, 1950) although one of lesser importance. Swallow holes which capture surface streams and divert them underground were also thought to be collapse features. A recent study in Wales (Thomas, 1954) suggests that swallow holes are more attributable to solution and enlargement of joint planes than to the collapse of pre-existing caverns. From the foregoing, it is evident that collapse of caverns is not now considered to be a major process in karst formation.

The Fluvial Process

In the context of this paper, the term fluvial erosion includes both surface and subsurface stream and surface sheet erosion. While subsurface drainage is common in karst areas, surface erosion remains to one degree or another. Therefore it cannot be ignored as a karst process even though it is a process in other landform development ar well.

Albrecht Penck in 1900 and William M. Davis in 1901 wrote of the conspicuous plains in the karst area of Dalmatia (Herak and Stringfield, 1972). The formation of these plains was attributed to denudation and fluvial erosion. They believed that fluvial erosion occurred first, producing a plain. Afterward, "karstification" occurred. Jovan Cvijic, who had been a student of Albrecht Penck, agreed with the priority given to fluvial processes (Herak and Stringfield, 1972). In 1909, he ascribed surficial erosion to the action of sinking water while underground rivers cut and enlarged the fissures through which they flowed. This double action characterized the erosion and planation of karst (Herak and Stringfield, 1972). A

Hungarian geologist, Terzaghi, challenged this view (Herak and Stringfield, 1972). He noted isolated plains which did not fit the fluvial theory. In his opinion, such plains had been formed from karst depressions which eventually reached ground water level. At that point, lakes were formed and lacustrine clays were deposited. At such lake margins, denudation and enlargement of the plains occurred.

The Davis-Penck concept of primary fluvial erosion has been widely rejected. At the surface of the karst plain there is normally no evidence of fluvial gravel or outwash, an important element in a fluvial plain (Herak and Stringfield, 1972). Therefore, the primary process in karst development is considered to be solution. Even long accepted fluvial features such as water gaps have been questioned. It has been suggested (Fridley, 1939) that many cases of water gaps can be attributed to the effect of stream piracy which was initiated by underground solution of calcareous strata. More recently, a study of dolines in Kentucky (Lavalle, 1967) re-emphasized the solution process.

Summary

The evolution of concepts of karst processes has occurred in three distinct periods. First was the period in which collapse of underground caverns was considered to be the dominant process. This period ended about 1900 when the primacy of the fluvial process was accepted. The fluvial period was short-lived and was replaced by a shift in emphasis to the solution process about 1913 when Terzaghi published his paper on a solution plain (Herak and Stringfield, 1972). Since that time, the solution process has been considered as dominant in the formation of karst. Even so, the other processes (collapse and fluvial) have been retained although in a subordinate role.

There is another aspect of the evolution of karst concepts--the shift in research away from processes and toward the controls which regulate karst formation. One can conclude that there is general acceptance of the dominance of solution among the karst processes and that this accounts for the shift in research. Such process research which continues relates to learning more about solution rather than evaluating the relative importance of various karst processes.

Concepts of Karst Controls

Control by Water Table

In 1903, Grund published a work which became a milestone in the development of karst concepts. He accepted the existence of karst ground water rising progressively from sea level toward the hinterland. Above this level, during the wet seasons, joints and fissures are periodically filled up by water (Herak and Stringfield, 1972). He also held that caves were formed in the upper portion of this continuous body of ground water. His concept became a matter for debate during this period (Thrailkill, 1968). Some speleologists pointed out that their exploration had not confirmed the existence of a water table (Herak and Stringfield, 1972) while others considered the water table unimportant as a control (Thrailkill, 1968). Still others agreed with Grund and considered the water table significant in determining lateral flow. For example, G.C. Matson (1909) stated that in all limestone regions there are water passages below the level of surface streams.

He believed that circulation of ground water extended below the water table.

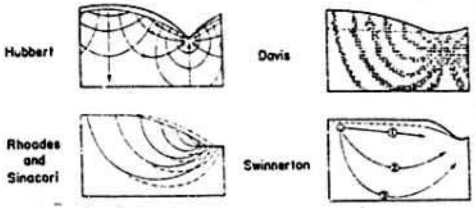
In 1918, Jovan Cvijic expanded Grund's concept by distinguishing three hydrographic zones of karst (Herak and Stringfield, 1972). These were a zone of permanent saturation, a zone of periodic saturation, and a dry zone. This concept was in conflict with other European views which held that there was no integrated body of ground water (Thrailkill, 1968). The opposition believed that ground water flowed through conduits under pressure.

In 1930, William M. Davis published his classic paper on the origin of limestone caverns. He challenged the concept of caves being developed above the water table by noting cave features which were, in his opinion, formed in the phreatic zone, that is below the water table (Thrailkill, 1968). He acknowledged that his concept was similar to Grund's but Davis argued for the formation of caves in the phreatic zone when Grund was arguing for the very existence of a phreatic zone.

In 1932, A.C. Swinnerton amplified the Davis concept and his own water table theory was published in 1929. He stated that it did not seem possible that continuous systems of caves could develop below the zone of actively circulating ground water. He also considered that if water were to flow beneath the water table by all possible paths, the nearly horizontal path just below the water table would carry the most water because it is the shortest (Thrailkill, 1968).

The water table theory of Swinnerton was not immediately accepted. For example, three years later a study attributed limestone caverns to the work of surface streams diverted to routes opened by the draining out of static water by valley cuts (Gardner, 1935). In 1940, an analysis of Swinnerton's work was attempted. This work (Hubbert, 1940) showed that ground water follows deeply curving paths and that alternate paths are impossible. The following year another study concluded that solution would be greatest where the flow was most concentrated (Rhoades and Sinacori, 1941). This study showed that cave formation occurs by concentration of the lateral flow through high level conduits. Further, cave development begins at the point of outflow to a surface stream and progressed horizontally away from the stream with flow lines adjusting continually.

PLATE 2. CONCEPTS OF GROUND WATER FLOW



SOURCE: John Thrailkill, Geological Society of America Bulletin, Vol. 79, pp. 22.

The water table controversy must have been fed by the discovery of cavities far below the water table (Moneymaker, 1941). It was found that in the Tennessee Valley cavities were present at depths in excess of one hundred feet below the water table. Some cavities were as much as two hundred feet below the river bed. This study concluded that within the phreatic zone cavities are more numerous and of greater size above the elevation of the river bed than below it. Moreover, cavities in the vadose zone are more numerous and larger than those within the phreatic zone. This suggests that development begins within the phreatic zone but major enlargement occurs within the vadose zone (Moneymaker, 1941). The possibility that the water table has occupied successively lower positions cloud these findings.

The water table as a control in karst does not appear to have achieved a consensus opinion. The Davis theory was accepted by E.L. Krinitzky (1947). He rejected Swinnerton's views. A later study (Sweeting, 1950) accepted Swinnerton's views and attributed cave levels as marks of former positions of the water table. The Gardner theory that surface valley cutting creates an outlet which drains salt water down dip and initiates the circulation of meteoric waters was revived by Arthur C. McFarlan (1950). He stated that cave forming levels correspond to the original salt water bearing porous zone. Cave forming would thus be concentrated on the region up dip from major valleys. McFarlan concluded that Mammoth Cave keeps this principle.

A study of the karst of Florida (Jordan, 1950) found that none of the water table theories applied to that area. There the water flow is artesian and in some cases flows up dip seemingly with little regard to structure. Flow is not confined beneath nor between impermeable beds of any great areal extent.

A recent textbook on karst (Jennings, 1971) accepts the Swinnerton concept but proposes that the term "shallow phreatic" be used to describe that portion of the phreatic zone in which most solution occurs.

From the foregoing, one can conclude that the mechanics of the exercise of the water table as a karst control have not been fully reconciled.

Control by Faults and Joints

Nearly all stratified rocks are cut by faults, joints, or fissures. Joints are roughly vertical openings offering ready-made paths for the flow of ground water which has percolated through the soil. As the water descends, solution occurs and the crevices are enlarged. The joint planes in effect control the lines of cavern extension. The intersection of two joint planes enlarges more quickly (Matson, 1909).

In some cases, faults have been accepted as the primary control in the creation of a linear cavern (Krinitzky, 1947). Still others accept faults and joints as a prerequisite to cavern formation (Moore and Nicholas, 1964). The presence of joints and bedding in dense limestone has been cited as of greater importance than high porosity in limestone (Thornbury, 1974).

Little controversy, if any, exists on the control exerted by faults, joints, and partings on the development of a karst landscape or a cave.

Control by Stratigraphy

Stratigraphy is that aspect of geology which considers the character, interrelationships, and sequence of stratified rocks. When a sequence includes a layer of rock which is not soluble--shale for instance--that insoluble layer controls the vertical development of karst and may divert the flow of ground water laterally. In addition, shale is generally considered to be impervious and to interfere with the downward movement of water (Thornbury, 1965). This characteristic has been noted by J.H. Bretz (1953) in a cave roofed by shale. He concluded that subwater table circulation, perhaps artesian, followed the joint system and dissolved the limestone up to the overlying shale.

Stratigraphic control is not limited to the occurrence of impermeable zones. It has been noted in southern Kentucky that the Salem and Warsaw strata are not as thinly bedded as the St. Louis. Therefore, openings for entrance by surface waters are more widely spaced (Thornbury, 1965). Facies variation may also be of significant influence. Additionally, very few karst landforms are said to develop in areas underlain by Devonian shale and lower Paleozoic dolomite and limestone (Quinlan, 1970).

There is general agreement that stratigraphy exerts control in karst formation. Ridges capped with sandstone and underlain by limestone are common in the Central Kentucky Karst, as are limestones underlain by shale (Dicken, 1935). The sandstone and shale direct the water flow and thereby control the formation of karst features. McFarlan (1950) believes this control is primary.

Control by Relief

In early writings, it was accepted that relief was a control in the formation of karst. For example, local base levels of surface streams control the downward development of caverns and cave levels are abandoned as the valleys descend (Matson, 1909). Thus, relief can be a major factor. Some general conclusions about the effect of relief have been developed (Glock, 1932):

> A relief of below 200-300 feet permits the simultaneous existence of two flats, an upper representing the original upland and a lower representing new valley flats. . . At 200-300 feet the relief attains the critical for most cases and the upper flat goes out of existence as the lower comes in. . . Beyond the critical relief, the upper flat is gone before the lower appears, and, when the lower appears, the general upland level has been lowered the amount by which the available [relief] exceeds the critical relief (p. 78).

Although this study did not address karst relief in particular, it may have general applicability.

It has been observed that the termination of karst forms occurs first in the valleys, while on the ridges karst forms persist (Dicken, 1935). Relief is considered by William D. Thornbury (1974) as a pre-condition for the formation of karst. He states that existing entrenched major valleys below uplands underlain by soluble and well jointed rock is necessary for karst development. Moore and Nicholas (1964) state that stream cuts causing seasonal fluctuation of the water table are necessary for cave development.

Relief appears to be considered by most authorities as an important control factor.

Control by Climate

The first scientific studies of karst did not include climate as a control of karst. Perhaps Cvijic, Grund, and other early investigators did not recognize this control because their work was accomplished in Europe where climatic variance was relatively slight from one karst area to another. Now, investigations have included Cuba, Puerto Rico, Jamaica, New Guinea, the British West Indies, and other areas of the world. From these studies, it is clear that karst topography is not identical worldwide. At least some of these differences may be attributed to the control of karst development by climate.

The requirement of adequate rainfall in karst development was of course recognized by early investigators. Concerning the controls exerted by climate, Weller (1927) wrote:

> Rainfall is the chief climatic factor which influences physiographic development. The rainfall in its amount and seasonal distribution largely determines the type of vegetation which will flourish in a region. Abundant vegetation is acknowledged an important factor in the retardation of erosion (p. 27).

It was also recognized that the water table oscillates with climatic changes (Emmons, Thiel, and Stauffer, 1949); that there is a zone that is above the water table in dry periods but below it in wet periods. A study of caverns in England (Sweeting, 1950) noted cave levels at three distinct elevations and concluded that these levels were produced by a changing water table. A direct link with climatic changes was not made however.

Later writings were more specific about the effect of climate. It was thought that humid to subhumid climates were necessary to supply sufficient rainfall for the rapid solution of limestone (Thornbury, 1974). Agreement was not universal. Some thought that underground solution is more significant in temperate and relatively dry subtropical climates where there is abundant vegetation on steep slopes (Birot, 1966). In damp tropical regions the area covered by enclosed depressions becomes greater than that of the residual relief (Birot, 1966). Another view (Ollier, 1969) was that:

> In general, tropical areas produce lower karst with steep limestone hills rising above surrounding flat plains, karst border plains, or separated from each other by steep sided,

> flat bottomed corridors like giant grikes. In temperate regions, doline karst is dominant where depressions of various kinds are sunk below the general level of the limestone surface (p. 226).

Ollier also noted that some landforms commonly attributed to different climates can occur in close proximity.

More recently, the emphasis on climate as a control has increased. The need to view karst and climate together, periglacial, hot arid, hot humid, etc., has been recognized (Jennings, 1971). A study of New Guinea karst (Williams, 1972) related the closed depression, as the significant karst landform in the tropics, to climatic control. A study of phytokarst, a landform resulting from borings into limestone by filamentous algae, also recognized the role of climate in the formation of tropical karst (Folk, 1973). Various climates produce special karst features. It may be possible to interpret previous climates (Herak and Stringfield, 1972). In karst relief, elements are preserved that originated under earlier climatic conditions. Such a relief is well conserved in karst because there is little or no surface dissection (Herak and Stringfield, 1972). Therefore, karst may be an important indicator of Pleistocene climatic conditions.

Summary

Some controls of karst development are generally accepted (stratigraphy and faults and joints) while others (water table, relief, and climate) are active subjects for research. Of these controls, climate appears to be the one which is least understood and which might be most productive for further research. In particular, paleoclimates seem to be a likely subject for study.

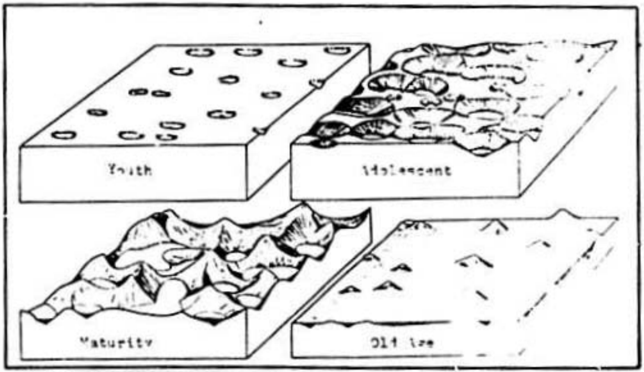
Concepts of Karst Stages

Stages of Karst Topography

Given the proper conditions, karst should develop. These conditions are: (1) the existence of soluble rock at or near the surface, (2) the existence of numerous joints and thin bedding in that rock, (3) the existence of entrenched major valleys below uplands underlain by these rocks, and (4) the existence of a humid to subhumid climate producing at least moderate rainfall (Thornbury, 1974). If these conditions are met, karst should develop in stages which are identifiable.

One of the first attempts to identify stages of karst development was made by Grund in 1914 (see Plate 3). He considered the doline as the basic karst feature, much as the valley is the basic feature of fluvial relief (Herak and Stringfield, 1972). He presumed the existence of a plain which in the Youth Stage would be marked with irregularly scattered dolines. These dolines would gradually destroy the vestiges of the initial plain surface, leaving ridges between the dolines. The continued expansion of the dolines would eliminate those intervening ridges. In the Maturity Stage, flat floors would appear with cone shaped hills remaining as relicts of the ridges. In Old Age, caves would collapse as would dolines and the result would be a corrosion plain with isolated hums. In none of these stages is climate considered (Jennings, 1971).

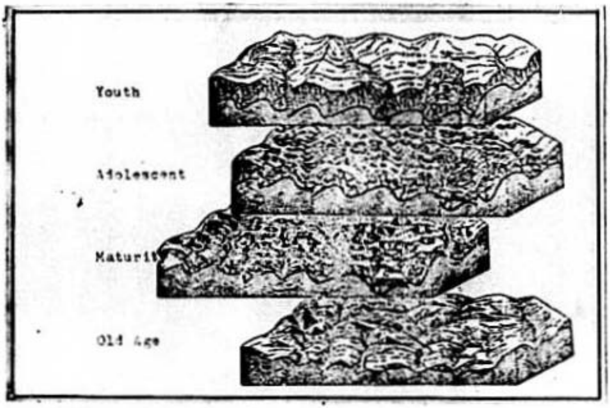
PLATE 3. GRUND'S KARST STAGES



SOURCE: M.M. Sweeting, Karst Landforms, pp. 310.

