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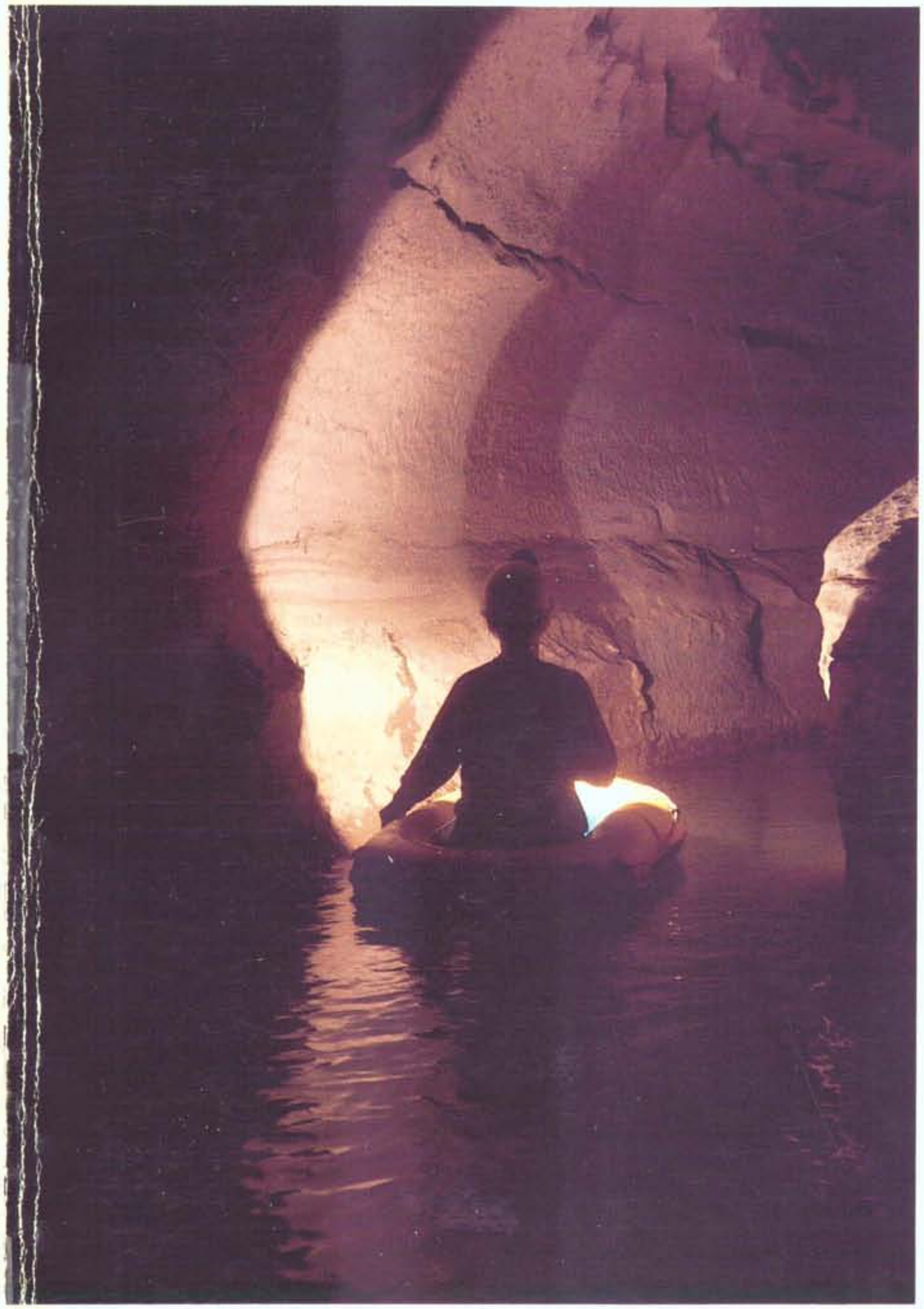
KENTUCKY GEOLOGICAL SURVEY
UNIVERSITY OF KENTUCKY, LEXINGTON
Donald C. Haney, State Geologist and Director



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SPECIAL PUBLICATION 12
Series XI, 1985

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CAVES AND KARST OF KENTUCKY

Percy H. Dougherty, Editor

Published in cooperation with the National Speleological Society

COVER PHOTOGRAPH

Caver rafting in the Martin's Creek section of Sloans Valley Cave. Pulaski County, Kentucky. (Photo by K. L. Day.)

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PREFACE

Members of the National Speleological Society are to be commended for the preparation of this publication on the caves and related karst features of Kentucky. Percy H. Dougherty, who was responsible for initiating the project, doing technical editing of the manuscripts, and furnishing typescript which was used as printer's copy, deserves special recognition.

The role of the Kentucky Geological Survey was to do minor copy editing, prepare the layout, paste up camera-ready copy, and make arrangements for getting the manuscript printed. In order to meet the printing deadline, it was necessary to utilize computer printout, prepared by the National Speleological Society, as typescript for the publication. Therefore, the publication does not conform to the usual style and editorial standards of the Kentucky Geological Survey.

It is felt that this publication will satisfy a widespread need for up-to-date information about caves and karst geology in Kentucky. The diverse range of topics covered should be of interest to a wide audience, including both scientists and laymen.

Donald W. Hutcheson
Kentucky Geological Survey
Lexington, Kentucky
June 1985

ACKNOWLEDGMENTS

Without the help of many people, this book would not have been possible. The authors of the chapters should be congratulated for working under a tight schedule and nearly impossible deadlines. In addition, the editor is deeply indebted to the following colleagues who critically reviewed sections of the book and made many excellent suggestions: Steve Justham, Ron Dilamarter, John Hoffelt, Patrick Munson, Al Scheide, George Crowthers, Horton Hobbs, III, Don Pollock, Harold Meloy, George Moore, Fred Grady, Russell Graham, Joe Saunders, George Huppert, Angelo George, and Charles Bishop.

Donna Moore, secretary of the Geography Department at Kutztown University, deserves much credit for spending many hours typing the text. The author also wishes to thank the Geography Department and administration at Kutztown University for providing the facilities and stimulating environment in which to complete this project.

The Kentucky Geological Survey also deserves special recognition. Donald C. Haney, Director and State Geologist, and Donald W. Hutcheson, Editor of the Survey, have provided guidance for this work since its inception. In addition, several staff members have provided valuable assistance in editing the text and laying out the graphics.

Finally, I am indebted to my wife, Anne, and sons, Thomas and Robert, for their continuing support and understanding. This book is dedicated to them and my father, Percy H. Dougherty, Sr., who is sadly missed since his death in April.

Percy H. Dougherty, editor

Kutztown University

June 1985

FOREWORD

CAVES AND KARST OF KENTUCKY is a special publication of the National Speleological Society and the Kentucky Geological Survey to commemorate the Annual Convention of the National Speleological Society at Kentucky State University in Frankfort, Kentucky on June 22-29, 1985. It is appropriate to hold the Convention in Kentucky since it is the home of Mammoth Cave, the world's longest cave, and the site of many other large caves and karst landforms. In addition, Kentucky has a long tradition of cave and karst research. The Convention and this book are dedicated to the explorers, mappers, and researchers who have added to our knowledge and appreciation of the State's caves.

When plans were being developed for the 1985 Convention, it was realized that there was a need for a book on the caves and karst of Kentucky. After reviewing the professional literature and examining grotto publications, a set of goals was formulated to guide the design of the book. The goals included: (1) to provide a state of the art approach to what has been done in Kentucky cave and karst reserch, written by people who are doing the work; (2) to accumulate diverse materials about Kentucky caves and karst in one publication, making available a quick and easy reference and research volume, (3) to fill a gap in the professional literature for no single statewide reference to Kentucky caves and karst exists, although the Kentucky Geological Survey has published several good case studies on caves; (4) to use the regional approach to compare and contrast various cave and karst regions in Kentucky, enabling the reader to appreciate karst processes and understand how regional differences create unique landscapes; (5) to show the status of Kentucky cave and karst research in applied areas; including paleontology, archeology, history, and biology, (6) to present extensive bibliographic material, and, (7) to discuss gaps in the literature, thereby possibly stimulating further research in Kentucky cave and karst environments.

These goals played a major role in structuring the book into three parts. Section I introduces two chapters of background information necessary to understand the caves and karst of Kentucky. Chapter 1, by Percy H. Dougherty, investigates the geology and geomorphology of the State in order to give the reader a basic background in order to understand the where and why of cave formation. The discussion takes the reader back 400 million years and traces the development of the present rock types and landforms so one can appreciate the processes that have created Kentucky's great caves. Angelo George expands upon this background by discussing where the known caves are located and analyzing the potential for further discoveries.

Section II divides the State into several cave and karst regions. Each region is discussed by an individual who has done substantial research in the area. The Blue Grass Region is written by John Thrailkill who has researched the karst hydrology of the Lexington area. The Cumberland Plateau is divided into two districts; a northern area centered on Carter Caves, presented by John Tierney; and a southern region, with its major cave area around Pulaski and Rockcastle counties described by Ralph Ewers. Although part of the same geologic and geomorphic regions, the two areas are discussed separately because of differences in their speleogenesis and their geographic separation into different drainage basins. The chapters on the Mississippian

Plateau are divided in a similar manner. Arthur Palmer presents an in-depth chapter on the Mammoth Cave area and adjacent parts of the Pennyroyal Plateau, while John Mylroie and Mike Dyas discuss the caves and karst of the Land Between the Lakes and the westward extension of the Mammoth Cave and Pennyroyal plateaus. Although similar geologically, the resulting caves differ substantially because of the factors producing them. Local hydrology and subtle differences in the geology between areas may result in a much different end product. Another chapter investigates the cave and karst processes operating on Pine Mountain. Joseph Saunders has done much caving and investigation of this unique thrust faulted region and shares his experiences in Chapter 6.

The subject matter in Section III is diverse. This section focuses upon the applied research that has taken place on the caves and karst of Kentucky. Ron Wilson looks at the early life in Kentucky by investigating the cave paleontological record. He explores how vertebrate bones got into caves, what the presence of the bones indicates, what animal species once lived in Kentucky, and concludes with a general overview of the paleontological work done in the State. Patty Jo Watson presents material on the early human population of the State, concentrating on the archeology of the Mammoth Cave Region, with reference to other parts of the State. She explores why primitive people were interested in the caves, shows evidence of their exploration in Mammoth Cave, and discusses how cavers can help archeological research. Stanley Sides discusses the saltpeter industry of Kentucky. Although concentrating on the Mammoth Cave area, the paper also discusses the impact of the saltpeter industry on the development of the United States and the early economy of Kentucky. The final selection, by Thomas Barr, shows the status of research in cave biology. The fragile ecosystem is explored and the reader is made aware of the unusual organisms inhabiting Kentucky caves today.

Caves and karst features form unique environments which are easily disturbed. Cave formations once broken and removed from the cave may never regenerate, resulting in the loss of a beautiful creation of nature for future generations. Such destruction may also eliminate research objects essential in unravelling the mysteries of cave processes. In addition, undue traffic in caves may have a negative effect upon bat colonies, endangering a valuable animal which does more good than harm through its eradication of harmful insects. Other cave organisms may also be seriously reduced or wiped out by careless action. Chemical spills, sewage, over-fertilization of farm fields, and many other human activities may have a severe impact on the well-being of caves and karst, so we must be extra careful and protect these areas.

The National Speleological Society is the leading organization engaged in the conservation of caves and karst areas. Their slogan is, "Take nothing but pictures, leave nothing but footprints, and kill nothing but time." They have embarked upon an educational campaign to develop an appreciation among lay people of the delicate nature of caves. The Society sponsors several conferences and workshops each year and publishes two journals, the NSS NEWS and the NSS BULLETIN. For further information on how you can help in the conservation of caves and karst environments, please contact: The National Speleological Society, Cave Avenue, Huntsville, Alabama 35810.

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Chapter 1

AN OVERVIEW OF THE GEOLOGY AND PHYSICAL GEOGRAPHY OF KENTUCKY

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Kentucky is the home of the big caves, a fact that cannot be doubted when one realizes that Mammoth Cave, at nearly 500 km is 300 km longer than its nearest competitor. Of the 10 longest caves in the United States, 2 are found in Kentucky; this number would have been 3 if it had not been for the recent connection of the 70-km-long Roppel System with Mammoth Cave. People working on the Mammoth Cave Project feel that the eventual mapped distance of the system will exceed 900 km by the turn of the century. Many other large cave systems in the State exceed 3 km, the distance needed to have a cave listed on the World's Longest Cave List published by the International Speleological Union. In fact, Kentucky has 45 caves on the list.

Why has Kentucky been so blessed with such long caves? Why are there so many caves in Kentucky? Where are the caves located? How have they formed? And, what is the importance of caves and their associated landscape? These and other questions will be answered during the course of his chapter and examined in more detail throughout the book.

Chapter 1 sets the stage on which all cave forming processes work. One must know the general geology and geomorphic history of the area in order to understand where and why caves form. In an area with flat lying rocks of homogeneous compositon, there would be little need for such a study because the existance of caves would be limited. Kentucky, on the other hand has a great diversity of earth materials and an ideal landform assemblage for the formation of caves and karst. Several factors are investigated throughout the book to show why Kentucky is the home of the "big ones." These factors include: (1) compositon of the limestones--porosity, permeability, thickness, impurities, jointing, and bedding, (2) composition of the caprock and adjacent strata, (3) the geologic structure and contribution to the enhancement of speleogenetic processes, (4) other factors such as weather, climate, and the impact of vegetation on karst processes, and (5) differential erosion and the impact of river systems on karst processes.

Formation of caves and karst features is a complicated process involving the interaction of many factors. In the following discussion, only those caves developed in limestone environments will be considered. Most caves in Kentucky are the result of karst processes, although there are examples of caves developed by tectonic movement, piping of sediments, and basal spring sapping. In the context of this book, a strict definition of karst will limit the discussion to those environments in which groundwater results in the solution of rock through carbonation. Karst landscapes are often characterized by extensive development of sinkholes, interior drainage, lack of surface streams, caverns, solution sculptured rock (karren), large springs, and other landforms assocated with such areas. For a more detailed discussion of caves and karst in general, the reader is encouraged to refer to one of the following: Jennings (1971), Sweeting (1972), Jakucs (1977), Sullivan and Moore (1978), or Bogli (1980).

The remainder of this chapter will discuss the spatial distribution of rock types and landforms in Kentucky. An understanding of the geologic history and the depositional history of Kentucky enables one to better understand why some areas have more caves. In addition, the explanation of differential erosion of the various rock types and a discussion of regional structural variations help one to understand why certain landforms are more conducive to cave and karst formation. Geomorphic history is discussed in relation to geology in order to facilitate the separation of the State into distinct regions. The potential for caves and karst in each region is introduced in this chapter and more fully discussed in Section II for those areas containing caves and karst.

GEOLOGY

Virtually all of Kentucky is composed of sedimentary rock formed from materials that were originally deposited as sediments in great inland seas or as near-shore deposits in ancient oceans. These sediments have been compressed and cemented into the variety of limestones, sandstones, conglomerates, shales, and coal deposits that form the layers of rock we see today. The story of their deposition is told by the many plant and animal fossils found in the rock, indicating that during the Ordovician Period deep seas once covered Kentucky. Later deposits of the Pennsylvanian, Cretaceous, and Tertiary periods show that water levels fluctuated greatly from near shore deposits to coastal plain, deltaic, and beach deposits. Great coral reefs of the Middle Silurian and Middle Devonian periods resulted in several limestone deposits in the State. Of the material deposited in the ancient seas, it is the limestone in which we are primarily interested, because most caves and karst topography in the State are formed in this rock type. By understanding the spatial distribution of limestone of different ages, and studying its relation to the surface, one can better understand where caves are to be found and how they are formed.

The oldest rocks in the State of Kentucky are those exposed in the Inner Blue Grass Region around Lexington. They date back over 400 million years to the Ordovician Period. In order to give a point of reference, Figure 1 shows the geologic calendar that will be referred to when the age of various rocks and events are mentioned. The areal extent of the Ordovician rock, shown in the geologic map (Fig. 2), covers most of the area between Lexington, Louisville and Cincinnati. The rocks of the Ordovician Period were deposited in deep seas. Toward the end of the period, seas became shallower, as evidenced by the amount of mud that was deposited and subsequently hardened into shale. The following Silurian Period was characterized by warm, clear, shallow seas, as indicated by the profusion of coral deposits and brachiopods in Silurian dolomites and limestones, although the presence of shale beds suggests periods of turbid

ERA	ROCKS EXPOSED IN KENTUCKY	PERIOD (DURATION IN MILLIONS OF YEARS)		AGE (MILLIONS OF YEARS)
CENOZOIC	▨	QUATERNARY	1	1
	▨	TERTIARY	69	70
MESOZOIC		CRETACEOUS	65	135
		JURASSIC	45	180
		TRIASSIC	40	220
PALEOZOIC		PERMIAN	50	270
	▨	PENNSYLVANIAN	50	320
	▨	MISSISSIPPIAN	30	350
	▨	DEVONIAN	50	400
	▨	SILURIAN	30	430
	▨	ORDOVICIAN	60	490
		CAMBRIAN	110	600
PRECAMBRIAN		PRECAMBRIAN	4,000	4,600

Figure 1. Geologic time chart showing the ages of rocks exposed in Kentucky (from McGrain, 1983, p. 3).

water must have occurred. Also during this period there was widespread warping of the strata, which resulted in the uplift of the Cincinnati Arch, a long, gentle arching of the earth's surface running from Cincinnati, Ohio, to Nashille, Tennessee. The Cincinnati Arch cuts across Kentucky and divides it in half, resulting in the formation of independent eastern and western basins. A north-south division between a higher zone near Lexington, Kentucky and a higher zone near Nashville, Tennessee, also exists. This lower gap or "saddle" along the crest of the Cincinnati Arch in south-central Kentucky, results in the preservation of Mississippian material that was stripped from the higher areas by erosion.

Warping of the Cincinnati Arch continued into the Devonian Period, during which more coral rich sediments typical of a shallow sea were laid down. Before the end of the period the sea floor was covered with an organic black muck that formed a pronounced shale layer, a distinctive characteristic of the Devonian. The black shale that outcrops in a zone around the Blue Grass Region of Kentucky may have important economic implications, for it is an oil shale (McGrain, 1983).

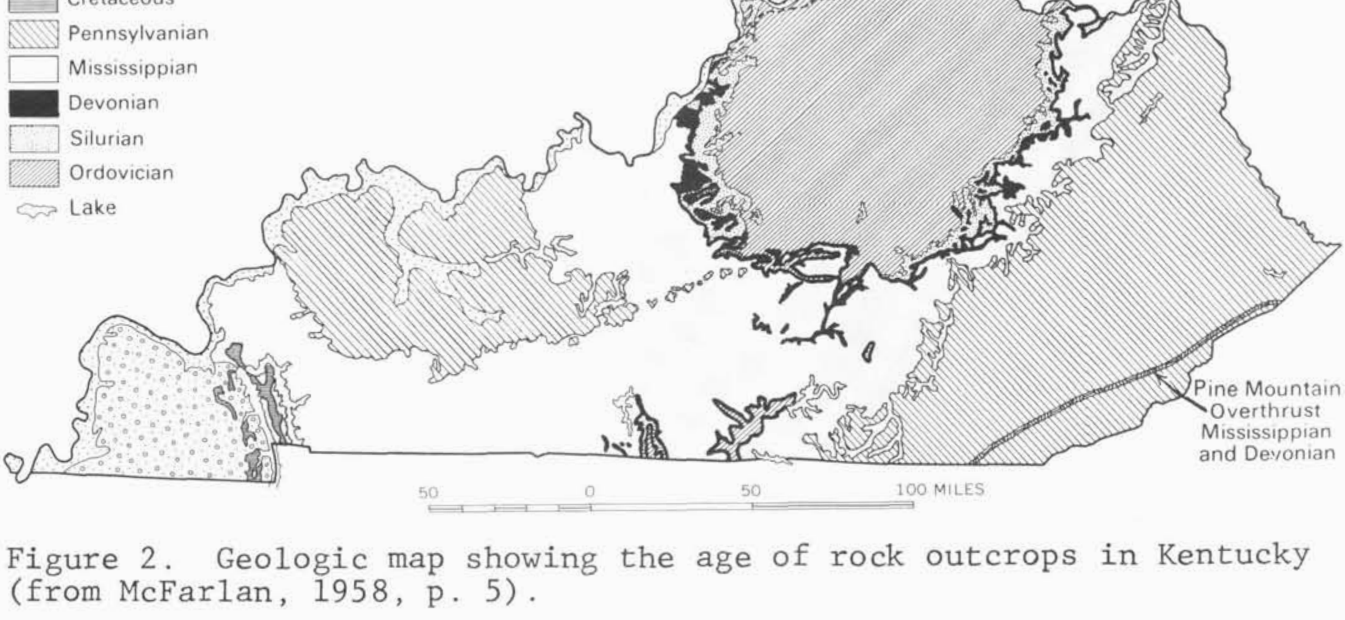

Figure 2. Geologic map showing the age of rock outcrops in Kentucky (from McFarlan, 1958, p. 5).

As the Mississippian Period progressed, the deposition of the black shales was replaced by an influx of sands, gravels, silts, and muds deposited by rivers eroding the nearby land masses. Deltaic deposits, with their characteristic crossbedding and water current worked materials were laid down. Long periods of clear, calm conditions followed; and massive beds of limestone, in which many of today's caves are located, were deposited. A period of recession of the seas occurred, followed by extensive erosion of the land surface. These events are recorded as an uncomformity between the Mississippian and later Pennsylvanian strata.

Pennsylvanian conditions were warm and contained intermittent transgressions of the sea, as evidenced by the presence of marine deposits in the predominantly fresh-water sediments. The period was characterized by the formation of great swamps and forests, as shown by the prolific fossil record. Great masses of vegetation were buried under deltaic deposits and silts. This vegetation, in the absence of oxygen, changed into coal. Similar developments occurred in both the eastern and western basins on either side of the Cincinnati Arch, resulting in the two major coal fields, which have made the State a leading producer of coal.

The Permian Period may have been well represented in Kentucky but its record was undoubtedly eroded away, for only minor evidence of its presence remains. The rock of this period is preserved in some small fault blocks and in small igneous dikes in Elliott County in eastern Kentucky and Caldwell and Crittenden counties in western Kentucky; the only non-sedimentary rock found in the State (McGrain, 1983). At the end of the period a series of uplifts occurred, leading to increased erosion, which obliterated much of the geologic record of the late Paleozoic. By the end of the Paleozoic, the Cincinnati Arch had formed, the western and eastern coal basins were present, the Pine Mountain Fault had been thrust 10 to 16 km to the northwest, and many of the high-angle faults of central and western Kentucky were present. Most of the State's depositional and diastrophic activity came to a close.

The only major deposition following the Paleozoic has been the Gulf Embayment flooding, during the Cretaceous Period, of the Jackson Purchase in extreme western Kentucky. Since that time, only alluviation from the major streams, aeolian deposition of loess, and minor Pleistocene deposits in northern Kentucky have occurred. None of these deposits have an impact on cave and karst formation or their spatial distribution. The major process at work on Kentucky's landforms has been differential erosion, the erosion of rock of different resistance at varying rates. Conglomerates and standstone, because of their greater resistence, have emerged as the higher landforms, such as cuestas, escarpments, and mountains; shales and limestones, because of their weakness and susceptibility to solution, form the valleys and lowland plains. Since most of the State receives in excess of 965 mm of precipitation a year, with some areas experiencing over 1,270 mm a year, the process of erosion has been rapid and has left a great imprint on the present landforms. Kentucky's modern landforms are therefore the remnant of past landforms rather than landscapes that were uplifted to their present position. These stages are summarized in Figure 3 which shows the regional evolution of the Kentucky landscape.

