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Karstification of the Pennyroyal Plain Behind the Retreating Chester Escarpment: Warren, Simpson & Logan Counties, Kentucky

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KARSTIFICATION OF THE PENNYROYAL PLAIN BEHIND THE RETREATING CHESTER ESCARPMENT: WARREN, SIMPSON, AND LOGAN COUNTIES, KENTUCKY

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
Anthony S. Able
November, 1986
KARSTIFICATION OF THE PENNYROYAL PLAIN BEHIND THE RETREATING CHESTER ESCARPMENT: WARREN, SIMPSON, AND LOGAN COUNTIES, KENTUCKY

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Hydrogeologic investigations were conducted on the drainage systems of an area of the Pennyroyal sinkhole plain of south central Kentucky. The degree of karstification of five area streams was studied to develop an understanding of the evolution of drainage as the landscape changes from a sandstone caprock plateau to a limestone sinkhole plain. The Chester Upland, capped by the Big Clifty Sandstone, possesses predominantly surface drainage and the Pennyroyal Plain, formed on Mississippian limestones, possesses considerable subsurface drainage. As the Chester Upland Escarpment retreats and surface streams are onto the limestones, the streams evolve to become subsurface streams. The five streams observed in the study (all flowing on limestones) demonstrated less karst development close to the Chester Escarpment and more karst development with increasing distance from the escarpment. Sediments derived from the escarpment and plateau blanket the stream beds thus perch ing the streams and preventing chemically aggressive water from forming karst solution features in the limestones. The streams farther away from the escarpment are removed from the sediment source and are therefore able
to downcut into the limestone and invade the subsurface to become cave streams.

Lithologic investigation of limestones exposed in stream beds revealed that minor resistant units can act to diminish downcutting and maintain short sections of surface flow. The stream investigated was not flowing on a perching layer, but instead was held on the surface by a stratigraphic control (spillover layer) that prevented subterranean stream invasion.

Dye traces conducted on groundwater flow in the sinkhole plain revealed that the area drainage pattern is changing as surface streams invade the subsurface and that intergration between drainage basins is taking place. Stream piracy and stream diversion are occurring in the subsurface causing alteration of the existing topographic drainage divides that developed before the surface streams invaded the subsurface.

A general model is presented which shows the evolution of surface drainage to subsurface drainage, as the Chester Escarpment continues its northwestward retreat.
CHAPTER I

INTRODUCTION AND STATEMENT OF HYPOTHESIS

Introduction

The evolution of surface drainage on the sinkhole plain which has developed upon the gently-dipping upper Mississippian limestones of the Pennyroyal Plain (Figure 1) of south-central Kentucky (Figure 2) was investigated through this study. Except for major base level rivers, the Pennyroyal sinkhole plain has few surface streams. Cave streams comprise most of the tributaries to the base level rivers. This study investigated the role of these streams in the evolution of the sinkhole plain from surface drainage to subsurface drainage. A model was designed to demonstrate the evolution of subsurface streams as they develop on gently dipping limestones exposed behind the retreat of a protective sandstone caprock. Although the model was developed for the study area (Figure 2), it should apply to other location where streams flow into and dissect the Chester Escarpment (Dripping Springs Escarpment) of Kentucky.

An investigation was conducted to determine whether a perching layer was responsible for maintaining the surface flow of a creek on the sinkhole plain. Dye tracing of cave streams was conducted to determine if subsurface flow patterns were concordant with topographic
FIGURE 1 Mississippian Upland of Kentucky

Source (Brown and Lambert 1963)
drainage boundaries.

Setting

The area chosen for study is located on the Pennyroyal sinkhole plain in southwest Warren, northwest Simpson, and northeast Logan Counties near the town of Rockfield, Kentucky. The sinkhole plain has numerous sinkholes, sinking streams, caves, and cave streams. The limestones upon which the sinkhole plain has formed are of the same geologic age (upper Mississippian) as those in which the upper passages of Mammoth Cave have formed. Approximately ten miles (16 kilometers) west of Rockfield is the Chester Escarpment capped by the Mississippian Big Clifty Sandstone. The study area is shown on the following four U.S. Geological Survey geologic quadrangles (scale 1:24,000): Auburn (Rainey 1965), Rockfield (Rainey 1964), South Union (Klemic 1963) and Woodburn (Shawe 1963). The maps show the sinkhole plain covering most of the area with the escarpment in the northwest. The five major streams of the area (Figure 3) flow from south to north ultimately to join the Barren River. These streams are primarily responsible for the northwestward retreat of the sandstone caprock, which in the past covered the entire study area. Gasper River, Black Lick Creek, and Clear Fork Creek flow on the surface. Brush Creek has a surface-flowing section that eventually sinks to become a cave stream and Lost River is almost totally a subsurface system. Unlike the Mammoth Cave area, where there is a very abrupt, almost linear Chester Escarpment, the streams in the study area have greatly dissected the sandstone-limestone contact into ridges and valleys.
AREA HYDROLOGY
Geologic Structure

The study area is located on the western flank of the Cincinnati Arch (Figure 1), causing the sedimentary formations of this region to dip at approximately one half to two degrees northwest. U. S. Geological Survey 7.5 minute geologic quadrangles of the area, Rockfield (Rainey 1964), and South Union (Klemic 1963), show the structure of the study area and the outcrop pattern associated with the northwestward dip. The geologic structure was drawn using the base of the Big Clifty Sandstone in the northwestern part of the area and on the top of the Chattanooga Shale in the southeastern part.

Lithology

Figure 4 illustrates stratigraphic section from the St. Louis Limestone to the Big Clifty Sandstone (upper Mississippian). The Big Clifty is a tan to brown sandstone that ranges from massive to thin bedded and in areas is crossbedded. The Big Clifty becomes silty and shaley near the base and near the top, and has minor areas of limestone near the base.

The Ste. Genevieve in this area is a light gray to gray, mostly crystalline limestone that is predominantly oolitic and fossiliferous. In places oolites and fossil hash are crossbedded. In areas it is fine grained and microcrystalline (Klemic 1963; Rainey 1964; Rainey 1965; and Shawe 1963). *Platycrinites penicillus* is a distinct index fossil for the Ste. Genevieve (Figure 5). Although it has been found in the St. Louis, below the Ste. Genevieve, it does not occur in the Girkin Formation above. *Lithostroton Siphonodendron genevievensis* Easton, also called *Lithostroton harmodites*, is
FIGURE 4 Stratigraphic Section of Upper Mississippian Rock Units, South-Central Kentucky.

(Source: Palmer 1981)
General Morphology—Skeletal Morphology

Morphology of synarthrial type of articulation.

2. Platycrinites sp. L. Carib., Belg., with elliptical articular facets oriented differently on opposite sides (Ubighs, a).

4. Diagrammatic facetal view and median longitudinal section of elliptical columnar (Moore, Jeffords, & Miller, 1968).
5. Diagrammatic transverse profile of juxtaposed synarthrial articular facets (Moore, Jeffords, & Miller, 1968).
6. Quadrangular columnar with elliptical articular facets oriented differently on opposite sides (Moore, Jeffords, & Miller, 1968).