Jovan Cvijic published his concept of karst stages in 1918 (see Plate 4). The karst cycle of erosion as he saw it began with the Youth Stage which appeared as scattered dolines. Progressively, surface drainage would be lost but parallel ridges would be formed. In Maturity, no surface water would exist except where uvalas were formed by the breakdown of cave roofs. The valleys become disorganized reaching their deepest vertical extent and having the steepest ridges. In the later period of Maturity, valleys form from cave collapse, surface streams reappear as impermeable rock is exposed. In Old Age, stream valleys normal to the fluvial process appear and scattered hums remain as relicts of the limestone ridges (Sanders, 1921 and Cvijic, 1924).

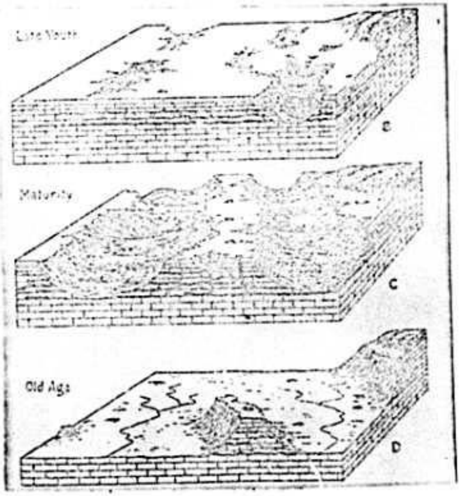
PLATE 4. CVIJIC'S KARST STAGES



SOURCE: E.M. Sanders, Geographical Review, Vol. 11, p. 598.

In 1928, yet another view of karst stages appeared. This work by A.K. Lobeck used the terms Youth, Maturity, and Old Age but his illustrations show a greater regard for the fluvial processes working in conjunction with the karst processes (Emmons, Thiel, and Stauffer, 1949) (see Plate 5).

PLATE 5. LOBECK'S KARST STAGES



SOURCE: W.H. Emmons, George A. Thiel, and Clinton R. Stauffer, Geology Principles and Processes, p. 97.

A different concept was offered by Samuel N. Dicken (1935). He too identified stages but initiated new names for them. The first stage was the Doline Karst, where well developed and numerous dolines were featured. This was followed by the Basin Karst stage in which dolines were choked with sediment which eventually widened them into basins. The final stage was the Streams and Basin Karst. In this stage the basin underwent infilling with sediment.

More recently, a three stage development of Central Kentucky Karst has been proposed (White et al. 1970). The first stage is the Prekarst Stage which features high relief topography with narrow steep walled valleys. The second stage is the Cuesta Stage with karst valleys and subterranean features extensively developed. The third and final stage is the Sinkhole Plain Stage which, as the name implies, features a plain dominated by dolines.

In a recent work (Sweeting, 1973), the idea of stages is challenged:

> Each karstification takes place only once and no stages in the development can be observed. All kinds of transitional landforms exist from the doline to the uvala and the polje, but the one is not necessarily the initial stage of the other. There is no cycle of landforms as described by Cvijic or Dicken. Morphology rests upon the principles of chemistry, hydrology. . ." (pp. 313-314).

This represents a change of view by Marjorie Sweeting. In an earlier study of karst in England, she described the area in the terms of karst erosion cycle as described by Cvijic, at the mature stage of evolution (Sweeting, 1950).

The studies of Florida karst (Jordan, 1950; Jordan, 1954; and Dodd and Siemers, 1971) reveal features which do not fit the karst cycles previously described. These include buried karst and sinkholes under water in the Florida Straits.

Whether textbook authors lean toward Cvijic (Cotton, 1941), Lobeck (Emmons, Thiel, and Stauffer, 1949), Grund (Scheidegger, 1961), or make no mention of stages (Garner, 1974), seems to be a matter of simple preference. Journal articles also show that preference--for Grund (Williams, 1972) and for Dicken (Hess, Wells, and Brucker, 1974).

Typically, the journals and textbooks describe only the preference and do not acknowledge that other views exist. In spite of this failing, there is an apparent urge to discover a universal description of karst stages. As yet, there does not appear to be one description which can be satisfactorily applied to all cases. Perhaps a link between stage and climate may offer an acceptable solution.

Stages of Cave Development

The urge to identify stages in karst applies to cave development as well as to topography. Prior to 1930, most explanations of caves were based on the work of underground streams. In 1930, William Morris Davis published the first paper which assigned stages to cave development. In his view, the primary formative stage was Phreatic where caves were formed by solution below the water table. The decline of the water table by rejuvenation created the second stage, the Vadose Stage, where further enlargement occurred by the flow of vadose water above the water table. Davis termed his ideas the Two-cycle Theory and the previous ideas the One-cycle Theory (Thrailkill, 1972).

An opposing idea was not long in coming--caves were formed by diversion of surface streams to routes opened by the draining out of static water by valley cuts (Gardner, 1935). This static water was saline, and therefore cave levels correspond to the original salt water bearing zones (McFarlan, 1950). This concept contained two stages. The Precavern Stage was of little importance since the ground water was static and little solution took place. In the second stage, the Cavern Stage, the static water emptied, and primary cave enlargement occurred by the invasion of caves by surface streams. Most caves in Indiana and Kentucky were thought to be runways for waters diverted from the surface to underground routes (Malott, 1937).

The Davis Two-cycle Theory received support by J. Harlen Bretz (1942) who added a third stage to the theory. The third stage was described as the Clay Filling Cycle. The clay filling of caves occurs between the Phreatic Cycle and the Vadose Cycle, and vestiges of the clay fill can be found in most caves. This study by Bretz remains as one of the most complete works on caves and their features.

The Davis concept found other support (Krinitzky, 1947) in a study of a cave in Virginia. The study rejected Malott's cave invasion theory and Swinnerton's theory that caves formed at the upper level of the phreatic zone. The Davis concept also found support in a study of Carlsbad Cavern (Horberg, 1949) which confirmed the two cycle formation. The cave clay filling stage was reaffirmed (Bretz, 1952) as being deposition in the nearly motionless water still filling the cave when the reduction of relief reduced the phreatic circulation. The three stage concept found support by Lawrence (1955) and McGregor, Pendery, and McGregor (1963).

A four stage approach to cave development has been proposed (Moore and Nicholas, 1964). The first stage is the enlargement of joints within the phreatic zone. The second stage is the development of master channels within the phreatic zone. The third stage is the seasonal fluctuation of the water table caused by stream cuts. The fourth stage is the external opening of the cave after which cave formation ceases.

The chemical evolution of cave waters also has been divided into stages (Holland et al., 1964). The first stage is the interaction of rain water with soil and air; the second is the passage of water into the carbonate rocks; and the third is the equilibration of cave waters with the cave air.

An analysis of 820 caves indicated a relationship between the relative frequency of caves with one, two, and three entrances and the maturity of the karst area (Curl, 1966). Conclusions were drawn that in the mature stage of the karst cycle a finer dissection of the karst may tend to produce both shorter caves and a greater number of cave entrances.

The Davis and Bretz concepts have been attacked (Quinlan, 1970) as being based on either fictional or inaccurate maps of the caves they studied. The one cycle concept has recently been stressed by noting that the streams flowing in caves may quite commonly be the very ones which originally formed the cave (Waltham, 1974). However, the work done on stream fluting (Maxon and Campbell, 1935 and Goodchild and Ford, 1971) provides a means of measuring the rate of stream flow and the resulting erosional effect of the stream. The length of scallops is correlated with the flow rate of water. In general, the faster the flow, the smaller the scallop. For example, a one inch scallop indicates a flow of 1.2 feet per second, four inches equates to 0.3 feet per second, and ten inches equals 0.09 feet per second. Scallops are attributed to streams which penetrate the cave late in its life.

The Bretz paper (1942) describes specific features which he concluded were of phreatic origin. Phreatic cave shapes are high, narrow, and straight slots which follow joints. Chambers and passageways develop in all directions along which water under hydrostatic pressure in the formation can move. Dissolution along the joints enlarges them, forming the cave passages. Jointing structure often shows clearly in the ceiling corresponding to the longitudinal alignment of the chamber. Another feature which Bretz attributes to phreatic origin is spongework. He found these sponge-like features in thirty percent of the caves he knew. Spongework is the result of the solutional work of water without definite current, without surface gradient, and without air above it. No network system is discernible. As dissolution continues, the cavities become increasingly larger until partitions completely disappear. A similar feature of phreatic origin consists of anastomoses, which are comprised of a row of holes of subequal size aligned along the bottom part of a stratum. These "pigeon holes" are rarely big enough to crawl into. They are unknown on solutional ceilings but can be found on the upper surface of fallen ceiling blocks. Thus they are not a result of chamber enlargement action but rather antedate the larger units of the cave system. They may represent the early phase of cave building, when water movement was essentially laminar and slow, allowing insoluble residue to settle to the bottom and protect the limestone below. The residual film preserves the original width at the bottom while dissolution continues at the top. The resultant shape is bulbous--higher than it is wide, and widest at the top where dissolution has continued into the overlying stratum. Wall, floor, and ceiling pockets are considered to be phreatic in origin. These crudely circular, round bottomed, kettle shaped features may have greater depth than width and may sometimes overlap. Partitions and pillars are also phreatic. They are residual masses determined by bedding or joint plane partings. Bretz concludes that no vadose stream could continue so long as to deepen a double channel and leave intact thin island walls reaching to the ceiling of a double chamber.

Bretz attributes several cave features to a vadose origin. Dome shapes in the ceiling commonly occur over pits in the floor. These dome-pits are solutional in origin, initiated by a subterranean piracy whereby water following a bedding plane high above the water table abruptly leaves that course to fall to a lower bedding plane route. For initiation, there must exist an older two-storied system of horizontal channels. Thus dome-pits require two phreatic passages to connect (Bretz, 1942). The dome-pit itself is vadose in origin as evidenced by the vertical grooves in the pit wall formed by flowing water. Consistently, the pits have greater height than width and often have sand, gravel, and chert in the bottom. Flutes constitute another vadose feature. Flutes on passage floors resemble ripple marks in sand. They are small, shallow asymmetrical cups, close set or overlapping, with the steep side invariably up stream. Crest lines are abeam of the current. Flutes are evidence of flowing vadose water. Potholes are vadose features similar to those in surface streams. The downstream wall is normally vertical while the upstream wall is overhanging. Some potholes have a cone in the middle and some have chert projecting from the walls suggesting a solutional origin. Rock shelves and terraces are other vadose features.

Summary

The evolution of concepts concerning karst topography and cave development is continuing. As in the case of processes and controls, there seem to be frequent exceptions to the concepts which have evolved. One must conclude that conceptual development will continue.

Central Kentucky Karst Literature

Descriptions of the Central Kentucky Karst area were included in early works published by the Kentucky Geological Survey. One of these publications (Sauer, 1927) concentrated on the geography of the area while another (Weller, 1927) was primarily geological in content. Both contributed to the understanding of the geomorphology of the area. Description of the area was extensively treated by Fenneman (1938), and an analysis of karst stages was attempted by Lobeck (1939). Both were general works not specifically nor exclusively oriented to the Central Kentucky karst.

Three journal articles have dealt with the Central Kentucky Karst area exclusively. One (Dicken, 1935) both described and analyzed the area and the processes which created it. Two others have re-evaluated the analysis of the stages of karst development in Kentucky (White et al., 1970) and provided new thoughts about karst processes (Quinlan, 1970).

Several works have specific applicability to the geology of the study area. The basic reference is the extensive description of the geology of Kentucky (McFarlan, 1950), which is the most comprehensive of the literature reviewed. A brief but valuable discussion of the economic geology of Allen County, Kentucky (Branson, 1966), provides information on the oil bearing strata in the area. A more extensive work oriented to the oil production in Allen County (Shaw and Mather, 1919) includes well logs which aid in the understanding of the geologic structure of the area.

The lithologic names associated with particular strata vary, depending upon the age of the literature in which they appear. For example, a Silurian limestone is referred to as Corniferous, Pegram, or Louisville. Other strata are similarly given duplicative names. As a result, several works were reviewed to make a correlation (Hopkins, 1963; Piper, 1932; Twenhofel, 1931; Freeman, 1951; Foreste, 1906; Savage, 1930; and Nelson, 1962). Each of these contributes to the understanding of the lithology of the area as well as clarifying the names associated with it. For the purposes of this study, the names used by Hopkins (1963) will be accepted.

The geomorphology of the study area is included in works by Jillson (1920, 1927), Miller (1919), Thornbury (1965), Shaw and Mather (1919), and Hopkins (1963). Each of these authors contributes to an understanding of the relationships among the Cincinnati Arch, the Nashville and Lexington Domes, the Nashville Basin, the Highland Rim, and the current topography. Piper's study (1932) of north-central Tennessee is also valuable in this regard.

Joint control in karst areas has been discussed by Weller (1927) and McFarlan (1950) in their treatment of Kentucky karst. The jointing of the Nashville Dome, which includes the study areas of this paper, has been described in detail by Wilson (1935) and Piper (1932).

Most of the works cited above contain some data about springs or underground water. However, several other sources were consulted.

The sinking springs phenomena of the Kentucky karst was described by Jillson (1928) and studies have been made of the springs along the middle reaches of Barren River (Hess, Wells and Brucker, 1974). A comprehensive study of the groundwater resources of the Scottsville, Kentucky, area was made by Hopkins (1963). Although the Hopkins study covers all of Allen County, the portion dealing with the southeastern part of the county is sparse. Nevertheless, it has been a major source of data for this paper. The works by Piper (1932) and Brown and Lambert (1962) also apply to the study area although less specifically so compared to the Hopkins work.

Summary and Conclusion

The history of the evolution of karst concepts has been relatively short. Most of the concepts have been developed in this century and are therefore new when compared to other geomorphic concepts which have existed for much longer periods. It is perhaps because of this short history that the concepts are, for the most part, still being refined, rejected, and replaced.

In this chapter, the evolution of concepts relating to karst processes, control, and stages has been traced. It may be concluded that climate has received very little consideration in conceptual development. Only in the most recent works is climate mentioned and even then not given a major influencing role. Climatic topics are becoming more influential in recent geomorphic writings and perhaps the future authors of karst studies will follow that lead.

Another conclusion is that almost no concept is universally accepted and therefore almost all are open to critical review and further research. Some of the names associated with the concepts are those of men held in awe by many. Perhaps those names have hindered criticism of the concepts. As time goes on this factor may diminish and the time honored concepts may undergo renewed critical review.

Textbooks have not indicated the questions which exist about the concepts which they selectively include. Readers are left with the impression that the concepts are unchallenged; that may reduce the amount of critical thought concerning them. The divergent views should be included in textbooks at least to a degree that would indicate that a major divergence exists. Students would thereby be freer in formulating their own opinion of the concepts and in choosing one for personal acceptance.

One must conclude that geography is losing its interest in the earth science tradition. The various journals of geography provided few references for this paper. The Journal of Geology provided most. The question arises whether climate would have been ignored in karst concepts had the impetus come from geography rather than geology.

Finally, one must conclude that the quantity of research work accomplished has been small compared to other geomorphic areas. For example, the evolution of slopes seems to have received much more analytical work than karst. Very few dissertations exist on the subject of karst. There is much work to be done if karst and its processes, controls, and stages are to be understood.

CHAPTER III

STUDY AREA

Geographic Scope

The geographic scope of this study extends from the confluence of Long Creek and Barren River upstream to the confluence of Doddy Branch, Emma Cook Hollow and Long Creek, and laterally along that length to the extent of the Long Creek drainage area (see Plate 6). It is within this area of about thirty-three square miles that the karst anomaly is well developed.

Within the study area, a two and one-half square mile subarea has been defined for a detailed survey of the sinking springs phenomena. This subarea is that portion of the Long Creek drainage area bordered by Long Creek to the north, Highway 100 to the west, and the interfluve extending southward from the Sink of Long Creek to the southern drainage divide (see Plate 6).

Carpenter's Cave is included in the study area even though its entrance lies outside the area. The collapsed terminus of the major passage of the cave is correlated with a large doline which is located within the study area. Further, the cave provides an opportunity to study the Louisville limestone from within.

PLATE 6. THE GEOGRAPHIC SCOPE

SOURCE: Adapted from E.R. Branson, Economic Geology of Allen County, Kentucky, Appendix

Physiography

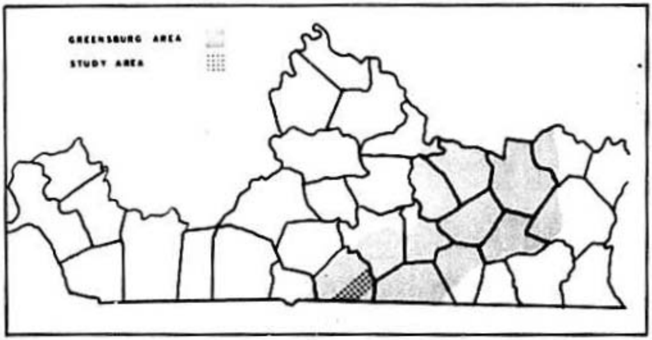
Central Kentucky Karst

The Central Kentucky Karst (Dicken, 1935) occupies the northern one-third of Allen County (see Plate 1). This area is a fairly typical karst plain, dotted with dolines, with few surface streams. Most drainage is by underground means. The southern extent of this area is generally agreed to be the surficial extent of the St. Louis limestone. By exclusion, the study area lies outside of the Central Kentucky Karst.