A major factor in the present landscape formation has been the river patterns and their subsequent entrenchment. Most rivers in Kentucky do not flow

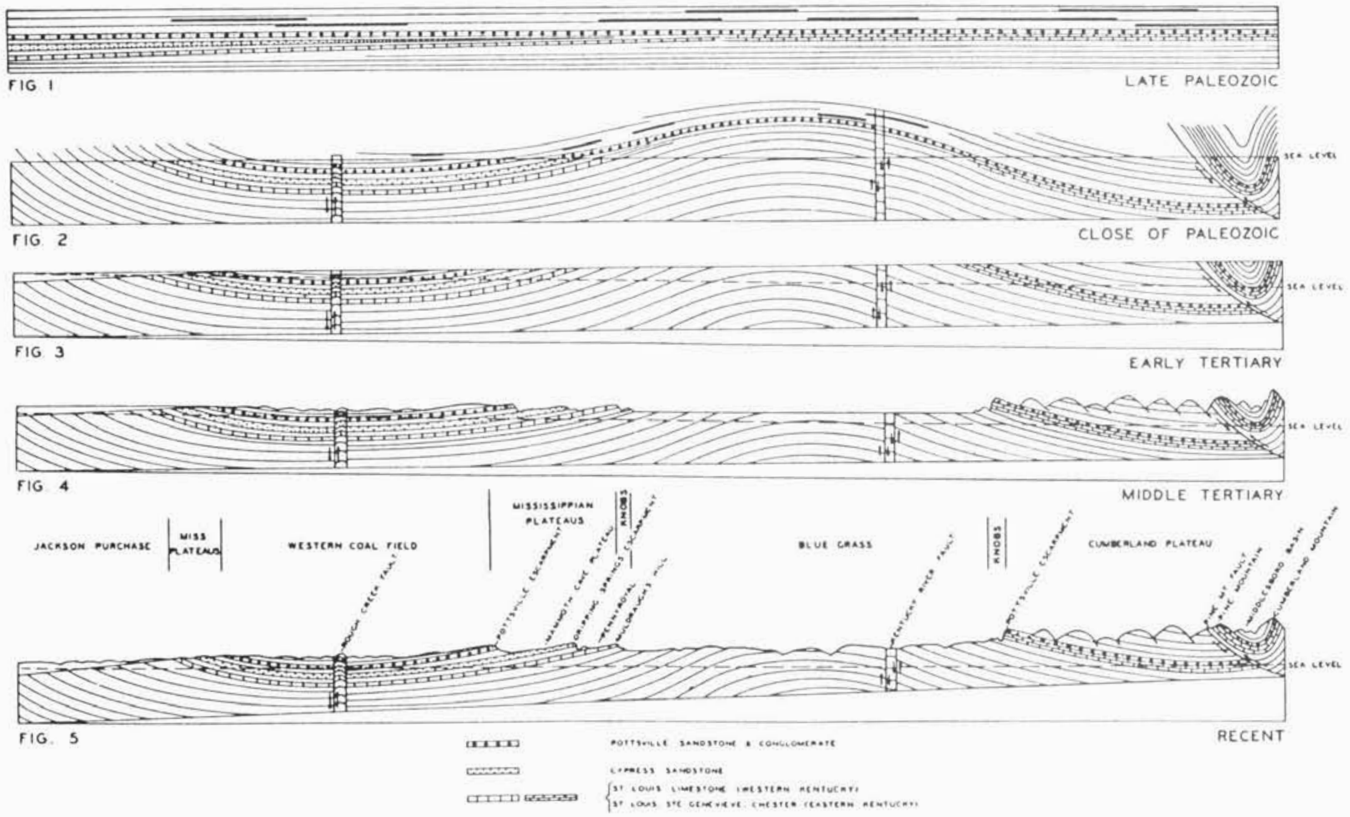

Figure 3. Regional evolution of the Kentucky landscape (from McFarlan, 1943, p. 159).

along the dip of the sedimentary strata. Major rivers such as the Kentucky, Green, Cumberland, and Licking flow across the strata as superposed streams that pre-date the present landforms. The rivers were able to maintain their courses over the more resistant strata being uncovered by differential erosion.

The most recent event of importance to the cave forming process was the development of the Ohio River during the Pleistocene. Prior to the Pleistocene, the Licking and Kentucky Rivers were part of the Teays River System. The Kentucky River flowed along the present course of the Ohio River to the area near Lawrenceburg, Indiana, where it flowed through the present valley of the Great Miami River. The Licking flowed through Cincinnati, via the present Mill Creek Valley, and joined the Kentucky River near Hamilton, Ohio. Both rivers then flowed north through Dayton to enter the Teays drainage from West

Figure 4. Map of the preglacial drainage of the Teays-age basin in Ohio and the midwest (from Thornburg, 1969).

Virginia and Eastern Ohio at a junction in west-central Ohio. The stream then flowed across central Indiana as the River Teays. Glacial advance blocked the northward flow and the present Ohio River breached the Madison Gap to flow in its present course. Because of the great flow of water in the new channel, downward cutting was rapid. This cutting left branch tributaries of the ancestral Ohio discordant with the main stream; rapid cutting occurred resulting in the entrenchment of the Kentucky, Cumberland, Tennessee, Green, and other rivers. Fluctuations in river flow and periods of rapid entrenchment lowered base level throughout the major cave areas of Kentucky, a process that has resulted in the profusion of levels in Kentucky caves.

REGIONAL DIVISIONS

The end result of all of the periods of deposition, uplift, faulting, and erosion is seen in the landform model in Figure 5. A wide variety of plains, plateaus, escarpments, and mountains have been sculptured out of the sedimentary rocks of Kentucky. Note the similarity between the geology map (Fig. 2) and the distribution of present landforms. Each of these regions will be discussed in detail in the following sections, with particular attention given to their potential for cave and karst formation. The Lexington Plain or Inner Blue Grass, the Cumberland Plateau, Pennyroyal Plateau, the Mammoth Cave Plateau, and the Pine Mountain Region offer the best conditions for cavern formation because of their rock type, structure, and hydrologic conditions.

Blue Grass Region

The Blue Grass is the central lowland of Kentucky, composed of Ordovician outcrops that form the axial portion of the Cincinnati Arch. Here one finds the oldest surface rocks in the State, primarily limestone and shale. Near the edges of the Blue Grass some areas of Silurian and Middle Devonian limestone and shale are included. The resulting landscape presents a gently rolling surface that appears relatively flat in comparison to surrounding thoroughly dissected regions. This area has been referred to as the Lexington Peneplain in the past because of its lack of substantial relief (McFarlan, 1943). Regions of greater relief develop in the outcrops of shale that surround the limestone interior of the region. The Lexington and Cynthiana limestones occupy the central position around the City of Lexington and constitute a fertile limestone basin called the Inner Blue Grass. This basin is surrounded by a zone of shales called the Eden Shale Belt, which, in turn, is bounded by the Outer Blue Grass, a region of limestone and shale that extends to the Ohio River in the north where it is mantled by a thin veneer of Pleistocene glacial deposits with little topographic significance to the landforms of the area. Where limestone is the dominant rock, the surface is mildly karstic, and small caves may be found. The greatest relief is not caused by karst landforms, but by the deeply entrenched courses of the Kentucky, Licking, and Ohio rivers. Their courses are superimposed up to 150 meters below the Blue Grass surface. The canyons display beautiful examples of entrenched meanders and, in the zone of shales, deep gorges have formed.

The northwestern portion of the region surrounding Louisville is not geologically similar to the Blue Grass but is included because of its topographic similarity and occurrence of the same geographical factors responsible for the historical development and

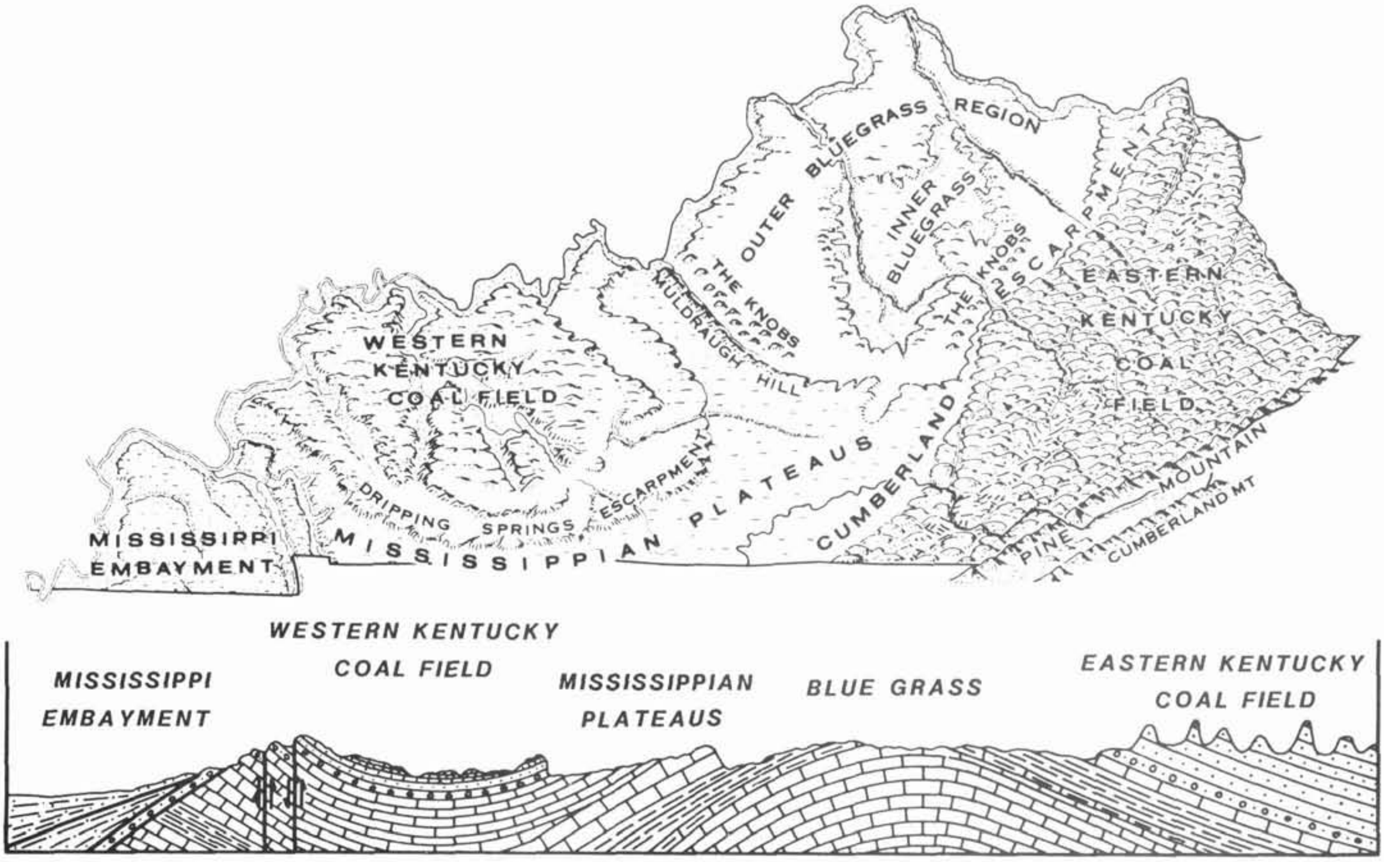

Figure 5. Physiographic map of Kentucky showing geomorphic regions and major escarpments. Generalized cross section depicts the structure of rock units from west to east across the State. (From McGrain, 1983, p. 13.)

economy of the Blue Grass. The Louisville part of the Blue Grass, called the Scottsburg Lowland, has developed on limestones of Middle Silurian and Middle Devonian age and more recent alluvium deposited by ancestral stages of the Ohio River. Geographically, the region constitutes one of the anchors of what Raitz (1980) has called the "urban triangle" of the Blue Grass, a joining by transportation arteries of Louisville, Lexington and Covington, the three largest urban areas in the State, and all within the Blue Grass.

Limestone within the Blue Grass is not only responsible for the karst features and caves, it has also played an important role in the economic growth of the region. Soils formed on the Inner Blue Grass are exceptionally fertile, brown silt loams with a high phosphatic level. The Woodburn Formation which once supported commercial production of phosphate rock. These formations have resulted in the Blue Grass becoming widely known as an agricultural island in central Kentucky, characterized by its beautiful mansions and extensive horse farms. In addition, the Blue Grass is the center of the burley tobacco region. Kentucky produces 80 percent of all burley tobacco grown in the United States, making tobacco Kentucky's number one legal agricultural crop. This crop accounts for 85 to 90 percent of the state's agricultural income per year and 20 percent of the total United States tobacco production in a good year (Raitz, 1980).

An outgrowth of the limestone agricultural bounty is the development of the bourbon industry. Early Blue Grass settlers had an excess of corn at the end of the season and had no convenient means of transporting the bulky commodity to Cincinnati or other markets. A bulk reduction of the corn to distilled spirits was a logical result. In 1789 Reverend Elija Craig, of Georgetown in Bourbon County, developed the recipe for a malt whiskey that now carries the name of the county in which it was first distilled. Even today, State law requires that 51 percent of the grain in bourbon must be corn, thus imparting the unique taste to the beverage. Kentucky at one time had over 400 distilleries producing in excess of 88 percent of America's bourbon whiskey. Through corporate mergers and the necessity of large scale operation, the number has dropped to 28 distilleries; all but 3 are in the Blue Grass. Experts in bourbon whiskey attribute the excellence to the use of pure, natural limestone waters that emerge from the karst springs of the area. Kentucky still produces 75 percent of all United States' bourbon (Raitz, 1980).

The karst springs were also instrumental in the early settlement patterns of the Blue Grass. Cities such as Lexington, Harrodsburg, and Georgetown were built at the sites of karst springs in order to assure a steady supply of water for the settlers. Even today, the city of Georgetown still gets its water supply from the great flow of Royal Spring.

Cumberland Plateau

The gently southeastward dipping upland surface east of the Pottsville Escarpment and west of the steeply rising Pine Mountain is referred to as the Cumberland Plateau. The Cumberland Plateau is often referred to as the Eastern Kentucky Mountains or the Eastern Kentucky Coal Field. The latter terms often include the Pine Mountain Overthrust and its associated basin and mountains as part of the region, but this discussion will consider these areas as part of the Cumberland Mountains. The reason for this separation is the independence of speleogenetic processes at work in the development of caves and karst in the two areas, and the great difference in the two areas' geomorphic history.

The Cumberland Plateau is a maturely dissected landscape where Mississippian limestones are capped by more resistant sandstones, shales, conglomerates, and coal-bearing deposits of Pennsylvanian age. The maximum development of karst features and caves is found along the Pottsville Escarpment. It is here that the extensive caves of Pulaski, Rockcastle, and Carter counties have developed. Especially important to the landscape's development have been streams like the Rockcastle River, Cumberland River, Buck Creek, Licking River, and Tygarts Creek. These rivers have entrenched themselves through the Pennsylvanian sediments, exposing the underlying Mississippian limestones.

Few level areas are present on the plateau surface. The maturely dissected Rockcastle Conglomerate and Corbin Sandstone are so dissected that only small ribbons of level interfluves are present. Soils on these flat areas are relatively poor and support only the barest, subsistence agriculture. In the valley bottoms the agricultural production is better, but the alluvial lowlands are severely constricted to small meander bends on present and paleo drainage. The largest lowland areas are related to shale outcrops that have been weathered and eroded into bottom flats that support limited agriculture. What this region lacks in agricultural productivity is offset by coal mining activity. Oil and natural gas are also produced in this region.

Through most of its extent the Pottsville Escarpment is a southeast-dipping cuesta capped by more resistant beds of Rockcastle Conglomerate of Pennsylvanian age. Near the Tennessee border the escarpment reaches 550 m, with a combination of Rockcastle, Corbin, and Lee strata forming the cuesta front. To the north, near the Ohio River, the escarpment is known as the Waverly Escarpment, a low relief feature resulting from a pinching out of the Rockcastle conglomerate.

Of geologic and geomorphic note in this area are Cumberland Falls and the sandstone arches. Cumberland Falls developed where the Cumberland River crosses resistant sandstones and conglomerates and then falls to the level of Lake Cumberland in the lower Pennyroyal Province. The falls have retreated upriver from the Burnside area to where they are today. Not far from Cumberland Falls one can visit the beautiful sandstone arches and Yahoo Falls in the Daniel Boone National Forest. Further north, at Red River State Park and at Carter Caves State Park, one can also see good examples of natural bridges formed in the highly eroded residual stream interfluves (Fig. 6).

Hydrologic divides separate the region into several cave and karst subregions. The most important in terms of the number of caves and the length of cave passages is the Pulaski/Rockcastle area where such caves as Sloans Valley, Coral, Cave Creek, Hails, Big Sink, Precinct 11, and Goochland are found. The caves are formed along the maturely eroded front of the Pottsville Escarpment, where it is crossed by the Rockcastle and Cumberland drainage. The second major cave region is at Carter Caves where Tygarts Creek has cut through the caprock exposing the Mississippian limestones and resulting in the formation of several caves and arches.

Figure 6. Portion of Pomeroyton Quadrangle showing the Red River gorge and associated natural bridge (from McGrain, 1983, p. 35).

Cumberland Mountains

East of the Cumberland Plateau is the zone of Pine Mountain or Cumberland Overthrust, whose northern and western boundaries terminate at the Russel Fork Fault. This highland region contains the highest elevation in the State, 1,265 m on Big Black Mountain in Harlan County. The western part of this province is the southeastward-dipping strata of the Lee Formation, which forms Pine Mountain. The eastern border is formed by the cuesta of the westward-dipping Lee Formation that forms Cumberland Mountain; with the Middlesboro Basin being a large synclinal valley between the two mountains. The whole area is a huge block 200 km long and 40 km wide that was elevated and displaced westward as much as 10 km from the southeast (McGrain, 1983).

The area has a diverse history of stream entrenchment and exhibits water gaps and wind gaps representing the effect of superposition and stream piracy. As in the Cumberland Plateau, the Mississippian limestones are overlain by Pennsylvanian shales, sandstones, conglomerates, and coal-bearing strata. Some of the most productive coal-mining in the State is on the elevated strata of the Middlesboro Basin. This basin is similar in composition and topographic expression to the lower Cumberland Plateau.

Because of the overthrust, the region presented a formidable obstacle to transportation and settlement in pioneer days. Settlers were forced to traverse this area by crossing the famous Cumberland Gap, a wind gap in Cumberland Mountain. Another topographic obstacle is the Breaks of the Sandy, where the Russel Fork of the Big Sandy River cuts through the northern end of Pine Mountain in a 300 m gash through the Lee sandstones. This rugged landscape exemplifies the topographic obstacles to development faced by the original settlers (Fig. 7).

Cave and karst development is restricted to the thin exposures of limestone that outcrop on the steeply dipping mountains. Because of the great relief in the area, the deepest caves and the largest pits in Kentucky are found in this district.

Mississippian Plateaus

Although composed of Middle to Upper Mississippian outcrops, this area is best characterized by its topographic expression. It is divided into two major parts, the upper Mammoth Cave Plateau ad the lower Pennyroyal Plateau. The Pennyroyal Plateau is adjacent to the lower Blue Grass Region being separated from it by The Knobs Region and Muldraughs Hill. The latter trends to the east and merges with the Pottsville Escarpment and pinches out the Pennyroyal on the eastern side of the Cincinnati Arch. The Pennyroyal extends on a westward arc, roughly following the Cumberland River through Kentucky and Tennessee. It then arcs northwestward to the junction of the Cumberland and Ohio rivers. On the west and north, the Pennyroyal is bounded by the Dripping Springs

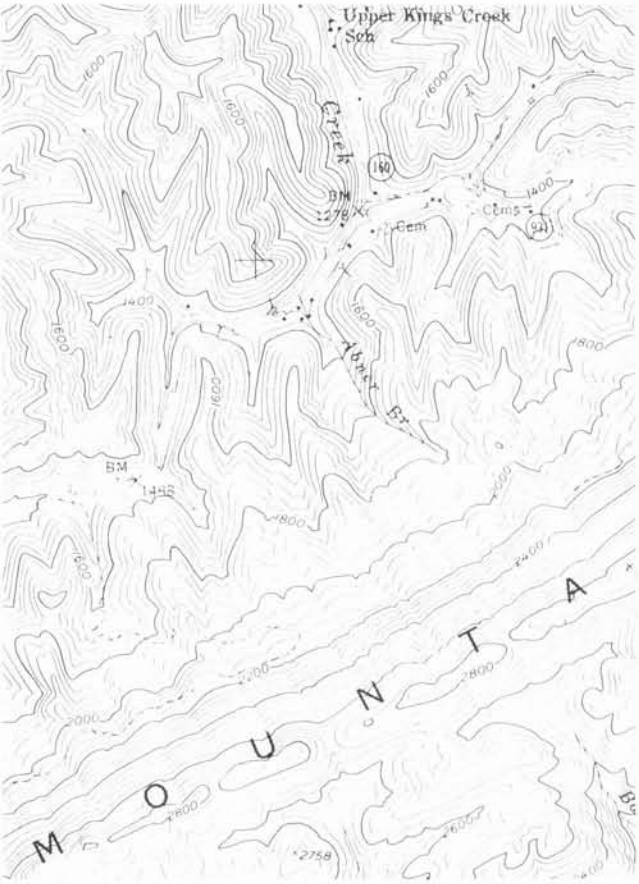

Figure 7. Topographic map of Pine Mountain and nearby Cumberland Plateau (from McGrain, 1983, p. 33).

Escarpment, which separates it from the Mammoth Cave Plateau.

The Pennyroyal Plateau forms a corridor extending away from the Ohio River between the Dripping Springs Escarpment and the Knobs Region. The corridor continues as it swings back toward the Ohio River, skirting the Western Kentucky Coal Field from which it is separated by the Mammoth Cave Plateau. It was through this plateau corridor that many of the original settlers found an easy transportation route. The limestone derived soils are very fertile and have been extremely productive agriculturally, although they are less fertile than the Blue Grass phosphatic soils.

Much of the Pennyroyal Plateau exhibits extreme karstification, with numerous sinkholes dotting the landscape (Fig. 8). Sinkholes become less noticeable as one approaches the axial section of the Cincinnati Arch, where the karst-prone St. Louis and Ste. Genevieve formations have been stripped away revealing the less soluble Warsaw and similar formations. On the eastern side of the Cincinnati Arch, the karst landscape is once again obvious; a large number of sinkholes and karst features have developed on the St. Louis formation.

The Mammoth Cave Plateau is bounded on the outer margin by the Dripping Springs Escarpment. The escarpment is capped by sandstone overlying the St. Louis, Ste. Genevieve, and Girkin formations that comprise much of the cave-forming limestone in the Mammoth Cave area. At the inner margin of this district is the higher Western Kentucky Coal Field of Pennsylvanian rock. In this text, the Mammoth Cave Plateau is divided into a Mammoth Cave Region and a Western Kentucky Karst Region because of differences in the drainage basins responsible for the karst processes. An argument could also be made for the inclusion of another district between Elizabethtown and the Ohio River, but this is not being done in this volume.

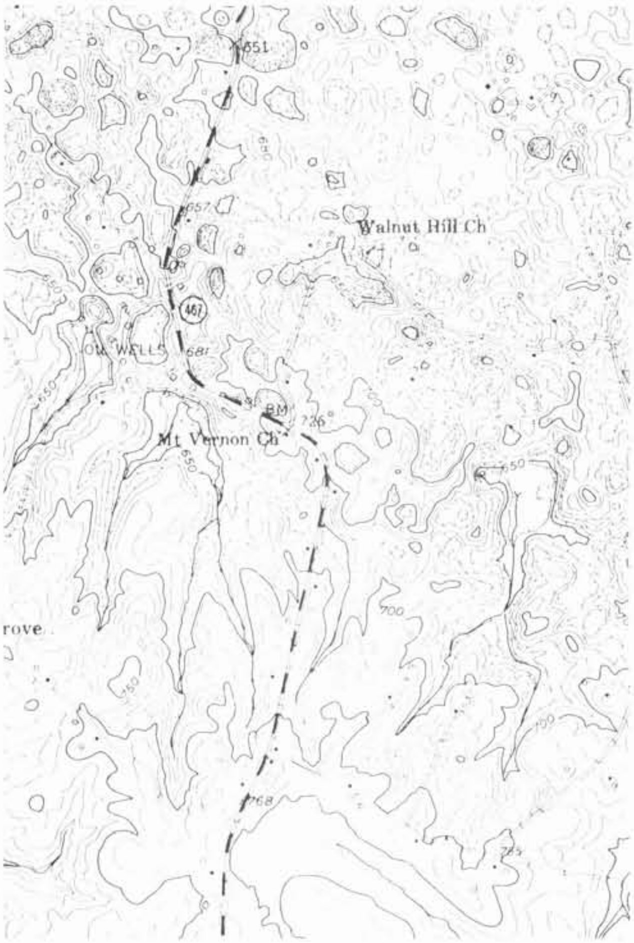

Figure 8. Topographic map of the Park City Quadrangle of the Pennyroyal Plateau showing its high density of sinkholes (from McGrain, 1983, p. 50).