FIGURE 5 Platycrinites: Index fossil for the Ste. Genevieve formation
Source: (Moore and Teichert 1978)
a colonial coral found mostly in the Joppa member of the Ste. Genevieve (Pohl 1970).

The Girkin formation differs very little in lithology from the Ste. Genevieve, although upper units in the Girkin do become shaley. Clear Fork Creek, Black Lick Creek, and Gasper River flow on the Girkin, and Brush Creek and Lost River flow on the Ste. Genevieve.

**Statement of Hypotheses**

Sinkhole plains are characterized by subsurface drainage, therefore surface flowing streams are rare. Brush Creek is on the sinkhole plain and has a surface flowing section. Hypothesis I was formulated to test lithologic and stratigraphic conditions necessary for surface flow on the sinkhole plain.

Karst drainage systems are not noted for having topographic surface expression of their drainage basins; however, Brush Creek and Lost River have topographic valleys. Hypothesis II was formulated to test the concordance between topography and flow patterns of the sinkhole plain, and to determine if intergration of the drainage systems is occurring in the subsurface.

Hypothesis I: The surface-flowing portion of Brush Creek is floored by an impermeable perching layer that prevents it from invading the subsurface. The stream sinks at the edge of the impermeable layer where it flows onto more soluble limestones.

Hypothesis II: Integration of the Lost River, Brush Creek, and
Clear Fork Creek drainage basins is taking place as a result of alteration of their flow patterns in the subsurface. Therefore, the drainage patterns indicated on topographic maps do not correspond to actual flow conditions, once streams enter the subsurface.
CHAPTER II

REVIEW OF LITERATURE

Introduction

Karst is "a type of topography that is formed primarily over limestone, dolomite, or gypsum by dissolving (solution), and that is characterized by closed depressions or sinkholes, caves, and underground drainage" (American Geological Institute 1976). Karst usually refers to solution features in soluble rock (limestone or dolomite), although other processes such as abrasion and collapse are important in the development of karst landscapes. The term karst is derived from the Slavic word "kra" which means crag or stone, but it is also the name of a limestone in western Slovenia (Jennings 1985).

Solution Processes

Karst solution processes are complex and therefore constitute a highly controversial topic among scientists in the field of karst studies. Charles Lyell in 1883 discussed the solution capabilities of atmospheric water, and the concept was soon accepted as being responsible for the development of karst. Piper (1932) suggested that rapid circulation of deep water must occur in order for deep caverns
to form. Moore and Nicholas (1965) concluded that 0.03 percent carbon
dioxide in the atmosphere was not enough to provide water with
sufficient carbonic acid to form caverns. It was then concluded that
decaying plant material contributed the necessary carbon dioxide.
Swinnerton (1929) suggested that a large volume of low concentration
solvent flowing through the rock was enough to dissolve large volumes
of rock, and W.M. Davis (in Kaye 1957) believed that most cavern
development took place where groundwater moved very slowly. Corbel
(1957) concluded that limestones must be 60 percent pure calcium
carbonate in order for karst development to begin and 90 percent pure
in order for karst features to develop fully.

Thrailkill (1968) suggested that the effects of temperature
change, the mixing of dissimilar waters, and floods in subsurface
streams can result in the undersaturation of phreatic water and
therefore restore its ability to dissolve limestone even after the
water has been saturated with calcium carbonate. Bogli (1964)
conducted similar studies and found that the mixing of two waters
saturated with calcium carbonate can result in unsaturated water.

Collapse Processes

Another process recognized in the development of karst is
collapse. Rock falls, block slides and rock slides are prominent
processes in karst (Varnes 1958). Solution is important in
undercutting of slopes and in the removal of cave walls and roofs. As
a result these features become subject to collapse or rock fall (White
and White, 1969; Renault 1967-1968). Therefore, in order for collapse
to occur, voids must develop, and in areas of thick soil cover,
subsidence can occur over voids. In early investigations karst cavern collapse was considered to be a major process (Herak and Stringfield 1972). The development of steep-walled dolines was thought to be a result of the collapse of cavern roofs. This idea was later refuted by Weller (1927), who found collapse dolines rare and solution dolines more common. The removal of superficial deposits or thick residual soils into joints and solution pipes in the underlying limestone results in collapse dolines (Cramer 1941).

Swallow holes (swallets) which divert surface streams to the subsurface were thought to be collapse features. Thomas (1954) suggests that swallow holes occur as a result of enlargement of joints or bedding plains.

Two types of collapse features that occur on the sinkhole plain of south central Kentucky are karst windows and collapsed dolines (Cubbage 1981). A karst window forms as result of the collapsed cave roof exposing the stream below. Karst windows vary in size from a few feet (meters) to a few miles (kilometers). Davis (1930) suggested that breakdown in the Central Kentucky Karst is a result of draining of water-filled cave systems or the undercutting of walls by free-flowing streams.

Landscape Evolution

After William Morris Davis proposed his "geographic cycle of erosion" many researchers interested in karst processes proposed models relating to cycles of karst erosion. Grund (1914) suggested an evolutionary model (diagram in Jennings 1985, p. 234) consisting of the following four stages:
1) Youth - dolines develop at points favoring solution.

2) End of Youth - dolines sizes increase and they are then separated only by ridges.

3) The more favored dolines expand to engulf the smaller ones thus creating uvalas.

4) Maturity - flat floors develop in depressions and cone-shaped hills result from ridge lowering.

Cvijic's (1918; cf. Sanders 1921) cycle of erosion (diagram in Jennings 1985, p. 235) is well known and is based on Dinaric karst features. In this model the limestone is sandwiched between impervious layers and geologic structure is considered. The evolution in this model is as follows:

1) As the impervious cover is stripped away the limestone is exposed and develops a normal surface drainage system.

2) Solution enlarges joints for faster infiltration of rain and engulfment of streams so that subsurface drainage takes over.

3) Dolines form and there may also be tectonic poljes. Elaborate cave systems feed risings (springs) around the karst margins and poljes.

4) The karst is destroyed, with normal valleys reappearing as the impervious basement is exposed.

Lobeck (1928) produced another model combining fluvial processes with karst processes and used stages from youth to old age to describe karst landscape evolution (Emmons, Thiel, and Stauffer 1949). Dicken (1935) suggested a model with the first stage called doline karst, which was a landscape consisting of a abundance of dolines. The next stage, the basin karst, developed when the doline karst became choked.
with sediment causing the dolines to widen into basins. Streams and basin karst, the last stage, resulted when the dolines filled in with sediment. Dicken's model was based largely on Kentucky karsts.

Sweeting (1973) argued that there were no cycles of evolution where one stage follows another, but that factors influencing landscape evolution are too numerous to allow a specific sequence of landscapes to occur.

A more recent model of the evolution of the Central Kentucky Karst was proposed by White, Watson, Pohl, and Brucker (1970) The stages of this model are as follows:

1) Prekarst Area - high relief topography with narrow steep walled valleys. Streams have not penetrated the limestone and sinkholes do not exist.

2) Cuesta Area - a terrain with karst valleys and well developed subsurface features.