Pennyroyal

The study area lies within the Greensburg Area of the Pennyroyal of Kentucky (Sauer, 1927) (see Plate 7). The description of the Greensburg Area of the Pennyroyal does not fit the topography of the study area. The study area exhibits more relief, steeper slopes, and narrower valleys. It should be noted that the Central Kentucky Karst as defined by Dicken (1935) corresponds in general terms to the Pennyroyal Plain as defined by Sauer (1927). In Allen County, the two designations are quite alike. The Greensburg Area is one which is predominantly fluvial in origin while the Pennyroyal Plain is primarily karstic.

PLATE 7. THE PENNYROYAL OF KENTUCKY



SOURCE: Carl O. Sauer, Geography of the Pennyroyal, p. 35.

Highland Rim

The study area seems to more easily fit the description of the Highland Rim which surrounds the Nashville Basin (see Plate 8). The geomorphic history of this area, as described by Thornbury (1965), began with formation of the Highland Rim Peneplain near the end of the Miocene Epoch. By mid-Pleistocene, the Nashville Basin had formed from the eroded surface of the Nashville Dome which structurally is part of the Cincinnati Arch. The boundary of the Nashville Basin is the Highland Rim escarpment which circumscribes the basin. The crest of the escarpment is as much as 450 feet above the basin floor. This escarpment lies some twelve to fifteen miles south of the study area. Both Long Creek and Barren River have their origins near the crest

PLATE 8. THE NASHVILLE BASIN

SOURCE: Adapted from U.S.G.S. Geologic Map of the United States, Appendix

of the Highland Rim escarpment. Both streams and their drainage lines have deeply incised into the old Highland Rim Peneplain; little remains of it except near the escarpment. The Highland Rim area is capped by Mississippian bedrock. In this regard it is like the Central Kentucky Karst to the north and unlike the Nashville Basin to the south, which has surficial rock from the Devonian, Silurian, and Ordovician.

Both the Nashville Basin to the south and the Pennyroyal Plain to the north are conspicuously karstic, but the Highland Rim is generally devoid of karst features. This is attributed to the Highland Rim's cap of Fort Payne chert which is considered to be relatively impermeable (Thornbury, 1965).

Geology

Nashville Dome

The study area lies on the western slope of the Cincinnati Arch. This arch consists of two domes, the Lexington Dome and the Nashville Dome. The study area lies on the northern flank of the Nashville Dome near the southern edge of the saddle separating the two domes. Thus the prevailing dip of the rocks in the study area is toward the northwest (Miller, 1919). The direction of this dip varies from North 30 degrees West to North 64 degrees West with a general dip rate of 33 to 43 feet per mile (Miller, 1919). Therefore, exposed at the surface in the study area are strata older than those in other portions of Allen County.

The Nashville Dome is severely jointed, with the joints consistently aligned with the axis and the contour of the dome. About 87 percent of about 350 joints are parallel to the axis while 13 percent follow the contour (Wilson, 1935). The axis of the dome trends North 20 to 30 degrees East, and the apex is located at the southern boundary of Rutherford County, Tennessee (Piper, 1932). The most prominent set of joints in Allen County trend between North 40 degrees East and North 60 degrees East (Shaw and Mather, 1919).

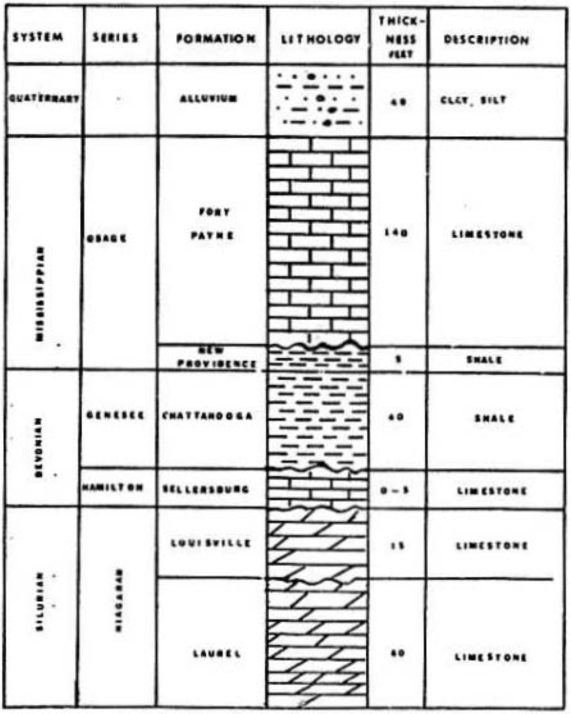
It has been calculated by Wilson (1935) that if the Chattanooga shale were restored to its former extent over what is now the Nashville Basin, its highest point would rise approximately 1,275 feet above sea level. This would make the apex of the Nashville Dome more than 600 feet higher than the study area.

Since the study area lies within the Highland Rim, which is structurally part of the Nashville Dome, one can expect a correlation between the joint pattern of the dome and that of the study area.

Surface Geology

The surface geology of the study area is varied (see Figure 1). The uplands and valley sides are covered with regolith, the lower portion of which is called residuum. This residual material consists of the chert and clay which remain after the limy portion of the parent rock is removed. In places, pseudobedding occurs. The chert and shaly part of the parent rock is virtually in place except for slumping and compaction. About seventy percent of the Allen County area is underlain by residual regolith and almost twenty percent by transported regolith. The thickness varies from near zero in the southeast to about sixty feet in the northwestern part of the county. Springs emerging from the regolith are usually seepage springs averaging about one gallon per minute in Allen County. Recharge of the ground water occurs by infiltration and percolation of rainwater (Hopkins, 1963).

FIGURE 1. STRATIGRAPHY OF THE STUDY AREA



SYSTEM	SERIES	FORMATION	LITHOLOGY	THICKNESS FEET	DESCRIPTION
QUATERNARY		ALLUVIUM		40	CLAY, SILT
MISSISSIPPIAN	OSAGE	FORT PAYNE		140	LIMESTONE
		NEW PROVIDENCE		5	SHALE
DEVONIAN	GENESEE	CHATTANOOGA		40	SHALE
	HAMILTON	SELLERSBURG		0 – 5	LIMESTONE
SILURIAN	NIAGARAN	LOUISVILLE		15	LIMESTONE
		LAUREL		60	LIMESTONE

SOURCE: Author

Stratigraphy

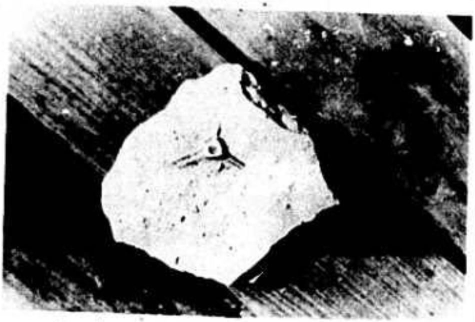
The Fort Payne chert formation caps the study area and is early Mississippian in age. This formation extends upwards from about 660 feet above sea level and reaches a maximum thickness of 140 feet in the study area. The formation is dolomitic and somewhat argillaceous (Nelson, 1962). It is typically light yellowish grey and massive to thick bedded; some beds contain numerous small quartz lined geodes. Large crinoid stems are common. Chert is especially abundant in the lower ten to twenty feet of the formation. This lower portion is often referred to in Allen County well logs as the "Beaver" formation which was productive in oil in the northern portion of the county (Branson, 1966). The joints and bedding plane openings have undergone some enlargement by solution. Some small tubular openings are visible in the upper portion of the formation. Within the study area, springs emerging from the Fort Payne formation are usually small. The average flow throughout the county for Fort Payne springs was five gallons per minute (Hopkins, 1963). The recharge of the ground water is by infiltration from the regolith above, but the downward movement is relatively slow. Spring response to rainfall occurs usually within 24 hours (Hopkins, 1963). The Fort Payne chert formation unconformably overlies the New Providence shale within most of the study area.

The New Providence shale is a greenish composite of crinoidal debris in a limy shaly matrix. It is non-fissile. This formation is four feet thick in the area of Carpenter's Cave in the northeastern part of the study area but thins to the north and west. It is absent over much of the southwestern portion of the study area. Where present, it conformably overlies the Chattanooga shale (Hopkins, 1963).

The Chattanooga shale is late Devonian in age (Nelson, 1962) and 40 feet thick within the study area. It is dark grey to black in color. It is nonfissile when fresh but fissile when weathered. It consists of silt and clay sized particles of quartz, pyrite, and clay minerals and is slightly radioactive (Hopkins, 1963). This shale is petroliferous and is estimated to contain from ten (Miller, 1919) to fifteen (Branson, 1966) gallons of oil per ton of shale. The Chattanooga shale is more resistant to weathering than the overlying Fort Payne formation and, as a result, often forms benches on the hillslopes (Hopkins, 1963). One such bench can be seen on the hillslope southeast of the Highway 100 bridge over Long Creek. The primary openings within the shale are intergranular and therefore too small to allow much passage of water. Secondary openings by joints and bedding planes amount to little more than hairline cracks (Hopkins, 1963). Since shale is insoluble, these openings are not enlarged. In effect, the Chattanooga shale is considered to be impermeable (Hopkins, 1963; Thornbury, 1965; and Miller, 1919). Therefore infiltration and percolation of rainwater and the downward movement of ground water is effectively stopped by this formation. Very little water is contained within the shale as evidenced by the rarity of springs and the minor amount of water obtained from wells within the formation (Hopkins, 1963). The Chattanooga shale rests in sharp unconformable contact upon the Sellersburg limestone where the Sellersburg formation is present.

The Sellersburg limestone is of middle Devonian age (Nelson, 1962). Its age was established on the basis of fossils collected near Brown's Ford, which is about one half mile northeast of the study area. One such index fossil was identified by Miller (1919) as belonging to the crinoid genus Dolatocrinus. This fossil and others typical of the Sellersburg are distinctive (see Figure 2). In the northeastern part of the study area, the Sellersburg limestone is about five feet thick. The formation thins to the north and west and is not present in the southwestern portion of the study area. The thinning of the limestone has been attributed to the PostHamilton-PreChattanooga erosion of higher levels in those areas

FIGURE 2. SELLERSBURG FOSSIL DOLATOCRINUS



SOURCE: Author

where the Sellersburg limestone is now thinned or absent (Hopkins, 1963). Where present, the Sellersburg limestone appears as a shelf extending outward from between the Chattanooga shale above and the Louisville limestone below. Spring discharge from the Sellersburg formation is negligible (Hopkins, 1963). The Sellersburg limestone unconformably overlies the Louisville limestone.

The Louisville limestone is of middle Silurian age (Nelson, 1962). The Waldron shale, which in other areas separates the Louisville limestone from the lower Laurel limestone, is missing throughout the study area. Since the Louisville and Laurel limestones are indistinguishable when the Waldron shale is absent (Shaw and Mather, 1919), the two limestones will be considered together and referred to in this paper as the Louisville limestone. The Louisville limestone is a dolomitic, greyish yellow, fine grained formation. Its weathered surfaces grade to brown. Fossils are rare. The Louisville limestone is cliff-forming (Miller, 1919) and all the near vertical cliffs along Long Creek are formed from it. The formation is highly jointed and both the joints and the bedding planes have undergone solution and enlargement. Many of these openings are interconnected and cavernous (Hopkins, 1963); the two largest springs in the county emerge from such caverns. Calvert's Spring, within the study area, has a flow rate ranging from 400 to 12,000 gallons per minute, while Big Spring, west of the study area, produces from 1225 to 20,900 gallons per minute (Hopkins, 1963). Louisville formation is the major oil bearing formation in Allen County, and is referred to in well logs as the "Corniferous" (Branson, 1966).

Local Structure

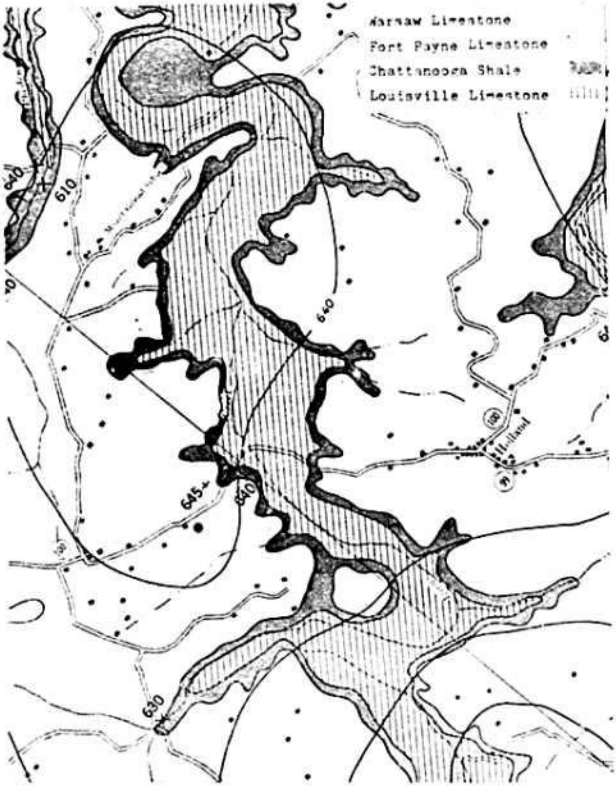
The subsurface structure of the study area has been mapped (see Plate 9) using the top of the Chattanooga shale as the basis for contours (Branson, 1966). The structure shows a general dip toward the northwest, but there are several structural highs and lows significant enough for mention here. Carpenter's Cave lies within a rather broad structural high (680 feet) which is elliptical in shape and longitudinally oriented about North 70 degrees East. It is about eighty feet higher than a structural low, similarly oriented, which is centered about one half mile northeast of the confluence of Long Creek and Barren River. A second structural high is located to the south of Holland and a low located northeast of that high. The difference in elevation between these latter two structures is sixty feet and the distance between their centers is about 2,200 feet. Finally, south of Oakforest, there is a structural low which is oriented generally east-west, and which is a severely flattened ellipse associated with the Dry Creek valley. Although none of these structures is immense, they do indicate that the northern slope of the Nashville Dome is not totally smooth, but has highs and lows within the general dip toward the northwest (see Plates 9 and 10).

Geomorphology

Long Creek Drainage Area

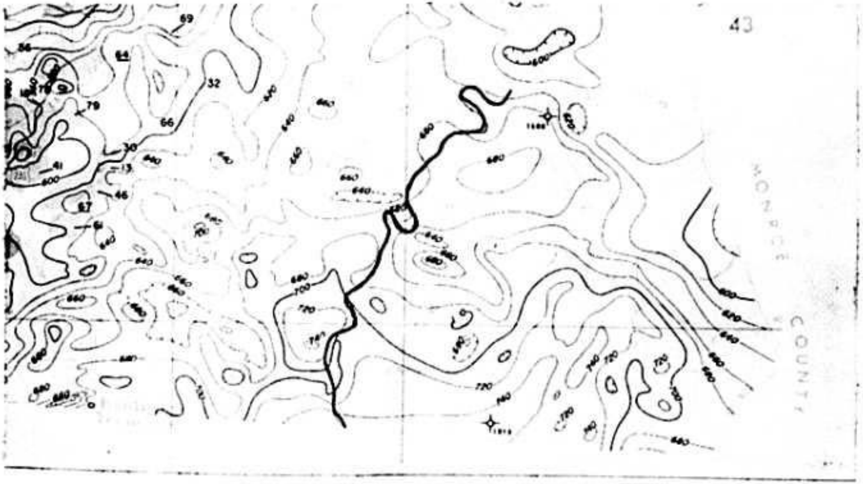
Long Creek's headwaters are near the Highland Rim escarpment in Tennessee. The stream flows in a generally straight line

PLATE 9. GEOLOGY OF THE STUDY AREA



SOURCE: William B. Hopkins, Geology and Groundwater Resources of the Scottsville Area, Kentucky

PLATE 10. LOCAL STRUCTURE, TOP OF CHATTANOOGA SHALE



SOURCE: Adapted from E.R. Branson, Economic Geology of Allen County, Kentucky toward the northeast (see Plate 6, p. 36), perhaps following joint controls of the Nashville Dome. The drainage area served by Long Creek features relatively deep, narrow, and steep sloped valleys. The area could be described as youthful in Davisian terminology. The Highland Rim Peneplain has largely been destroyed, with only narrow ridges remaining as relicts of that surface. Long Creek has incised approximately 240 feet below the interfluve crests. Tributary valleys are usually less than one mile in length. These steep gradients are assumed to be the result of an uplift which occurred during the late Pleistocene and Recent Epochs (Thornbury, 1965).