Mammoth Cave is unsurpassed in length because of the ideal conditions for speleogenesis on the Mammoth Cave Plateau. The permeable nature of the overlying sandstone permitted maximum water penetration of the limestone layers. Meanwhile, caprock continued to provide a stable ceiling for the area (Fig. 9). Gently dipping toward the Green River, which became entrenched following the Pleistocene formation of the Ohio River, the plateau developed several levels

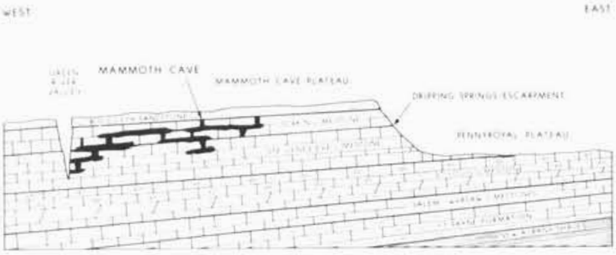

Figure 9. Mammoth Cave Region cross sections showing multi-level development of the cave and the resistant protective sandstone caprock (from McGrain, 1983, p. 54).

of cave passages. The thickness of the rock, the rock structure, and the factors just identified have resulted in the formation of a cave system that may some day exceed 900 km in length.

Knobs

The Knobs Region is a thin belt of conical knobs that surrounds the Blue Grass. The Knobs are erosional remnants of Muldraugh Escarpment to the west and the Pottsville Escarpment to the east. As the upland surfaces are eroded back, interfluve areas, protected by caprock of sandstone and shale, remain as isolated hills surrounded by a base level at the elevation of the Blue Grass. On the western side of the Cincinnati Arch the knobs are primarily Silurian to Middle Devonian limestones, and on the east they are predominently shale. The region is, therefore, sandwiched between the Blue Grass Ordovician rocks and the younger Mississippian rocks of the Pennyroyal Plateau. The Knobs Region reaches its greatest width south of Louisville, where there is a gentle dip and no faulting. In the southern Blue Grass, faulting is present and the dip is steeper, resulting in Knobs that are narrow in areal extent. Although both areas are rugged topographically, the stream bottoms are often flat and broad (Fig. 10). Regional soils are of inferior quality. The major resource of the area may be the oil shales found in some of the knobs. Caves may be found in the knobs, but they are limited in length.

Western Kentucky Coal Field

The Western Kentucky Coal Field is a large structural basin separated from the lower Mammoth Cave Plateau by the Pottsville Escarpment. The escarpment is capped by the Pennsylvanian Caseyville Sandstone, forming a belt of rugged hills rather than

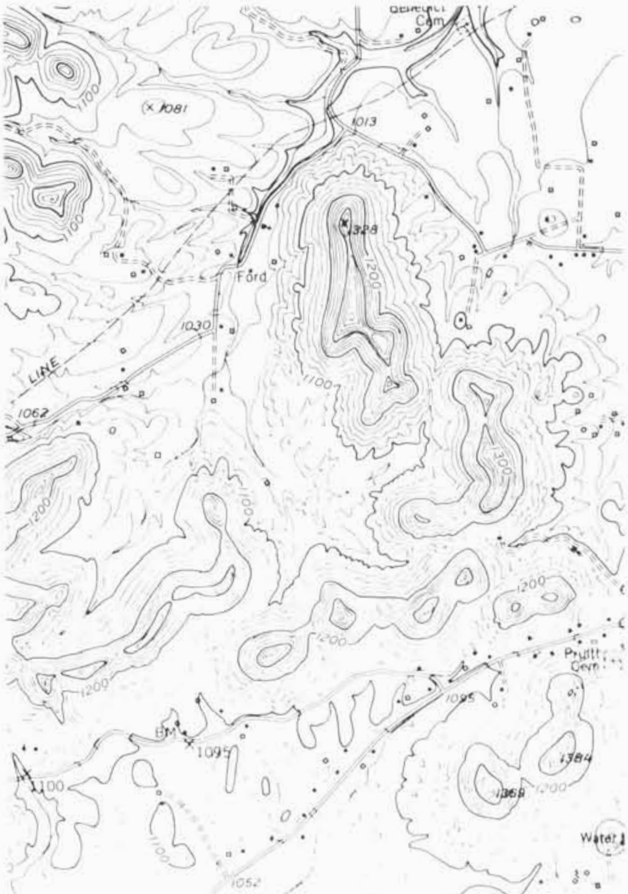

Figure 10. Topographic map of the Junction City Quadrangle showing the residual hummocky terrain and the broad lowlands between the knobs (from McGrain, 1983, p. 47).

an imposing cliff face. This area is structurally a virtual duplicate of the Eastern Kentucky Coal Field of the Cumberland Plateau, although the elevation is lower and the relief is not as great. The presence of sandstones and faulting has resulted in several hilly areas standing in relief against broad valleys formed from eroded shales. River valleys such as those of the Green and Tradewater rivers were eroded deeply prior to the Pleistocene, and subsequently filled in with alluvial deposits during ponding caused by ice blockage of the Ohio River. The resulting broad flat areas are readily amenable to agriculture. The agricultural productivity of the area is in sharp contrast to coal mining which results in ruinaton of agricultural land. Few caves are found in this area because of the lack of exposed limestone on the predominently Pennsylvanian rocks.

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Chapter 2

CAVES OF KENTUCKY

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The caves of Kentucky have been important in the history of settlement patterns for both the American Indians and the pioneers. Many of the cave entrances served as living quarters to the Indians. The Indians explored some of these caves and exploited the mineral resources such as water, gypsum, epsomite, flint, and calcite. The best examples are Mammoth Cave, Salts Cave (Edmondson County) and Great Wonderland Cavern (Hardin County). By the middle part of the 18th century, pioneers were moving westward into a land called Kentucky. Like the Indians, the pioneers used caves for shelter (Cave Hut, Muhlenburg County); they too exploited the mineral resources found in the caves, especially water, epsomite, copperas, and saltpeter. Caves have been used as storehouses for foodstuffs (Breeding Saltpeter Cave, Adair County), mushroom farms (Constantine Saltpeter Cave, Hardin County), and livestock quarters (Hidden River Cave, Hart County). During these early times, few records of caves are known. What is known about this early period is based upon contemporary investigations into the history and archeology of the site.

The first inventory of caves in Kentucky sprang out of a need to exploit their economic worth in the early 1800s. This inventory was followed by academic inquiries into the distribution of caves because of their unique fauna, flora, and archeological significance. The contemporary inventory of caves in Kentucky began with early efforts by the National Speleological Society, followed by local grottos and individuals collecting and mapping caves in this state.

In 1806 a Lexington saltpeter-gunpowder entrepreneur by the name of Samuel Brown wrote of 6 caves, giving their name, location, some notes on each cave, and a detailed description of one of them. He knew of others, but concentrated on the ones that he owned in present day Rockcastle, Jackson, and Hardin counties.

In 1817, Luke Munsell was hired by the state government as chief surveyor and directed to produce a high quality, detailed map of Kentucky. By using existing maps and his prior survey field work, coupled with new field investigations, Munsell by 1818 had published his "Large Map of Kentucky." This was the first really accurate map of the State which showed the positions of cultural and natural features in their true spatial relationships with one another. Munsell took it upon himself to include remarkable geographic places. The completed map thus shows a number of karst features, sinking streams, springs, dry stream channels, and cave entrances. No other single map in the State was to include so many karst features up to the time of our modern topographic mapping program. The first real catalog of caves and their distribution was published by Constantine S. Rafinesque in 1832. This catalog is based upon his tenure at Transylvania College (Lexington, Kentucky) between 1818 and 1826. He was the first to examine the caves' geological and zoological content. He devised seven different classificatons of caves: cliff caves (rock castles or rock houses), fissure caves, sinking caves, spring caves, crater or funnel caves, saltpeter caves, and stalactical caves. He gave names, locations, and physical descriptions of eight caves in Kentucky. Four of the caves studied occur in the Inner Blue Grass, two caves in the Cumberland Plateau of Rockcastle County, and two caves in the Mississippian Plateau of Edmonson County.

Kentucky historians have played a key role in the preservation of accounts of early cave explorations and discoveries. Lewis Collins (1847), followed by his son, Richard Collins (1874), in their "History of Kentucky," recorded the location and physical descriptions of caves by county. Data were gathered without credit from old newspaper accounts, travelogues, and a smattering of scientific publications. Cave descriptions selected were usually of the kind with bottomless pits (Frenchman Knob Pit, Hart County) or lost Roman treasure caves (Lovell Cave, Muhlenburg County). If the cave contained animal bones, especially mammoth bones, the finding of such in a cave was a favorite vignette of the Collins'. All succeeding 19th century historians followed their outline of cave descriptons.

Throughout the 19th century, the fame of Mammoth Cave dominated the cave scene with a host of descriptions and maps published on this famous wonder of the world. There would be sporadic references to nearby caves, such as Dixon, Long, Short, Hundred Domes, James, Diamond, Hidden River, and Mammoth Onyx caves. Occasionally, a travelogue would describe other caves in the State. Alexander Wilson (1810) wrote of Bleedinghearts Cave (Warren County), and the anonymous (attributed to Constantine S. Rafinesque, 1820) account of Russell Cave (Fayette County) made for a fine addition to the speleo history of the State. But, all in all, caves outside the Mammoth Cave Region seem to have little to offer in comparison.

Between the time of Rafinesque and Alpheus S. Packard there is a hiatus with little regional collection of cave sites. Packard conducted an extensive inventory of cave life from the caves of Kentucky and published his findings in 1888. He mentioned more than 50 caves from site data and collections by Nathaniel S. Shaler and his Kentucky Geological Survey in 1875. Arthur M. Miller (1919), State Geologist, listed 16 representative caves and 5 areas where caves occur. Gerard Fowke (1922) describeed 39 caves in the State as part of his midwest archaeological investigations.

From 1923 to 1957, William D. Funkhouser and William S. Webb explored, excavated, and cataloged caves as part of a Statewide inventory of archeological sites in Kentucky.

The massive publicity resulting from Floyd Collin's entrapment in Sand Cave, Edmonson County, generated a demand for more newspaper articles on caves, and not just caves in the Mammoth Cave vicinity, but caves all over Kentucky. There was a plethora of newspaper articles published between 1925 and 1935. The maximum amount was in 1925 during the Collins incident and just after his death.

In 1943, the fledgling National Speleological Society undertook the cataloging of all known caves in the United states and the world; Robert Morgan began this task and produced the first modern catalog of caves. By 1944, he had inventoried 102 caves in the State and the list was documented with an extensive bibliography. From that time, grottos, surveys, and individuals have maintained extensive catalogs of caves in Kentucky.

Collection efforts over the last 20 years has yielded 3,770 caves and 1,057 cave maps spread out in 87 of the 120 counties in Kentucky (Fig. 1, Table 1). The gridwork display in Figure 1 was constructed by plotting cave entrances on 2.5 minute centers of latitude and longitude.

GEOGRAPHIC DISTRIBUTION OF CAVES IN KENTUCKY

Kentucky is contained in parts of the Coastal Plain, Interior Low Plateaus, and Appalachian Plateau Province in the southeastern United States. The State can be divided into six major geomorphic regions that closely align themselves with prominent lithological, structural, hydrological, and geomorphological changes in the topography (Fig. 2). The geomorphic regions are (from east to west): Eastern Kentucky Coal Field, Knobs, Blue Grass, Mississippian Plateaus, Western Kentucky Coal Field, and Jackson Purchase. Caves are developed in Paleozoic carbonates ranging in age from Middle Ordovician through Late Mississippian. Well developed pseudocaves occur in Lower Pennsylvanian conglomerates and clastics. No caves hae been reported in anything younger than Early Pennsylvanian in age.

Structural development of the Cincinnati Arch coupled with sediment downloading of the Eastern and Western Kentucky Coal basins at the close of the Paleozoic Era set the stage for the present distribution of caves in Kentucky. Major landscapes as we see them today have been in existence since the end of the Cretaceous Period. Generally, cave

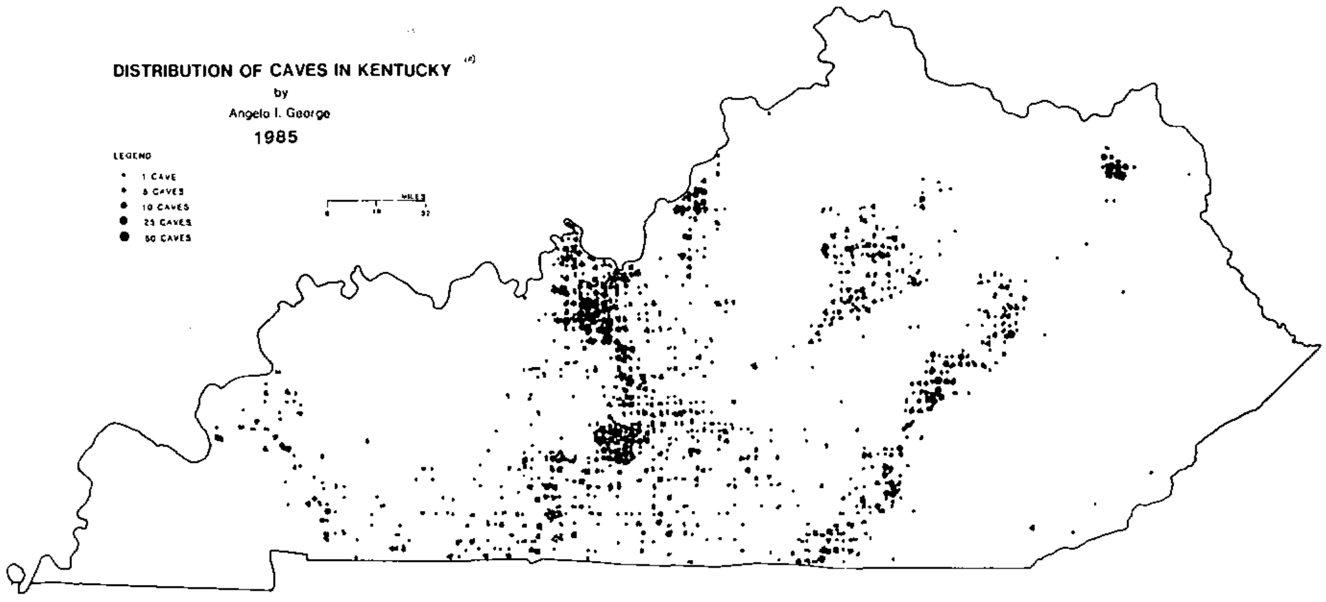


Figure 1. Distribution of caves in Kentucky, plotted on 2.5-minute centers of latitude and longitude.

Table 1
Listing of Caves in Kentucky by County

Total No. Caves	3770
Co. with Caves	87
No. Mapped Caves	1057

COUNTY	NO. CAVES	NO. MAP CAVES	COUNTY	NO. CAVES	NO. MAP CAVES
Adair	35	6	Laurel	1	
Anderson	18		Lee	43	14
Allen	20	7	Letcher	27	15
Barren	135	43	Livingston	14*	7
Breckinridge	425	71	Logan	55*	32
Bell	8	3	Lyon	9*	1
Boone	8		Madison	27	5
Bourbon	12	6	Magoffin	2	
Boyde	1		Marion	9	
Boyle	8		Mason	1	1
Bullett	30	30***	McCreary	14	2
Butler	10		Meade	212	43
Caldwell	39*	25	Menifee	4	1
Carter	187	36	Mercer	37	4
Carroll	1		Metcalfe	19	3
Casey	6		Monroe	22	1
Christian	24	15	Morgan	1	
Clark	9	1	Montgomery	4	
Clinton	8	3	Muhlenburg	3	2
Crittenden	25	8	Nelson	21	12***
Cumberland	16	4	Nicholas	1	
Edmonson	173	44	Ohio	4	
Elliott	2	1	Oldham	13	3
Estill	37		Owen	5	1
Fayette	72	21	Pike	1	
Floyd	2		Powell	37	1
Franklin	28	1	Pulaski	168	114
Garrard	10		Rockcastle	181	69
Grayson	41	9	Russell	10	1
Green	71	8	Scott	12	5
Greenup	1		Shelby	3	
Handcock	1		Simpson	48	11
Hardin	297	62	Taylor	8	
Harlan	2		Todd	18	11
Harrison	1		Trigg	66	53
Hart	207	74	Trimble	10	2***
Henderson	2		Union	2	
Henry	23	3	Warren	198**	80
Hopkins	2		Washington	1	
Jackson	134	10	Wayne	94	16
Jefferson	109	32***	Whitley	1	
Jessamine	50	12	Wolf	7	
Knott	1		Woodford	40	10
Larue	23		Miscellaneous	3	2

*John Mylroie, personal communication, 1984.

**Central Kentucky Cave Survey, Bull. No. 1.

***Phillip DiBlasi, personel communication.

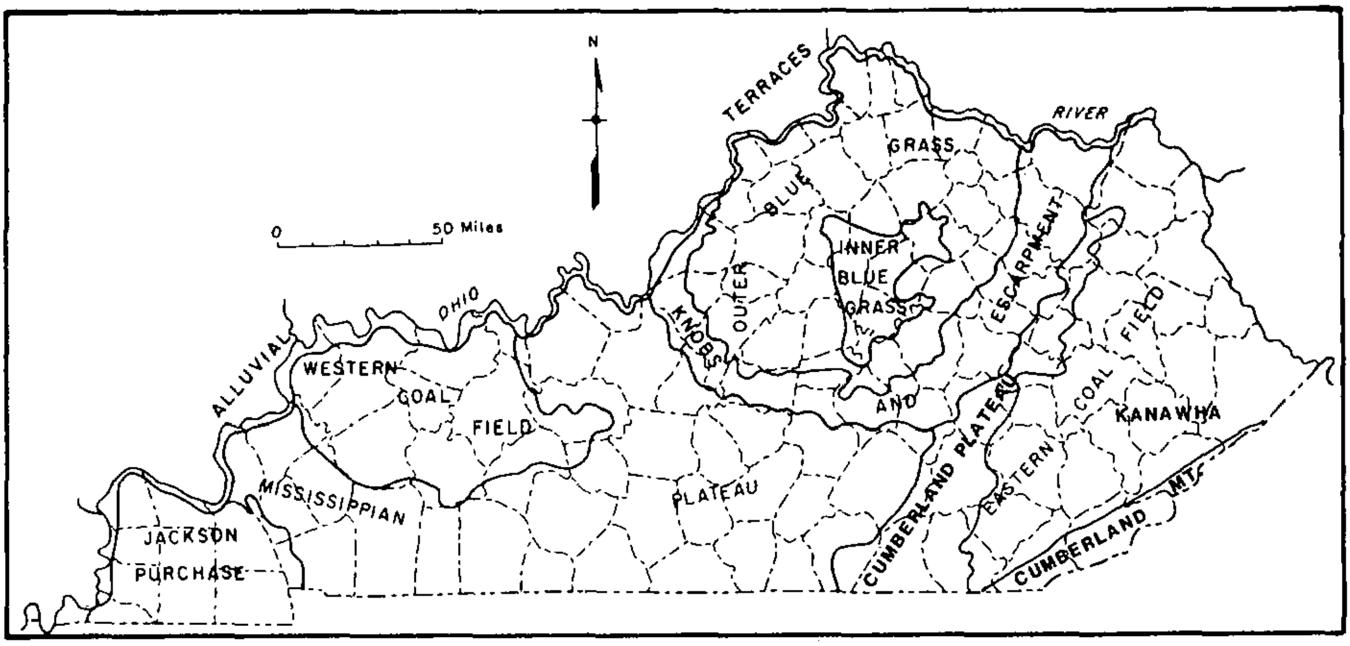


Figure 2. Six major geomorphic regions of Kentucky.

development sought out structurally favorable areas where there was a maximum amount of relief between the point of recharge and the point of discharge along base level streams. The great caves of long extent are all found adjacent to structurally induced Chesterian (Mammoth Cave System, Edmonson County) and Pottsville escarpments (Cave Creek System, Pulaski County) or along the crests of anticlines (Hayes Cave, Grayson County) and synclines (Big Bat Cave, Breckinridge County). Frequency of cave entrance occurence, passage size, and groundwater yield decreases in the direction of recharge boundaries. This generalization can be seen in the north-central Kentucky karst and is consistent with Swinnerton's (1932) theoretical speleogenesis model.

Eastern Kentucky Coal Field Region

The Eastern Kentucky Coal Field Region is a synclinal structural basin filled with Mississippian carbonates and clastics on the updip side, and overlain with Pennsylvanian cyclothemic sandstones, shales, coals, siltstones, and limestones on the downdip side (Fig. 2). The basin can be subdivided into three sections: Cumberland Mountain, Kanawha, and Cumberland Plateau. Caves are found in all three sections. The majority of the caves are developed within the Cumberland Mountain and Cumberland Plateau sections.

Cumberland Mountain Section

Along the southeastern boundary of the Eastern Kentucky Coal Field is the Pine Mountain Overthrust Fault. This fault has formed a synclinal trough flanked by two parallel mountains, Cumberland and Pine. The northwestern slope of Pine Mountain contains the majority of caves in this locality. Here, Mississippian carbonates have been overthrust to the northwest out and on top of the Kanawha section of Pennsylvanian clastics. The carbonates are extensively fractured and caves have formed along the strike and Pine Mountain. Pine Mountain stretches for more than 160 km through

Kentucky and contains over 91 m of carbonates. This karst area represents probably one of the greatest untapped caving localities in the State. There is much potential for big cave, deep pits, and systems to keep cavers busy for years. The most famous caves are Linefork Cave, Icebox Cave, the Payne Gap Cavern, Payne Gap Water Cave, and Angel Cave. The Colehole is a 73-m-deep pit with no passage at the bottom. Sand Cave is a pseudokarst feature formed in the Lee Sandstone. Carbonate cave passage configuration is similar to that seen in the Valley and Ridge areas of Virginia.

Kanawha Section

The Kanawha Section is the heartland of the Eastern Kentucky Coal Field. It is a paradise for the coal and oil barons, and a bane for the caver, with impossible roads, rugged terrane, and few caves. Few caves are memorable, and the geologic section is full of Pennsylvanian clastics, coals, shales, and thin carbonate units. There are less than 20 caves indexed from this section in Kentucky.

Cumberland Plateau Section

Stretching for more than 190 km across the east central part of Kentucky is one of the paramount cave and karst localities in the State. The locality is bounded on the west by the Highland Rim Escarpment and on the east by the Pottsville Escarpment. More than 840 caves are known from this area. Caverns of every possible description can be found in this section, whether large, dry walking passage, or wet and muddy slush tube. Representative caves are: Sloans Valley System, Cave Creek System, Goochland-Smokehole Complex, Great Saltpetre Cave, Triple S Cave, and Eureka Cave.