3) Sinkhole Plain - a plain with numerous sinkholes and most of the drainage is underground.

Their model demonstrates a sequence of karst development through time. The sequence of events is controlled by existence of the Big Clifty sandstone caprock and position of the Green River (base level). No significant karst development occurs while the Green River flows on the caprock, but as the caprock is breached, forming outlets for groundwater flow, conduit flow routes develop. When the caprock is removed the landscape is quickly lowered to base level and only the sinkhole plain and subsurface drainage remains. Wells (1976) conducted investigations south of Mammoth Cave and found that two different cave levels indicate evolution of the sinkhole plain was controlled by successive lowering of the regional base level.
Crawford (1979) proposed a model of surface–subsurface erosion stating that subterranean stream invasion of surface streams on the Cumberland Plateau results from faster chemical erosion of carbonates underlying the plateau sandstone caprock. His study indicated that erosion due to karst drainage was partly responsible for retreat of the Cumberland Escarpment. The investigation revealed that stream invasion occurs near the contact of the caprock and the underlying carbonates. Surface streams highly aggressive to limestone flow through the carbonates to resurgences near the base of the escarpment. The caves are enlarged by corrosion and corrosion of swallow streams, particularly during floods. The streams take a stair step flow route down the escarpment as they flow over sections of impermeable strata. A sinkhole plain follows the the retreating escarpment, forming on carbonates at the base of the escarpment.

Cavern Development

Opinions on cavern development are as plethoric as opinions on methods of landform development. Crustal movement (faulting) was accepted in early explanations of their occurrence (Jennings 1985). Ewers (1977) developed a model explaining the development of flow networks in carbonate aquifers.

Early reports by Grund (1903) suggested that the water table rose during wet periods into joints and bedding plane partings to enlarge voids. Cvijic (1893) proposed three zones of water movement in the subsurface: the vadose zone, where water moves vertically through normally dry rock or soil; the saturated zone below, where the rock remains full of water year round; and the water table between the two.
The intermediate zone between the vadose and the saturated (phreatic) zone is an area where the water table (intermediate zone) rises and falls leaving this zone dry during some periods and saturated during others. After the introduction of this theory, opinions differed as to which zone cavern development occurs (Jennings 1971).

Davis (1930) proposed that the early stages of cavern development occurred in the phreatic zone or below the water table. Applying his theory of "Cyclic Evolution", he suggested that the second stage of development occurred when the water table dropped as a result of uplifting of the landscape, and cavern enlargement occurred as a result of water moving through the vadose zone. Bretz (1942) added a third stage to the Davis Two-Cycle Theory. This third stage, the Clay Filling Cycle, occurs between the Phreatic Cycle and the Vadose Cycle as very slow moving water in the cave allowed the deposition of sediment.

Fluvial Processes

The character of a stream channel is determined primarily by the size of the bedload and the volume of water in the stream (Ritter 1978). If one of these variables changes, the erosion capabilities of the stream and the channel shape, size, and gradient may be adjusted. If the variables are changed the stream is left in a state of disequilibrium and the stream must adjust its channel in order to return to equilibrium. Different rock types produce different sediment types, therefore stream character is influenced greatly by the geology of its basin (Judson and Ritter 1964). Hack (1960) proposed the dynamic equilibrium concept stating that landforms of a
drainage basin are a result of equilibrium between the geology and the prevailing erosional processes. The equilibrium concept resulted from the observations and studies of G.K. Gilbert in the 1870s. The geographic cycle concepts of landscape evolution of William Morris Davis overshadowed Gilbert's graded river (equilibrium) concepts during this period, and as a result the dynamic equilibrium concept did not become popular until after Davis' death. Hack (1966) made comparisons of streams flowing on the clastic Cumberland Plateau with streams flowing on the limestones of the Highland Rim of south-central Tennessee and northeast Alabama. In the study he observed that streams were in a state of equilibrium with the rock types on which they flow.

Sinking Streams

Streams in karst terrain can sink in several ways; they can enter a cave either horizontally or vertically, they can sink through fissures in the bedrock, or they can sink gradually through the soil or gravel (Jennings 1985). Palmer (1976) demonstrated how the Lost River of Indiana flows as a surface stream where it is floored by unconsolidated sediment and sinks as it flows onto uncovered limestone bedrock.

Sinking streams in some cases are responsible for forming karst valleys. Blind valleys occur when all of a surface stream sinks (no water flows beyond the stream sink). Dry valleys do not have stream channels in their floors because surface flow is not large enough to form streams with the capacity to cut channels. In half-blind valleys stream flow is in the subsurface part of the time and on the surface...
only after heavy rains and after snow melt when the stream sink cannot transmit the entire discharge to the subsurface (Jennings 1985).

Structural Controls

It is widely accepted that geologic structure plays an important role in karst development. Palmer (1981) found a close correlation between the local dip and passage orientations in Mammoth Cave. He explains that cave passages formed in the vadose zone tend to develop as canyons that parallel the dip, and passages formed at or below the water table develop tubular shapes and flow along the strike. He demonstrates how the ancient stream that formed Boone Avenue in Mammoth Cave flowed in a canyon type passage down the trough of a syncline, but changed to flow along the strike of the bedding once it reached the water table. Dilmamart and Cubbage (1984) concluded that a sinking stream on the Chester Upland of south central Kentucky flowed down the dip after invading the subsurface, and drainage under the Chester Escarpment near Mammoth Cave greatly parallels the regional dip of the western limb of the Cincinnati Arch (White et al. 1970).

In limestones with little or no dip, complex drainage patterns can develop because lithologic units favorable to cavern development are flat-lying. Without a strong force of gravity pulling water down the dip, tributary streams can converge and remain within the same stratigraphic horizon (White 1977).

Ford and Ewers (1978) concluded that early stages of cavern development begins as microcaves form along joints and bedding planes, and Moore and Nicholas (1964) concluded that joints and faults must
preexist in limestone for cavern development to occur. The beginning
of karst landscape development is dependent on water infiltrating the
subsurface through joints, fractures and faults (White 1979).

Lithologic and Stratigraphic Controls

Differences in lithology have an effect on the movement of water
through limestones. The presence of less permeable and less soluble
units such as shales, cherts and sandstones can act as perching units
for cave streams. These units have the function of preventing the
vertical movement of water through limestones and causing water to
move horizontally. Aside from lithologically distinct units, the
limestone itself may contain impurities that render it less soluble
without changing its basic appearance. The presence of magnesia,
silica, and clastic materials (clays) can cause the solubility of the
limestone to be reduced. Palmer (1981), however, demonstrates that
limestone with high silt and clay contents erode more rapidly in cave
walls; but on the other hand, clay and shale layers are noted
confining layers in many aquifers (Fetter 1980). It could be that
silt and clay layers are easily removed in turbulent flowing water
(mechanical erosion), thus forming recessions in cave walls where
streams flow, but they are not solutionally eroded.

White (1976) argues that many of the conceptual models on cavern
development ignore structure and stratigraphy. Many of these models
assume a massive flat-lying limestone and as a result the models
contain inaccuracies. Crawford (1979) found that cave streams take a
stair step route down the Cumberland Plateau Escarpment of Tennessee.
The cave streams fall vertically where they breached resistant
stratigraphic layers as they flow down the escarpment.