Springs

Virtually all first order valleys have springs at their head. The flow from these springs in the lower reaches of Long Creek seldom reaches the creek by an entirely surficial route. Most springs sink one or more times and virtually all sink before reaching the Long Creek floodplain. Calvert's Spring is an exception, emerging from the same strata which captures other springs and, with a flow of up to 12,000 gallons per minute, completes its short run to Long Creek.

The Long Creek valley exhibits at least five abandoned stream routes. It appears that Long Creek abandoned these routes in favor of more meandering ones. These abandonments appear to have occurred when the stream bed occupied the 600 to 620 foot level, about twenty to forty feet above the current level of the stream. The cause is not readily apparent, not is it discussed in any literature reviewed.

Karst Features

Long Creek Sink and Resurgence. The most prominent karst feature of the study area is the piracy of Long Creek. The primary swallow hole which captures the normal summer flow of Long Creek is known locally as the Sink of the Creek and is identified on the topographic quadrangle map as the "The Sink". Other swallow holes of the creek are not identified in the literature reviewed. The resurgence of Long Creek is unnamed on the geologic map but is indicated by a resumption of surface stream marking. No description of the resurgence was discovered in the literature review. In the analysis portion of this study, several swallow holes and resurgence points are identified.

Springs. The study area exhibits its karstic tendency in that the springs are often recaptured after their resurgence. These springs are indicated on the geologic map as intermittent streams. One tubular spring, Calvert's Spring , is identified on the map by name.

Carpenter's Cave. Underlying the northeastern portion of the study area is Carpenter's Cave. This well developed cave is the only known cave of such development in the southeastern part of Allen County. The cave is located on the side slope of a valley which is typical of the immediate area. The elevation of the head of the valley is 800 feet above sea level, the length of the valley is 1,800 feet, and the valley's mouth at the bank of Barren River is 540 feet in elevation. The slope of the valley head is particularly steep, dropping 100 feet within the first 600 feet of the valley's length.

Climate

Allen County receives from 45 to 50 inches of precipitation per year (Cockrill, 1975). This amount is generally spread over the entire year, and is capable of recharging the springs in the study area. Specifically, during the period of the field survey of the springs in the detailed study area, enough precipitation fell to preclude the possibility that the sinking springs phenomena was due to insufficient recharge (see Table 1). During the month of November, 1975, the area received 5.37 inches of rain.

TABLE 1

PRECIPITATION DATA, NOVEMBER 1975

November	Precipitation, Inches
4	.08
7	2.11
9	.42
10	.29
12	.04
13	.04
20	.27
27	.48
30	1.64

SOURCE: Weather Records for Scottsville, Kentucky.

CHAPTER IV

HYPOTHESES

The problem of a karst anomaly in a non-karst area was identified by the author in 1975 while investigating Carpenter's Cave which lies under the study area. The cave's major passageway is longitudinally aligned with a tributary valley of Long Creek. The head of that valley coincides with the location of the collapsed end of the cave's major passageway. The Sink of Long Creek is only slightly off line with an extension of the axis of the valley and the cave. The valley was investigated to ascertain if it had been formed as a result of cave collapse. No such evidence was discovered. However, it was discovered that the valley contains numerous springs in its branch valleys. All these springs are pirated before they reach the primary valley floor. This observation led to a more detailed study of this and adjacent valleys. Thirty-four springs were located and mapped. All were pirated at least once and none reached Long Creek or its floodplain.

Having established that karst features are common in this area acknowledged to be non-karst, several hypotheses were developed concerning the origin and control of this anomaly.

Hypothesis One: Karst features within the study area are controlled by stratigraphy. It seems likely that this hypothesis is true since most karst features appear to be in Silurian age strata. If it can be established that karst features are either exclusively or predominantly found in one stratigraphic interval the hypothesis could then be accepted.

Hypothesis Two: Major karst features within the study area are phreatic in origin. The Devonian age shale which overlies the Silurian limestones seems to be impermeable. Therefore it seems likely that the karst features contained in the Silurian age limestones are phreatic in origin if they were formed after the shale was laid down. If it is established that the major karst features are limited to one stratigraphic interval and if the Devonian age shale can be established to be generally impermeable, this hypothesis could then be accepted.

Hypothesis Three: Primary surface drainage valleys in the study area are joint controlled in their orientation. The valley orientation within the study area is unlike that in the northern part of the county. Since joint control is common in the formation of karst landscapes, it seems probable that this control is exerted in the study area. If it can be established that valleys within the study area are oriented consistently with the general joint pattern of the area, this hypothesis could be accepted.

Hypothesis Four: The Long Creek karst topography does not conform to the stages of karst development as described by Cvijic, Grund, Lobeck, Dicken, and White. Observation indicates that the topography of the study area does not closely resemble the stages of karst development advocated by these authors. If it can be established that the Long Creek karst does not in fact conform to those stages, then this hypothesis can be accepted.

If all these hypotheses can be accepted, then some conclusions may be drawn concerning the origin and the time of karst development in the Long Creek study area.

CHAPTER V

RESEARCH DESIGN

Methods of Data Collection

Long Creek Sink and Resurgence

Data concerning the sink and resurgence of Long Creek were collected by a field survey conducted by the author. Locations were confirmed by compass triangulation to known map points. Stratigraphy was established by close examination of the rocks and fossils present; comparison with the geologic map confirmed that the map was generally accurate. The swallow holes were identified visually and no attempt was made to discover others by mechanical means. Those swallow holes which were above the stream level at the time of discovery were resurveyed when the water level was higher to confirm that they were indeed active swallow holes. The resurgences were identified visually. Dye tracing was not attempted since the relationship between swallow holes and resurgences was sufficiently distinct. Photographs were taken of the major features within this locale.

Springs

Data for the detailed study of the springs were collected during the period 16 through 28 November 1975. A field survey of the detailed study area was made to locate the springs, including their origins, sinks, and resurgences. Each valley within the detailed study area was investigated from its confluence with Long Creek to its head. All secondary valleys within the detailed study area were likewise investigated. Field notes were made on general terrain features, the elevation of spring origins, sinks and resurgences, spring flow, and stratigraphy when it could be determined. Springs were assigned numbers since few springs are locally known by names.

For the purposes of this paper, spring flow has been generalized. The term "small flow" indicates that the stream bed occupied by flowing water is less than two feet wide. A "moderate flow" indicates two to four feet water flow width. A "large flow" indicates flows more than four feet wide.

Most elevations were determined by field comparison of stratigraphy with the United States Geologic Quadrangle map of the Holland area. In the few cases where such comparisons could not be made, a Taylor hand held aneroid barometer/altimeter was used. This instrument is compensated for temperature and has a manufacturer claimed accuracy of about twenty feet.

Beyond the detailed study area, a field survey was made along the length of Long Creek within the study area. The purpose of this survey was to determine which valleys contain flows which reach Long Creek. Each valley mouth was investigated to locate, where present, the drainage gully or flow. No attempt was made to locate all the springs at the valley heads outside of the detailed study area because the karst character had already been established from the detailed study area.

Carpenter's Cave

Carpenter's Cave was investigated by field survey. Length measurements were made using a tape, width and height of the passageways were estimated, and slope was measured with a Brunton Compass. Passageway orientation was determined by compass readings at thirty foot intervals, centered in the passageway. Field notes were made concerning the structure and other notable features.

Long Creek Drainage Area

Data for analysis of the Long Creek drainage area were collected from 1:24000 topographic quadrangle maps. A tracing was made of the valleys beginning at a point at the valley head where contour lines appear as acute angles. Rounded contour lines at the valley head were excluded even though slope continued, because the drainage line above was not well defined. From this tracing of the drainage area, a map was prepared and the valleys were numbered and assigned orders according to the Strahler system of stream ordering (Gregory and Walling, 1973).

Methods of Analysis

Analysis of all data, except those of the Long Creek drainage area, was made using maps prepared by the author. The detailed study area data were analyzed using a compilation of the altitudes of the spring origin, sink, and resurgence. Where consistencies were noted, the stratigraphy was reviewed to determine if it was a factor. Since there were, for the most part, correlations between lithology and the spring features, the subsequent analysis was primarily inductive rather than mathematical.

The Long Creek drainage area data were mathematically analyzed. Mean valley lengths for each valley network were determined for each valley complex. The cumulative mean lengths were compared to discover if there were any unusual aspects of the drainage network. The orientation of the valleys was determined by the azimuth from the point of designation of the highest order valley in each valley complex to that valley's confluence with Long Creek. The latter point was that of the gully entry into the Long Creek or, lacking that, the last point of sink of the stream flow within the valley. These orientations were then compared to the jointing pattern of the study area and a statistical comparison was made to determine the correlation between the two.

CHAPTER VI

ANALYSIS

Introduction

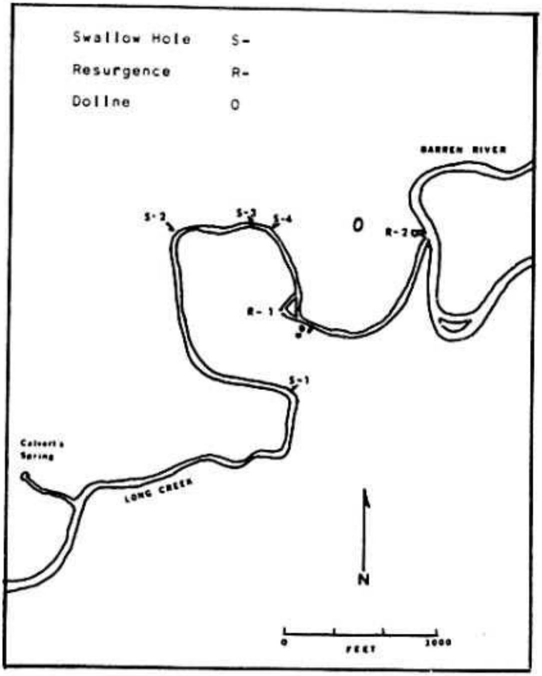
The analysis of the data collected is presented according to the separate focal subjects of this paper: the piracy of Long Creek; the springs; the Long Creek drainage area; and Carpenter's Cave. In each of the following sections, the data collected is presented and the results of the analysis indicated. Where appropriate, tables and maps illustrate the data; photographs are used when needed to aid in visualization of the feature being discussed. Data analysis formulas, when used, include enough of the calculation process to allow replication in future studies of the area. In each section, a summary ends the discussion of the data and its analysis.

The Piracy of Long Creek

The Swallow Holes

The first piracy of Long Creek occurs at a point about 2.34 miles from the confluence of Long Creek and Barren River (see Plate 11). This distance is that measured along the stream bed which continues in the form of a reverse S meander to the river. The point of the first piracy is known locally as The Sink and that name is used on the topographic map of the Holland Quadrangle. For this analysis, the designation Swallow Hole One (S-1 on Plate 11) will be used for the location of the first piracy.

PLATE 11. THE PIRACY OF LONG CREEK



SOURCE: Author Field Survey

Swallow Hole One is in actuality more than one hole. In fact, seven swallow holes are identifiable at this location. All are located within a distance of about 75 feet, so they are considered collectively in the analysis. The seven swallow holes are located on the east side of Long Creek immediately upstream from the point where the creek bends westward away from the very steep interfluve which it parallels for a short distance (see Plate 11). The four tertiary swallow holes are subfluvial (see Figure 3) but can be located by the water flow and can be seen when the water is clear. The largest of these four is about six inches in diameter. About 25 feet further downstream, two secondary swallow holes can be seen. These two appear to be joint enlargements with about two vertical feet of each of the holes being visible above the water (see Figure 4). The largest of these two holes is about one and a half feet wide and about four feet in vertical extent. The seventh swallow hole is the primary one for this location (see Plate 11). It is a horizontally aligned elliptical opening approximately eight feet in width and an estimated four feet in depth. Local residents have entered this opening and reportedly have explored the cavern for a considerable distance when Long Creek was in a period of very low flow. However, during normal flow only a small portion of the opening is visible above water (see Figures 5 and 6). The collective Swallow Hole One is sufficiently large to pirate the entire flow of Long Creek during periods of relatively low flow, usually limited to the summer season. When total piracy is achieved, a current forced pond is formed just downstream from Swallow Hole One from which a reverse flow to the swallow hole can be observed.

FIGURE 3. SWALLOW HOLE ONE, TERTIARY

SOURCE: Author

FIGURE 4. SWALLOW HOLE ONE, SECONDARY

SOURCE: Author

FIGURE 5. SWALLOW HOLE ONE, PRIMARY

SOURCE: Author

FIGURE 6. SWALLOW HOLE ONE, SIDE VIEW

SOURCE: Author

When the flow of Long Creek is sufficient to avoid total capture at Swallow Hole One, the uncaptured portion of the flow follows the channel for approximately 0.8 mile before encountering Swallow Hole Two (see Plate 11). Swallow Hole Two is a single horizontal slit which is about fifteen feet wide and about one to three feet deep (see Figure 7). During periods of normal winter flow, Swallow Hole Two pirates all the flow which has escaped capture by Swallow Hole One, and the stream bed downstream from it is dry (see Figure 8) except for some residual ponds (see Figure 9) which remain from periods of heavy flow. Swallow Hole Two, on the opposite side of the creek from that of Swallow Hole One, is located on the south side of the interfluve between Rhodens Creek and Long Creek.

During periods of heavy flow, the portion of Long Creek which has escaped capture by Swallow Holes One and Two continues in the channel for approximately 0.45 miles where it enters Swallow Hole Three (see Plate 11). Swallow Hole Three is a single hole about six feet wide and about three feet in height (see Figure 10). It is about four feet higher than the bottom of the channel but it was observed to receive flow before the creek reaches floodstage.

A final act of piracy occurs during periods of heavy flow approximately 400 feet further downstream (see Plate 11). At this point, Swallow Hole Four captures part of the flow (see Figure 11). Swallow Hole Four is about two feet high by eight feet wide (see Figure 12). It, like Swallow Hole Three, requires a heavy flow of Long Creek to raise the water to a capture level (see Figure 13) and the two are not successful in total capture.

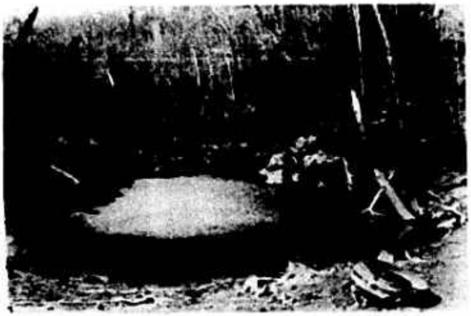
FIGURE 7. SWALLOW HOLE TWO

SOURCE: Author

FIGURE 8. DOWNSTREAM FROM SWALLOW HOLE TWO

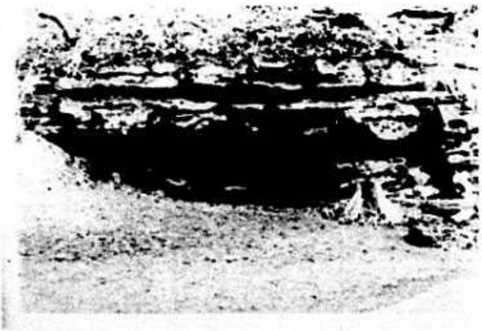
SOURCE: Author

FIGURE 9. STREAM BED PONDING



SOURCE: Author

FIGURE 10. SWALLOW HOLE THREE

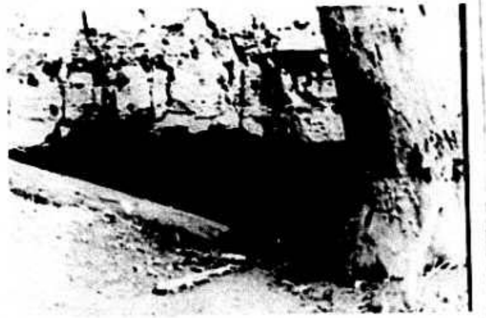


SOURCE: Author

FIGURE 11. SWALLOW HOLE FOUR IN ACTION

SOURCE: Author

FIGURE 12. SWALLOW HOLE FOUR WHILE INACTIVE



SOURCE: Author

The Resurgences

Resurgence of Long Creek occurs at two widely separated locations. The location of Resurgence One (R-1 on Plate 11) is on the east side of the interfluve separating it from Swallow Hole One. The flow emerges from a horizontally aligned arcuate opening which is approximately 62 feet in breadth (see Figure 14). Bifurcation of the flow occurs immediately (see Figure 15), with a portion of the flow moving north-northeast while the other portion flows south-southeast. The northern flow enters the meander channel of Long Creek downstream from Swallow Hole Four. The bifurcated streams rejoin immediately downstream from the Mill Dam (see Figure 16). The dam and the foundations of the old mill are still in place although no remains of the mill building are in evidence. The dam is on the south fork of the resurgence flow. This indicates that the flow was sufficient and consistent enough to power the mill.