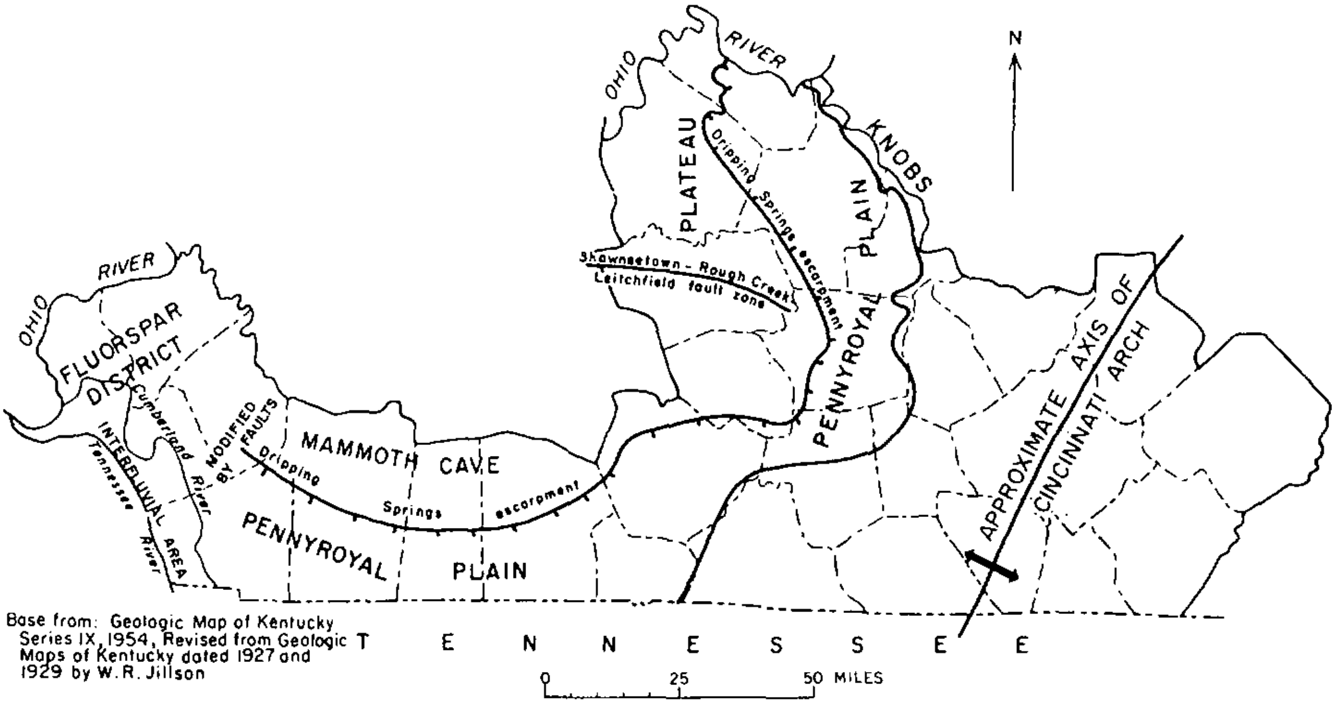
By rights, the Carter County karst should be in the Kanawha section; rather, it exists as a finger of Mississippian carbonates within the northwestern portion of the Kanawha section. Nearly 200 caves are known from this area. Many of these caves are long braided networks or maze caves. Best known are Bat Cave, Saltpeter Cave, Burchetts Cave, Carter City Connection, Iron Hill System, and the Cascade System. The highest density of caves occur along the axis of a syncline, truncated by deeply entrenched Tygarts Creek. This structural setting provides for maximum rock fracturing along the axis of the syncline, giving rise to network cave development. Cave entrance distribution in Carter County shows a northeast-southwest stike orientation along the Pottsville Escarpment. Major streams follow this trend toward the Ohio River.

Pseudokarst in the form of natural bridges, rock shelters, lighthouses, and dolines are well developed adjacent to valleys breaching the Pottsville Escarpment. These features have formed in the Lee Formation, a sandstone-conglomerate of Early Pennsylvanian age. Best recognized are the natural bridges and pseudokarst caves of the Red River Gorge in Powell County and the Natural Arch in McCreary County.

Inspection of cave entrance density reveals a dominant northeast-southwest trend parallel to the strike of the Pottsville Escarpment. Dominant cave passage trends are to the northeast and northwest. This same pattern is repeated in most of the major caves throughout the State. Structural upwarping of the Cincinnati Arch and development of the Appalachian Mountain System are responsible for fostering the original fracture pattern, visible today in this dominance of cave passage trends.

Mississippian Plateaus Region

The Mississippian Plateaus Region (Fig. 3) is the largest single continuous sequence of exposed fractured karsted carbonate rocks in Kentucky. The



Base from: Geologic Map of Kentucky Series IX, 1954, Revised from Geologic Maps of Kentucky dated 1927 and 1929 by W.R. Jillson

Figure 3. The Mississippian Plateaus Region, which contains 2,125 known caves, including Mammoth Cave.

region contains the largest compliment of caves with 2,125 known; the largest cave system in the world, Mammoth Cave; and a collection of lesser systems that are among the great long caves in the world: Whigpistle, Hicks, Big Bat, Lost River, Lisanby, Big Sulphur, and Gradys.

There is a distinct regional clustering of cave entrances along the Chester Escarpment from Brandenburg in Meade County through Bowling Green in Warren County. Cave entrance density declines in both directions away from the escarpment. The largest of the cave systems are all found beneath the Chester upland or below outliers from this landform.

Large graded trunks and bedding plane tubes are the typical cave passages. These passages occur in the Middle Mississippian carbonate units. In contrast, the character of the cave passages in Chesterian rocks is joint determined maze.

Just north of Mammoth Cave is a Pennsylvanian conglomerate and sandstone filled fossil river valley. Contained within the Brownsville Channel are pseudokarst caves, dolines, springs, and ponors. Representative are: Big Spring, Holley, and Lines caves. Deep shafts have formed as a result of initial pseudokarst development followed by interstratal karstification at clastic-carbonate contacts. Good examples can be seen at Frenchman Knob Pit and Lost Hound Pit, Hart County.

In the far northwestern part of the region is the Western Kentucky Fluorspar District. The Rough Creek Fault Zone has intensively fractured this part of the State. It is the site of hydrothermal activity. Karstification has occurred along the faults, joints, and bedding planes. These features have been filled in with minerals from the hydrothermal activity. Over 50 caves are known from this locality. The relationship between hydrothermal activity, and cave development is a subject for further investigation.

Western Kentucky Coal Field Region

Like the Kanawha Section in the Eastern Kentucky Coal Field Region, cave development is sparse in this region of Kentucky. The few caves that are found are mostly clustered along the strike of the Pottsville Escarpment, and rapidly decrease in number westward into the interior of the structural basin. More than 60 caves are known from this region.

Tectonic activity along the Rough Creek Fault Zone has fostered the conditions for cave development in central Grayson County. More than two thirds of the caves known in the county occur on or adjacent to faults. A large scale polje, called The Sink, is developed along the Rough Creek Fault Zone in Mississippian carbonates. This polje is more than 40 km west of the nearest surface outcrop of Middle Mississippian rocks.

Jackson Purchase Region

The Jackson Purchase Region in western Kentucky is part of the northern extension of the Mississippian Embayment. The embayment was filled in with continental sediments at the close of the Cretaceous Period. These sediments have buried the western end of the Mississippian Plateaus Region. There are no enterable caves in this section of Kentucky; but, well drilling activity has recorded karren topography with 15 to 30 m of relief, buried beneath more than 305 m of sediment. Karst cavities or better yet, caves, occur below the karren zone of Paducah.

Blue Grass Region

The Blue Grass Region can be divided into three main sub-regions: Inner Blue Grass, Eden Shale, and Outer Blue Grass (Fig. 4). The geomorphic subdivisions are defined upon lithologic and structural controls of the Cincinnati Arch and the upwarped Lexington Dome. The overall picture is one of concentric bands of contrasting rock types. The Inner Blue Grass contains Middle Ordovician carbonates and shales; the Eden Shale Belt contains Upper Ordovician shales; the Outer Blue Grass contins Upper Ordovician and Silurian-Devonian carbonates and shales.

Inner Blue Grass Subregion

The cave and karst area of the Inner Blue Grass is a triangular area centered in Fayette County. Its base is just east of Lexington and its apex extends into Woodford County. The highest density of caves occurs in central Woodford, Fayette and Jessamine counties. In southern Fayette and in Jessamine counties, cave and pit entrances show good parallel alignment along the strike of master streams.

Few caves are developed east of the Lexington Fault System, which is the eastern limits of the

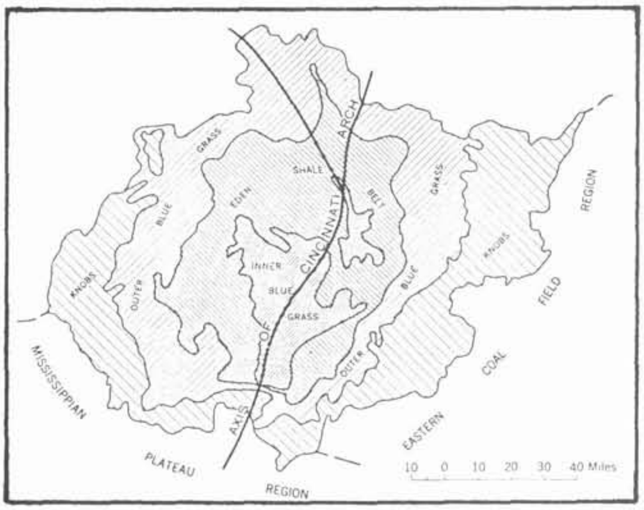


Figure 4. Divisions of the Blue Grass Region, showing the concentric bands of contrasting rock types.

Lexington karst. There is a recurrence of caves in central Bourbon and Clark counties. The caves and karst of Clark County are in one of the few areas where the Eden Shale is thin, and caves have formed in the underlying carbonates adjacent to stream valleys. This situation also holds true for the karst in the vicinity of Harrodsburg, Mercer County.

Representative caves in this locality are: Bryants, Russell, Phelps, and Boggs. Over 260 caves have been inventoried in this locality.

Eden Shale Belt Subregion

Generally, the Eden Shale Belt is devoid of cave development, except where the shale aquitard is thin and the underlying carbonates are in close proximity to base level drainage.

Outer Blue Grass Subregion

The Outer Blue Grass marks the recurrence of high density cave and karst development. As in the Inner Blue Grass, cave entrances tend to cluster near base level drainage and rapidly decrease toward drainage divides. There are two areas where most of the caves occur. Several caves, such as Adams Saltpeter Cave in Madison County are found in the southern part of the subregion. The majority of the caves are related to the deep entrenchment of the Ohio River and its tributaries along the following counties: Henry, Oldham, Trimble, Shelby, Jefferson, Bullitt and Nelson. About 280 caves are known and most are small in lateral extent, rarely exceeding 150 m in length. Caves tend to have big entrances whose passages degrade into crawlways.

Knobs Region

The Knobs Region contains about 15 caves. Most of the knobs are made up of siltstone and shale, which are not conducive to cave development. As Muldraughs (Highland Rim) Escarpment is approached, basal carbonates of Early Mississippian age are present on top of the knobs, and this is where the caves are located.

CONCLUSION

This discussion has only been a brief overview of the distribution of caves in Kentucky. There are many caves known in addition to the ones used in the compilation of this report. Continuous effort during the last 20 years has allowed the inventory of 3,770 caves in Kentucky. If the past is any indication of the future, the next 20 years looks very bright.

ACKNOWLEDGMENT

Much thanks to all individuals who contributed cave data over the years.

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Chapter 3

THE INNER BLUE GRASS KARST REGION

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This discussion of the Inner Blue Grass Region of central Kentucky has been extracted from chapters A and F of Thrailkill and others (1982). Only minor changes have been made to correct typographic errors and delete references to other chapters and omitted portions of chapters A and F.

The principal method used to study the area was water tracing, and a description of the dyes and techniques used, as well as related laboratory studies (Society of Dyers and Colouriets, 1971; Quinlan 1977; Quinlan and Rowe, 1977; McCann, 1978; Byrd, 1981; Quinlan and Ewers, 1981; Spangler, 1982; Spangler and others, submitted for publication) are described in Thrailkill and others (1982).

The focus of work in the region has been on the geological, water supply, and environmental aspects of the karst and its aquifer, and although valuable information on these subjects has been obtained from studies in caves (as will be discussed), such studies have been incidental to the regional study to date. No listing or cave locations will be presented, both because such a listing would be incomplete and because of the sensitive landowner relationships that exist in many areas in the region.

The information that has served as the basis of the discussion that follows has largely been derived from area studies in portions of the region outlined on Figure 1. The field investigations in these areas were conducted by M. R. McCann (Northeast Woodford County area), M. W. Hooper, Jr. (Mercer County area), L. E. Spangler and J. W. Troester (northern Fayette and southern Scott counties area), and D. R. Gouzie (Walnut Hill area). None of what follows would have been possible without their efforts. A description of each of these areas, as well as detailed information on the dye traces made and spring discharges determined, is found in Thrailkill and others (1982).

Portions of the work described in the present report have already appeared (McCann, 1978; Thrailkill and Troester, 1978; Thrailkill, 1980; Thrailkill and others, 1980; Spangler and Thrailkill, 1981; Thrailkill and others, 1981; Spangler, 1982) or have been accepted for publication Thrailkill and others, accepted for publication).

Major support for this work was provided by the Office of Water Research and Technology (now within the United States Geological Survey), United States Department of Interior, as authorized by the Water Research and Development Act of 1978, Public Law 95-467. Additional funding was from the McFarlan Fund of the Department of Geology, University of Kentucky; Dames and Moore; the Georgetown Municipal Water and Sewer Service; the National Speleological Society; and the Institute for Mining and Minerals Research, and the Research Committee of the University of Kentucky. The support of these agencies, as well as the landowners of the region and the many others who have assisted the research is gratefully acknowledged.

Work has, and is, continuing in the 3 years since the discussion that follows was written. Some of the research is described in Byrd and Thrailkill (1983), Hooper and

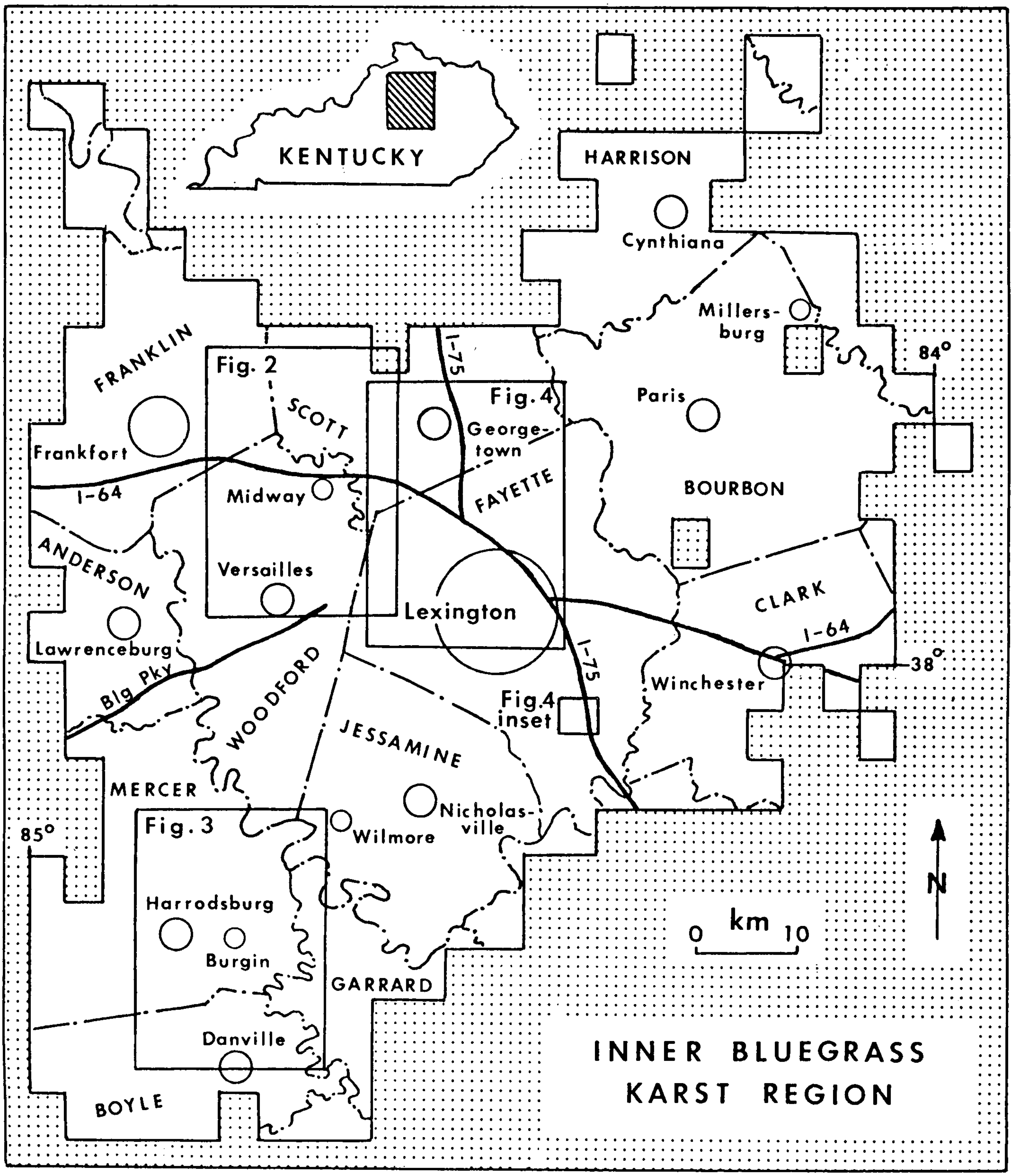

Figure 1. Map of Inner Blue Grass Region. Coverage of larger scale maps in Thrailkill and others (1982) is also shown.

Thrailkill (1983), Thrailkill (1983), Thrailkill (1984), Thrailkill and Gouzie (1984), and Thrailkill (accepted for publication).

INNER BLUE GRASS REGION

The Inner Blue Grass Region is an area of 5,600 km² in central Kentucky. It is largely a gently rolling upland at an altitude of 250 m, with generally less than 50 m of relief, that has been termed the Lexington Peneplain (Jillson, 1961). Most of the streams which drain the area are on the upland, but the Kentucky River, that crosses the region, has incised a gorge more than 100 m deep. Altitudes range from 350 m in the southeastern portion of the upland to 130 m along the Kentucky River where it leaves the region in the northwest.

Although the streams on the upland surface appear to provide normal surface drainage, numerous karst landforms (especially sinkholes) are present, and portions of the region, some with areas in excess of 10 km², have no surface drainage. The outlines of the region (Fig. 1) were defined by including within its boundaries all 7.5-minute quadrangles (1:24,000) that depict at least one sinkhole by topographic contours (interval 3.0 to 6.1 m) in rocks of Middle Ordovician age. The Inner Blue Grass Region is both geographically and stratigraphically distinct from another extensive karst area (a portion of which has been termed the Central Kentucky Karst) in Mississippian rocks, as well as from smaller karst areas in Kentucky in Upper Ordovician and Silurian rocks.

The mean annual precipitation is about 1,150 mm, fairly evenly distributed throughout the year. Mean July and January temperatures are about 25 and 0°, respectively. The regolith is often a meter or more thick and is generally considered to be residual. The entire region is south of the area modified by Pleistocene glaciation. The present populaton is in excess of 350,000, of which more than half is concentrated at Lexington, the second largest city in Kentucky, which lies near the center of the region (Fig. 1).

Geologic Structure

The region occupies the area where carbonate rocks of Middle Ordovician age have been exposed by erosion on the crest of the Cincinnati Arch, a regional structural feature of the eastern United States. Regional dip is generally away from the highest point on the arch in Jessamine County (Fig. 1) in all directions except to the southeast, where the rocks have been down faulted. Regional dip is gentle (on the order of 10 m/km), and the beds seen in outcrops generally appear nearly horizontal.

The southeastern boundary of the region follows the Lexington Fault System in the south and the intersecting Kentucky River Fault System to the east (Black and others, 1977). The eastern and southern sides of these fault systems are downdropped, and unkarstified Upper Ordovician limestones and shales cover the Middle Ordovician carbonates.

There are a few areas of substantial faulting within the region, such as the Switzer Graben in Scott County and the extension of the Lexington Fault System to the north. There are also a number of short, high-angle faults and mineralized veins.

Stratigraphy

The boundary of the region approximately coincides with the depositional or fault contact of relatively pure Middle Ordovician carbonates with the overlying, thinly interbedded Upper Ordovician limestones and shales. The overlying limestone and shale sequence has been designated the

Clays Ferry Formation, and the underlying carbonates are, from highest to lowest, the Lexington Limestone, Tyrone Limestone, Oregon Formation, and Camp Nelson Limestone.

All of the area studied to date has been in the lower portion of the Clays Ferry Formation and the upper two-thirds of the Lexington Limestone. The lower third of the Lexington Limestone (including the Logana and Curdsville members) and the three formations below it are exposed only in the gorge of the Kentucky River and the lower reaches of its tributaries, and underlie areas not yet investigated. Furthermore, it is believed the subsurface circulation of meteoric water within the area studied does not extend into these units; therefore these units will not be further considered.

The principal lithologic characteristic of hydrogeologic interest in the Lexington Limestone and overlying Clays Ferry Formation is the amount of insoluble material in the latter and in units of the former. This factor has been considered a major control in the development of solution openings by most earlier workers (Hamilton, 1948, 1950; Palmquist and Hall, 1961; Mull, 1968; Faust, 1977). Stratigraphic descriptions of the Clays Ferry Formation and the various subunits of the Lexington Limestone accompany the published geological quadrangles of the area studied (Black, 1964, 1967; Cressman, 1964, 1967, 1972; Kanizay and Cressman, 1967; Miller, 1967; MacQuown and Dobrovolney, 1968; Pomeroy, 1968, 1970; Cressman and Harbar, 1970; Allingham, 1972). These descriptions are believed to be based generally on hand specimen examination and usually state the approximate percentage of clay, chert, and other insoluble components, as well as note the occurrence of minerals such as dolomite and apatite.

In a study of the Lexington Limestone in Franklin County, Fisher (1968) found that the maximum insoluble content of the Grier and Tanglewood limestone members was 15 percent and averaged less than 5 percent. His data also indicate that the maximum content of insoluble minerals in units generally considered argillaceous (Macedonia Bed and Brannon Member) was only 25 percent, and that lithologies usually described as shales are usually more than 50 percent calcite and dolomite.

Cressman (1973) calculated normative mineral percentages based on chemical analysis of 15-cm core segments from the Clays Ferry Formation and the Millersburg, Brannon, Tanglewood Limestone, and Grier Limestone members of the Lexington Limestone. Analyses were performed on five core segments selected randomly from the core available for each of the five units. The mean quartz plus clay content calculated for the Grier and Tanglewood limestone members was 8 percent and 5 percent respectively. For the remaining three units (considered argillaceous) these amounts were: Brannon Member, 38 percent; Millersburg Member, 35 percent; and Clays Ferry Formation, 44 percent.

Although dolomite is present in most of the units, especially the more argillacious ones, it generally occurs as isolated rhombs. Fisher (1968) found the dolomite-calcite ratio to be generally less than 0.2 and to exceed unity only in one thin (less than 1 m) bed in the Grier Limestone Member. The normative mineralogy calculated by Cressman (1973) yields mean values of this ratio to be 0.1 and 0.17 for the Grier and Tanglewood limestone members, respectively; the three argillacious units he examined range from 0.23 to 0.46 (above).

The stratigraphic nomenclature used on the various geologic maps is not always consistent, and the terminology of Cressman (1973) will be used in this report. Except for the Clays Ferry Formation and Millersburg Member, all of the argillaceous units (11 units of the Lexington Limestone except the Clays Ferry) are less (actually considerably less) than 6 m thick. The delineation of the various units is based on lithology, and the units show complex gradational and intertonguing relationships, which often result in multiple occurrences of a unit in the stratigraphic section.

In the northeastern Woodford County, northern Fayette and southern Scott counties, and Walnut Hill areas, the relatively pure Tanglewood and Grier limestone members make up most of the section. The argillaceous Millersburg Member, Greendale Lentil, and Stamping Ground Member occur within the Tanglewood, the Brannon, and Cane Run members at or near the Tanglewood - Grier contact, and the Macedonia Bed occurs within the underlying Grier. In the Mercer County area, two relatively pure units overlie the Tanglewood, and only two of the argillaceous units within the Lexington Limestone are present. These relationships, which are considerably simplified, are shown in Table 1. Subdivisions of the Perryville in the Mercer County area (i.e., Cornishville and Salvisa beds) and the thin pure Devils Hollow Member within the Tanglewood in the northeastern Woodford County area have been omitted.

Previous Hydrogeologic Investigations

A number of hydrogeologic studies of the Inner Blue Grass Region have been published. The earliest of these, by Matson (1909), dealt with the larger Blue Grass Region, which includes extensive non-karst areas outside the Inner Blue Grass Region. He presented data on a number of wells in the present study area (e.g., 48 in Fayette County, 30 in Scott County, and 20 in Mercer County), but with such general locations that they could not be utlized in this study. His discussions of the hydrogeology are general and lack conclusions regrading controls of groundwater occurrence and movement in the Inner Blue Grass Region. Although he mentioned a trace to a spring with oil and NaCl, and that NaCl was used in an examination of Royal Spring (Matson, 1909, p. 80-81), he gives no location information. The only published information on water tracing in

Table 1.--Stratigraphic Units in the Study Area. All (Except Clays Ferry Formation) are Units of the Lexington Limestone. *Indicates Unit Present Only in Mercer County Area: **Indicates Unit not Present in Mercer County Area.