Palmer (1981) points out that the waterfall trail in Floyd Collins' Crystal Cave has an abnormal shape because it is flowing on a resistant impure limestone unit. The passage should form as a canyon because it is flowing down the dip in the vadose zone, but the resistant unit (the Upper Aux Vases Limestone) prevents downcutting which causes the passage to widen into a tubular shape.
CHAPTER III

COLLECTION AND ANALYSIS OF DATA

Analysis of Brush Creek Surface Flow

Introduction

Observations of Brush Creek revealed the presence of a swallet (stream sink) that diverts the surface flow underground thus forming a cave stream. It was suspected that the surface-flowing section was perched on a resistant, impermeable layer (shale or chert) and the stream sink was located at the edge of the perching layer where the stream flowed onto more soluble limestones.

The Lost River Chert acts as a perching layer for surface stream flow on the sinkhole plain near Mammoth Cave (Quinlan and Ewers 1981). The streams invade the subsurface as they flow off the chert layer and onto the more soluble limestones.

Lithology

In order to test for lithologic variation that might be responsible for such a perching layer, it was necessary to collect rock samples. Rock samples of the units exposed in the Brush Creek stream channel were collected from the area between U.S. Highway 68
and State Highway 1083 (Figure 6). Sample 1 was taken at York Spring #2, which is the first large cave-stream tributary. At the point where this tributary enters Brush Creek, the flow of the creek increases sufficiently to scour the channel down to the bedrock. Samples 1 through 7 were taken from the surface flowing portion of the creek south of Warner Swallet. Samples 8 through 12 were taken from the dry stream channel north of Warner Swallet. No samples were collected south of U.S. Highway 68 (the head waters) because of sediment covering bedrock exposures. The samples were then described using Folk's Classification of limestones (Folk 1959). All 12 samples exhibited similar lithologies in hand specimen; thus, there was no evidence of a perching layer. The samples next were analyzed using X-ray diffraction to determine whether compositional differences existed that were not detectable in the hand samples.

X-Ray Diffraction

Samples 1 through 12 were tested on an EG&G Ortec System 5000 X-Ray diffractometer to determine changes in the rock chemistry with respect to distance downstream. The reliability of the instrument was tested first by analyzing samples of mineral and rock types that might be encountered in the Brush Creek rock samples. Test samples were crushed to a powder and loaded into a drilled hole in an aluminum mount block. The samples were then analyzed for three minutes each. Tables I through IV demonstrate the chemical constituents for the known samples of calcite, dolomite, chert and shale. The instrument cannot detect elements lighter than sodium, thus carbon and oxygen were not detected. However, calcium, silicon, magnesium, aluminum,
Bedrock Sample Locations
Brush Creek Channel Floor

Steenbergen Spr.
Clow Spr.
Hwy 1083
Warner Swallet
York Spr.
Rockfield

McCurry Cave
Dickerson Cave

FIGURE 6
0 1 mile
and other cations were detectable. The calcite was found to contain 100 percent calcium, the dolomite contained both calcium and magnesium, and chert contained 100 percent silicon. The presence of potassium, aluminum and silicon indicated that the shale sample contained significant amounts of clay. The instrument provided two quantitative values for the major cations found in each sample. The weight percent is the actual percentage by weight of each element while the atomic percent is the percentage of each type of atom in the sample.

Each sample collected in the field was a variety of limestone, thus it was assumed that each cation (element) detected represented a mineral associated with limestone. Calcium represented calcium carbonate (calcite), magnesium represented dolomite, and silicon represented either chert or quartz. The elemental constituents were grouped into soluble and less soluble categories with calcium representing the soluble components and magnesium and silicon representing the less soluble components.

A plot of the weight percentages of less soluble constituents (magnesium plus silicon) versus soluble constituents (calcium) revealed a considerably higher concentration of the insoluble constituents existing in the limestones just before the point where the stream sinks (sample 7, Figure 7).
X-Ray Analysis of Bedrock Samples
Brush Creek Channel Floor

Weight % of calcium
(representing soluble mineral)

Weight % of magnesium and silicon
(representing less soluble minerals)

Sample Number
TABLE I
MAJOR CATIONS OF CALCITE CRYSTAL

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

TABLE II
MAJOR CATIONS OF DOLOMITE CRYSTAL

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>34.25</td>
<td>46.19</td>
</tr>
<tr>
<td>Ca</td>
<td>65.75</td>
<td>53.81</td>
</tr>
</tbody>
</table>

TABLE III
MAJOR CATIONS OF LOST RIVER CHERT

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

TABLE IV
MAJOR CATIONS OF SHALE (LOCATION MUHLENBERG CO. KY)

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>24.03</td>
<td>27.99</td>
</tr>
<tr>
<td>Si</td>
<td>49.63</td>
<td>55.53</td>
</tr>
<tr>
<td>K</td>
<td>6.87</td>
<td>5.52</td>
</tr>
<tr>
<td>Fe</td>
<td>19.47</td>
<td>10.95</td>
</tr>
</tbody>
</table>
Corbel (1957) believes that in order for karst development to begin limestones must be 60 percent pure calcium carbonate; for full karst development they must be 90 percent pure. Thus, karst may not fully develop at sample points 7 and 8 because the limestone is less than 90 percent pure calcium carbonate. Samples 7 and 8 have calcium concentrations less than 90 percent, samples 5, 10, and 11 have calcium concentrations between 90 and 100 percent, and samples 1, 2, 3, 6, 9 and 12 have calcium concentrations of 100 percent (100 percent calcium carbonate).

The stream actually sinks between sample points 7 and 8, but it should flow over point 8 and sink near point 9 where there is a greater chance for karst development (according to Corbel 1957). The 20 percent insolubles at point 7 apparently is enough to retard karst development, but the 12 percent at sample eight appears to allow such development and permits the creation of conduits in the subsurface.

Stratigraphy

Lithostrotion (Siphondendron) genevievensis was located on the east side of Brush Creek in exposures north of Highway 68. Existence of this fossil indicates that the rocks belong to the Joppa Member of the Ste. Genevieve Limestone (Pohl 1970). Geologic structure maps indicate that the creek is flowing up the geologic section, therefore in the study area it crosses younger rock units above the Joppa Member (Figure 4). The upper Aux Vases exists above the Joppa and is possibly encountered by Brush Creek as it flows up section. Palmer (1981) found that in places in the Mammoth Cave system the upper Aux Vases acts as a perching or confining layer.
The location of sample 7 is downstream from the occurrence of Lithostracion genevievensis and is stratigraphically higher than the Joppa Member. Therefore, sample 7, with its high concentrations of magnesium and silicon, may be the upper part of the Aux Vases Member of the Ste. Genevieve Limestone. The presence of chert in the stream bedload downstream of sample 7 also suggests the presence of a resistant layer at sample point 7.