About 500 feet downstream from the confluence of the bifurcated resurgence flow, a secondary resurgence point is located (black rectangle on Plate 11). Although it is only three feet wide and has the appearance of a spring (see Figure 17), it is a resurgence from Swallow Hole One, flowing turbid when the creek is turbid.

The combination of the flow from the two resurgence points composing Resurgence One is visually comparable to that pirated by Swallow Hole One.

Two dolines are present near the secondary resurgence point (see Plate 11). The dolines are small, about eight to twelve feet in diameter, with small trees growing within them (see Figures 18 and 19). The smaller of the two dolines is located up slope from the

FIGURE 13. LONG CREEK IN HEAVY FLOW. COMPARE WITH FIGURE 9.

SOURCE: Author

FIGURE 14. RESURGENCE ONE, PRIMARY

SOURCE: Author

FIGURE 15. BIFURCATION OF RESURGENCE ONE

SOURCE: Author

FIGURE 16. REUNION OF BIFURCATED FLOW

SOURCE: Author

FIGURE 17. RESURGENCE ONE, SECONDARY

SOURCE: Author

FIGURE 18. SMALL DOLINE

SOURCE: Author

FIGURE 19. LARGER DOLINE

SOURCE: Author

larger one and the two are aligned parallel to the flow from the secondary resurgence point. It seems possible that these two dolines were formed by collapse of yet another resurgence route from Swallow Hole One. However no flow could be located nor was any evidence of past flow visible.

Another karst feature is located about twenty feet up slope from the primary resurgence point of Resurgence One (see Plate 11). Here a solution joint has been opened to the surface. It is approximately three to seven feet wide and about thirty feet in length. Its depth, varying with the slope, is from ten to twenty feet. The resurgence flow can be seen flowing at right angle to the length of the joint (see Figure 20).

Resurgence Two is located on the floodplain of Long Creek about one half mile from Resurgence One (see Plate 11). Resurgence Two emerges from a subcircular depression in the floodplain. The depression is about sixty feet in diameter and is about fifty feet from the nearest hill slope (see Figure 21). The channel extending from this depression is twenty feet wide (see Figure 22) and joins Barren River about 525 feet away. The confluence of Resurgence Two and Barren River occurs ninety feet downstream from the confluence of Long Creek and Barren River (see Plate 11 and Figure 23). Resurgence Two is the emergence of that portion of Long Creek pirated by Swallow Holes Two, Three, and Four as indicated by the visually comparable turbidity. However, Resurgence Two continues to flow at a much reduced rate even when Swallow Hole One has totally pirated Long Creek. Therefore, it is likely that Resurgence Two also receives

FIGURE 20. SOLUTION JOINT

SOURCE: Author

FIGURE 21. RESURGENCE TWO

SOURCE: Author

FIGURE 22. RESURGENCE TWO CHANNEL

SOURCE: Author

water from an underground source within the slopes to the north. The absence of springs on the hills contiguous to the floodplain on which Resurgence Two is located supports this conclusion.

On a pediment located on the north side of Long Creek, about midway between Resurgences One and Two, is an elongated closed depression longitudinally aligned north-south (see Plate 11). The depression is in a cultivated area, and evidence of temporary ponding is visible (see Figure 24). The length of the depression is about 330 feet, and its depth is about fifteen to twenty feet at the lowest point. About 200 yards northwest of the rim of this depression, and located on the lower portion of the hill up slope, is a unique exposure of Louisville limestone. This small exposure of about fifty by fifty feet appears to consist of solution relicts. Blocks, separated by solution channels two to three feet wide and up to six feet deep, are exposed (see Figure 25). The maze of channels is near the supposed flow route from Swallow Hole Two to Resurgence Two. However, no specific correlation could be made.

Summary

Long Creek, which flows uninterrupted for the first fifteen miles or so, is pirated at four locations within a distance of 1.3 miles. Piracy occurs at different points depending upon the level of the creek flow. As a result, the creek's surface channel is filled with water to differing extents beyond Swallow Hole One. During periods of low volume flow, Long Creek is totally pirated by Swallow Hole One, flows at least 1400 feet

FIGURE 23. RESURGENCE TWO CONFLUENCE WITH BARREN RIVER

SOURCE: Author

FIGURE 24. PEDIMENT DEPRESSION

SOURCE: Author

FIGURE 25. RELICT SOLUTION FEATURES

SOURCE: Author

underground, emerges at Resurgence One, and continues its surface flow to Barren River, having shortened its route by at least 1.5 miles. During periods of moderate volume flow, a 0.83 mile surface route is added to the point where Swallow Hole Two totally pirates the flow (minus the piracy by Swallow Hole One). The water flows at least 5000 feet by underground route, emerges at Resurgence Two, and flows some 500 feet by a surface route to Barren River, having shortened its route by about one half mile. During periods of high volume flow, the piracy by Swallow Holes One, Two, Three, and Four is incomplete and a portion of Long Creek flows by surface route, occupying its channel in its entirety, even as the pirated flows continue as noted in the two cases above. In effect, at periods of high volume flow, Long Creek simultaneously has at least five different courses, only one of which is surficial. This assumes that Swallow Holes Two, Three and Four are feeders to a single conduit emerging at Resurgence Two.

It is interesting to note that Swallow Hole One, the primary point of Resurgence Two, and Swallow Hole Four are almost perfectly aligned (see Plate 11). Swallow Hole Two, Swallow Hole Four, and Resurgence Two are also aligned, with Swallow Hole Three being slightly off that line. These two lines are nearly at right angles. The orientation of these two lines is very similar to the orientation of the passageways of Carpenter's Cave.

All swallow holes and resurgences of Long Creek occur within the Louisville limestone of Middle Silurian age. The exposures of these strata along this portion of Long Creek are deeply pitted by solution, with pit diameter reaching as much as twenty inches. Tubular openings up to six inches in diameter are not uncommon. Little of the exposed surface of the Louisville limestone is unaltered by solution. As will be seen in following paragraphs, the Louisville limestone exhibits these characteristics throughout the study area.

Springs

Introduction

Virtually all valleys in the detailed study area contained springs and several were categorized as large. Within each valley complex. the combined flows of the springs appeared to be sufficient to produce a major tributary to Long Creek. However, no such tributary is produced because of the piracy of the flows either before or after confluence with the primary drainage line. In no case does a flow reach Long Creek by a surficial route and, with one exception, no flow has incised through the Long Creek floodplain. This indicates that the addition of runoff from rain within the two and a half square mile detailed study area is insufficient to produce a confluence with Long Creek.

The following paragraphs provide an analysis of the collected data and establish a basis for conclusions about the anomaly of sinking springs in a nonkarst area. The data collected (Tables 2 and 3) is analyzed in three groups: origins; sinks; and resurgences.

TABLE 2

SPRING FLOW DATA, VALLEY COMPLEX A-D

Spring	Flow	Origin MSL	Dis- tance	Sink MSL	Dis- tance	Resur- gence MSL
			Valley Complex A			
1	Small	720'	900' 50'	640' 600'	1100'	600'
			Valley Complex B			
2	Mod.	760'	900' 1200' 1000'	680' 620' 610'	700' 100'	660' 615'
3	Mod.	760'	700'	(Joins with Spring 2)		
4	Small	740'	200'	(Entire flow contained by dam)		
5	Small	740'	300' 200'	710' (Joins with Spring 2)	700'	660'
6	Mod.	720'	900'	(Joins with Spring 2)		
7	Small	720'	700'	620'		
			Valley Complex C			
8	Large	760'	1600' 1100'	680' 620'	400'	660'
9	Small	660'	200'	(Joins with Spring 8)		
10	Small	660'	100'	(Joins with Spring 8)		
			Valley Complex D			
11	Small	720'	1300'	640'		
12	Small	720'	1100'	640'		
13	Small	680'	200'	640'		
14	Small	680'	200' 50'	640' 615'	100'	620'
15	Small	680'	300'	620'		

SOURCE: Author Field Survey.

TABLE 3

SPRING FLOW DATA, VALLEY COMPLEX E

Spring	Flow	Origin MSL	Dis-tance	Sink MSL	Dis-tance	Resur-gence
16	Small	750'	400'	720'	20'	720'
			500'	(Entire flow contained by dam)		
17	Small	680'	400'	640'		
18	Small	720'	900'	640'		
19	Small	720'	50'	710'	50'	700'
			50'	690'	50'	680'
			500'	640'		
20	Small	720'	400'	(Joins with Spring 21)		
21	Mod.	720'	1000'	640'		
22	Small	750'	200'	730'		
23	Mod.	720'	1200'	640'		
24	Mod.	720'	400'	(Joins with Spring 23)		
25	Small	720'	500'	660'		
26	Mod.	720'	400'	700'	60'	700'
			600'	660'		
27	Small	750'	100'	730'	100'	700'
			200'	660'		
28	Mod.	750'	200'	(Joins with Spring 29)		
29	Mod.	750'	300'	(Joins with Spring 30)		
30	Mod.	750'	800'	660'		
31	Large	720'	500'	660'		
32	Small	720'	10'	(Joins with Spring 34)		
33	Small	720'	10'	(Joins with Spring 34)		
34	Small	720'	900'	620'		

SOURCE: Author Field Survey.

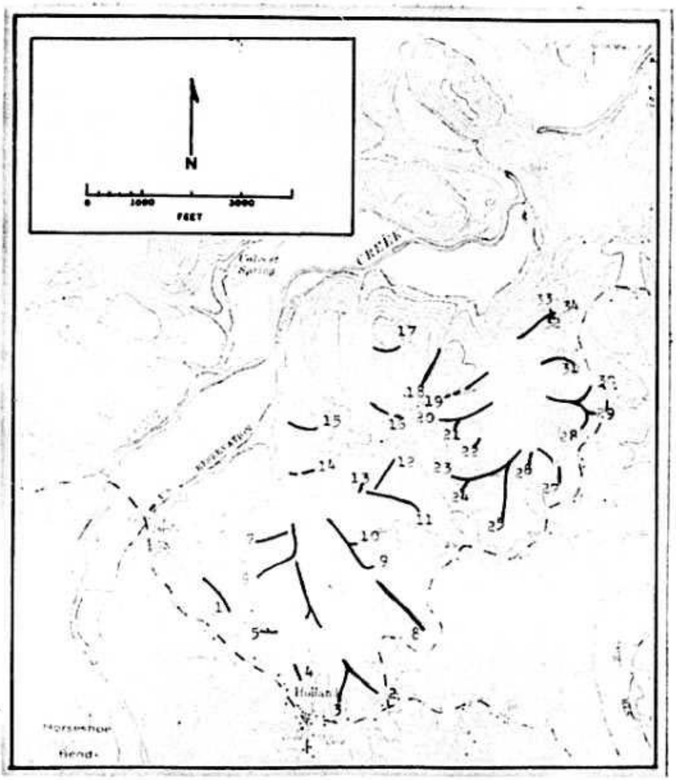
Origins of Springs

Only the highest point of spring emergence within each valley is, for this paper, designated as a spring origin. Emergence at a lower point in a valley containing a spring at a higher elevation is designated as a resurgence of the higher spring. Because the valley slopes are so steep, this distinction seems proper.

Valley complex A contains one spring (see Table 2 and Plate 12). As Table 2 shows, Spring 1 emerges at an elevation of 720 feet mean sea level. It flows on the surface for a distance of 900 feet where it sinks at an elevation of 640 feet mean sea level. About 1100 feet down valley, resurgence occurs at 600 feet mean sea level. After a surface flow of 50 feet, a final sink occurs at an elevation of 600 feet mean sea level.

The valley complex designated B contains six spring origins (see Table 2 and Plate 12). The highest origins are at the valley head where Springs 2 and 3 emerge at an elevation of 760 feet above sea level. Both of these springs are classified as having a moderate flow to their confluence, below which the flow must be classified as large. Springs 4 and 5 emerge at 740 feet above sea level with flows classified as small. Springs 6 and 7 emerge at 720 feet above sea level with a moderate and small flow respectively. All six springs within this valley complex originate from the Fort Payne formation but the elevations of the origins decrease from 760 feet to 720 feet. These decreases trend north-north-west toward Long Creek.

PLATE 12. SPRINGS LOCATION AND FLOW



SOURCE: Author Field Study

The ridge separating valley complex B and valley complex C has no springs emerging from its slopes. It is the only ridge within the study area which is devoid of springs.

The valley complex C (see Table 2) contains three springs. The primary one is Spring 8 which originates at an elevation of 760 feet above sea level at the valley head, with a flow classified as large. Spring 8 emerges from the Fort Payne formation. Springs 9 and 10 emerge at an elevation of about 660 feet from the contact between the New Providence shale and the Chattanooga shale.

There are five springs within valley complex D. Springs 11 and 12 originate at 720 feet above sea level with small flows from the Fort Payne formation. Springs 13, 14, and 15 emerge at an elevation of 680 feet above sea level from the contact between New Providence shale and the Chattanooga shale. The contact between these two formations is slightly higher in this valley because it is closer to the structural high centered about one half mile to the east.

Valley complex E (see Table 3) exhibits similar characteristics. With one exception (Spring 17), the springs first emerge from the Fort Payne formation with origin elevations being highest at the valley head. Spring 17 originates from the contact between the New Providence shale and the Chattanooga shale.

Spring flow is strongest in springs whose origin is at the valley head and weakest at origins near the valley mouth.. This is true throughout the study area.

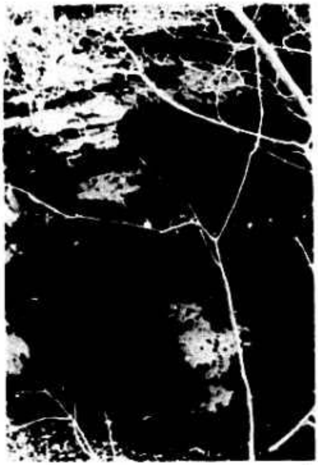
Spring Sinks

None of the spring flows within the detailed study area reaches Long Creek by a surficial route; all are pirated. There is consistency in the piracy within a valley complex but each valley complex differs from the others.

There are four levels of sinks within the valley complexes A through D (see Table 2). One occurs at 710 feet above sea level (Spring 5), which is about fifty feet above the base of the Fort Payne formation. Two sinks occur at 680 feet above sea level (Spring 2 and 8), which is about twenty feet above the base of the Fort Payne formation. Five sinks occur at 640 feet above sea level (Springs 1, 11, 12, 13, and 14), which is the contact of the Chattanooga shale and the Louisville limestone. These five sink immediately upon contact with the Louisville limestone. The fourth level of sinks is about 620 feet above sea level (Springs 2, 7, 8, 14, and 15). This level is occupied by the Louisville limestone although only the beds of Springs 2 and 8 have exposed it to this depth.

The highest level sinks of Springs 2 and 8 at 680 feet above sea level deserve special note. The flow of both springs at this point is large, and both are flowing through a gully about four feet deep. At the point of sink, each flow falls vertically over a limestone precipice about four feet high into a gravel filled plunge pool (see Figure 26). The basin of the plunge pool is about five feet in diameter and is filled with water to a center depth of about six inches. No water escapes from these small basins but the

FIGURE 26. SPRING SINK



SOURCE: Author

swallow holes which they must contain are not visible. These holes are apparently filled with gravel.

The sinks within valley complex E (see Table 3) occur at levels corresponding to those in the other valleys except that the structural high has raised all strata about twenty to thirty feet. The highest sinks occur about fifty feet above the base of the Fort Payne formation; another sink level is about twenty feet above the Fort Payne formation; a third level is at the top of the Louisville limestone; and the lowest sinks are within the Louisville limestone. As in the other complexes, all flows sink immediately upon contact with the Louisville limestone.

The valley complex E differs in two respects from the other complexes. First, all spring flows are pirated before they reach the primary valley, the head of which is marked by the sinks of Springs 23, 26, and 27, whereas the primary valleys in complex B and C contain flows (see Plate 12). Two factors appear to be involved in this difference. The structural high has exposed the Louisville limestones at higher elevations and the valley is more deeply incised. As a result, this formation is totally successful in pirating the flows because of the increased opportunity.

The second difference noted in valley complex E is that a drainage gully reaches Long Creek. This gully is in the valley of Spring 16 and is about eight feet deep below the dam which stems the flow of Spring 16. The gully is joined by one from the valley occupied by Spring 17 and continues to a confluence with Long Creek. Within the detailed study area, this is the only drainage line which has a gully which reaches the creek and is the only one which even reaches the Long Creek floodplain. This indicates that rain runoff is also pirated, except for this valley, throughout the detailed study area.

Spring Resurgences

The resurgence of spring flow is primarily influenced by the apparently impermeable Chattanooga shale. In all cases where sinks occurred above these strata, resurgence occurred at the top of the Chattanooga shale. Some seepage occurred from the two to three foot strata of the New Providence shale but the major resurgence always emerged at its contact with the Chattanooga shale. Therefore, a perched water table can be said to exist above the Chattanooga shale.