LIMESTONE UNITS	ARGILLACEOUS LIMESTONE UNITS
	Clays Ferry Formation
	Millersburg Member**
Sulpher Well Member*	Greendale Lentil**
Perryville Limestone Member*	Stamping Ground Member
Tanglewood Limestone Member	Brannon Member
Grier Limestone Member	Cane Run Member**
	Macedonia Bed

the region prior to the present study was presented by Jillson (1945), who established flow connections in the Roaring Spring ground water basin in Woodford County.

Hamilton (1950) reported an inventory of 964 wells in a four county area (Bourbon, Fayette, Jessamine, and Scott). Although he lists the total depth of all but a few of these, he reports water levels in only 56 and hence could not prepare a map of the potentiometric surface. He states that only about one out of five wells drilled is productive (Hamilton, 1950, p. 47-48) and concluded (also in Hamilton, 1948) that solution porosity is limited to a depth of 25 meters, that such porosity is developed mainly along joints and is greatest in topographically low areas. He states that argillaceous limestone units within the Lexington Limestone play a major role in that they severely inhibit the downward circulation of meteroic water and hence retard the development of solution porosity in the rocks that underlie them. His maps, which delineate areas of high, intermediate, and low probability of obtaining a satisfactory yield and quality of groundwater, are apparently based mainly on stratigraphy.

A series of hydrogeologic maps covering the Inner Blue Grass Region (Hall and Palmquist, 1960a-d; Palmquist and Hall, 1960a-c) were issued as part of a statewide project, and a discussion of the hydrogeology of the larger Blue Grass Region (whose area is nearly 30,000 km²) was published in Palmquist and Hall (1961). The hydrogeologic maps indicate areas of high, intermediate, and low probability of satisfactory well yield and quality. Although this approach is the same as the one used by Hamilton, the two assessments are often quite different for the same area (Hamilton, 1950; Palmquist and Hall, 1960c). Variations between the assessments are probably due to differing evaluation criteria and the density of well control. Palmquist and Hall's map (1960c), of the same four counties studied by Hamilton (1950) is apprently based on 64 wells and 31 springs, as opposed to the 964 wells listed by Hamilton. Their summary states that 35 wells and springs were inventoried in each county and that water levels were measured in most wells (Palmquist and Hall, 1961, p. 3, 15), but they give neither the water level nor a map of the potentiometric surface.

The summary (Palmquist and Hall, 1961) covers the entire Blue Grass Region, and it is difficult to separate their conclusions on the Inner Blue Grass Region from the largely unkarstified areas that surround it. They appear to ascribe differences in well yields in the Inner Blue Grass Region more to topographic position than to stratigraphy (reflected in their hydrogeologic maps), which is more or less the reverse of Hamilton's (1950) criteria. They also state that less than half of the wells drilled in the bedrock are successful (Palmquist and Hall, 1961, p. 21).

Henderson and Krieger (1964) presented a summary of the geochemistry of waters of the entire Blue Grass Region. A brief report and map on the hydrogeology of Fayette County by Hopkins (1966a) explains groundwater flow in terms of regional and local potential gradients controlled mainly by topographic factors, and evaluates areas along mapped surface streams as having the best prosects for groundwater development.

A report by Mull (1968) also dealt with the hydrogeology of Fayette County, but the most detailed groundwater investigation was in the Georgetown Quadrangle extending to North Elkhorn Creek in Scott County. Mull considered that the direction of groundwater movement was controlled by the dip of the rocks and the topography, and presented his data on water levels in 54 wells on the structure contour map.

A study of wells in the Centerville Quadrangle in Bourbon, Fayette, and Scott counties (Johnson, 1970; Johnson and Thrailkill, 1973) was designed to evaluate the relative importance of the various factors proposed by earlier workers. Based on information (much of it from Hamilton, 1950) from 82 wells classified as adequate, sulfur, salt, or dry, nonparametric statistical methods were used to test the effect of a number of topographic, stratigraphic, or structural variables. Although apparently significant relationships were found, the interdependence of topographic and stratigraphic variables in an area of nearly horizontal beds made the results difficult to interpret.

Faust (1977), in a study of a six-county area (Bourbon, Clark, Fayette, Jessamine, Scott, and Woodford), prepared the first potentiometric map in the region. At the small scale of the map, it appears to conform rather closely to topography. The map was based on data from more than 500 wells (Faust, 1977, p. 9), but the data are not shown. Faust also outlined the recharge areas of a number of springs and wells, including Royal Spring, Spring Station Spring, and Versailles Spring. Like earlier workers, he believes the yield of wells is related both to topography and stratigraphy.

There are also a number of Statewide reports that furnish specific hydrogeological informaton within the region. These reports include Van Convering (1962) on large springs, Hopkins (1966b) on the elevation of the fresh-saline water interface, Whitesides (1971) on specific capacities of wells, and a series of annual water resources reports containing daily water level data in (currently) four wells in the Inner Blue Grass Region (United States Geological Survey, 1983, is the most recent).

Other publications dealing primarily with other aspects of he geology of the region have included data and discussions of the hydrogeology. MacQuown (1967) located 16 springs and 2 wells in a study of the Curdsville Limestone Member, the basal unit of the Lexington Limestone. He found that some of the springs emerged at or near the contact of limestone beds and thin bentonites and other shale units, and that the vertical intergranular porosity and permability of the Curdsville was quite low. Another aspect of his investigation showed that trends of sinkhole and stream allignments were similar to joint orientations in the Bryantsville Quadrangle in the southern part of the region. An expanded discusson of this relationship can be found in Hine (1970), who also showed that joints and fracture traces (identified by soil tone on aerial photographs) tended to be parallel as well, and who located 5 wells in the Bryantsville Quadrangle, at least one of which was on sinkhole trend.

GROUNDWATER BASINS

The present day study has shown that the major flow of subsurface water in those portions of the Inner Blue Grass Region investigated is in at least 38 individual basins. The term "groundwater" is usually reserved for potable water in saturated voids which is beneath the potentiometric surface and hence at pressures greater than atmospheric. Because these basins contain such water, they will be referred to as "groundwater basins" although much of their flow is unsaturated and above the potentiometric surface in what is termed the "vadose zone." These concepts will be discussed later.

Flow within each basin is dentritic, in that recharge from swallets, sinkholes, and elsewhere successively coalesces to emerge at a spring that drains the basin. A few such springs, such as Roaring Spring, Burgin Spring, and Cove Spring have multiple outlets, usually within a few tens of meters of each other; in two or more of the outlets dye was detected during some traces. In no instance, however, did dye detection indicate flow between adjacent basins. In a few basins (Roaring Spring, Distillery Spring, Slacks Spring, and Vaughans Spring), major flow appears at the surface at the bottom of deep sinks (karst windows), and discharge from Spring Lake Spring feeds a surface stream that flows into a swallet of the Lindsay Spring Basin.

Although groundwater basins are a fundamental element of the hydrogeology of the region, there has been little discussion by previous workers. Palmquist and Hall (1961, p. 14) considered groundwater in the entire Blue Grass Region (including the Inner Blue Grass Region) to occur in small, self-contained units that, with few exceptions, coincide with surface watersheds. Faust (1977, p. 12-13), outlined the recharge areas of selected points, including Royal, Spring Station, and Versailles springs. He states that such recharge areas generally coincide with surface drainage basins, and apparently based his delineation of recharge both on topography and his potentiometric surface map.

Basin Identification, Size, and Location

Outlines of the 38 basins were drawn to enclose swallets from which dye traces were made to major springs. Although subsurface drainage from untraced swallets within the basins as outlined probably also discharges at the spring, details of basin shape are largely unknown, especially for basins identified by only a single dye trace.

The area of each basin (Table 2) was estimated from the area outlined and ranges from less than 0.5 km^2 up to 15 km^2 for the two largest. It should be emphasized that the areas given are those that are believed to be underlain by an integrated conduit system, and that the catchment area of the spring is usually much larger, since it includes areas of shallow subsurface or surface flow outside the basin boundaries. The areas given in this report (Table 2) are thus generally much smaller than earlier estimates (Spangler and Thrailkill, 1981; Thrailkill and others, 1981; Spangler, 1982), which were based on the catchment area. These relationships are shown in Figure 2.

In one location where surface flow was observed between a spring (Spring Lake Spring) and a swallet (in the Lindsay Spring Basin), the length of the surface flow path suggests that the two basins should be identified separately. Other instances where such flow is seen, are in the bottom of a deep sinkhole or blind valley, and the feature is considered a karst window within the basin. Groundwater basins were not defined for the short dye traces to Bailey and Paxton Springs because of lack of evidence of the existence of deep integrated flow conduits considered characteristic of groundwater basins.

Some of the smaller groundwater basins appear to underlie surface drainage basins (e.g., Baker Cave, Gano Spring, and Santen Spring), while others do not (e.g., Cove Spring, Elkhorn Spring, and Sharp Swallet). At least some flow indicated by dye traces in all of the larger basins (5 km^2 or more in area) passes beneath surface divides, and the shape of most larger basins shows little correspondence to present or inferred former surface drainage (e.g., Roaring Spring, Slacks Spring, Russel Cave, and Burgin Spring basins). In a few basins

Table 2.-- Springs and Groundwater Basins in the Study Area.

	SPRING		GROUNDWATER BASIN	
	Name	Magnitude	Name	Area (km^2)
1.	Bailey Spring	-	-	-
2.	Baker Cave Spring	4+	same	2
3.	Big Spring	3+	same	9
4.	Blue Spring	-	same	1
5.	Boggs Spring	4-	same	1
6.	Boone Spring	4-	Distillery Spring	<.5
7.	Bryan Station Spring	-	-	-
8.	Burgin Spring	3-	same	11
9.	Cougar Spring	5+	-	-
10.	Cornett Spring	4-	same	1
11.	Cove Spring	4+	same	1
12.	Distillary Spring	-	same	2
13.	Elkhorn Spring	-	same	<.5
14.	Eureka Spring	3-	same	2
15.	Gano Spring	3-	same	2
16.	Gay Sink Spring	3-	Roaring Spring	7
17.	Hartman Spring	3-	same	1
18.	Holland Spring	-	same	<.5
19.	Humane Spring	3-	same	1
20.	I-75 Pond Spring	-	same	<.5
21.	Jennings Spring	-	same	1
22.	Lindsay Spring	3+	same	5
23.	McGee Sink	-	Vaughan Spring	4
24.	Nance Spring	-	same	3
25.	Paxton Spring	-	-	-
26.	Pin Oak Spring	4-	same	2
27.	Railroad Spring	-	same	2
28.	Roaring Spring	3+	same	12
29.	Royal Spring	2-	same	15
30.	Russell Cave Spring	3+	same	9
31.	Santen Spring	4+	same	2
32.	Shawnee Copper. Spring	4+	same	1
33.	Shawnee Hefer Spring	3-	-	-
34.	Shawnee Run Spring	3-	same	4
35.	Silver Springs	3-	same	7
36.	Slacks Spring	3-	same	15
37.	Slacks Cave	-	Slacks Spring	13
38.	Sloans Spring	4-	Slacks Spring	12
39.	Spring Lake Spring	3-	same	1
40.	Spring Station Spring	3-	Royal Spring	10

Table 2.-- Continued.

41.	Steeles Spring	-	same	1
42.	Swopes Spring	-	Roaring Spring	-
43.	Tevis Spring	5-	same	1
44.	Spring 13	4-	same	2
45.	Spring 13B	4-	-	-
46.	Vaughans Spring	3+	same	5
47.	Versailles Spring	4+	same	2
48.	Votah Spring	3-	same	3
49.	Wests Spring	3-	-	-
B3	-	-	Sharp Swallet	1
C16	-	-	Duval Cave	1
D57	-	-	Ansley Swallet	1

(e.g., Lindsay Spring and Vaughans Spring), underground flow is known to pass beneath perennial surface streams.

Interbasin Areas and Basin Shape

Relatively few dye traces were conducted in the northeast Woodford County and Walnut Hill areas, and further work would probably result in the enlargement of the known groundwater basins and the discovery of new basins. While similar results would be likely near the margins of the Mercer County area and the northern Fayette and southern Scott counties area, intensive reconnaissance in the central portion of these areas (especially the latter) has shown that swallet are much less common between the outlined basins. Furthermore, dye introduced in each swallets emerged at small springs a short distance down slope after following shallow flow paths. Examples of such traces (none over 500 m long or with a vertical drop of more than 3 m) were those to Paxton Spring and to Bailey Spring.

This absence of deep, integrated, subsurface drainage between basins is more marked than the simple reduction in size of conduits that might be expected as the divide between basins is approached, and the term "interbasin areas" will be used for these portions of the region.

Within interbasin areas, infiltrating water from slopes and shallow sinkholes is believed to flow in small conduits at or just below the interface between the bedrock and overlying regolith. Flow is generally down the topographic slope and emerges at small, often ephemeral, high-level springs. Streams fed by such spings generally flow on the surface but may be diverted into shallow subsurface conduits adjacent to the stream channel for short distances. If and when such a stream enters a groundwater basin, its flow is diverted underground by a swallet to emerge at a major spring, often several kilometers distant.

The bottoms of most of the major stream valleys (e.g., South Elkhorn Creek, North Elkhorn Creek, Town Branch, Lower Cane Run, and the Salt River) appear to lie in interbasin areas. Faust (1977, p. 12 and plate 3) described losing reaches on both North and South Elkhorn Creeks, and gaging stations on these creeks not uncommonly report no surface flow (U.S. Geological Suirvey, 1983). It is likely, therefore, that a portion of the flow of the major surface streams

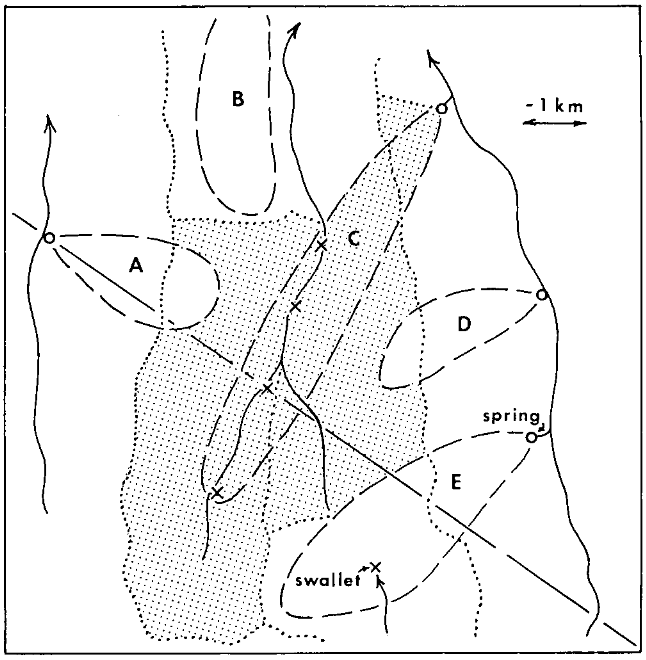

Figure 2. Map showing relationship of groundwater basins (dashed outlines) to surface streams (solid lines) and surface divides (dotted lines). Catchment area of spring C shown by dotted pattern. Although diagrammatic, map approximates the eastern portion of the northern Fayette and southern Scott counties area, where A through E are the Silver Spring, Slacks Spring, Royal Spring, Vaughans Spring, and Russell Cave Spring basins, respectively. Long dashes indicate line of section of Figure 3.

is diverted into conduits through swallets in the channel and returns in inconspicuous springs in the stream bed. Such conduits are probably shallow, as are the conduits in interbasin areas at higher elevations, but may be of considerable size because of the larger flow volumes. They are probably present mainly in the vicinity of the channel, but may cut across bends and meander loops.

Thus while there is only shallow subsurface flow in interbasin areas, the interbasin areas form part of the catchment area of major springs draining groundwater basins; the boundaries between adjacent catchment areas within an interbasin area probably conform closely to surface divides.

Although the shallow subsurface flow described above is characteristic of interbasin areas, it also occurs within the basins as outlined. As an example, the traced swallets in the Shawnee Run Spring Basin are fed by flow from high level springs within the basin, and there appear to be extensive and numerous areas of such shallow subsurface flow within many of the basins. An alternative way of depicting such basins would be as narrow strips adjacent to the major flow conduits, but since the location of these conduits is generally unknown, and because there is some evidence from wells that at least the Slacks Spring Basin is developed over a considerable area, as discussed below, this was not done.

Attempts to more closely define the boundaries between basins and interbasin areas were also complicated by evidence that such boundaries cannot be simply depicted in two dimensions, because basin flow conduits appear to be developed beneath what appear to be interbasin areas in a few cases. This situation is illustrated by the Lindsay Spring and Silver Springs basins, in which the major flow conduit passes beneath streams (fed by high-level springs) that remain entirely on the surface.

In contrast to the conduits in upland interbasin areas that are just beneath and roughly parallel to the land surface, the major flow conduits in groundwater basins appear to have gradients similar to surface streams and thus are nearly horizontal and only slightly above the level of the discharging spring. Although the path followed by water immediately after it enters a swallet is usually unknown, in a few instances where it can be observed in caves and pits it is usually steep and often nearly vertical. Such high gradients were observed as often near the margins and upstream portions of basins as in the center and downstream portions.

The evidence available, therefore, suggests that the base of the zone of active meteoric water circulation is nearly flat in groundwater basins (and as much as 30 m deep beneath topographically high areas), rises abruptly at basin margins, and is within a few meters of the surface in interbasin areas. Thus groundwater basins in the Inner Blue Grass Region are believed to resemble U-shaped valleys, as shown in Figure 3.

GROUNDWATER BASINS AND KARST LANDFORMS

The Inner Blue Grass Region is characterized by landforms such as "sinkholes," the distribution of which was used to define the area of the region, and which will be discussed in some detail below; "blind valleys" which terminate downstream as the entire flow of a surface stream is diverted underground; "pocket valleys," which begin abruptly upstream at a major spring; and "karst windows," depressions in which a major underground flow emerges at the surface as a spring and is then diverted underground (the length of the surface flow varies from what appears to be a pool in the bottom of a deep sinkhole (e.g., McGee Sink) to a stream several hundred meters long flowing in what may be described as a combination of a pocket valley and a blind valley (e.g., the channel below Spring Station Spring). The flow in these landforms is major subsurface flow at or very near the potentiometric surface. The numerous sinkholes in the region that contain a small stream fed by a high-level spring which sinks in the bottom of the sinkhole are not karst windows); and "paleovalleys"

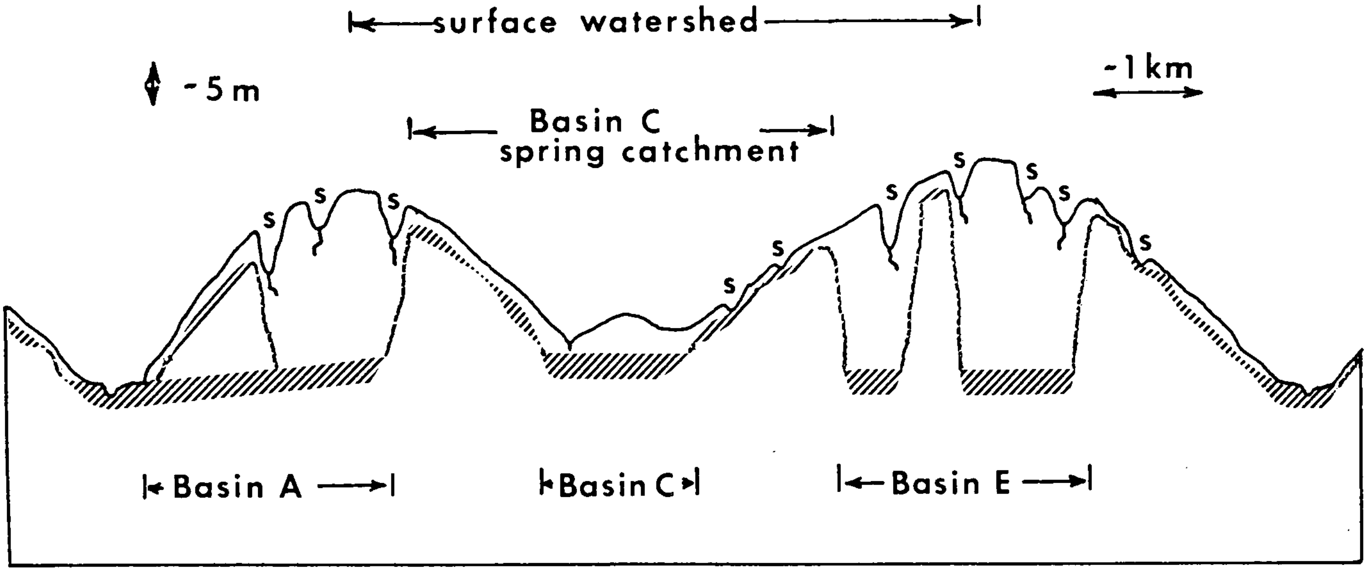

Figure 3. Cross section of groundwater basins and interbasin areas along line on Figure 2, showing aquifer (lined pattern) and base of zone of meteoric water circulation (lower limit of lined pattern and dashed line). Note portions of basins A and E with interbasin area characteristics (penetrated by deep flow in basin A). The relationship of basin C to the catchment area of the draining spring and the surface watershed of the stream that overlies it is also shown. Sinkholes indicated by S. Vertical exaggeration approximately 100X.

which appear to be normal surface valleys but contain no surface stream channel. Paleovalleys usually contain a series of sinkholes in their bottom, and apparently formed when their surface stream was diverted underground at several points along its course, forming a series of blind valleys, followed by complete abandonment of surface flow except possibly during high discharge events.

Except for some sinkholes, all five of these landforms are the result of deep circulation of subsurface water, and their presence in an area should indicate the existence of a groundwater basin, allowing the location and extent of basins to be at least estimated from an examination of the topographic maps. Although some correlation appears to exist, it has not been possible to rely heavily on it because of sinkhole modifications and the inadequacy of available maps. Before examining these factors further, a discussion of the origin of sinkholes in the region is appropriate.

Sinkhole Origin

Contrary to widely held and stated opinion, the collapse of the roofs of caves is *not* the principal cause of sinkholes in the region (nor, for that matter, in any other karst area with which the author is familiar). Of the many sinkholes examined in the region, cave roof collapse is not believed to be a major factor in the origin of any. Rather, they are produced by solution of the limestone bedrock at the contact with the overlying regolith by water that has infiltrated from the surface, the same process that occurs nearly everywhere in the region and has probably been the principal agent in the lowering of the bedrock surface through time.

Although there will be some penetration of the bedrock under a hill slope through many closely spaced, very small diameter conduits, solution at the base of the bedrock will be accelerated in the vicinity of the larger conduits, and the more rapid lowering of the bedrock interface nearby will cause the capture of more flow from adjacent conduits, and hence increased bedrock solution. When the resulting subsidence of the overlying regolith (which initially is reflected by a simple flattening in the surface slope) is sufficient to reverse the downhill slope, a topographic depression is formed and a *type one* sinkhole results.

The existence of a topographic depression will further accelerate the enlargement of the conduit, since most of the water that infiltrates the surface within the depression will flow through it (although some of the flow will probably still be carried by smaller conduits). Major deepening and widening of the sinkhole will probably not occur, however, until the conduit becomes enlarged by solution throughout its length to the degree that the water flowing through it can transport particles of regolith, after which time the depression becomes a *type two* sinkhole. The volume of regolith removed may now exceed the amount of limestone dissolved, to the extent that bedrock is exposed on its sides or bottom. Although it seems likely that a topographic depression is generally formed prior to the onset of regolith removal (i.e., type one precedes type two), this may not always be the case, especially since the general downslope movement of regolith on hillslopes will tend to fill type one depressions or prevent them from forming.

A *type three* sinkhole is formed when the conduit is large enough and flow velocities are high enough for insoluble or otherwise resistent beds that tend to perch the conduit to be eroded through. Type three sinkholes have steep or near vertical drains to depth and their flow is integrated into the dendritic system of a groudwater basin. The various types of sinkholes are shown in Fig. 4.

Conduits draining type one and type two sinkholes, as well as those draining pre-type one areas (incipient sinkholes), are usually nearly horizontal, as would be expected from their being perched on resistent beds. They emerge on nearby hillslopes or the heads of small valleys as small, often ephemeral, high-level springs, some of which become turbid during high discharges, indicating the sinkholes they drain have reached their type two stage.