The resistant upper Aux Vases layer exposed in Brush Creek appears to act as a spillover layer by controlling the rate of downcutting (Figure 8). A spillover layer is a resistant rock unit exposed in a stream valley that acts as a temporary local base level control (Crawford 1979). The spillover layer crops out in a small area and controls the stream level in the upstream direction. The stream is able to downcut only as fast as it can erode the less soluble spillover layer. Once the stream flows over the spillover layer it is able to downcut its channel into the limestones and invade the subsurface to become a cave stream.

Other than the upper Aux Vases, the Ste. Genevieve in this area has no continuous perching units in its section, yet there are numerous cases where surface streams exist. If the Ste. Genevieve has no major units acting to perch streams then minor units must control downcutting and permit short sections of surface flow on the sinkhole plain. Without controls to slow the rate of entrenchment, entire streams, from their head waters to their confluence, would lower to base level. If the Ste. Genevieve were a homogeneous (100 percent pure) limestone without minor resistant units to control downcutting its entire channel would lower to near the base level of the major
Brush Creek Surface and Subsurface Flow
Controlled by Upper Aux Vases Spillover Layer
area streams.

Conclusion

No impermeable perching layer was found in the bedrock floor of the surface channel of Brush Creek, but the outcrop of a resistant spillover layer indicated that minor resistant units can act as controls to prevent downcutting and maintain, in a few cases, surface flow on the sinkhole plain. The evidence collected does not support Hypothesis I.
Subsurface Flow

Introduction

Investigation of groundwater flow in the area of Brush Creek and Clear Fork Creek was conducted using dye tracing techniques. The directions of cave stream flow provided further information concerning behavior of groundwater flow as the karst landscape evolves. Since karst landscapes are characterized by underground drainage systems, understanding the nature of groundwater flow is important for understanding the development of the sinkhole plain. Information obtained from studying the groundwater flow in the vicinity of Brush Creek and Clear Fork Creek was related to the development of the other stream systems in the study area.

Dye Tracing

Dye tracing is often used to determine flow routes of cave streams that are inaccessible to human exploration. A variety of materials has been used to trace water movement. Painted ducks, bales of hay, wheat chaff, corn cobs, and geese have been used as tracers in the past. Examples of some of the materials used presently are soluble chemicals such as salt and phosphates, radioactive materials, fluorescent dyes, and minute biological materials such as Lycopodium spores, and bacteriophage. Fluorescent dyes are the most desirable because they are easy to use and cause less harm to water quality (Aley and Fletcher, 1976).
Dye tracing with fluorescent dyes involves injecting a predetermined volume of dye into the system in question and recovering it at the points where the water resurges (springs). There are several methods of recovering dyes. Rhodamine can be absorbed onto activated charcoal, but best results are achieved by recovering water samples that can be tested on a fluorometer. Fluorescein dye works well both with activated charcoal collectors and with fluorometrically tested water samples. Optical brighteners, also used in detergents to brighten fabrics, can be absorbed onto surgical cotton and detected by viewing the cotton under ultraviolet light.

The traces in this study were conducted using fluorescein dye and activated charcoal dye collectors. On each trace after sufficient time had passed for the dye to flow through the system, the collectors were recovered and treated with a solution of alcohol and potassium hydroxide to elute the dye to the surface of the charcoal. The dye traces were conducted by the author (Able 1984; 1985) under the direction of Dr. Nicholas Crawford and by students under the direction of both Dr. Crawford and the author (Lopez and Hill 1985; Frauenfelder and Smith 1985; and Lassaline and Butoryak 1986).

Dye tracing cave streams is not always an easy task. Before dye can be injected into a system all possible points of resurgence must be located and dye collectors must be placed at each. Several unsuccessful dye traces resulted in this study due to failure in locating the proper point of dye resurgence. Other problems can occur when dye collectors are taken by humans or animals. Automatic water samplers can be used to collect dye samples, but they may malfunction causing the loss of samples at the time the dye is
emerging from the spring.

A dye trace from Perkins Swallet indicated that Cloud Spring is beginning to pirate water from the Lost River system. The dye trace was begun near an obvious indentation in the Lost River Basin boundary (Figure 9) indicating that cloud spring is advancing its drainage basin headward into the Lost River basin, changing the drainage divide, and capturing water that used to flow to the Lost River. It appears therefore that the area drainage systems are becoming integrated through underground streams.

Other evidence of stream piracy was discovered by the author during attempts to dye trace the stream in Dickerson Cave at the upper end of Brush Creek Valley (Figure 10). It was expected that the dye would remain in the Brush Creek topographic valley because prior traces in this area had remained in their respective surface drainage basins. In other words, subsurface drainage divides correspond with surface drainage divides. Accordingly, it was believed that the injected dye would be detected downstream at springs within the Brush Creek valley. Loss of the dye led to the conclusion that the cave streams were flowing out of the Brush Creek valley and into some adjacent valley. A later dye trace from Dickerson Cave (Dickerson Cave Stream) revealed the cave stream flowed northwestward to Finney Spring in the Clear Fork Creek valley.

The surface drainage divide between Brush Creek and Clear Fork Creek (Figure 10) is drawn along the topographic high separating the two valleys. Surface drainage east of the boundary flows into the Brush Creek basin. West of the boundary, surface drainage flows into the Clear Fork Creek basin. Groundwater flow in each basin is roughly
Piracy of a Portion of Lost River Drainage Basin by Cloud Spring

FIGURE 9
the same as that on the surface — except for the Dickerson Cave Stream, where the water flows out of the Brush Creek basin and into the Clear Fork Creek basin.

In every case except at Dickerson Cave, dye traces have remained within the same topographic valley where the dye was injected. It is evident that Dickerson Cave is part of the topographic valley of Brush Creek, but the dye trace clearly shows that the groundwater in the upper end of Brush Creek leaves the valley and flows to the Clear Fork Creek valley. Diversion out of this valley occurs only near the headwaters of the Brush Creek system. To the north (downstream), no dye traces performed to date have crossed the surface drainage divide.

Speleology

Cave mapping provided information concerning the character of the streams that formed the caves and flow routes of area drainage in the past. Tape and compass surveys of Indian Cave and Drab Cave were conducted by the author. Straight line distances were measured between marked points in the cave and the azimuth of the line was measured. Passage dimensions and features along the measured line were noted on a sketch during the survey. The sketch and measurements were then used to produce a map of the cave. Another map of Indian Cave was provided by the Western Kentucky Speleological Survey (Dyas 1984).

Figure 11 is Drab Cave, located at the southern end of Finney Sinkhole (Figure 10). Drab Cave has a perennial stream flowing northward toward its entrance. It makes an abrupt northwestward turn and sumps under the west wall about 50 feet (15 meters) from the
DRAB CAVE

Surveyed by
Tony Able and Tom Feeney

FIGURE 11
entrance. Dye was injected at this sump and recovered at Finney Spring, approximately one mile (1.6 kilometers) to the northwest. The 50 feet (15 meters) of passage between the sump and the entrance is dry and is of the same size and shape as the rest of the cave. The similar size and shape indicates that the stream once passed through this now-dry section.