Spring flows pirated by the Louisville limestone do not have a resurgence except for Springs 1 and 14. In both exceptions, the resurgence is short-lived (see Table 2). It is clear that the Louisville limestone is so effective in piracy that resurgence is precluded.

Solution Features

Although not related to springs and their flow, two locations exhibited solution features which lend support to the karstic inclination of the study area. Thus, a description of these features is included here.

Within a dry gully in the valley occupied by Spring 27 (see Plate 12) and about one hundred feet down valley from its final sink, a dry sink exists. This sink is about five feet deeper than the floor of the dry gully. Louisville limestone can be seen around the lower sides of the sink. The limestone shows distinct solution features with many solution pockets visible. On the upstream side of the bottom of the sink, a small opening is visible; it is about six inches high and about one foot wide. The downstream side of the sink is about three feet deep. The evidence shows that this sink is a swallow hole for surficial runoff during rains and that little flow continues downstream by a surface route.

The second karst feature observed is located on the slope between the resurgences of Springs 2 and 5. Fort Payne limestone is visible showing enlarged joints and many solution pockets. At the base of the exposure is a small opening about one foot wide and about two feet high. No water flowed from it nor is there evidence that it now serves as a swallow hole.

Summary

Within the detailed study area, thirty-four springs were located. All spring flows are pirated at least once. A total of thirty-two sinks were identified. This total is less than the total number of springs because many sinks occur after the confluence of two or more springs. Eleven resurgences were located and all subsequently are pirated again. No spring flow reaches Long Creek by a surficial route and only one gully reaches or crosses the creek's floodplain.

Within the study area, there is a perched water table. It is perched above the Chattanooga shale which is about forty feet thick throughout the area. The top of this unit slopes from east to west across the detailed study area from an elevation of 700 feet in the east to an elevation of 660 feet in the west. The saturation zone of this perched water table appears to be within the lower portion of the Fort Payne formation. All springs which sink at elevations above the contact between the Fort Payne and the Chattanooga formations have a resurgence at that contact.

The Chattanooga shale is impermeable. No sinks occur in or through this formation. As noted above, all sinking springs above this formation have a resurgence where the top of it outcrops.

The Louisville limestone exhibits many more karst features than the Fort Payne. No spring flow across this strata escapes capture and, with few exceptions, the capture is total and final. Even the exceptions succumb quickly. The presence of only one gully across the Long Creek floodplain is evidence of the totality of the piracy. Further evidence is provided by valley complex E where the primary valley is dry because piracy within the rock unit is complete. The piracy of the entire flow of Long Creek also occurs within these strata. Clearly, the Louisville limestone is easily dissolved and well developed conduits exist.

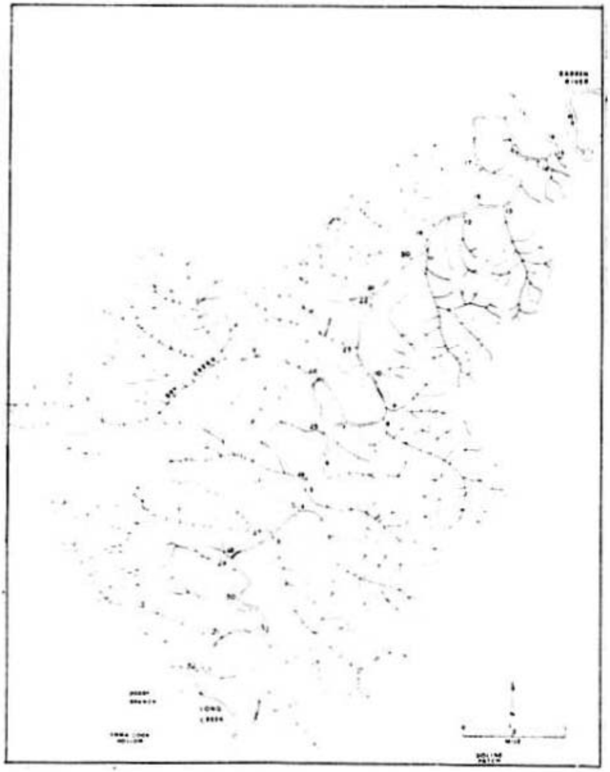
The Areal Extent of Sinking Springs

After the foregoing detailed study of a portion of the Long Creek drainage area to establish the existence of karst characteristics, the next step was to determine the areal extent of this anomaly. To accomplish this, the eleven miles of Long Creek from its confluence with Barren River to the upstream confluence with Doddy Branch and Emma Cook Hollow were subjected to field survey. The results of the survey were very similar to that noted in the detailed study area. Along this eleven mile reach, there are thirty-two second or higher order valleys which drain into Long Creek (see Plate 13). Only the flow from Calvert's Spring provides a major surficial input to Long Creek. Valley 1 contains a moderate flow which reaches the creek and Valleys 4 and 5 reach the creek with what could generously be called a trickle. The other 29 valleys are dry and contribute no surface flow to Long Creek under normal conditions.

The absence of surface flow from these valleys cannot be attributed to the lack of springs at the valley heads. A previous work on the water resources of this area (Hopkins, 1963) confirms the existence of a number of springs in this area although that work clearly did not locate them all. In the detailed study area alone, the Hopkins work identified only three of the 34 springs located in this study.

One of the areas having more complete spring data in the Hopkins work was the drainage basin of Dry Creek, one of the major valleys which open to Long Creek (see Plate 13). His work documents a total of 17 springs within the Dry Creek drainage basin which have a combined flow of 242,640 gallons per day. None of this water reaches Long Creek by the Dry Creek channel which is, in fact, dry. However, about 150 feet downstream from the confluence of the dry Dry Creek and Long Creek, a very large spring (not identified by Hopkins) emerges, filling a four feet wide channel which flows into Long Creek after a surface run of about

PLATE 13. LONG CREEK DRAINAGE AREA



SOURCE: Author

thirty feet (see Figure 27). It seems likely that this spring is the wet Dry Creek reappearing.

This spring is not unique. Two other springs of similar strong volume were identified, as well as two smaller springs. All emerge within thirty feet or less of the Long Creek channel and all but one emerge essentially at the creek surface level.

In addition to the dry valleys and the tubular springs, other karst features were discovered. One of these was an interesting patch of dolines. In an area of about 150 by 100 feet, nine dolines appear (see Plate 13 and Figure 28). One of these is open at the bottom and it appears to capture sheet flow from the surrounding slopes. The other dolines were closed at the bottom. They ranged in size from four to fifteen feet in diameter. No evidence along the near edge of Long Creek indicates an opening to the creek. However, about 500 yards downstream one of the major springs discussed above appears (see Figure 29) and just up slope from it another small sink occurs (see Figure 30). However, no correlation other than simple proximity could be established with the doline patch.

Between the mouths of Valleys 8 and 9, two small caves are located about five feet up slope from Long Creek. Both caves are blocked by sapped blocks, but air flow from cave exhalation can be felt indicating that passageways are developed to some extent. Because of the blockage, the orientation of the passageways could not be determined.

From the foregoing, it seems clear that the karst anomaly extends along Long Creek upstream to at least its confluence of Doddy Branch, and Emma Cook Hollow. Although karst features appear

FIGURE 27. SPRING NEAR CONFLUENCE OF DRY CREEK AND LONG CREEK

SOURCE: Author

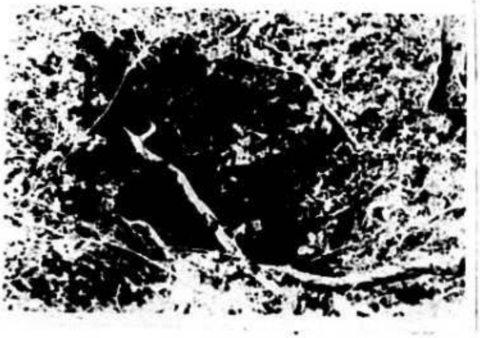
FIGURE 28. THE DOLINE PATCH

SOURCE: Author

FIGURE 29. SPRING NEAR THE DOLINE PATCH

SOURCE: Author

FIGURE 30. DOLINE NEAR DOLINE PATCH SPRING



SOURCE: Author

upstream from that confluence, they do not dominate. Both Doddy Branch and Valley 1 provide a major flow to Long Creek. These two tributaries therefore seem to mark to the end of the area of predominant karst features. However, the sinking springs phenomena occur wherever the flows cross the Louisville strata; for example, Emma Cook Hollow has its large flow pirated twice. Spot checks of valleys south of the study area confirmed that piracy occurs wherever a flow encounters the Louisville limestone.

Long Creek Drainage Area

Introduction

The analysis of the Long Creek drainage area began with a collection of data from the geologic maps of the area. The valleys were traced from their head, where contour lines first formed an acute angle, to their confluence with Long Creek (see Plate 13). From this resultant map, the valleys were assigned orders using the Strahler method; the number of valleys in each order for each valley complex was calculated; the total length for each order for each valley complex was measured; the mean length was computed and cumulated; the bifurcation ratios were determined; and the azimuth orientation of third order or higher valleys was measured (see Tables 4, 5, and 6). A summation of this data is shown in Table 7.

Valley Orders

Within the study area, valley numbers include one fifth order valley, seven fourth order valleys, 27 third order valleys, 132 second order valleys, and 575 first order valleys. A comparison of the number of streams in each order (see Figure 31) reveals that

TABLE 4

VALLEY DATA, VALLEYS 1-12

Order	Number	Total Length	Mean Length	Cumulative Means	Bifurcation Ratio	Mean Bifurcation Ratio	Azimuth
Valley 1							
1	22	6.06	.28	.28	3.66	4.83	303°
2	6	1.29	.22	.50	6.00		
3	1	1.04	1.04	1.54			
Valley 2							
1	2	.04	.02				
2	1	.05	.05				
Valley 3							
1	45	6.89	.15	.15	5.63	3.88	338°
2	8	2.27	.28	.43	4.00		
3	2	.76	.38	.81	2.00		
4	1	1.38	1.38	2.19			
Valley 4							
1	29	4.73	.16	.16	4.14	5.57	316°
2	7	1.82	.26	.42	7.00		
3	1	1.25	1.25	1.67			
Valley 5							
1	17	2.72	.13	.13	3.40	4.20	296°
2	5	.95	.19	.32	5.00		
3	1	.91	.91	1.23			

TABLE 4--Continued

Order	Number	Total Length	Mean Length	Cumulative Means	Bifurcation Ratio	Mean Bifurcation Ratio	Azimuth
			Valley 6				
1	7	.49	.07				
2	1	1.06	1.06				
			Valley 7				
1	3	.38	.13				
2	1	.76	.76				
			Valley 8				
1	43	4.96	.12	.12	3.31	3.52	308°
2	13	3.33	.26	.38	3.25		
3	4	.80	.20	.58	4.00		
4	1	1.10	1.10	1.68			
			Valley 9				
1	12	1.44	.12	.12	6.00	4.00	280°
2	2	.76	.38	.50	2.00		
3	1	.11	.11	.61			
			Valley 10				
1	4	.68	.17				
2	1	.34	.34				

TABLE 4--*Continued*

Order	Number	Total Length	Mean Length	Cumula-tive Means	Bifur-cation Ratio	Mean Bifur-cation Ratio	Azimuth
				Valley 11			
1	31	4.32	.14	.14	3.88	3.29	350°
2	8	2.12	.27	.41	4.00		
3	2	.80	.40	.81	2.00		
4	1	.76	.76	1.57			
				Valley 12			
1	5	.45	.09	.09	2.50	2.25	003°
2	2	.45	.23	.32	2.00		
3	1	.15	.15	.47			

TABLE 5

VALLEY DATA, VALLEYS 13-26

Order	Number	Total Length	Mean Length	Cumula-tive Means	Bifur-cation Ratio	Mean Bifur-cation Ratio	Azimuth
Valley 13							
1	18	2.88	.16	.16	3.60	4.3	342°
2	5	1.17	.23	.39	5.00		
3	1	.72	.72	1.11			
Valley 14							
1	3	.72	.24				
2	1	.15	.15				
Valley 15							
1	2	.11	.06				
2	1	.08	.08				
Valley 16							
1	4	.80	.20				
2	1	.68	.68				
Valley 17							
1	9	1.29	.14	.14	3.00	3.00	263°
2	3	.64	.21	.38	3.00		
3	1	.49	.49	1.06			

TABLE 5--Continued

Order	Number	Total Length	Total Length	Cumulative Means	Bifurcation Ratio	Mean Bifurcation Ratio	Azimuth
Valley 18							
1	4	1.02	.26				
2	1	.90	.90				
Valley 19							
1	12	1.67	.14	.14	4.00	3.50	281°
2	3	.72	.24	.38	3.00		
3	1	.68	.68	1.06			
Valley 20							
1	5	.80	.16				
2	1	.64	.64				
Valley 21							
1	15	1.74	.12	.12	3.75	3.88	287°
2	4	.80	.20	.32	4.00		
3	1	.57	.57	1.01			
Valley 22							
1	3	.53	.18				
2	1	.27	.27				
Valley 23							
1	19	2.54	.13	.13	3.17	4.59	288°
2	6	1.21	.20	.33	6.00		
3	1	.83	.83	1.16			

TABLE 5--Continued

Order	Number	Total Length	Mean Length	Cumula-tive Means	Bifur-cation Ratio	Mean Bifur-cation Ratio	Azimuth
			Valley 24				
1	110	19.02	.17	.17	4.23	3.66	262°
2	26	7.35	.28	.45	6.50		
3	4	3.33	.83	1.28	2.00		
4	2	.60	.30	1.58	2.00		
5	1	.95	.95	2.53			
			Valley 25				
1	2	.15	.08				
2	1	.45	.45				
			Valley 26				
1	22	2.46	.11	.11	4.40	4.70	284°
2	5	1.44	.29	.40	5.00		
3	1	.91	.91	1.31			

TABLE 6

VALLEY DATA, VALLEYS 27-32

Order	Number	Total Length	Mean Length	Cumula- tive Means	Bifur- cation Ratio	Mean Bifur- cation Ratio	Azimuth
Valley 27							
1	48	7.08	.15	.15	6.00	4.00	286°
2	8	1.89	.24	.39	4.00		
3	2	1.06	.53	.92	2.00		
4	1	1.14	1.14	2.06			
Valley 28							
1	2	.38	.19				
2	1	.04	.04				
Valley 29							
1	5	.83	.17				
2	1	.57	.57				
Valley 30							
1	9	1.29	.14				
2	1	.87	.87				
Valley 31							
1	34	4.32	.13	.13	5.67	3.56	280°
2	6	1.44	.24	.37	3.00		
3	2	.68	.34	.71	2.00		
4	1	.83	.83	1.54			

TABLE 6--Continued

Order	Number	Total Length	Mean Length	Cumula-tive Means	Bifur-cation Ratio	Mean Bifur-cation Ratio	Azimuth
			Valley 32				
1	3	.42	.14				
2	1	.19	.19				
			First Order Tributaries				
1	26	6.59	.25				
			Total (All Orders)				
	742	148.29	.20		5.03	302.7	

TABLE 7

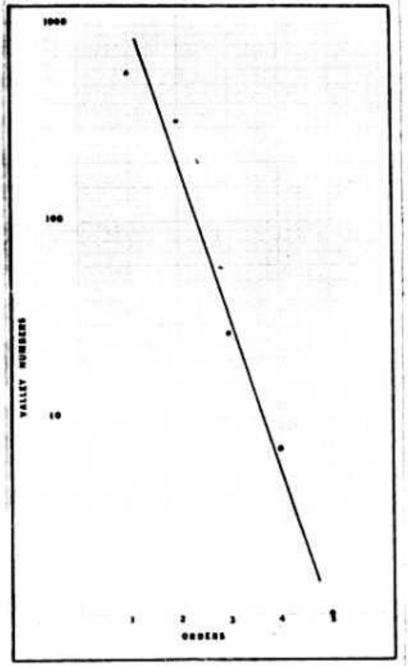
VALLEY DATA SUMMARY

Valley	Order 5	Length	Order 4	Length	Order 3	Length	Order 2	Length	Order 1	Length
1					1	1.04	6	1.29	22	6.06
2							1	.05	2	.04
3			1	1.38	2	.76	8	2.27	45	6.89
4					1	1.25	7	1.82	29	4.73
5					1	.91	5	.95	17	2.72
6							1	1.06	7	.49
7							1	.76	3	.38
8			1	1.10	4	.80	13	3.33	43	4.96
9					1	.11	2	.76	12	1.44
10							1	.34	4	.68
11			1	.76	2	.80	8	2.12	31	4.32
12					1	.15	2	.45	5	.45
13					1	.72	5	1.17	18	2.88
14							1	.15	3	.72
15							1	.08	2	.11
16							1	.68	4	.80
17					1	.49	3	.64	9	1.29
18							1	.90	4	1.02
19					1	.68	3	.72	12	1.67
20							1	.64	5	.80
21					1	.57	4	.80	15	1.74
22							1	.27	3	.53
23					1	.83	6	1.21	19	2.54
24	1	.95	2	.60	4	3.33	26	7.35	110	19.02
25							1	.45	2	.15
26					1	.91	5	1.44	22	2.46
27			1	1.14	2	1.06	8	1.89	48	7.08
28							1	.04	2	.38
29							1	.57	5	.83
30							1	.87	9	1.29
31			1	.83	2	.68	6	1.44	34	4.32
32							1	.19	3	.42
First Order Tributaries										
									26	6.59

TABLE 7--Continued

Valley	Order 5	Length	Order 4	Length	Order 3	Length	Order 2	Length	Order 1	Length
					Total					
	1	.95	7	5.81	27	15.09	132	36.70	575	89.76
					Mean Length					
		.95		.83		.56		.28		.16
					Bifurcation Ratio					
			7.00		3.86		4.89		4.36	

FIGURE 31. VALLEY NUMBERS VERSUS ORDER



SOURCE: Author

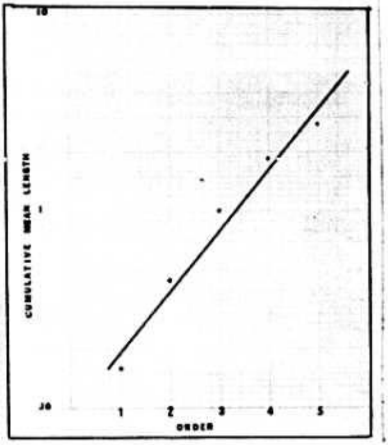
this aspect of the Long Creek drainage area conforms to Horton's Law of Stream Numbers. That law states that the numbers of stream segments of successively lower orders in a given basin tend to form a geometric series, beginning with a single segment of the highest order and increasing according to a constant bifurcation ratio (Gregory and Walling, 1973).