Type one and type two sinkholes are found throughout the region, both in groundwater basins and interbasin areas, and imply no deep circulation of subsurface flow. Type three sinkholes, on the other hand, do characterize groundwater basins.

The tendency of sinkholes to occur along former lines of surface drainage is due mainly to their development being favored by the increased infiltration and subregolith flow in such areas. In some cases, however, the location of such drainage lines was controlled by reduced resistence to erosion of the bedrock, due to jointing or other factors, which would also promote more rapid conduit enlargement.

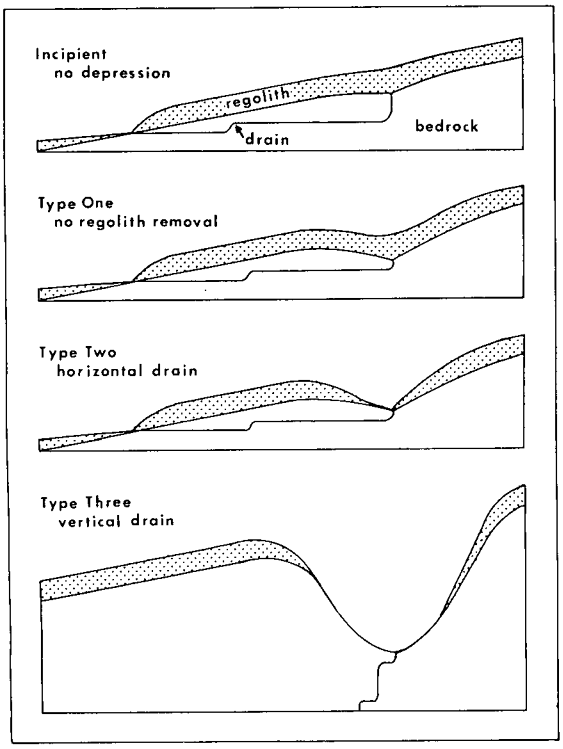

Figure 4. Types of sinkholes.

Returning to the idea that sinkholes are due to the collapse of cave roofs; the growth, and especially the deepening, of a type three sinkhole obviously is highly dependent on the efficiency with which regolith and other debris can be removed through its near vertical drain. Sinkholes located above conduits in the underlying groundwater basin system need relatively short drains to discharge sediment into the effective transport environment of the larger conduit, and are more likely than other sinkholes to deepen rapidly, possibly to the point where they break through into the underlying conduit. A relatively minor factor in this process (which is believed to be responsible for the formaton of karst windows in the region) may be some collapse of the roof of the underlying conduit in response to the deepening of the overlying sinkhole and enlargement of its drain.

Finally, it should be noted that in every instance of collapse at the surface in sinkholes known to the writer, the collapse has been caused by the rapid subsidence due to transport of regolith by infiltrating water within a type two or more commonly a type three sinkhole, and no collapse of bedrock is involved. The balance between water and regolith transport through the sinkhole drain suggests that such events should be common, but their occurrence has been greatly influenced by the practice of sinkhole filling, discussed below. Regolith collapse outside of sinkholes (i.e., not in topographic depressions) is not uncommon as well. All such collapses the writer has examined were due to the failure of the roof of a shallow conduit developed at or above the regolith-bedrock interface.

Sinkhole Filling and Map Inadequacy

In some cases, type three sinkholes, which indicate the presence of a groundwater basin, can be identified rather easily on the 1:24,000 topographic map (contour interval 3.0 or 6.1 m) of the region. The method used is to determine the minimum length necessary for the bottom of the sinkhole to be drained by a near horizontal conduit. If this length is greater than two or three hundred meters it is quite unlikely that such a horizontal sinkhole drain exists and the sinkhole is judged to be a type three. Unfortunately, the depth of sinkholes, especially the deeper ones of small areas, is almost always several meters greater than the depth depicted on the map by topograhic contours, since shadows and dense vegetation obscure their bottoms on aerial photographs. Deep sinkholes less than 50 m across are seldom shown at all on the topograhic maps. Many type three sinkholes can be identified as such only by field reconnaissance.

A second factor hinders the identification of the type three sinkholes, and hence groundwater basins, even after field reconnaissance. Deep sinkholes with steep walls provide convenient sites for rural waste disposal; often the long-term goal is to nearly fill them and render them suitable for pasture or even row crops. This effort by farmers has presumably been underway for much of the 2 centuries of agriculture in the region, with the result that many sinkholes that are actually type three now have a shallow saucer shape more characteristic of type one or type two.

The topographic maps of the region do not accurately depict many of the other karst landforms that indicate the presence of a groundwater basin. Few of the streams in pocket valleys and karst windows are shown, probably because they are so short and hidden by vegetation and shadows. Many blind valleys and paleovalleys are shown as normal surface valleys, especially when the reversed slope below swallets is gentle and short. Finally, swallets are too small to be termed landforms or to be shown even by accurate maps, although their presence is indicated in some blind valleys. Swallets along surface streams and in sinkholes (many sinkholes do not contain open swallets) can only be located in the field.

GEOLOGIC AND OTHER FACTORS INFLUENCING SUBSURFACE FLOW AND GROUNDWATER BASIN DEVELOPMENT

A major objective of the study on which this chapter was based was to evaluate the degree to which subsurface flow and the location of groundwater basins delineated by dye tracing during this study could be explained by geologic and other factors. Such an explanation would not only contribute substantially to an understanding of the nature of subsurface flow in the region, but would allow the prediction of flow directions and location of groundwater basins in portions of the region where dye tracing has not been done.

A particular emphasis was placed on the relevance to subsurface flow of the geological information contained on the U.S. Geological Survey geologic maps of the area investigated (Black, 1964, 1967; Cressman, 1964, 1967, 1972; Kanizay and Cressman, 1967; Miller, 1967; MacQuown and Dobrovolny, 1968; Pomeroy, 1968, 1970; Cressman and Harber, 1970; and Allingham, 1972), inasmuch as similar large-scale (1:24,000) maps are available for the entire Inner Blue Grass Region.

Previous hydrogeologic investigations of the region have dealt mainly with the availability of subsurface water, and have reached varying conclusions as to the importance of various factors. Hamilton (1950) believed the argillaceous units in the Lexington Limestone were the most important control of solution development, and Mull (1968) considered them a major factor. Palmquist and Hall (1961), Hopkins (1966a), and Faust (1977), on the other hand, did not emphasize the role of lithology, and considered topography to be the major factor. Mull (1968) ascribed such an important role to the dip of the rocks that he presented his well data for the Georgetown Quadrangle on a structure contour map. Hamilton (1950), Palmquist and Hall (1961), Hopkins (1966a), and especially Faust (1977) believed joints and faults played a significant role in subsurface flow and solution development. The only previous work utilizing traced flow paths was by Jillson (1945), who emphasized the geomorphic development of the flow to Royal Spring and indicated indirectly that downdip flow was a factor in its development (Jillson, 1945, p. 25-27).

Lithology of Stratigraphic Units

draining groundwater basins in the study area, two are interpreted as being perched on argillaceous units in the Lexington Limestone. In one, the perching is observable and seemingly clear cut; Shawnee Hefer Spring in the Mercer County area flows from a number of hillside outlets over a distance of 60 m along the outcrop of the Macedonia Bed. Although no dye introductions were detected at the spring, its groundwater basin probably lies to the southeast, updip from the spring. The interpretation is only slightly less certain for Spring Lake Spring in the northern Fayette and southern Scott counties area, which emerges at about the stratigraphic position of the Cane Run Bed, well above the level of major streams, and is downdip from its traced groundwater basin.

None of the other 37 major springs draining groundwater basins in the study area indicate control by stratigraphic units in the Lexington Limestone. It would seem reasonable that the few that emerge somewhat above the level of major surface streams (e.g., Gano and Steeles springs) are perched on argillaceous or otherwise resistant beds, but such beds, if present (such as the Macedonia Bed at Gano Spring) are not indicated on the geologic maps or accompanying lithologic descriptions, and were not observed in the field.

The control of shallow subsurface flow in interbasin areas (including such areas within groundwater basins) by mapped or unmapped argillaceous limestones appear to be more common. Not infrequently, two or more high-level springs will emerge at the same stratigraphic level, and in the Sinkhole Plain paleovalleys a number of such springs emerge at the top of Macedonia Bed.

There may be occasional perching of surface streams for short distances on argillaceous units (e.g., the middle reaches of Cane Run on the Cane Run Bed and the stream in the Joyland Cave blind valley on the Brannon Member), but such instances are not obvious nor widespread.

Because of the general parallelism between bedding and the overall topographic surface in the areas studied, most of the major flow conduits and springs are in the lower exposed units of the Lexington Limestone, especially the Grier Limestone, but the stratigraphic position of springs emerging from this unit varies over more than 12 m, and there is no evidence of lithologic control. Similarly, those smaller groundwater basins that approximately coincide with surface drainages have their margins beneath surface divides that are often underlain by higher argillaceous units such as the Millersburg Member and the Clays Ferry Formation. The numerous examples from both small and large basins which do not show this accord with topography, however, indicate lithologic variations in the Lexington Limestone are of little or no importance in controlling the development of major flow conduits or the location of groundwatr basins. Subsurface flow in major conduits occurs beneath all seven of the argillaceous units mapped in the area (Table 1), as follows (the location of an example is in parentheses): Macedonia Bed (Burgin Springs Basin), Cane Run Member (Royal Spring Basin), Greendale Lentil (Silver Spings Basin), Millersburg Member (Russell Cave Spring Basin), and the lower part of the Clays Ferry Formation (Cove Springs Basin).

Bedding Attitude

The parallelism between bedding and the overall topographic surface mentioned above also complicates the evaluation of the importance of the dip of the rocks in determining flow directions in groundwater basins. There is no evidence, however, of any useful relationship between flow directions as indicated by dye traces and the dip as shown by structure contours on the geologic maps. Although flow in some of the smaller basins is approximately downdip (e.g., Versailles Spring, Votah Spring, Jenning Spring basins), in others it is nearly updip (e.g., Distillery Spring, Duvall Cave, Gano Spring basins). Flow directions in the larger basins appear to be similarly unrelated to local dip. In the Lindsay Spring and Silver Springs basins, flow conduits cross mapped anticlines and synclines at right angles, and in the Russell Cave Spring basin the discharging spring and dye input points are on opposite limbs of an anticline that appears to represent the crest of the Cincinnati Arch.

Because of the problems associated with detailed structural mapping of stratigraphic units that often show rapid lateral changes in thickness and lithology, and whose exposures may be subject to slumping and rotation on hillslopes, the structure contours shown on the geologic maps may not accurately reflect local bedding attitude everywhere. If such local structure is ignored and the orientation of flow directions to the original dip is examined, no more consistent relationship is found. In the northern Fayette and southern Scott Counties area, while flow in the Royal Spring, Slacks Spring, and Nance Spring basins is to the north-northwest and down the regional dip, flow in the adjacent Silver Springs and Lindsay Springs basin is to the southwest along regional strike. In the Mercer County area the regional dip is to the west, as is the general flow directions in basins draining to the Salt River (e.g., Big Spring and Eureka Spring basins). In basins draining to the Dix and Kentucky Rivers (e.g., Burgin Spring and Shawnee Run Spring basins), however, flow is generally to the east and hence up the regional dip.

Faults, Joints, Sinkhole Trends, and Similar Features

A number of steeply dipping or vertical planar structural features, including faults, mineralized veins, and joints, are shown on the geologic maps of the areas studied. In addition, linear trends of sinkholes are shown by topographic contours and others are visible on aerial photographs (Thrailkill and others, 1983).

Four of the 39 major springs draining groundwater basins emerge at or within a few tens of meters of a mapped fault. In two of these, I-75 Spring and Nance Spring, the dye introduction points (only one for I-75 Spring) were along the fault or an apparent (but unmapped) extension, and the major flow conduit for the basin is probably along or very near the fault. In the Shawnee Run Spring Basin, the spring is on the downthrown (about 2 m) side of a small fault that trends at nearly right angles to the line of flow from dye introductions on the upthrown side. A more complex relationship exists in the Shawnee Copperhead Spring Basin, where a major flow conduit intersects an unmapped fault and may follow it to its intersection with a mapped fault near which the discharging spring is located.

Dye introductions were made in swallets located on mapped faults in three other groundwater basins. In the Sharp Swallet Basin, flow appears to follow the fault, and the discharging spring is probably on an unmapped extension. In the Boggs Spring Basin, however, the flow was away from the fault (part of the same system as the I-75 Spring Basin Fault) at a high angle to the spring located some distance away from its trace. Similarly, in the Silver Springs Basin, flow from several swallets located along a series of parallel mapped faults is at right angles to their trend, as was flow from a swallet on the opposite side of the faults from the spring.

The northern Fayette and southern Scott counties area is bounded on the southeast by the northeast-trending Lexington Fault System, a series of parallel faults with up to 150 m of mapped displacement. The single dye trace made to Bailey Spring, which lies on the southeast (downthrown) side of a major mapped fault in the system, was from a swallet on the northwestern side of the fault. The line of the trace, which was so short and apparently represented such swallow flow that no groundwater basin was defined, crossed the fault at nearly right angles.

It was possible to examine the relationship of a flow conduit to an unmapped mineralized vein in a cave in the Shawnee Copperhead Spring Basin. The conduit intersects the barite vein in several places at various angles and appears to be unaffected by its trend. In the Silver Spring Basin the major flow conduit appears to cross a mapped barite vein at about a 45° angle.

No general relationship was evident between traced flow lines and joint directions, although in a few cases, as in the Silver Spring Basin near the barite vein discussed above, the orientations of flow lines and mapped joints are similar. It should be noted, however, that except in a few places where a conduit is accessible and has been mapped, the only indication of the orientation of flow line is the relative positions of the dye input and detection points.

Linear trends of sinkholes are not uncommon in the Inner Blue Grass Region. Based on a sample, there are about 1,000 such trends identifiable on topographic maps in the region (Thrailkill and others, 1983), and hence approximately 120 in the area studied assuming uniform distribution. Most are less than 1 km long, and more trend between northwest and north than in any other direction. Faust (1977, plate 2, p. 16) gave the location of 40 such trends and stated that they were probably favorably placed to obtain goundwater.

Aligned sinkholes are present along the mapped faults in the I-75 Spring, Boggs Spring, Sharp Swallet, Nance Spring, and Silver Springs basins discussed above. Traces from swallets on opposite ends of a linear trend in the northwestern Woodford County area showed that the trend extends from the Roaring Spring to the Pin Oak Spring basins. Investigations in the Royal Spring, Slacks Spring, Cornett Spring, and lower Roaring Spring basins strongly suggest that the major conduit in each of these basins follows sub-parallel linear sinkhole trends. Furthermore, the principal conduit in the adjacent Sharp Swallet and Nance Spring basins follows mapped faults (as discussed above) that are roughly parallel to these linear sinkhole trends. These relationships are shown in Table 3, where the basins are listed from west to east.

The aligned sinkholes, similarity of orientation, and occurrence of mapped faults in two of the basins suggests the existence of a fracture set of regional dimensions, with the possibility that the fracture may be regularly spaced at intervals of 2 to 3 km. This hypothesis would suggest an additional fracture between the Royal Springs and Slacks Springs basins and two between the Cornett Spring and Roaring Spring basins. The first interval was intensively investigated but no groundwater basin was discovered in this area, which is on the northeastern side of the valley of Cane Run. The interval between the Cornett Spring and Roaring Spring basins has not yet been investigated.

Note that, except for the Roaring Spring Basin (which has the least well defined sinkhole trend), the orientation of the hypothesized fractures varies rather smoothly from N 10° W in the west (Cornett Spring Basin) to N 45° W in the east (Sharp Swallet Basin). The pattern does not extend farther to the east, since the major basin is the Vaughans Spring Basin, whose flow appears to follow a very well developed line of sinkholes which trends N 20 E. Flow in all of the basins is down the regional dip to the northwest, except in the Cornett Spring Basin, where flow is updip to the southeast.

The presence of major subsurface flow conduits beneath liner sinkhole trends was discovered early in the study, but the nature of the features responsible was unknown. They were initially referred to as diaclases (Thrailkill and others, in press), a term which includes major ("master") joints, a set of closely spaced joints, or unmapped faults.

Late in the study, the opportunity arose to examine one of these features underground in the major downstream conduit of the Slacks Spring Basin. The conduit, which is nearly straight, is typically about 6 m wide and 5 m high. It is developed in the Grier Limestone Member, and the thin, irregularly bedded limestone typical of this unit is exposed in the sides of the conduit. Individual beds are seldom thicker than 30 cm and generally cannot be

Table 3.-- Sub-Paralled Groundwater Basins.

BASIN	ORIENTATION	INTERVAL	FLOW DIRECTION
Roaring Spring	N 25 W		N to So. Elkhorn Cr.
		8 km	
Cornett Spring	N 10 W		S to So. Elkhorn Cr.
		2.5 km	
Nance Spring	N 15 W		N to No. Elkhorn Cr.
		2 km	
Slacks Spring	N 25 W		N to No. Elkhorn Cr.
		5 km	
Royal Spring	N 25 W		N to No. Elkhorn Cr.
		2 km	
Sharp Swallet	N 45 W		N to No. Elkhorn Cr.

traced laterally more than a few tens of meters. Visible joints can seldom be traced more than a meter or so vertically, and those parallel to the conduit seldom extend for more than 10 meters.

Over most of the 1-km accessible length of the conduit, the ceiling is the nearly flat underside of an unusually continuous tabular limestone bed, a lithology more characteristic of the Tanglewood Limestone Member. The trace of a joint, apparently little enlarged by solution, is visible in the ceiling in many places. This joint parallels the conduit and can be observed in several places to be continuous for at least 50 meters. The flat ceiling (often several meters wide) is due to collapse of weaker beds up to a more resistant and continuous bed, which is a common process in the nearly horizontal beds of the region.

Thus, it is beleved that alignment of sinkholes and localization of major conduits in the absence of faults is controlled by the presence of a joint that, unlike most of the joints in the region, is continuous both horizontally and vertically (at least 30 m in the one observed, judging by the depth of the conduit beneath the surface). The presence of such a joint will promote the development of deep sinkhole drains near the surface, and hence type three sinkholes (as discussed earlier). At depth it will furnish a favorable path for initial conduit development if it trends at a small angle to the early potential gradient (as will be discussed below). Such conduits will more likely form in thin bedded limestones with closely spaced joints, and little enlargement of the joint in massive and horizontally extensive beds (such as forms the ceiling of the conduit as described above) would be expected with the exception of occasional near-vertical sinkhole drains.

This interpretation may explain the rather anomalous situation in the lower Vaughans Spring Basin, where the path of the major conduit down flow from a karst window is along a linear trend of sinkholes, but then passes beneath North Elkhorn Creek to the spring on the opposite side. It is presumed that the conduit is developed along a fracture that has localized the sinkhole trend but is beneath a resistant bed at the creek, rising through it on the far bank at the margin of the bed or at one of the few points it is penetrated by a solution opening. It would seem likely that the spring, which is on the inside of a meander loop, was once on the opposite (southern) side of the creek, and that the creek channel has migrated laterally on the resistant bed.

Topography

There appears to be no consistent correlation between groundwater basins and surface drainage basins. Several of the smaller groundwater basins (e.g., Baker Cave Spring, Humane Spring, Gano Spring, Santan Spring, and Tevis Spring basins) appear to at least approximately underlie surface drainage basins. In other small basins, however (e.g., Pin Oak Spring, Cove Spring, Hartman Spring, Sharp Swallet, and Elkhorn Spring), subsurface flow lines cross surface divides. All of the larger groundwater basins extend beneath surface divides. Examples include (surface divide is in parentheses): Big Spring Basin (Salt River-Kentucky River), Nance Spring Basin (North Elkhorn-South Elkhorn creeks), Silver Springs Basin (North Elkhorn Creek-Cane Run). In addition, in no instance were the boundaries of groundwater basins related to the divides of paleovalleys, such as the Lees Branch paleovalley in the northeastern Woodford County area or the Sinkhole Plain paleovalley in the Mercer County area. In contrast, the flow direction of the shallow subsurface flow in interbasin areas is believed to be generally accordant with surface drainage as discussed earlier.

Although the flow direction in groundwater basins appears to bear no consistent relationship to the details of present topography, there does seem to be a tendency for such flow to be toward the nearest major surface stream. In the Mercer County area, groundwater basins apper to be developed on either side of a line drawn midway between the Salt River to the west and Herrington Lake (Dix River) and the Kentucky River to the east. Similarly, in the northern Fayette and southern Scott counties area, groundwater basin flow is generally away from a line midway between South Elkhorn Creek and Town Branch on the southwest and North Elkhorn Creek to the north and east. These flow directions would correspond to the slope of the potentiometric surface of a regional aquifer (which does not now exist) discharging along these major streams.

Geomorphology

There have been easily interpreted changes in the landscape related to the development of underground drainage. The upper portions of a number of surface valleys have been converted into blind valleys and in a few cases paleovalleys have been created by the diversion underground of essentially all surface drainage. Similarly, in several of the caves of the region passages that are not now carrying subsurface flow are found a few meters above the active flow conduits, and there are high-level openings near a few of the major springs (e.g., Roaring Spring, Lindsay Spring) that probably represent abandoned conduits (although most of these are utilized during high flow). None of these higher level conduits, however, indicate earlier flow directons or groundwater basin boundaries that are different from those now active.

Prior to the Mercer County area study, it was hypothesized that the degree of groundwater basin development would be less near the margins of the region and in other areas where the Lexington Limestone has more recently lost its cover of the overlying argillaceous Clays Ferry Formation. Such a relationship, which was discussed briefly in Thrailkill and others (in press), was not born out by the Mercer County area study, where well developed groundwater basins (e.g., Baker Cave Spring and Cove Springs basins) are adjacent to and even beneath outcrops of the Clays Ferry Formation.

Conclusions and Utility of Geologic Maps

The preceding analysis indicates that no single factor or simple combination of factors appears to control the location of groundwater basins or direction of subsurface flow within them. The best predictor of general flow direction would seem to be proximity to a major surface stream, in that most of the flow in most of the basins in the areas investigated was generally toward such streams, probably in response to a potentiometric gradient in existence early in the development of the subsurface flow systems.

Groundwater basins will be found beneath deep sinkholes, blind valleys, and paleovalleys, but the lack of such landforms does not necessarily indicate the presence of interbasin areas. Where the trend of aligned deep sinkholes does not deviate from the direction of the early potentiometric gradient by a large angle, it is likely that major basin conduits are developed beneath such an alignment.

All of the above features are shown, with varying degrees of accuracy, on the topographic maps of the region. The principal information presented on geologic maps, the areal extent and lithologic nature of stratigraphic units in the Lexington Limestone, is of little or no utility in locating the boundries of and flow directions within groundwater basins, nor does bedding attitude as shown by structure contours provide useful information. About the only features delineated on geologic maps (and not on topographic maps) that may be of interest are faults along which aligned sinkholes are not present, although no conduits were shown to follow such faults in the area studied. It is possible that there is a slight tendency for basins in which the flow is down the regional dip to be enlarged relative of those in which flow is updip, but no real evidence of this was seen during the study.

NATURE AND DEVELOPMENT OF THE HYDROGEOLOGIC SYSTEM

The following discussion may be premature, inasmuch as no studies in the region of important topics such as water budget or carbonate geochemistry have yet been completed. The relationships established during the present study, however, provide a framework for an explanation of the nature and development of the hydrogeology of the system that is sufficiently different from the views of earlier workers to justify its presentation.

The ideas that will be presented are based on arguments that are rather highly deductive. The only portions of the subsurface system that can be directly observed in any detail are conduits that are large enough to enter and are not completely water filled. Although consistent with observations made during the study, the properties of, and processes occurring within, the smaller conduits must mainly be deduced from physical principles.

The differences between the hydrogeology of the region and that of areas underlain by granular material are so substantial that virtually the only feature the two systems have in common is the presence, flow, and availability of water beneath the surface to wells. Because a fundamental starting point for the description of the hydrogeology of granular aquifers, and the overlying vadose and regolith zones, is that the type of flow is such that Darcy's Law is followed, an examination of the types of subsurface flow in the Inner Blue Grass Karst Region is appropriate.