At the northern end of Finney Sinkhole is Indian Cave. Indian Cave is a dry passage containing considerable ceiling breakdown for the first 200 feet (61 meters) (Figure 12). Approximately 9,000 feet (2743 meters) (Figure 13) of passage has been surveyed (Dyas 1984). Indian Cave trends for almost 3,000 feet (914 meters) at 30 degrees and the mapped portion of Drab Cave trends 12 degrees for approximately 400 feet (122 meters). A dye trace from Indian Cave proved that the stream near the entrance flows to Clear Fork Spring (Figure 9).

Sinkholes and small valleys are visible on the surface along the trace of these two caves. The general trend of Drab Cave, Finney Sinkhole and Indian Cave forms a topographic lineament suggesting that some common factor has influenced the formation of these features. It is logical to assume that Indian Cave and Drab Cave were previously connected by a single cave which occupied the position of Finney Sink. The cave roof later collapsed to form the present sink with caves at either end. Other evidence supporting the "one cave" hypothesis is that the streams in both caves have a very similar northward trend (Figures 11 and 13). Their trends are similar up to the point where the Drab Cave stream is diverted to the northwest to Finney Spring.

The floor of Finney Sink consists of breakdown blocks from the
INDIAN CAVE

Low and Wet
Dye Injection Point
Flow Stone

To
NE Section of Cave

Large Breakdown Block

Dome Room

Entrance

0  50
feet

Surveyed by
Tony Able and Cindy Walton

FIGURE 12
FIGURE 13

INDIAN CAVE
Warren Co., Ky.

2.7 km. surveyed, Nov. 1980 - Nov. 1982, by Saunders, Mulbreakt, P. & S. Forsythe, Tilkens, Shifflett & Dyas

© 1982, Ky. Speleo. Survey
assumed collapse of a cave roof. These blocks also occur in the entrance of Indian Cave, which indicates further that there was a cave in the position of Finney Sink and the roof collapse is progressing into Indian Cave. When the collapse occurred, it blocked the stream that flowed from Drab Cave to Indian Cave, causing it to make a diversion around the breakdown. The new flow route took the water across the Drab Cave-Finney Spring subsurface drainage divide. As the water crossed this divide, it formed its own cave which now connects the two basins and diverts all the water from Drab Cave to Finney Spring instead of Clear Fork Spring (Figure 10).

A dye trace completed during high discharge indicated that the stream in Drab Cave flows to both Finney and Clear Fork Springs. Dye was also detected in springs and karst windows in Finney Sinkhole, between Drab Cave and Indian Cave. The dye recovered in Indian Cave indicated that during high flow conditions some water returns more or less to its original route across Finney Sinkhole, into Indian Cave and on to Clear Fork Spring (Lassaline and Butoryak 1986). A duplication of the Dickerson Cave Stream dye trace revealed that the cave stream flows through Drab Cave before emerging at Finney Spring (Figure 10). The dye trace indicates that the head waters of Brush Creek were first pirated by Clear Fork Spring, but later Finney Spring pirated the stream away from Clear Fork Spring.

Geologic Structure

Strike orientations of area jointing were measured using a Brunton Compass. Joints exist both as solutionally enlarged cracks and as calcite-filled veins. The joint orientations were used to
construct a rose diagram to determine if the area jointing pattern is similar to the area drainage pattern.

A lack of suitable outcrops made dip measurements impossible. Although many limestone exposures exist in the area they have weathered severely, leaving few surfaces for accurate dip measurements. Since exposures were not continuous, leveling of bedding planes over distance was not possible.

Although detail is lacking, geologic structure is shown on the U.S.G.S. geologic quadrangles of the area (South Union and Rockfield). Structure contours on these maps indicate that the dip in the area is approximately 0.5 degree with an azimuth of approximately 315 degrees.

To compare the influence of geologic structure on subsurface flow patterns in this area, a rose diagram (Figure 14) was prepared to show the orientations of the completed dye traces in the study area. To produce the rose diagram, a circle was divided into segments of 20 degrees each. Each dye trace was then placed in one of these segments according to its azimuth. Each segment was then given a value according to the sum of the lengths of the traces in that segment.

The diagram indicates that the major groundwater flow direction is very close to the regional direction of dip. Other flow directions are at orientations between the northeast strike and the dip. The influence of dip appears to be the controlling factor on groundwater movement in the area, but the dip gradient is greater than the gradient of the cave streams, therefore the streams are flowing up the stratigraphic section, across rock layers, in order to reach their resurgence points (Figure 15). Wells (1976) found the same to be true of the sinkhole plain in the Graham Spring basin north of Bowling
ROSE DIAGRAM OF DYE TRACE ORIENTATIONS
BRUSH CREEK - CLEAR FORK CREEK
WARREN CO. KY

Prepared from orientations and length (miles) of traces.

FIGURE 14
FIGURE 15  Cave stream flowing up the geologic section.  Stream gradient less than dip gradient.

FIGURE 16  Cave stream flowing along bedding plane.  Stream gradient equal to dip gradient.

FIGURE 17  Cave stream flowing down the geologic section.  Stream gradient greater than dip gradient.
Jointing Along the Traverse of the Pirated Brush Creek Stream
PROMINENT JOINT ORIENTATIONS

Brush Creek Bedrock Channel Floor

FIGURE 19
Green, Kentucky; the direction of dip is approximately the same as the groundwater flow paths, but the dip is greater than the stream gradient, therefore, flow direction is not controlled by the amount of dip. If the dip of the strata was equal to or greater than the gradients of the cave streams, one could conclude that the dip is influencing groundwater movement (Figures 16 and 17).

Since the piracy of Brush Creek could not be explained by the structural dip, jointing was considered as providing a possible avenue for the groundwater to flow out of the Brush Creek valley. Rose diagrams (Figures 18 and 19) were produced from joints measured on outcrops along the traverse of Dickerson Cave Stream dye trace and on outcrops in the Brush Creek channel floor. Comparing the dye trace rose diagrams to the rose diagram of the area jointing indicates that jointing has little influence on the major flow direction of the cave streams. At this time an explanation for the mechanism that caused the Dickerson Cave Stream (Brush Creek) piracy is not apparent, but possible explanations have been considered. At the time of the piracy the hydraulic gradient (water table) between the head waters of Brush Creek and Clear Fork Creek may have been greater than the hydraulic gradient of Brush Creek. The groundwater in this area flowed towards Clear Fork Creek, developing conduits large enough to pirate all of the flow from the Brush Creek head waters. Faulting is another possible explanation for the pirated waters. Although no faults have been identified in the immediate area, there are faults identified on adjacent 7.5 minute geologic quadrangles. An undetected fault may have provided an avenue for the piracy.
Conclusion

Dye traces proved that intergradation is taking place between the drainage basins of Lost River, Brush Creek, and Clear Fork Creek. As each system alters its drainage pattern through stream piracy and stream diversion in the subsurface, it abandons the drainage boundaries that were established on the surface. Hypothesis II is accepted through supportive evidence.
CHAPTER IV

PRESENTATION OF MODEL

Introduction

Studies of surface streams and cave streams in the Brush Creek and Clear Fork Creek drainage provided information concerning behavior of groundwater flow in a developing karst landscape. Since karst landscapes are characterized by underground drainage, understanding groundwater flow was important for understanding the development of the sinkhole plain. Information obtained from studying the groundwater of Brush Creek and Clear Fork Creek was related to the development of the other stream systems in the study area.