Valley Lengths

Within the study area, there are 148.29 miles of valleys which drain into Long Creek. The data for each valley complex (see Tables 4, 5, and 6) provided a mean length for each order of 0.16 miles for first order, 0.28 miles for second order, 0.56 miles for third order, 0.83 miles for fourth order, and 0.95 miles for fifth order valleys. A comparison of the cumulative mean lengths with the orders (see Figure 32) reveals that Horton's law of stream lengths applies. That law states that the cumulative mean lengths of successive stream orders tend to form a geometric series beginning with the average length of the first order segments and increasing according to a constant length ratio (Gregory and Walling, 1973). The study area conforms with this law, indicating that valley length is not karst controlled.

A further comparison was made between the valleys east of Long Creek with those to the west. This comparison was limited to third order or higher valleys which are contiguous to the Long Creek floodplain. This limitation was imposed because it encompasses the Silurian exposures which appear to be the karst development area and generally excludes the younger strata which are not predominantly karstic. The results of the comparison of cumulative

FIGURE 32. VALLEY ORDER VERSUS CUMULATIVE MEAN LENGTH



SOURCE: Author

mean lengths of third order or higher valleys east of Long Creek with those west of Long Creek revealed no significant difference at the $t_{.05}$ level.

Bifurcation Ratios

The next analysis of the study area was the determination of the bifurcation ratios of the valley networks using the method discussed by Gregory and Walling (1973). The mean bifurcation ratios varied from a low of 2.25 for valley complex 12 to a high of 5.57 for valley complex 4 (see Tables 4, 5, and 6). However, when the totals of all valley segments were compared the resultant total mean bifurcation ratio of 5.03 resulted. This means that, on the average, there are five times as many segments in any order as there are in the next higher order. The mean bifurcation ratio of 5.03 is not significantly at variance with Horton's "normal" valley bifurcation ratio of between three and five. This indicates that bifurcation ratio has not been affected by the karst development.

An additional analysis was made between the valleys east of Long Creek with those west of it. This computation revealed that there is no significant difference at the $t_{.05}$ level between the bifurcation ratios of the valleys east and west of Long Creek.

Valley Orientation

If joint control has been affecting the valley development within the study area, there should be some correlation between the valley orientation and the predominant joint orientation. To make this comparison, it was necessary to measure the orientation of the primary valleys. The method chosen was to determine valley azimuth measured from the point where such primary valleys bifurcate into lower order valleys to the point of confluence with Long Creek. The reciprocal of the azimuth was used for valleys west of Long Creek. Only third order or higher valleys were accepted as being enough developed to show a correlation with joint patterns if one exists. Seventeen valleys were used for this analysis (see Table 8). The mean azimuth orientation of these seventeen valleys was 302.7 degrees. Using the same method, Long Creek itself is oriented 033 degrees in azimuth as measured from the Doddy Branch-Long Creek confluence to the Long Creek-Barren River confluence. The ninety degree difference would seem to be evidence to joint control since, as calculated by Piper (1932), the axis of the Nashville Dome is oriented to an azimuth of 020-030 degrees from the apex. Long Creek's orientation of 033 degrees thus conforms to the axial azimuth of the Nashville Dome. However, the most prominent set of joints in Allen County (Shaw and Mather, 1919) has an azimuth of 040-060 degrees. Therefore the correlation between Long Creek's azimuth and the joint pattern is unclear. The Shaw and Mather (1919) determination of the joint orientation does not reveal the area from which their samples were taken. It could be that their data were weighted with joints from other parts of the county.

It was calculated by Miller (1919) that the orientation of the dip in Allen County varies from an azimuth of 296 to 333 degrees. The mean orientation of the valleys in the study area is 302.7 degrees, which correlates with the dip orientation.

TABLE 8

VALLEY ORIENTATION

Valley Number	Highest Order	Orientation
	Valleys East of Long Creek	
1	3	303°
3	4	338°
4	3	316°
5	3	296°
8	4	308°
9	3	280°
11	4	350°
12	3	003°
13	3	342°
	Valleys West of Long Creek	
17	3	263°
19	3	281°
21	3	287°
23	3	288°
24	5	282°
26	3	284°
27	4	286°
31	4	280°

Note: West Valleys Orientation is Reciprocal True Orientation

SOURCE: Author.

A final analysis of the orientation data was made comparing the valleys east and west of Long Creek. In this analysis it was found that a highly significant difference existed at the one percent level between the orientation of the valleys east and west of it. The mean azimuth of the eastern valleys is 321.78 degrees while the mean of the western valleys is 281.38 degrees. This may indicate the effect of the local structure which is more pronounced and varied on the eastern side of Long Creek. Valleys 11, 12, and 13 are located over a local structure which dips to the north. These three valleys are also oriented more to the north than all others. When these three valleys were excluded from the computation, the remaining eastern valleys still showed a highly significant difference from the western valleys at the one percent level. The western valleys vary little in orientation but the eastern valleys vary from 280 degrees to 003 degrees. Perhaps the more varied local structure on the eastern side is the determinant.

Summary

The Long Creek drainage area analysis revealed no unusual or abnormal ratios of valley orders, lengths, or bifurcation. These aspects appear to be unaffected by the karst development in the Long Creek drainage area. On the other hand, the mean valley orientation closely follows the dip of the underlying structures and conforms to the axial and contour lines of the Nashville Dome. There is a significant difference between the valley orientation east of the Long Creek compared to that of the valleys to the west. The cause of this difference could not be assuredly determined.

The most significant feature of the Long Creek drainage area is the almost total lack of surface flow reaching Long Creek. When one considers the over 149 miles of valleys draining the study area of about 9,206 acres and the abundance of springs, this absence of surface flow near the Long Creek is amazing evidence of the efficiency of the karst piracy. In addition to the volume of spring flow, rainfall within the study area produces an additional surface flow of water during storms. Even so, a relatively small portion reaches Long Creek by entirely surficial means as evidenced by the small number of drainage lines which show frequent use by surface flow. The subsurface drainage network must be greater now than that of the surface network.

Carpenter's Cave

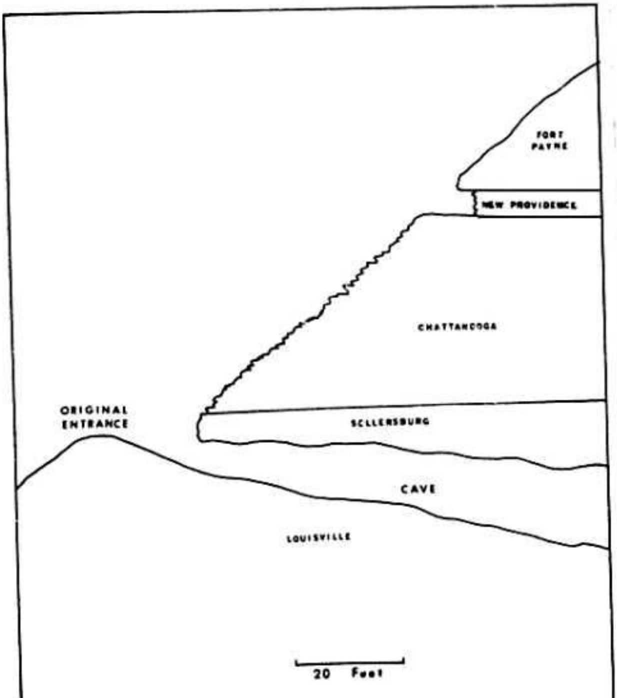
Introduction

Carpenter's Cave is a well developed cavern which, for the most part, lies outside the study area. However, the terminus of the major passageway underlies the study area and is in other ways correlated with it. The cave is almost wholly within the Louisville limestones of Silurian age and within a structural high. It is within these strata that the karst development within the study area is most extensive. The cave offers an opportunity to view this formation from within and to deduce the cave's origin.

External Features

The cave entrance was found to be 365 feet from Barren River on the eastern flank of a tributary valley. The first effort of the field work was to locate the top of the Chattanooga shale which is mapped at 680 feet above sea level. From that, measurements of the hill slope and the distance to the floor of the cave entrance enabled the determination of the elevation of the cave and provided a starting point for subterranean slope measurements. The contact between the Chattanooga and New Providence shales is exceptionally distinct, being dark grey-black fissile shale underlying green non-fissile shale. The New Providence shale is four feet six inches thick at the contact. It has receded as much as four feet leaving an overhang of Fort Payne strata above. Approximately three and a half feet up into the Fort Payne formation a spring emerges along a bedding plane for the total width of the exposure of about 31 feet. Water from this spring flows down slope into the cave entrance. From the top of the Chattanooga shale, the slope to the cave entrance floor is 39° and the distance is 79 feet. The elevation of the entrance floor was calculated to be about 630 feet above sea level. There is ample evidence of cave mouth retreat. Outside the present cave mouth, there is an upward slope extending about 25 feet away from the entrance (see Figure 33). Then a slope reversal occurs, with the hill slope resuming its descent to an alluviated valley floor. The current cave entrance provides some clue to this retreat. The spring water flowing over the overhanging slope has covered the cave entrance floor with large pebbles and debris from the drainage slope. Added to that is the sapping of the lip of the cave ceiling at the entrance. The combination of these actions caused the floor of the cave to rise by deposition while the ceiling retreated by erosional processes. The relict floor remains for about 25 feet external to the present entrance.

FIGURE 33. PROFILE OF CAVE ENTRANCE SLOPE



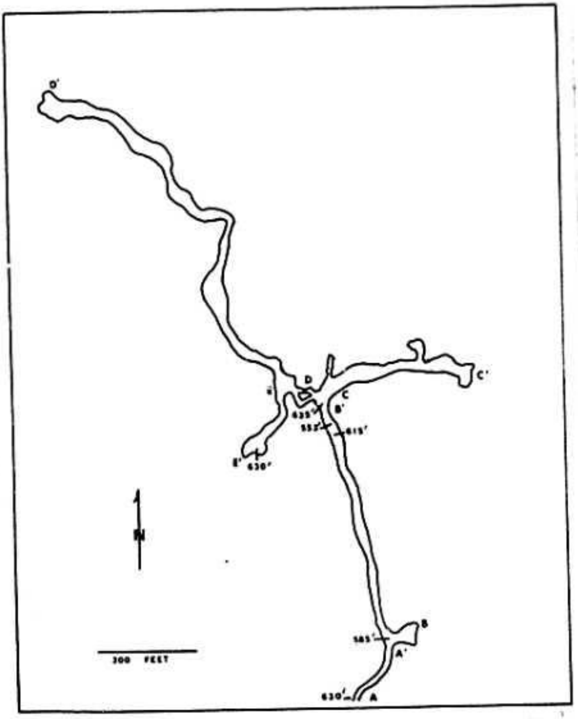
SOURCE: Author

The cave was mapped (see Plate 14) and floor measurements for elevation were made for a portion of it. No attempt was made to profile the cave in detail. For ease of discussion and because of generalized differences, the cave has been divided into five sections. The following paragraphs will discuss the findings and observations made in those five sections.

Section A

The first section of the cave (A-A' in Plate 14) is dominated by the spring water flowing in from the mouth. The floor of the cave for the first eighty feet is covered with pebbles and organic matter. The size of the pebbles diminishes as the distance from the entrance increases indicating that the spring water transported them from the cave entrance. At the eighty foot mark, the flowing water is pirated to a lower level through an opening on the west side of the passage. Within the next 100 feet of passageway, there are two collapse pits and one dome-pit. The dome is small, 4 to 5 feet in diameter and has a small stream of water falling from it into a small pit below. The two collapse pits are larger, the largest being at least ten feet across and about eight feet deep. All three are presumed to connect with the pirate passage, and all show signs of receiving overflow from the point where the spring flow is pirated. Beyond these pits, the passageway narrows and a thin coating of silt covers the floor. There are a few dripstone features on the ceiling. At the point A', the passageway joins the section marked B-B'. This juncture occurs about 25 feet above the floor of B-B', the drop being essentially vertical. It would therefore seem probable that

PLATE 14. CARPENTER'S CAVE



SOURCE: Author

these two sections of the cave formed under different controls. Section A-A' trends toward the northeast and slopes downward in that direction as well. Ceiling heights vary from about four feet to about 15 feet, being highest in the dome area.

Section B

Section B-B' of the cave is different from all other sections in that it is virtually filled with clay. At point B, reddish-brown clay is packed with selenite crystals (see Plate 14). The clay-crystal relation is much like that of a mud-ice occurrence. Here the clay is within three feet of the ceiling. Legend is that it is in this area that saltpeter was extracted during the Civil War period. Imprints of wood planks can still be seen in the clay at some places and isolated wood fragments remain. On the ceiling in this area, fossil coral Halysites-catenularia (Shimer and Shrock, 1944) was found in abundance. This index fossil confirms that this portion of the cave is within Silurian limestone. At the juncture with section A-A', the clay has been eroded away to a depth of about twenty feet exposing large (four by eight by two feet) ceiling blocks which fell before the clay was deposited. In some places they are still partially covered with the clay. At the deepest part directly under the juncture, an opening to a lower level can be seen. One would surmise, because of the clay's greater moisture content below, that it connects with the lower passage which pirated the spring flow. However, the opening is too small to enter for verification. Nevertheless, it is clear that the clay has been eroded from below, as evidenced by the presence of a smooth funnel-shaped clay area around the hole with no evidence of rills. Approximately 150 feet further along the passage B-B', another opening appears on the west side, leading down about eight feet to the pirated stream. The stream bed is filled with gravel. Leaves and seeds could be seen among the debris. The opening leading down to this stream has the same funnel shape as that mentioned above. Again no rills could be detected in the clay.

The last half of B-B' has meander scars in the clay floor. The meanders show no signs of above normal moisture and therefore appear to be abandoned. They are about four feet deep and vary in width from six to ten feet. The sides are smooth and no sand, pebbles, or gravel exists. Some meander loops complete an "S" within a 15 by 15 feet area although most are not so convoluted. The meanders are discontinuous, some ending at the side of the passageway and others having what appear to be clogged openings. Meanders are found nowhere else in the cave except in this relatively level portion. The origin of the water which formed them is a mystery. Perhaps they are relicts of the cave draining period because the floor slopes downward toward the south-southeast.

Near the point B', a stream crosses the chamber almost at right angles flowing toward the southeast. The stream bed is the deepest part of the cave, at least that which we could enter. Phillip Parrish, who assisted in this portion of the field work, had previously explored upstream during a dry period. He reports that a part of this flow can be traced to the pirated spring area near the entrance. He also found another stream joining the spring flow nearer to the point where it crosses the main passageway. Its source is unknown. On this exploration, the channel was flooded and no investigation could be made. The stream bed as it crosses the main passage is some 40-60 feet deeper than the clay slope crests on either side. A core sample was taken near the bottom of the very steep clay slope to a depth of three feet. There were no signs of varves, sand, gravel, or change of color or consistency.