Types of Flow

Subsurface flow in an area underlain by granular material is largely through pores of such small diameter that the flow velocity is linearly related to the potential gradient by the hydraulic conductivity, a relationship described by Darcy's Law. In addition, flow in small planar fractures (e.g., joints and bedding surface) will also obey this relationship if the width of the fracture is sufficiently small. The term "capillary size" will be used here, although capillary effects are pertinent only in unsaturated flow. If the pores (and fractures) are not saturated with water, the flow will be termed "unsaturated intergranular flow" (and the degree of saturation is an added parameter in flow relationships); otherwise the flow will be termed "saturated intergranular flow." Although other types of flow may occur, as in large soil fractures and in areas of high potential gradient near pumping wells, they may usually be safely neglected in describing the hydrogeologic system. The body of saturated granular material at depth in which saturated intergranular flow occurs, and in which the water pressure is greater than one atmosphere, is considered the "aquifer" (and its contents "groundwater") if its hydraulic conductivity is high enough for water to be yielded to wells. Above the "potentiometric surface" (termed the "water table" if the aquifer is unconfined), at which the pressure is atmospheric, most of the flow is unsaturated intergranular flow although a region of saturated intergranular flow (lower portion of the capillay fringe) is usually present just above the potentiometric surface in the "vadose zone" and, locally and temporarily, in portions of the regolith as a result of high recharge.

In contrast, subsurface meteoric water in the Inner Blue Grass Region is transported by six different types of flow, all of which are significant in describing the nature and development of the hydrogeologic system. In the regolith, flow is similar to that in the regolith overlying granular material, and water is transported largely by unsaturated intergranular flow, with areas of saturated intergranular flow beneath ponds and surface streams as well as elsewhere following heavy rains or snow melt. Unlike many areas of granular rocks with appreciable hydraulic conductivity, however, a zone of saturated intergranular flow is often present above the regolith-bedrock interface due to the very low hydraulic conductivity of the bedrock if no conduits are developed. In addition, one or more of the four types of conduit flows discussed below may occur in the regolith (especially its lower part) in conduits excavated by piping and other non-solution processes.

Flow in the bedrock outside of conduits will be by saturated intergranular flow as well. Although this is overwhelmingly the largest region in the subsurface, intergranular hydraulic conductivities in the bedrock are so low that this flow is of no interest on a short time scale as a source of water to wells nor on an intermediate time scale of a few weeks to a few years in considering the water budget of the region. As will be discussed, however, such flow is important on a long (i.e., geological) time scale in understanding the development of the hydrogeologic system of the region. Note that the two types of intergranular flow include flow along narrow fractures, as well as that between grains.

The other four types of flow are in conduits, which are solutionally enlarged openings larger than the capillary size openings so far discussed. Although many conduits are tubes rather than regular cross sections that change little along the length of the conduit, the term will also be applied to all large openings in the rock regardless of their shape.

"Pipe flow" occurs when the conduit is completely filled with water and (since there are no capillary effects and the venturi effect of high velocities is negligible) the pressure is greater than atmospheric. The other types of conduit flow are unsaturated (i.e., the conduit contains both water and air). In "bedrock channel flow", flow is on bedrock beneath a free surface, and hence the width, depth, and gradient are fixed for a given discharge except for solution and abrasion of the bedrock on a long time scale. "Gravity flow" differs from bedrock channel flow in having a very high gradient, lacking a well defined cross-sectional area, and having poorly defined contact (or none in the case of water falling free) with the bedrock, which precludes the application of open channel flow relationships (e.g., Chezy-Manning) used for other types of unsaturated conduit flows. Finally, "equilibrium channel flow" is similar to bedrock channel flow (and is describable by open channel flow relationships) except that the bottom and sides of the channel are largely on sediment, mainly transported regolith and bedrock fragments, and its width, depth, and gradients on a long and possibly intermediate time scale are determined by an equilibrium between water and sediment transport. Such flow has been extensively discussed(under a variety of names) by many authors for surface streams (e.g., Leopold and others, 1964; Hammer and MacKichan, 1981).

Although other types of subsurface flow may occur in the region, such as in saturated or unsaturated conduits in areas of ponding or in saturated conduits partly filled with sediment, it may be assumed, at least initially, that such flow may adequately be described as one of the types described above. The proprties of the six types of flow considered are summarized in Table 4.

Table 4.-- Types of Subsurface Flow in the Inner Blue Grass Region.

TYPE OF FLOW	SATURATED OR UNSATURATED	TYPE OF OPENING	PRESSURE REL. TO ATM.	PREDOMITANT FLOW MODE	POTENTIAL VELOCITY RELATIONSHIPS
Saturated intergranular flow	Saturated	Capillary	Greater (occ.about equal or less)	laminar	Darcy
Unsaturated intergranular flow	Unsaturated	Capillary	Less	laminar	Darcy (modified)
Gravity Flow	Unsaturated	Conduit	About equal	turbulent	Gravitational acceleration vertical film, etc.
Pipe Flow	Saturated	Conduit	Greater	turbulent	Turbulent pipe flow
Bedrock channel flow	Unsaturated	Conduit	About equal	turbulent	Chezy-Manning, etc.
Equilibrium channel flow	Unsaturated	Conduit	about equal	turbulent	Chezy-Manning, Leopold, etc.

The Non-Meteoric System

Before proceeding further with a discussion of the nature and development of the subsurface meteoric water flow system, some mention of what will be termed the non-meteoric system is in order. As discussed earlier in the section on water supply, many wells drilled in the region encounter water of unsatisfactory quality, in some cases at depths of less than 25 m. This water is variously characterized as containing sulfur, salt, iron, etc., and may be present in appreciable quantities in some wells.

Although little is known of this subsurface water, several observations can be made. First, at least some of the water is in conduits (and presumably by pipe flow at these depths), inasmuch as the intergranular hydraulic conductivity is too low to transmit the amounts of water that have been encountered. Second, the chemistry of the water indicates that it is isolated from the meteoric water system. Third, the absence of such water in many deep dry holes and underground quarries suggest tht this system does not completely permeate the bedrock. Fourth, the apparent difference in chemistry of this water suggest that it may be in small, relatively isolated bodies, and that a continuous system does not exist. Finally, the fact that some wells that initially yield water of unsatisfactory quality later produce meteoric water, suggests that pressure communication between the non-meteoric and meteoric systems may exist, and continued pumping of the former allows the latter to invade the conduits and flush them out. Alternatively, these cases may be explained by the well initially producing from both systems which then exhausts the non-meteoric system, supporting the suggestion that these are actually a series of isolated systems.

Conduit Initiation

Virtually by definition, the flow in bedrock to conduit development is by saturated intergranular flow, and such flow is now occurring in bedrock where conduits are not present. An examination of the transition from intergranular to conduit flow would thus seem to be an essential part of the development of the flow system, but as the following will show, no very satisfactory conclusion can be reached regarding this phase of the hydrogeolgic history of the region.

The principal mechanism responsible for the initiation of conduits is solution of the mineral calcite, and principal constituent of limestone, and although various attempts have been made to quantify the relationships between solution and flow (e.g., White, 1977), much work remains in this area. It is evident, however, that conversion of an intergranular flow path to a conduit flow path requires the passage of large amounts of water simply to remove the solution products, regardless of the details of the soluton kinetics or degree of chemical undersaturaton of the water as it enters the flow path. Assuming a high and constant carbon dioxide partial pressure, no dissolved calcite in the water as it enters the flow path, and complete saturation with respect to calcite as it leaves the flow path (all unrealistically generous specifications), a volume of water at least 1,000 times the volume of the initial conduit (neglecting the volume of the intergranular flow path) is needed during the period of intergranular flow.

Assuming a potential gradient of 0.01 (based on the region's topography), a flow path length of 5 km, and a minimum time for water to traverse the flow path of 10 years (thus providing the above volume in 10,000 years), an application of Darcy's Law yields a minimum hydraulic conductivity along the flow line of a little more than 10^{-5} m/s.

Intergranular hydraulic conductivities of the limestones and thin shales of the Lexington Limestones are low. MacQuown (1967, p. 68), presents a determination equivalent to about 10^{-9} m/s for a specimen of the Curdsville Member, which is lithologically similar to the Tanglewood Limestone Member. Freeze and Cherry (1979, p. 29) indicate that a hydraulic conductivity of 10^{-9} m/s is about the lower limit for limestone, and hence this probably represents intergranular, as opposed to fracture, hydraulic conductivity.

The actual flow velocity along a flow path will be inversely related to the bulk velocity (suggested by the hydraulic conductivity) by the void ratio, assuming the flow path is straight. A void ratio of 10^{-3}, and a degree of tortuousness of the flow path such that it is 10 times the straight line distance, yields a flow velocity of 10^{-7} m/s, two orders of magnitude too low for conduit initiation under the conditions assumed.

Because the Lexington Limestone is thin-bedded and the individual beds are jointed, pre-conduit flow along bedding and joint surface, which will collectively be called "fractures," would seem likely. Such flow in a system of narrow fractures (assuming certain conditions of their interconnection and spacing are met) will obey Darcy's Law and is here considered saturated intergranular flow, even though the flow paths are not between grains.

MacQuown (1967, p. 47) found the average spacing of bedding surfaces to be 0.05 m and the average joint spacing to be 0.24 m in the Curdsville Member, which yields a value of 24.2 fractures/m^2. Assuming a width of 0.1 mm (10^{-4} m) for a fracture that has not been solutionally widened, a hydraulic conductivity of about 10^{-11} m/s is obtained using methods described in Freeze and Cherry (1979, p. 74), and the void ratio (assuming all fractures are parallel to flow) is about 2.5×10^{-3}. Even if no path lengthening due to tortuousity is considered, a flow velocity within a fracture of 4×10^{-9} results, one and a half orders of magnitude less than that of an intergranuar path.

Although this admittedly crude analysis suggests the intergranular flow paths should be favored over fracture flow paths during the pre-conduit flow stage, the reverse is probably true, since small conduits observed in outcrop are usually, but not invariably, localized along a joint or bedding surface. Thus, there may be errors and inconsistencies in the assumptions, most notably in the specification of fracture width. Since hydraulic conductivity along a fracture is directly related to the third power of the fracture width (Freeze and Cherry, 1979, p. 74), if the width is 1 mm (10^{-3}) rather than 0.1 mm, the hydraulic conductivity is increased by 3 orders of magnitude, favoring fracture paths over intergranular paths. Such a width for non-solutionally widened fractures at depth seems too great (0.1 mm is probably too generous), but it is likely that some solutional widening (and even conduit development) has occurred in at least some fractures prior to the initial entry of meteoric water. Openings large enough to transmit the non-meteoric system discussed earlier are certainly present in some places in the rock.

The apparent near-comparable efficiency of intergranular paths suggests that pre-conduit flow along such paths cannot be ignored, however. If a steep potential gradient were present at an angle to bedding where no joints were present, enlargement of intergranular paths parallel to the gradient would be expected. Such paths would probably even cross shale interbeds up to several millimeters thick (which probably includes most such interbeds in the Lexington Limestone), inasmuch as the shales generally contain more than 50 percent calcite (and dolomite) and less than 25 percent clay minerals (Fisher, 1968, p. 780), and hence even their vertical hydraulic conductivity may be comparable to the hydraulic conductivity of the limestones. Conduit development in such shales would be inhibited by the accumulation of insoluble residue, however.

Ewers and Quinlan (1981) have presented the most persuasive explanation for the initial development of conduits from saturated intergranular flow along a fracture. Ewer's (1981) experiments (utilizing salt and plaster) indicate conduit development begins at the input point and extends down the flow as a complexly branching dendritic pattern of small conduits. Because potential loss in the conduits, is much less than in the intergranular flow region, the steepest potential gradient is between the outlet and the end of the conduit nearest the outlet resulting in increased flow and accelerated conduit growth along this line. Once the first conduit reaches the outlet, potential falls in all the conduits and flow within the growth of the other conduits in the dendritic pattern virtually ceases. If dendritic patterns of conduits are growing from other input points, a steep potential gradient develops in the intergranular flow region between these conduits and those of the pattern that first reached the outlet, causing conduits in the pattern that first reached the outlet. Thus, the first type of dendritic pattern (branching downflow) is converted to a more familiar second type (branching upflow).

Stages of Conduit Growth

Further solutional (and abrasion) enlargement of the conduits and integration of the conduit system has led to the present hydrogeologic system of the region. During this enlargement and integration, individual conduits have passed through a number of significant stages. The transition to the first stage occurs when the cross-sectional area of a conduit becomes sufficiently large, and the flow velocities (due to integration of the conduit system) sufficiently high, for the flow to become pipe flow, and hence no longer described by Darcy's Law. Prior to this transition, the flow would be saturated (usually) intergranular flow, even though it was in the embryo conduits described in the preceding section. Because both the plan and cross-section of the conduits are probably quite irregular, the transition to the first stage probably occurs well before the flow becomes turbulent.

The transition to the second stage occurs when conduit size throughout its length is great enough for sediment (both regolith ad the insoluble residue from the solutional enlargement of the conduits) to be transported through te system. The third stage is reached when the size of the conduit and the flow velocities are sufficiently high for conduits on bedding surfaces above thin shales or otherwise resistant beds to erode through to the underlying less resistant limestone. The conduit size and flow velocity necessary is obviously a function of the extent, thickness, and degree of resistance of the underlying bed.

It seems unlikely that significant sediment transport can occur unless the flow is turbulent, and conduits that are able to erode shales (probably mainly by solution, inasmuch as the "shales" are dominantly carbonates, as discussed earlier) must be able to transport the insoluble residue out of the conduit. Thus, the three stages would seem to be sequential. There is another transition that occurs at some point during the enlargement of a conduit and integration of the system whose position in the sequence may vary, although it probably occurs most often during the second stage. This transition occurs when the size of the conduits and integration of the system reaches the point where the amount of water being supplied to the conduit is insufficient to fill it, at least during times of low recharge, and the flow becomes unsaturated, either bedrock channel flow, if the gradient is low, gravity flow, if the gradient is high (most common in a third stage conduit), or equilibrium channel flow in larger and deeper conduits.

Where the conduit serves as a sinkhole drain, this classification corresponds to the classification of sinkhole types outlined earlier, in that incipient and type one sinkholes are drained by first stage conduits, type two sinkholes by second stage conduits, and type three sinkholes by third stage conduits.

As stated earlier, geochemical studies of the ability of recharging meteoric water to accomplish the conduit enlargement have not yet been completed in the region. A considerable body of literature exists on this question based on studies in other areas, however (e.g., Thrailkill and Robl, 1981), and it is believed that this model of conduit initiation and development is consistent with the geochemistry.

Groundwater Basins, Interbasin Areas, and the Aquifer

Groundwater basins have been identified as areas within which dye tracing has indicated that the subsurface conduit system appears to be deep, extensive, and well integrated, while there is no evidence that the subsurface conduit system in interbasin areas has any of these characteristics. In groundwater basins, at least the major flow of meteoric water infiltrating the surface descends steeply through stage three conduits from stream swallets or as type three sinkhole drains.

In two of the groundwater basins identified (Shawnee Hefer and Spring Lake Spring basins), the major basin conduits are believed to be perched on a resistant bed, and thus have not reached the third stage of development relative to this bed (although third stage conduits are probably developed through thinner resistant beds above it).

In the remaining 36 groundwater basins, flow within them appears to be in large, nearly horizontal conduits, whose elevation is unrelated to lithology. Where major conduits can be entered and examined, they consist of open passages traversed by a stream flowing over sediment, with accessibility terminating both upstream and downstream when the conduit becomes completely filled with water. The nearly horizontal gradient of these major conduits is believed to be controlled by the equilibrium flow occurring in the unsaturated portions of the major conduits.

As discussed earlier, the width of the zone of near horizontal flow at depth in underground basins is uncertain. Although potentiometric surface elevations in the middle Slacks Spring Basin suggest that it may be extensive, other evidence would seem to indicate that conduit development between major flow lines within the basin is minor or absent, and that the basin flow is largely through a single conduit or, in a few cases, conduits parallel to and very near the major conduit. Such evidence includes well data from the lower Slacks Spring Basin and other basins in the Georgetown Quadrangle, the fact that most of the springs either have a single outlet or multiple outlets very close to each other, and the fact that impoundment of springs has not led to their abandonment and a major diversion of flow as the potential is increased.

Subsurface flow within the groundwatr basins (neglecting the saturated and unsatrated intergranular flow in the regolith and saturated intergranular flow in the bedrock outside of conduits) is thus different in different parts of the basin. Water entering the basin from stream swallets and type three sinkhole drains, initially descends steeply by gravity flow and short reaches of bedrock channel flow to the floor of the basin. It then is transported to the discharging spring mainly by equilibrium channel flow and pipe flow, although reaches of low gradient bedrock channel flow several hundred meters long have been observed in the upstream portion of smaller conduits.

Although it is rather easy to explain the near horizontal flow in the groundwater basins as being due to equilibrium channel flow in at least major portions of the larger conduits, it should be noted that other, and unknown, factors promoting this horizontal flow may be operating. By its very nature equilibrium channel flow requires that large amounts of sediment are being transported in the subsurface. While this is certainly true in the Inner Blue Grass Region, it may not be in other karst areas where near-horizontal flow also occurs. This equilibrium flow explanation is not, therefore, necessarily a general explanation of the causes of shallow versus deep phreatic flow that has been extensively debated in the literature (e.g., Thrailkill, 1968).

In hydrogeologic systems, an aquifer is considerd to be a body of rock that contains water that is available to wells in useful quantities and that is under a pressure greater than atmospheric. In addition, the water should be of usable quality. The term has been avoided so far in this report because the nature of the subsurface flow system in the region is so different from that in granular materials that the term is essentially meaningless unless carefully characterized. Similarly, since the term "groundwater" is best reserved for water in the aquifer, the term "subsurface water" has been employed.

In the Inner Blue Grass Region, therefore, the aquifer consists only of rock in which conduits are developed (since intergranular flow does not satisfy the yield criterion) that contain meteoric water (the non-meteoric system fails the quality criterion) at greater than 1 atmosphere pressure. Because shallow bedrock channel flow and equilibrium channel flow, as well as gravity flow, are at atmospheric pressure, only rock with conduits with pipe flow and the deeper water filled portions of larger conduits in which bedrock channel flow and equilibrium channel flow occurs are included.

Within groundwater basins, the potentiometric surface is represented by the water surface in the larger conduits in which eqilibrium channel flow is occurring. Adjacent conduits are completely water filled if they are below this level, with the water pressure determined by the depth below the potentiometric surface. Flow in other conduits that are partly above this level will be mainly by bedrock channel flow, with equilibrium channel flow in those carrying large amounts of sediment from the surface. Well data from the middle Slacks Spring Basin shows that at least in one basin the communication between these various conduits is sufficient to produce the expected nearly flat potentiometric surface over a wide area.

It should be noted that fairly high gradient bedrock channel flow occurs in many places and at many elevations in the groundwater basins. Since the gradient is high, the flow is rapid and shallow. This water was excluded from the aquifer in the above definition because it is essentially at atmospheric pressure and, since it is unlikely that the surface of such flows is reflected in the surface of nearby unsaturated flows or the pressure in pipe flow conduits; it is meaningless as a potentiometric surface.

In the smaller conduits in the interbasin areas, pipe flow and occasionally large channel flows may be encountered near the surface, and a consistent potentiometric surface may be definable over a small area. Along major streams, larger flows beneath a more continuous potentiometric surface at or just above the stream level would be expected. The margins of groundwater basins in topographically high areas are probably so steep that no aquifer exists.

Thus the Inner Blue Grass aquifer is discontinuous on two scales. Since it exists only where conduits are developed, it can be tapped by only a fraction of the wells that are drilled. In addition, since it can be defined only when pipe flow and low gradient channel flow are occurring, it may be characterized as being extensive in groundwater basins and along major surface streams, discontinuous and local in topographically high portions of interbasin areas, and may be absent at basin boundaries.

Influence of Human Activities

Some mention should be made of the effects of underground flow in the region as a result of human activities. The widespread practice of filling sinkholes mentioned earlier has probably decreased subsurface flow, since precipitation that formerly entered the subsurface rapidly through swallets in deep sinkholes is not retained in the regolith (and occasionally in ponds established in sinkholes) and evapotranspired. On the other hand, surface runoff into small streams and into swallets that divert their flow underground, has been increased by land clearing and urbanization. Although the net effect (to either increase or decrease recharge) may have been substantial, it cannot be evaluated with the present data. Because of the high hydraulic conductivity and low specific storage of the aquifer, however, such changes in recharge rate have a small effect relative to what would be expected in a granular aquifer.

Human activities have also modified the flow in conduits by causing subsurface sedimentation. The impoundment of major springs such as Russell Cave and Royal Spring has apparently produced extensive deposition in the downstream portion of the main conduit, and it is likely that the series of low dams that have been constructed on North and South Elkhorn creeks has had a similar effect on some of the springs flowing into these streams. In addition, there are extensive fills of transported regolith in several of the accessible conduits in the region. In some cases these are in upper level conduits (mainly sinkhole drains) in which the water transport is by bedrock channel flow and gravity flow. Although some sediment would be expected to be transported through such conduits (and equilibrium channel flow might develop locally), the observed fill is far in excess of the amount expected and does not appear to be transported by even the highest recharge events. Similarly, the accessible portions of the major conduit in the Slacks Spring Basin (whose spring is not impounded) contain large amounts of transported regolith on either side of the active equilibrium channel flow, and dates scratched into the fill indicated that much of it is not inundated, or transported during high flows in the conduit. It is believed, therefore, that much of this excess sediment may have been introduced into the subsurface as a result of initial land clearing operations, probably in the early part of the 19th century.

Finally, it may be noted that underground basins exist within parts of the city of Lexington, as evidenced by the presence of major springs, deep sinkholes, karst windows, and blind valleys. No dye tracing has yet been attempted within this heavily urbanized area, however, due to the difficulty of clearly distinguishing natural, subsurface flow from that in storm drains.

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Chapter 4

PATTERNS OF CAVERN DEVELOPMENT ALONG THE CUMBERLAND ESCARPMENT IN SOUTHEASTERN KENTUCKY

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The Cave Creek area contains six known units of subsurface conduits totaling 17 km in length. These units form part of a once fully integrated system of limestone caves. The inputs to this system are confined to a narrow zone, no more than a few hundred meters across, where stream erosion has breached an impermeable caprock consisting of sandstones and shales. This system of conduits and inputs is relatively isolated from others and provides one of the clearest examples of the most common pattern of cavern development in the region. Likewise, it provides an almost ideal location to study the process by which the caves of the region evolve.

GEOGRAPHICAL SETTING

Cave Creek, a tributary of the Cumberland River, is located in south-central Kentucky, in Pulaski County. The area is depicted on the Hail 7.5 minute geologic quadrangle map (Smith and others, 1973). The area is part of the larger karst region that extends from just south of the Ohio River, southward along the Appalachian Highlands Escarpment through Tennessee.

GEOLOGICAL SETTING

Lithology

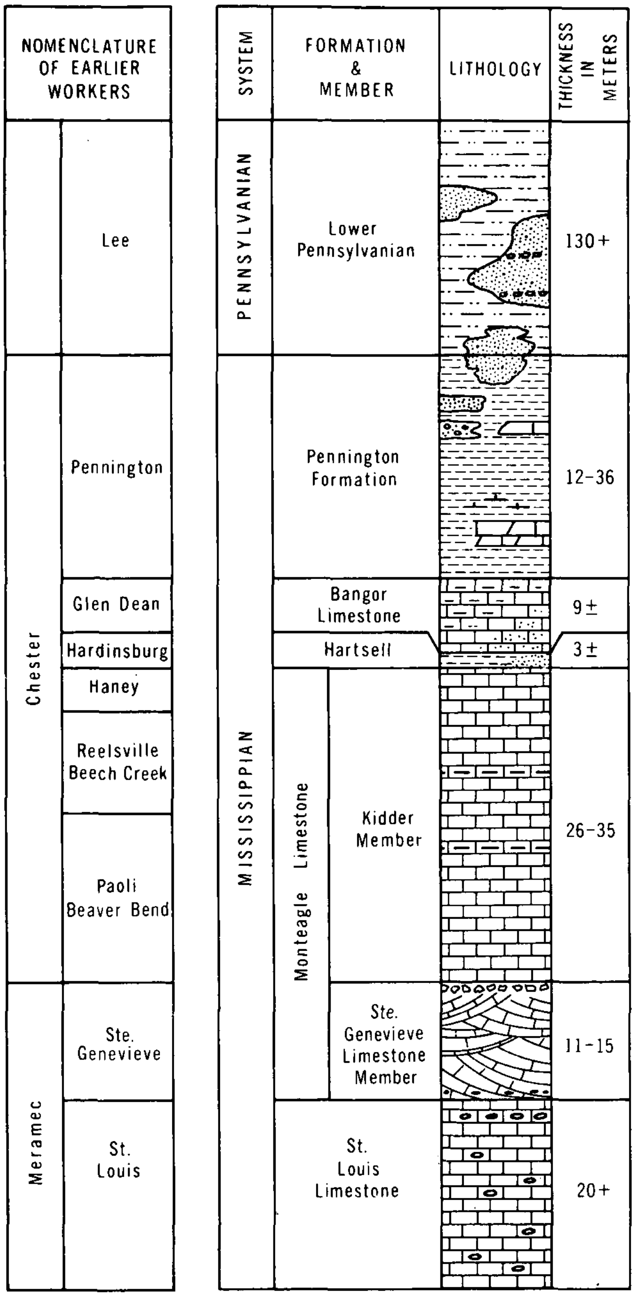
The region is underlain by sedimentary rocks, largely limestones, sandstones, and shales of Upper Mississippian and Lower Pennsylvanian age. Figure 1 shows a representative stratigraphic section from the area. The nomenclature used here is that adopted for the Shopville Quadrangle (Lewis, 1972).