Within the study area there is a landscape transition as one moves from the base of the escarpment. Close to the escarpment little karst development is visible, but farther away sinkholes and underground drainage are abundant. Limestone lithologies are similar throughout the entire study area, indicating that lithologic variation between the Girkin and Ste. Genevieve formations does not explain the observed transition. This chapter uses information obtained from testing the two hypotheses to explain the transition in the landscape along with the transition in the degree of karstification of the five
area streams as they evolve to become subsurface streams.

Review of Literature

Limestone primarily weathers chemically instead of mechanically, thus there is less input of clastic sediment into streams that flow on limestone terrains than into those flowing on less soluble terrain. Low volumes of suspended and bedload sediments allow these streams considerable downcutting ability. However, sediment may be contributed to the stream channel from nearby clastic rock units, interbedded clastic layers in the limestone, or impurities in the limestone itself. If present in sufficient quantities, the sediment lines the stream bed while perching the stream on sediment and insulating the limestone from the aggressive water of the stream (White and White 1968).

This idea was purposed for cave streams, but other literature suggests that clastic sediments are influential in the perching of surface streams. Palmer (1976) maintains that the Lost River of Indiana flows on the surface where it is floored by clastic sediments, but invades the subsurface as it flows onto uncovered limestone bedrock.

Evidence in support of the surface-to-subsurface flow transition of the study area is discussed by Dickens (1935). He observed that systems like Brush Creek and Lost River that still have the outline of their former surface systems must have developed karst drainage recently. Karst drainage basins are not noted for having topographic drainage basins; therefore, if surface streams have only recently invaded the subsurface, the remnant topographic drainage basin may
still exist.

Data Collection

To understand the development of karst drainage in the study area, features and characteristics of each of the five streams were noted through field investigations along with observations from geologic and topographic maps. Data compiled in the investigations consisted of 1) degree of karstification (stream sinks, sinkholes and springs), 2) type of stream sediment load, 3) drainage divides, 4) drainage basin relief and, 5) stream gradients. These allowed each stream to be categorized with respect to its karst development and position relative to the retreating escarpment.

Stream bedload observations were made for each of the five area streams in order to determine the general size and caliber of the sediment in the channel floor. Topographic and geologic maps were used to determine the relative rate and the source of clastic materials entering each system. Drainage basins with high relief and steep gradient tributaries were considered to have rapid erosion rates, therefore larger volumes of washed-in sediment than low relief basins. Basins with sandstone out crops were considered to have a large source of sand-sized sediment contributed to the stream. Steep-sloping limestone valley walls were considered to erode rapidly contributing clastic sediment from interbedded cherts, silts, and clays.

Stream Evolution

The streams farthest away from the sandstone caprock have more
karst development than those closest to it. The most distant stream, the Lost River, has evolved almost totally into a subsurface stream, while the Gasper River, closest to the caprock, has very little karst development. A steady progression of karst development is observed for each stream to the east of the escarpment. The following streams illustrate the progression with the first being the least karstified and the last being the most karstified: Gasper River, Black Lick Creek, Clear Fork Creek, Brush Creek and Lost River (Figure 3).

Gasper River originates and flows on the Girkin Limestone exposed in a steep valley of the dissected Chester Escarpment. It has very few karst features other than small springs originating in limestone exposures in the valley walls. It flows as a surface stream for its full extent and merges with Brush Creek and Clear Fork Creek before flowing into the Barren River (Figure 3).

Black Lick Creek, the stream immediately east of the Gasper, is downcutting its channel into the underlying limestones and some karst features are evident. Black Lick begins as a large karst spring at Auburn, Kentucky. It sinks and resurges several times before becoming totally a surface stream. Other than the spring at its source, there are no large karst springs feeding the system, and any additional water entering the creek is supplied by surface tributary streams and a few minor springs. The creek has downcut its channel leaving behind steep channel walls of alluvium.

The next stream to the east, Clear Fork Creek, has more karst hydrologic development than Black Lick Creek. Like Black Lick, Clear Fork also originates as a large karst spring (at Shakertown, Kentucky on U.S. Highway 68) but has two large springs, Finney Spring and Clear
Fork Spring, feeding it downstream. Instead of surface tributaries, this system is fed by cave stream tributaries. The stream also has steep alluvium channel walls, and in places a limestone bedrock floor, indicating that it is downcutting its channel.

The next stream to the east, Brush Creek, displays more karst features than Clear Fork Creek. It originates as a seep, but is fed in many places by large karst springs. The upper (southern) portion of Brush Creek Valley is a dry valley with cave streams that are accessible at two locations. Other evidence of karst development in the Brush Creek system is the fact that during low flow conditions the entire creek sinks to become a cave stream at Warner Swallet (Figure 6) leaving an half-blind valley below the swallet. The stream sink, the half-blind valley, the dry valley, the steep channel walls, and a limestone bedrock floor indicate that this system is in the process of downcutting and is in an advanced stage of karst development.

Lost River, the next system to the east, demonstrates the most advanced karst development of the hydrologic systems in the area. It is characterized by large cave passages, springs, karst windows and sinkholes. Of the entire drainage basin of the Lost River, less than one percent of the streams flow on the surface. This system has almost totally invaded the subsurface.

Escarpe Influence

Although the area streams no longer flow on the sandstone caprock they are still under its influence. The Gasper River is bordered on both sides by the caprock and Black Lick Creek is bordered on one side by the caprock. The influence of the caprock and the escarpment is
manifest in the sediments they contribute to the streams. Although Gasper River has downcut to the Girkin Limestone it cannot invade the subsurface because of large volumes of incoming sediment from the escarpment and caprock.

The sediment, in the form of sand from the caprock and chert cobbles from the limestone of the escarpment, prevents the Gasper from invading the subsurface in two ways. First, the stream uses most of its energy to transport sediment, therefore it has little potential for downcutting into the limestones. Second, the sediment acts as insulation to prevent most the chemically aggressive stream water from coming in contact with the soluble limestones. This idea is derived from White and White (1968). They suggested that sediments can insulate the floors of cave streams, and in this study their idea is used to support sediment insulation of surface streams. Field investigations revealed that the Gasper River is flowing on coarse alluvium. The valley walls of the Gasper are steep, with 150 feet (46 meters) of relief, allowing rapid sediment input due to erosion.

The Black Lick Creek system comes to the surface as it encounters the influence of the escarpment. The southern part of the system flows as a cave stream under the sinkhole plain and resurges in the city of Auburn, Kentucky. It is in the resurgence area that the relief of the landscape increases because of the presence of escarpment remnants. The stream valley has 150 feet of relief, but the walls are not as steep as those of the Gasper River valley. Only downstream and on the crest of the western side of the valley does the sandstone caprock occur. Residual sediment from the escarpment is still abundant and has the same perch ing effect as it does on the
Gasper. Large cobbles and sand line the channel floor and only short sections flow over limestone bedrock.