The passageway B-B' throughout its length has been filled with clay. Clay remains trapped in ceiling pockets sixty feet above the current stream. The source of this pebbleless, flowstone-free clay is unknown. The reddish-brown color is quite unlike that which is presently found in the surface regolith, but is more like that found on higher exposures of the Fort Payne formation elsewhere in the quadrangle. Similar color is found in the regolith of Salem and Warsaw limestone areas which at some time must have covered the Fort Payne in this area. One can only conclude that the clay fill is not recent. The stream has attacked the clay from below rather than from above and has not significantly enlarged its cross passageway. Throughout the length of B-B', the ceiling is covered with pockets ranging in size from a few inches to a few feet. Ceiling height varies from ten to fifteen feet except over the stream where heights are estimated to be sixty feet. Ceiling slopes were not measured. The passage trends north-northwest and slopes upward in that direction conforming to the structural high. At point B' the clay fill ends and the cave beyond takes on a different character.

Section C

Passageway C-C' does not have the vertical cross-section seen throughout B-B'. Instead, its cross-section is markedly horizontal, being wider than high. It is dry and shows no evidence of recent water flow. The floor is covered with a relatively thin covering of clay which is only a few inches thick in the immediate area of C'. Two pits are located in this area, one of which is an estimated thirty feet deep. Above it is a shallow dome. The pit walls are rock but they do not show the grooves one would expect to see in such a typical pit. The bottom is covered with rubble and may indicate crumbling from the pit walls which in turn could explain the absence of grooves. Passageway C-C' trends toward the east-northeast. No slope measurements were taken but it appears that the slope is very slight. Ceiling heights vary from two to eight feet.

Section D

The juncture of passageways B-B', C-C' and D-D' is marked by a large column (see Plate 13). From this point, an up sloping crawlway of about twenty feet leads to a high narrow cross-sectioned passageway. This occurs at the juncture with passage E-E'. From this point on to D', the cave width remains fairly constant but the height gradually increases from about ten feet to about 40 feet. The middle third of this passageway has a ceiling that is greatly pitted, with clay remaining in many of the pits. There is a rock shelf extending from both walls about three feet above the floor. White powdery gypsum coats the undersides of these shelves and selenite is plentiful in the hard clay floor below them. Selenite crystals more than three inches long were found, but most are less than one half inch. In this same section, there is a solution joint in the ceiling about two feet wide, six feet long, and three feet deep. The last third of this passageway is strewn with fallen slabs from the ceiling. The slabs are 2 to 3 feet thick and 8 to 10 feet long. The fracture surfaces are still sharp, indicating that sapping occurred after this area had been drained. Otherwise, dissolution would have altered the fracture surfaces. At point D', the passageway is filled to the ceiling with breakdown slabs and no route through them was found. Here the ceiling is estimated to be 40 feet high but it does not reach the Chattanooga shale. Therefore when compared to E' it is deduced that the passageway slopes downward from D to D'. The trend is north northwest and the passage is dry throughout. Several piles of bat guano are found along this passage, some up to six feet high. Although the age of the passageway is not known, the large size indicates that a considerable length of time was involved in its formation. Some guano from Mammoth Cave has been dated at 38,000 years old (Herak and Stringfield, 1972), demonstrating the presence of an external opening in that cave during the Wisconsin glacial period.

Section E

Passageway E-E' is a short low (five to six feet high) route ending in a dome which has sapped into the Chattanooga shale. Beneath the dome is a cone shaped pile of shale flakes about six feet high accumulated from the sapping. Since shale is not visible in any other part of the cave, the point E' must be the highest point in the cave.

On the basis that the bottom of the shale is 640 feet above sea level, the floor was determined to be at about 630 feet. Therefore the Sellersburg limestone must house most of this short passage.

Surface Doline

Directly above the mapped terminal point of passageway D-D', a large doline can be seen. It is located at 790 feet above sea level on a gentle slope atop the ridge separating Springs 26 and 27 (see Plate 12). The doline is approximately forty feet in diameter and about fifteen feet deep at its center (see Figure 34). It is not noticeably elongated but the southern rim (up slope side) is about five feet higher than the northern rim (down slope side). The doline is occupied by grass and small trees and no hole exists. The location of this doline coincides with location of the collapsed end of the major passageway of Carpenter's Cave. It therefore appears that the doline is a surficial reflection of the cave collapse.

Summary

Carpenter's Cave was formed within the Silurian Louisville limestone. It has more phreatic characteristics than vadose, although both occur. The major passageways trend in two major directions at approximate right angles. Orientation conforms to the local structure as does the slope of the passageways. The highest point in the cave is near the intersection of passageways B, C, D, and E. Passageways B and D slope downward from this intersection toward points B' and D'. The structural high slopes in

FIGURE 34. CAVE RELATED DOLINE

SOURCE: Author

the same manner. This indicates that the intersection is at or near the apex of the structural high.

The clay which has filled and to a large extent still fills the cave is most interesting. Bretz (1942) explains clay as a record of a subterranean reservoir completely filled with very quiet water up to the ceiling. He found cave clays to be typically pebbleless and free of flowstone. Such was the case in Carpenter's Cave. It is safe to say that the clay is younger than the passageways in which it is deposited and older than the vadose flow which has partially removed it.

The Chattanooga shale appears impermeable because no vadose water is entering the cave through it. There seems to be no reason to believe that the Chattanooga shale was ever permeable. The cave also indicates the extent of solution within the Louisville limestone. A network of similar size may produce the flow of Calvert's Spring nearby.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

This study of the lower reaches of Long Creek in Allen County, Kentucky, fulfills its purpose of adding to the body of knowledge from which karst concepts evolve. The review of literature revealed the extent of the evolution of these concepts and the variance in them. The literature associated with karst processes, controls, and stages was reviewed in detail. It was established that the generally accepted boundary of the Central Kentucky Karst excludes the study area and, by that exclusion, designates the area as non-karst.

The study area was delineated and described in terms of physiography, geology, geomorphology, and climate. It was determined that the study area properly belongs to the Highland Rim of the Nashville Basin. The influence of the Nashville Dome on the substructure of the study area was established, and the regional dip and joint orientation was discussed. The stratigraphy of the study area was described in detail, drawing from prior available studies of Allen County and its environs. The relation between the stratigraphy and the ground water was discussed. The geomorphic features of the study were described and the more prominent karst landforms were identified.

The objectives of this study were to establish the karst character of the lower reaches of Long Creek and to offer some explanation of this anomaly in a non-karst area. To achieve these objectives, several hypotheses were developed. Each of these hypotheses concerned the karst characteristics which the study area exhibits.

To test the hypotheses, data were collected primarily by field survey, and an analysis was made. The analysis focused on the piracy of Long Creek, the sinking springs phenomena, the Long Creek drainage area, and Carpenter's Cave. Each of these focal subjects was described in detail and the results of the analysis were summarized for each.

Conclusions

From the analysis of the data collected and in concert with the literature review, it is possible to draw conclusions about the processes, controls, and stages of development of the karst anomaly in the lower reaches of the Long Creek area. The analysis also provides the test for the hypotheses which were formulated. Finally, inferences can be drawn as to the origin and the time of development of the karst features found in the study area. The following paragraphs present the conclusions drawn from this study.

First Hypothesis Considered

The first hypothesis was that karst features within the study area are stratigraphically controlled. Analysis of the data collected presents the Louisville limestone as the primary formation within which karst features develop and the lower portion of the Fort Payne as the secondary. The Silurian age Louisville limestone contains all the swallow holes and resurgence points of the Long Creek piracy. These strata also contain dolines and exhibit severe effects of solution where exposed in the area of the Long Creek piracy. The Louisville limestone also houses Carpenter's Cave and is the formation which contains Calvert's Spring. These two features indicate an extensive and greatly enlarged network of subterranean passages within the Louisville strata.

Within the detailed study area, thirty-four springs were investigated. None of these springs escape capture by the Louisville limestone pirate. The capture is sufficiently effective to include surface runoff in addition to spring flow. This is indicated by the almost complete absence of surface flow lines which reach the Long Creek.

The analysis revealed that for the length of Long Creek from Barren River to Doddy Branch, spring flows rarely totally escape capture by the Louisville limestone although two valleys produce a trickle which reaches Long Creek under normal flow conditions. The rare exceptions are the springs which originate initially from the Louisville limestone. Calvert's Spring and a few others emerge from the strata with large flows that escape capture before entering Long Creek. Of these, only Calvert's Spring is located more than fifty feet from the banks of Long Creek.

The doline patch near the southern end of the study area occurs within the Louisville limestone. While the field survey did not locate other areas of doline development, it seems likely that a comprehensive search would reveal additional ones.

The large doline associated with the distal end of Carpenter's Cave is formed within the Fort Payne formation. However, the association suggests that the doline is a collapse of the strata below rather than a solution feature.

Within the detailed study area, most springs were first pirated by the lower strata of the Fort Payne. This indicates the development by solution of joints and bedding planes at this level. Other studies, Branson (1966) inter alia, have noted that this lower portion of the Fort Payne is porous and was known as the "Beaver" formation of oil production in the northern part of the country.

No karst features were discovered in any strata other than the Louisville limestone and the Fort Payne chert. Conversely, the Louisville limestone was characteristically karst wherever exposed and the Fort Payne's lower strata showed occasional karst tendencies.

Based on the foregoing results of analysis, the hypothesis that karst features within the study area are stratigraphically controlled is accepted. Further, the Louisville limestone is concluded to be the predominant parent of karst features within the study area.

Second Hypothesis Considered

The second hypothesis was that the major karst features within the study area are phreatic in origin. The testing of this hypothesis hinges upon when the karst features were first developed. Several possibilities are considered.

The Chattanooga shale is considered to be impermeable in all the literature reviewed. This view was substantiated by the analysis of the data collected in this study. Exploration of Carpenter's Cave revealed no percolation of water into the cavern other than very near the entrance. Even in one passageway where the Chattanooga shale is exposed in the ceiling, no seepage is visible. Additionally, all springs which were pirated upslope from the Chattanooga shale resurged at the top of the shale. No exceptions were noted. Further, no springs emerged from within the Chattanooga shale and more importantly none were captured by it. From these facts, it is clear that in this study area the Chattanooga shale is impermeable and little, if any, ground water percolates through it.

Accepting that the Chattanooga shale is impermeable and that a perched water table is above it, one must conclude that the formation of karst features within the Louisville limestone below could not have been from vadose solution if the Chattanooga shale were present at the time the solution of the limestone took place. On the other hand, phreatic solution would have been at best slow, since no replenishment of carbonic acid needed for phreatic solution could penetrate the shale layer. Such replenishment would have had to come from lateral sources where the shale had been breached by streams or faulting. Local breaching of the shale occurred when Barren River incised through it. After that time, phreatic flow could have begun the solution process. This process could have continued until Barren River incised about five to ten feet at which time it would have truncated Carpenter's Cave's ceiling. Vadose action would then have prevailed until the river incised through the cave floor. Thereafter, the cave would have been drained and enlargement would have ceased. The total elapsed time in the foregoing scenario equals the time required for Barren River to incise through about five feet of Sellersburg limestone and about ten feet of Louisville limestone. It seems highly unlikely that a conduit the size of Carpenter's Cave could have developed during such a short time.

One possible explanation is that the downcutting by Barren River was interrupted or significantly slowed thereby increasing the time available for karstification. If this occurred after the truncation of the cave, vadose features should dominate. The extensive clay fill remaining in the cave indicates that the vadose flow was too short lived to totally remove it. Thus, if an interruption occurred, it must have been after the breaching of the Chattanooga shale but before the truncation of the cave. In this case, the time involved is the time required to cut through five feet of Sellersburg limestone. The extensive karstification requires a long period of development and an interruption of downcutting would have to have been comparably long. The exposures of the Sellersburg limestone provide no evidence to support such an extended interruption.

This dichotomy is more easily resolved if the karst features originated before the Chattanooga shale was laid down. In this case, development could have been by either vadose or phreatic water or from a combination of both. After the Chattanooga shale was laid down and the water table subsequently lowered, the enlargement of the already existing solutional openings by laterally flowing vadose water would have been possible.

The analysis of Carpenter's Cave points toward the latter scenario. The phreatic features of the cave, such as joints aligned with the passageways, ceiling pockets, partitions, pillars, and the clay fill, are predominant. Further, the extent of karstification of the area as revealed by the sinking springs and dolines and the apparent extent of the Calvert's Spring network indicate a relatively long period of development.

In Allen County, all of the large springs of the Louisville formation emerge from twenty to forty feet below the top of the formation. This may indicate that this was the level to which large scale solution had progressed before the Chattanooga shale was laid down (Hopkins, 1963). This view agrees with Jillson (1920) and Miller (1919). According to Miller (1919), the Cincinnati Arch had been elevated and eroded after the deposition of the Louisville and before the deposition of the Sellersburg limestone. Hopkins (1963) considers that the connate saline water contained in the Louisville formation of the northwestern portion of the county is evidence that the openings which contain them are pre-Chattanooga in age. He states that these openings were probably formed before the last submersion of the area beneath the sea and probably during the erosional interval between the Sellersburg and Chattanooga time. Of interest in the context of this paper is the indicated areal extent of these saline water filled openings. Some explanation other than the breaching of the shale is required because the shale has not been breached by surface streams in the northwestern part of the county.

No literature reviewed disputed the fact that the Sellersburg formation was subjected to erosion prior to the deposition of the Chattanooga shale. Within the study area, no more than a five foot thickness of the Sellersburg formation remains and in most of the area it is missing altogether. It is therefore clear that the underlying Louisville limestone was at or very near the surface while the extensive erosion of the Sellersburg limestone was occurring. One must conclude that the opportunity for karstification then existed. It is improbable that karstification would not have occurred during this relatively long period but would have formed later during the short period required for Barren River to incise fifteen feet.

From the foregoing, it is concluded that the evidence points to the development of solutional openings within the Louisville limestone before the Chattanooga shale was laid down. The hypothesis that the major karst features within the study area are of phreatic origin is accepted.

Third Hypothesis Considered

The third hypothesis was that the primary surface drainage valleys in the study area are joint controlled in their orientation. The analysis demonstrated that there was a positive correlation between the mean orientation of Long Creek and its primary tributary valleys and the joint pattern associated with the Nashville Dome. Further, the right angle difference between the Long Creek orientation and its tributary valley mean orientation supports the joint control concept.

The analysis revealed an unexplained difference in orientation between the valleys east of Long Creek with those to the west. Even so, both sides are in general agreement with the orientation of joints in the area and with the dip of the Nashville Dome.

Because of the unexplained variance and because insufficient specific identification of joints within the study area exists, the hypothesis of joint control of the primary valley orientation is not accepted. Perhaps future studies may produce data which can clearly accept or reject this hypothesis.

Fourth Hypothesis Considered

The fourth hypothesis was that the Long Creek topography does not conform to the stages of karst development as described by Cvijic, Grund, Lobeck, Dicken, and White. It is clear from the analysis of the Long Creek drainage pattern that the study area is fluvial in topography and does not conform to the theories of karst stages of these authors. If the major karst features originated before the Chattanooga shale was laid down, the current surface topography would not necessarily reflect karst characteristics. Since the pre-Chattanooga age of major karst features in the Louisville limestone has been accepted in this study and the study area's fluvial topography has been established, the hypothesis is accepted.

The topography suggests that is of fluvial origin and that the fluvial action has uncovered the paleokarst of the Louisville limestone. If one projects continued fluvial removal of the slopes, the emergence of an already developed paleokarst plain would occur. Karstification would presumably continue to form new karst features amid paleokarst features. The review of literature did not reveal recognition of such an occurrence in this area. Nevertheless, the thought of new karstification of a paleokarst surface is an intriguing one.

Final Thoughts

The lower reaches of Long Creek are a most interesting area and this study has been an enjoyable endeavor. As with most studies, this one creates as many new questions as it answers old ones. For example, there are undoubtedly subfluvial springs in Long Creek. Where are they and how much contribution do they make? Likewise, it seems likely that there are underwater sinks. Where are they and how much do they capture? Is there a subterranean connection between Long Creek and Rhoden's Creek to the north? There are enough questions arising from the results of this study to provide the basis for a new study. It is to be hoped that such a study will be attempted in the future.

Literally hundreds of oil wells have been drilled into and through the Louisville limestone in Allen County. Perhaps some future researcher will review the well logs to determine the frequency of encounters with caverns within the formation. Such a study could provide additional information on the age of the karstification of the Louisville limestone and on the areal extent of it. A direct application of such a study might result in further oil exploration within the county.

Finally, it must be noted that the swallow holes and resurgence points of Long Creek are under water for a considerable part of the year. This occurs as the water of Barren River Reservoir extends up Long Creek nearly a third of the length of the study area. What long term effect this will have upon the geomorphic anomalies described in this study remains to be seen. A re-study of the area in the future may provide the answer.

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