Clear Fork Creek is even further removed from the escarpment, but it still must contend with residual sediment. The creek has entrenched its channel in the alluvium, but the channel floor is still lined with cobbles and sand. Remnants of the escarpment create a topography with 150 feet of relief in some parts of the valley, but few of the outliers are still capped with sandstone. The alluvium of the valley floor and the sediment washing in from the outliers are sufficient to perch the stream and prevent it from invading the subsurface.

Brush Creek displays advanced karst development in that its headwaters have been pirated to Clear Fork Creek and the surface portion of Brush Creek invades the subsurface at Warner Swallet. The valley relief is gentle, therefore the rate that sediment can be washed into Brush Creek is considerably less than the valleys to the west with steep valley walls. Only two, small, sandstone capped outliers exist in the valley; thus, the source of clastic sediment is low. Without a large sediment load the stream is able to downcut and invade the subsurface.

The stream farthest from the escarpment is the Lost River. The highly advanced stage of karst development is evident in the extensive subsurface drainage in this system. The relief of the Lost River Drainage Basin is less than that of the other valleys and any former exposures of the sandstone caprock have been completely eroded away. As a result the stream expends little of its energy in the transport
of sediment and is therefore capable of downcutting and invading the subsurface.

Subsurface Flow Alteration

As the area surface streams evolve into subsurface streams their flow patterns will be altered. The detailed investigation of the Brush Creek and Clear Fork systems provided information relating to the type of changes that will take place. The dye trace of Dickerson Cave Stream revealed that, surface drainage divides are sometimes ignored by karst drainage systems. The trace from Warner Swallet to Steenbergen Spring demonstrated that Brush Creek abandoned its surface route to adopt a shorter subsurface cutoff route, and the trace from Perkins Swallet indicates that Cloud Spring is beginning to pirate water from the Lost River System. As the escarpment retreats each of the area streams will alter its drainage in the subsurface; stream bends and meanders will be left dry because of cave stream cutoffs and piracy across drainage divides will result in integration of adjacent drainage basins.

Although Brush Creek maintains a surface flowing section it is not controlled by sediment load as is Gasper River, Black Lick Creek, and Clear Fork Creek. Brush Creek does not contend with a sediment control, but rather a resistant stratigraphic spillover layer. Although they are different types of controls, both the spillover layer and the escarpment sediment prevent downcutting and subsequent subterranean stream invasion. The sediment is a major factor in perching large sections of streams, but the spillover layer of Brush Creek controls only a short section of stream. When the sinkhole
plain covers the area in the future, short sections of surface flow may exist due to the presence of minor spillover layers and minor perching layers, but the dominant drainage will take place in the subsurface.

Model of Retreating Escarpment and Sinkhole Plain Development

Development of the study area landscape is presented in the form of a model (Figure 20) showing the past (frame A) when the Big Clifty Sandstone caprock covered the entire area, and all five streams flowed on the surface. The present situation is shown in frame B. The caprock has retreated and an escarpment has formed, the streams have all been lowered onto limestones, and karst drainage has developed farther away from the escarpment. The Lost River has become a subsurface system and Brush Creek is transitional between surface and subsurface flow. Frame C represents the future when the escarpment retreats out of the area, the streams all invade the subsurface, and the sinkhole plain covers the entire area.

The model (Figure 20) demonstrates the evolution of the study area from a caprock covered area with surface drainage to sinkhole plain with underground drainage. In the future as the Chester Escarpment retreats further to the northwest, removing the sediment source, the five area streams will become cave streams. The streams that now flow totally on the surface will invade the subsurface and develop underground flow routes. When the escarpment has retreated far to the northwest the Gasper, as well as the other streams, will develop into highly advanced karst drainage systems similar to the present Lost River System. The Chester Upland surrounding the Gasper
River will evolve into a sinkhole plain with underground drainage.

Since the model appears to apply to the study area it may apply in other areas where streams flow into the Chester Escarpment. Rivers to the west of the Gasper, Town Branch and Mud River near Russellville, Kentucky, come to the surface as springs as they approach the escarpment and probably do so because of the influence of the increased sediment load coming from the escarpment and sandstone caprock.

A model showing development of the Mammoth Cave area (White et al. 1970) demonstrates that downcutting of the Green River in back of the escarpment causes drainage through cave streams flowing under the caprock plateau instead of surface streams dissecting it as in this study area. Similarity in the two models exists in, the first stage where there is a sandstone covered area with surface drainage, and the final stage where there is a sinkhole plain resulting from exposure of the limestones after removal of the Big Clifty Sandstone Caprock. The intermediate stage in the two models is different in that Mammoth Cave karst drainage is fully developed and shows no transitional stages of development from surface drainage to subsurface drainage. Base level in the Mammoth Cave area influences the drainage to flow under the escarpment, but base level in this study area influences the drainage to flow parallel to the escarpment resulting in different karst flow development.
The five streams in the study area become more karstic with increasing distance away from the Chester Escarpment. Clastic sediments from the escarpment act as a control on downcutting, causing the streams closest to it to flow on the surface. Sediments allow streams flowing on limestones to remain as surface streams in two ways. First, they create a perching layer on which the stream can flow, and second, they act as insulation and prevent the chemically aggressive waters of the stream from coming in contact with the soluble limestone. The Lost River receives no sediment from the escarpment and has developed an advanced karst drainage system. The Gasper River recieves large volumes of sediment from the escarpment and displays little karst development. The streams between Gasper River and Lost River display more karst development with distance from the escarpment.

Investigation of the surface and subsurface flow of the five streams in the area provided information concerning the processes involved in the development of the sinkhole plain as the drainage alters from surface to subsurface. As the streams invade the subsurface they are controlled less by the topography and in some cases alter alter flow routes and disobey surface drainage divides.
Dye traces near the headwaters of Brush Creek proved that the cave stream in this area flows out of the Brush Creek Valley (crossing under the drainage divide) and into the adjacent Clear Fork Creek Valley. Dye traces also proved that the stream in Drab Cave which once flowed to Clear Fork Spring was diverted and now flows to Finney Spring. Another case of subsurface flow alteration is evident as dye tracing demonstrated that Cloud Spring is pirating water from the western boundary of the Lost River Drainage Basin.

Also discovered in the investigation were minor resistant rock units which play a role in the rate of downcutting of streams on the sinkhole plain. The surface and subsurface sections of Brush Creek were found to be controlled by a resistant spillover layer (the Upper Aux Vases) that determines the rate that the stream can downcut its channel. The surface portion of the creek is prevented by the spillover layer from invading the subsurface to become a cave stream; the stream cannot flow underground because it cannot flow through the resistant layer in order to reach its outlet. The stream therefore remains on the surface until it flows over the spillover layer and is then able to invade the subsurface.

This investigation revealed that the evolutionary nature of karst development in the area is related to three main factors:

1) Distance from the escarpment and caprock supplying clastic sediment to the streams.

2) Presence of lithologically resistant units, resulting in spillover layers and perching layers.

3) Flow pattern alterations as streams encounter geologic controlling factors in the subsurface that are different from those encountered on
the surface.
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