Structure

The area lies on the eastern flank of the Cincinnati Arch, a broad, low, north-south trending anticlinal feature that can be traced from southern Michigan through Cincinnati to northern Alabama. On a regional basis, the rocks may, therefore, be described as dipping gently toward the east-southeast at 3.5 to 9 m per km. Locally, however, a considerable amount of subtle structure can be discerned. In the region of specific interest, a small anticlinical feature extends over the point of confluence between the Cumberland River and Cave Creek (Fig. 2).

Geomorphology

The region lies at the edge of the maturely dissected western margin of the Cumberland Plateau. The plateau is capped with basal Pennsylvanian clastics of a highly variable nature. They range from cross-bedded conglomerates, locally referred to as the Rockcastle Member by Hatch (1964), to siltsones, shales, and coals. The hilltops in the plateau region have an elevation of 375 m; maximum relief here is 155 m.



After McFarlan & Walker (1956)

After Lewis, (1972)

Figure 1. Stratigraphy in the Cave Creek area, Kentucky.

An area of knobs occurs in a narrow strip normally 5 to 6 km wide along the edge of the plateau. These detached plateau remnants have summit heights up to about 365 m and rise about 100 m above the intervening surface. This surface is developed on the Kidder and Ste. Genevieve limestones and is marked by numerous sinks and solution valleys. To the west of the knobs is a gently rolling surface, continuous with that between the knobs, which forms the Highland Rim, a part of the Interior Low Plateau Province (Fenneman, 1938).

The Cumberland River flows in a narrow gorge for 64 km through the dissected portion of the escarpment. Evidence suggests that the gorge here was formed, in part, by the retreat of Cumberland Falls from near Burnside, Kentucky, to its present location upstream from the town. The falls retreats as it undermines the resistant Rockcastle Conglomerate caprock, exposing the easily eroded shales, siltstones, and poorly cemented sandstones of the Lee and Pennington formations (McFarlan, 1943). The development of the gorge is closely related to the evolution of the karst in Cave Creek, as will be demonstrated below.

The erosion of Cave Creek Valley has breached the caprock and exposed the Monteagle and Ste. Genevieve limestones along the valley sides and bottom. This exposure extends for 5.75 km eastward and southward from its confluence with the Cumberland River.

Cave Creek valley can be characterized as a karst valley, due to its irregular profile and its internal drainage. There are many other valleys of similar character along the escarpment.

Hydrology

The drainage in the region is controlled by the Cumberland River and, since 1952, by the artificial pool created by Wolf Creek Dam. The normal pool elevation for Lake Cumberland is 220 m, 5 m above the pre-impoundment level at the mouth of Cave Creek. The areas of discontinuous sandstone and conglomerate act as granular aquifers, perched upon the

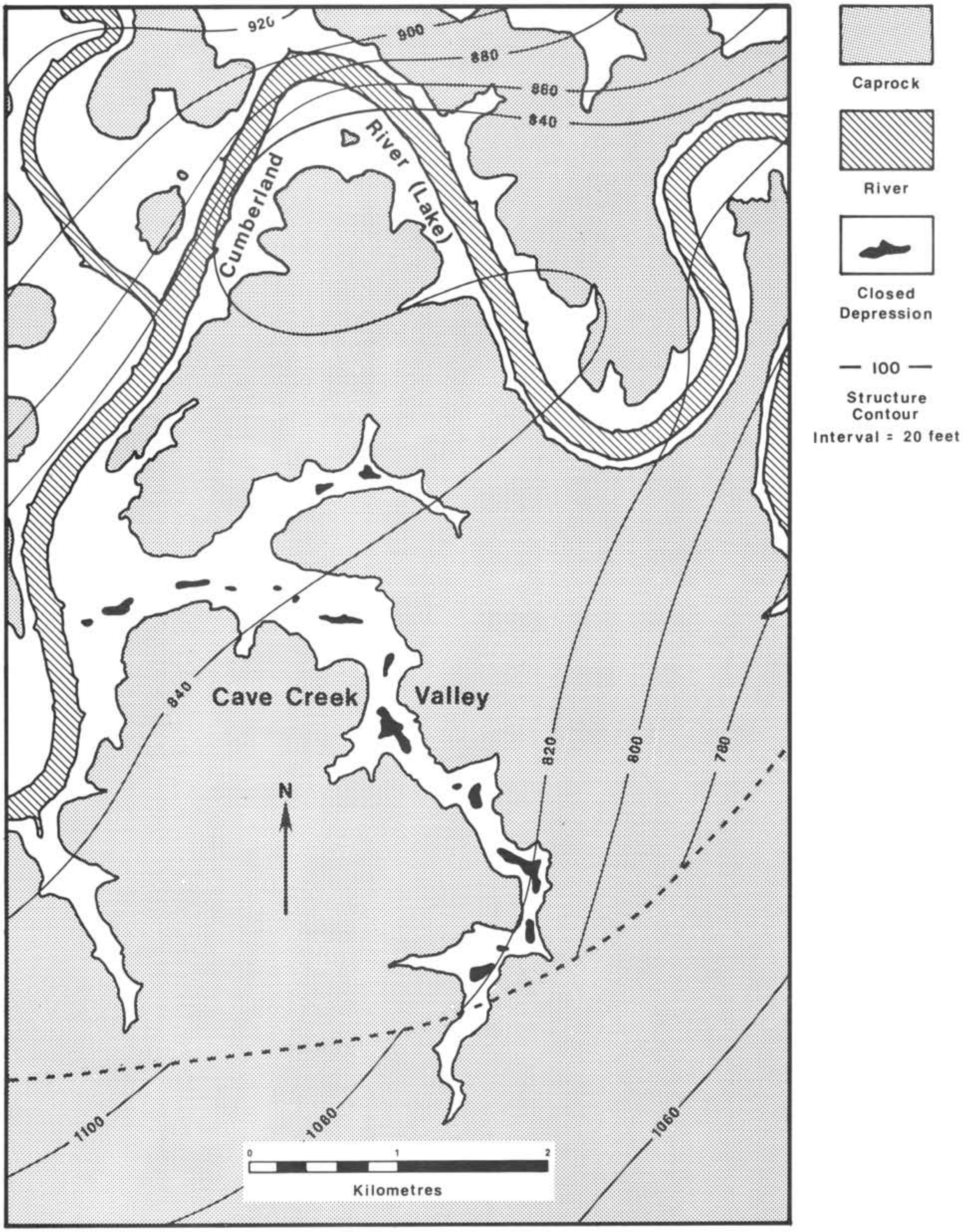


Figure 2. Structure and caprock distribution in the Cave Creek area, Kentucky (adapted from Smith and others, 1973). Structure contours are drawn on the Hartselle Formation in the north and on the Rockcastle Member in the south.

impermeable shales of the Lower Pennsylvanian and Upper Mississippian. These aquifers give rise to numerous diffuse seeps and springs. Where exposed, the limestone units develop subsurface conduit drainage. This secondary solution porosity is not restricted to any particular stratigraphic horizon within the limestone, although there is some tendency for surface streams to be maintained where the upper St. Louis limestones lie directly beneath the surface. This tendency suggests that this unit may be less soluble, or otherwise less conducive to karstification.

Cave Creek Valley contains several hundred closed depressions and is without continuous surface flow, even under conditions of extreme precipitation. At least 30 well defined wet-weather tributaries, carrying allogenic waters from the caprock, extend to the valley bottom, where they sink (Fig. 2). The resurgence for these waters is assumed to lie at the Cumberland River beneath its present artificial pool. A large spring, downstream from the valley mouth and on the same side of the river, appears on early topographic maps (Mayfield and Withers, 1929) and is reported by long-term residents of the area. This spring is presumed to be a resurgence.

The Cave

The known passages associated with Cave Creek Valley form a three dimensional network that closely follows the valley axis (Fig. 3a). The conduits are formed along bedding planes and are virtually without joint control. The network ranges vertically between 207 m and 263 m. The course of the subsurface flow which traversed these conduits, neglecting minor deviations, extends for a distance of 4.8 km. Figure 3b depicts this generalized path as solid line "A-B." There is no reason to believe that flow from the region of the sink at "A" could not be conducted along path "A-C" or on the direct course to "B." No structural or lithologic barriers to such flow are known or seem likely. In fact, a considerable advantage would seem to exist along these latter courses. Their lengths are 3 km and 3.6 km, compared to 4.8 km. Thus, they should have 62.5 and 75 percent, respectively, of the resistance of the longer course. The gradient would be 1:3 and 1:3.6, respectively, compared to 1:4.8, a significant increase. Stratigraphically, point "C" is about 2 m lower than point "B," and, therefore, if the entrenchment of the Cumberland River proceeded uniformly, point "C" may not have been able to discharge waters from the limestone as early.

In the face of these theoretical advantages, the known conduits follow the longer, lower gradient course. It seems reasonable, given the geomorphic setting, that the following events would have occurred. As the falls receded past the mouth of Cave Creek Valley, the stream flowing on the caprock sequence began to gradually expose the limestone along Cave Creek to significant hydraulic pressure gradients. This exposure, by reason of the dip as well as the gradient of the stream, would have proceeded from the valley mouth in an upstream direction. The localization of the first breaching at the creek mouth, rather than at other points along this reach of the river, is assured by the presence of a minor anticline at this point (Fig. 2). Second, upon the exposure of a suitable structural discontinuity for admitting water to the limestone bedding planes, the development of one or more subsurface conduits between this input and the Cumberland River would have occurred. Third, as additonal inputs evolved, they developed conduits linking to the previously completed conduits.

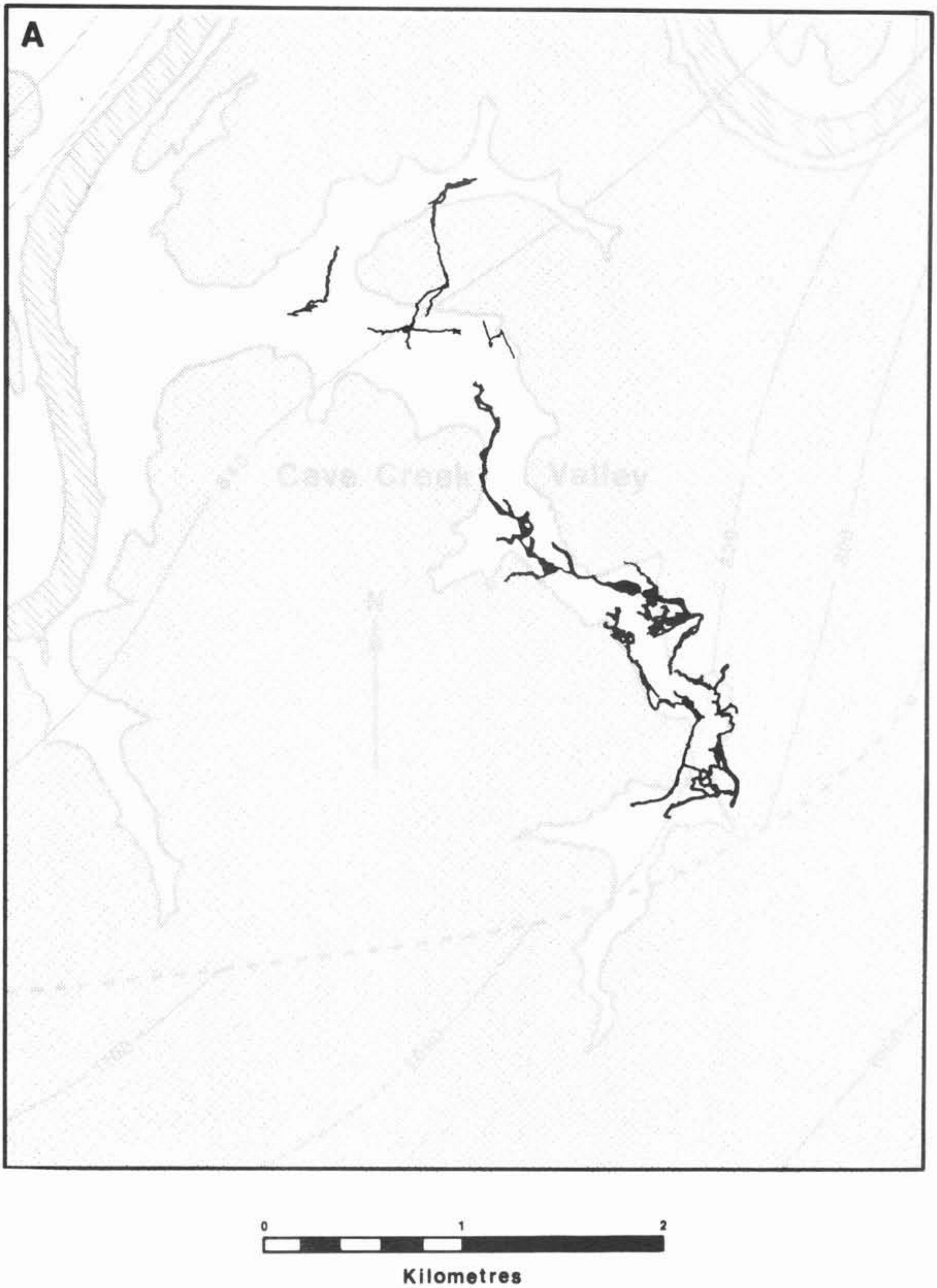


Figure 3-A, B. Conduit pattern and generalized subsurface flow route beneath the Cave Creek area. Cave information was provided courtesy of Mr. Louis Simpson.

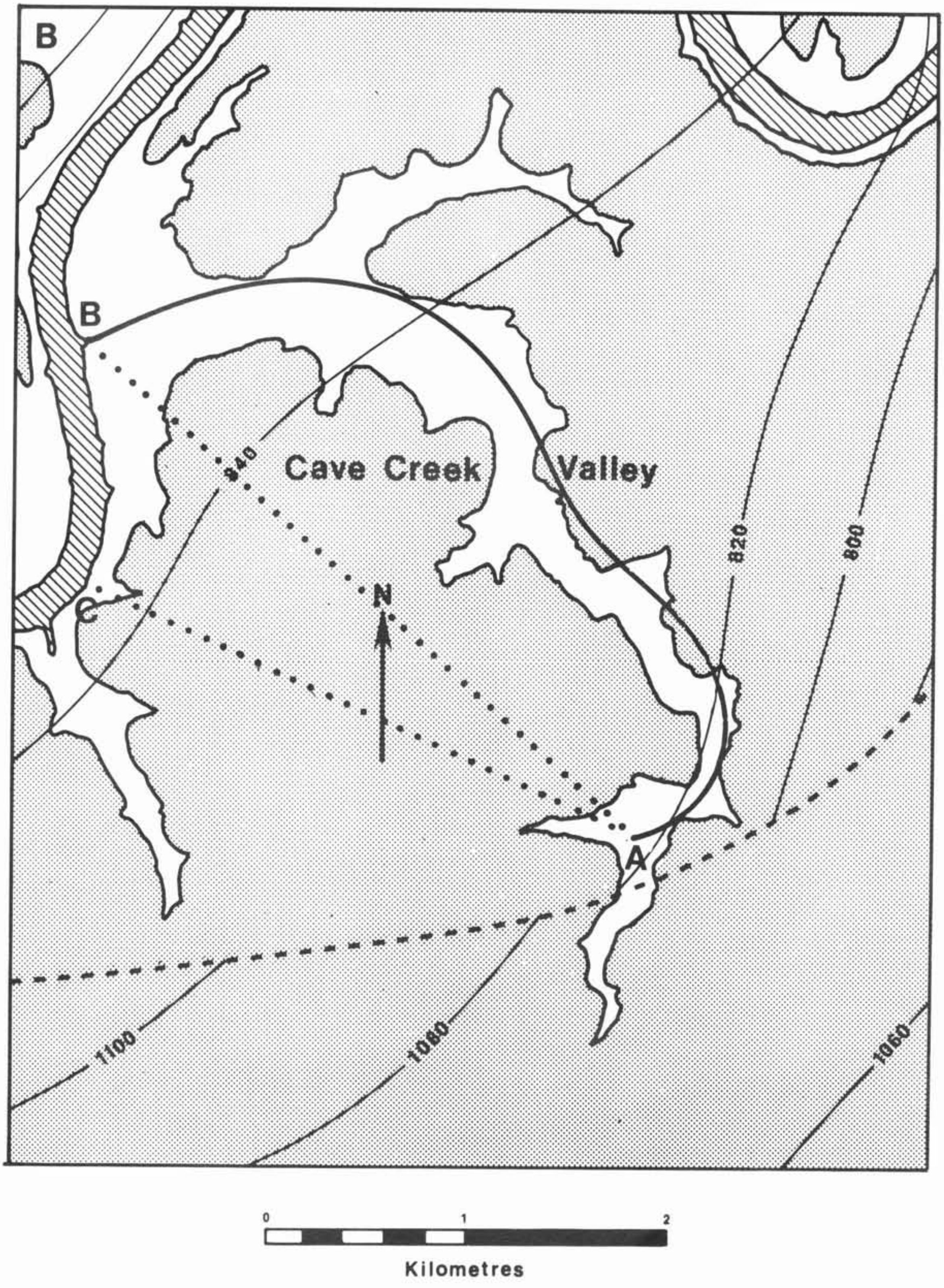


Figure 3-A, B. Conduit pattern and generalized subsurface flow route beneath the Cave Creek area. Cave information was provided courtesy of Mr. Louis Simpson.

In support of this scenario are three pieces of evidence. First, only 4 km of passage, less than 25 percent of the total known, extends beneath the caprock on the valley flanks. This scarcity indicates that the targets for conduit development lay along the valley bottom. Second, there are several regions of conduit mazes directly connected with the trunk conduits that presently lie close to the surface and near the valley center. These regions appear to have functioned as specific sites of input. The most complicated mazes are located in the upper part of the valley, suggesting that those in the lower part, and so formed earlier, may have been partly destroyed. Third, many of the high elevation mazes are in the form of phreatic canyons. The morphology of these conduits suggests that they have enlarged upward from a horizontal bedding plane network (Fig. 4) or from a descending primitive tube network, following a combinaton of joints and bedding planes. This enlargement normally occurs in a turbulent regime when sediments are carried into the conduit. The enlargement would have occurred only after a conduit had established a low-resistance link to its discharge target. The sediments armor the lower portion of the conduit and concentrate dissolution at the ceiling. Frequently, the passage shows meander forms that propagate upward and downstream, similar to the presumed growth of eskers in glacial ice (Embleton and King, 1971, p. 370-382), thus verifying the presence of this mode of enlargement. The donstream direction of flow is deduced from scallops on the walls, the imbrication of gravels where they exist, and from the assumption that flow was from the valley inputs toward the major trunks. All of these methods give a consistent flow direction. This mechanism has been discussed by Ewers (1977), Passini (1973), who used the term "antigravitational erosion," and Renault (1967) who used the term "paragenesis." This latter evidence strongly suggests that the main conduit development was truly phreatic, not simply epiphreatic. Furthermore, it supports the contention that the mazes were input points.

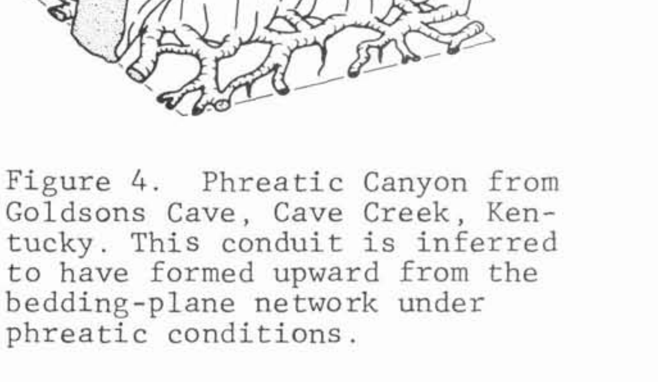


Figure 4. Phreatic Canyon from Goldsons Cave, Cave Creek, Kentucky. This conduit is inferred to have formed upward from the bedding-plane network under phreatic conditions.

The passages illustrated in Figure 3 represent two fairly distinct levels of conduit development, one betweeen 200 m and 225 m, and another between 225 m and 240 m. Although these ranges overlap, the juxtaposition of passages confirms that they are parts of two distinct trunks. This distinction suggests that development of primitive phreatic tubes may have occurred at several horizons, with the upper level enlarging to trunk proportions first. Later, when the river had entrenched further, the lower level enlarged and became active.

A THEORETICAL CONSIDERATION

The scenario presented above is consistent with analyses of cavern evolution based upon three fundamental factors: the porosity distribution, the head distribution, and the solution kinetics. The porosity distribution sets strict limits on the location of the initial solution porosity. The head distribution within this porosity controls the rate and direction of the initial groundwater movement. The rate at which the moving groundwater approaches saturation may have a profound effect upon the pressure distribution as the solution porosity evolves. If the kinetics are fast, undersaturated water will emerge from the limestone mass and the fracture porosity, which conducts this flow, will enlarge uniformly throughout its length. On the other hand, if the kinetics are slow, saturated water will be discharged and the fracture porosity will enlarge initially in the region of the input and will gradually propogate toward the discharge region. Such a non-uniform change in the porosity will alter the pressure distribution in the surrounding limestone, thereby affecting further change.

Solution Kinetics

Figure 5 shows the dissolution rate experiments of Berner and Morse (1974) plotted as functions of the deviation of pH from its equilibrium value. The plot can be readily divided into three regions covering five orders of magnitude. Each of these regions has a characteristic rate of change in the solution rate. Of particular interest here is the dramatic drop in the dissolution rate in region 3. This drop suggests that aggressive (undersaturated) water might penetrate to great distances, but the rate at which it accomplishes geomorphic work should be quite small except near the point of input.

White (1977) reviewed the Berner and Morse results in a karst context. He pointed out that for karst waters the break in slope occurs at about 90 percent saturation, which corresponds to the region 3a - 3b boundary. He then calculated the travel distance required to reach 90 percent saturation for a range of capillary openings and groundwater flow gradients (Fig. 6). For this, he used the rate equations of Plummer and Wigley (1976) which suggest a second order surface reaction control, and the diffusion control model advocated by Weyl (1958). He selected carbon dioxide partial pressure values of 10E-2.5 and 10E-1 for the reaction-limited calculations. These values correspond to typical conduit spring values and typical soil-water values for carbon dioxide concentrations, respectively. These plots cover the full range of pertinent, published, experimental data and theoretical arguments. As White pointed out, he substantially agrees with Berner and Morse that for small capillaries and fractures representative of virgin pore space of tectonic, diagenetic, and sedimentary origin in limestone, the bulk of the geomorphic work accomplished by the dissolution process takes place within a few meters or tens of meters of the point where groundwater first gains access to the limestone.

In a more recent series of calcite dissolution experiments, Plummer and others (1978) have extended the pH, carbon dioxide partial pressure, and temperature range of previous experiments. They proposed a mechanistic model that describes their observations. Their results, in general, corroborate the results of Berner and Morse (1974).

These laboratory investigations are supported by three types of field observations. First, Bogli (1966) and Cogley (1972) have demonstrated that thin films of water from rain and snowmelt traversing exposed limestone surfaces quickly saturate to levels appropriate for open-system waters in contact with atmospheric concentrations of carbon dioxide.

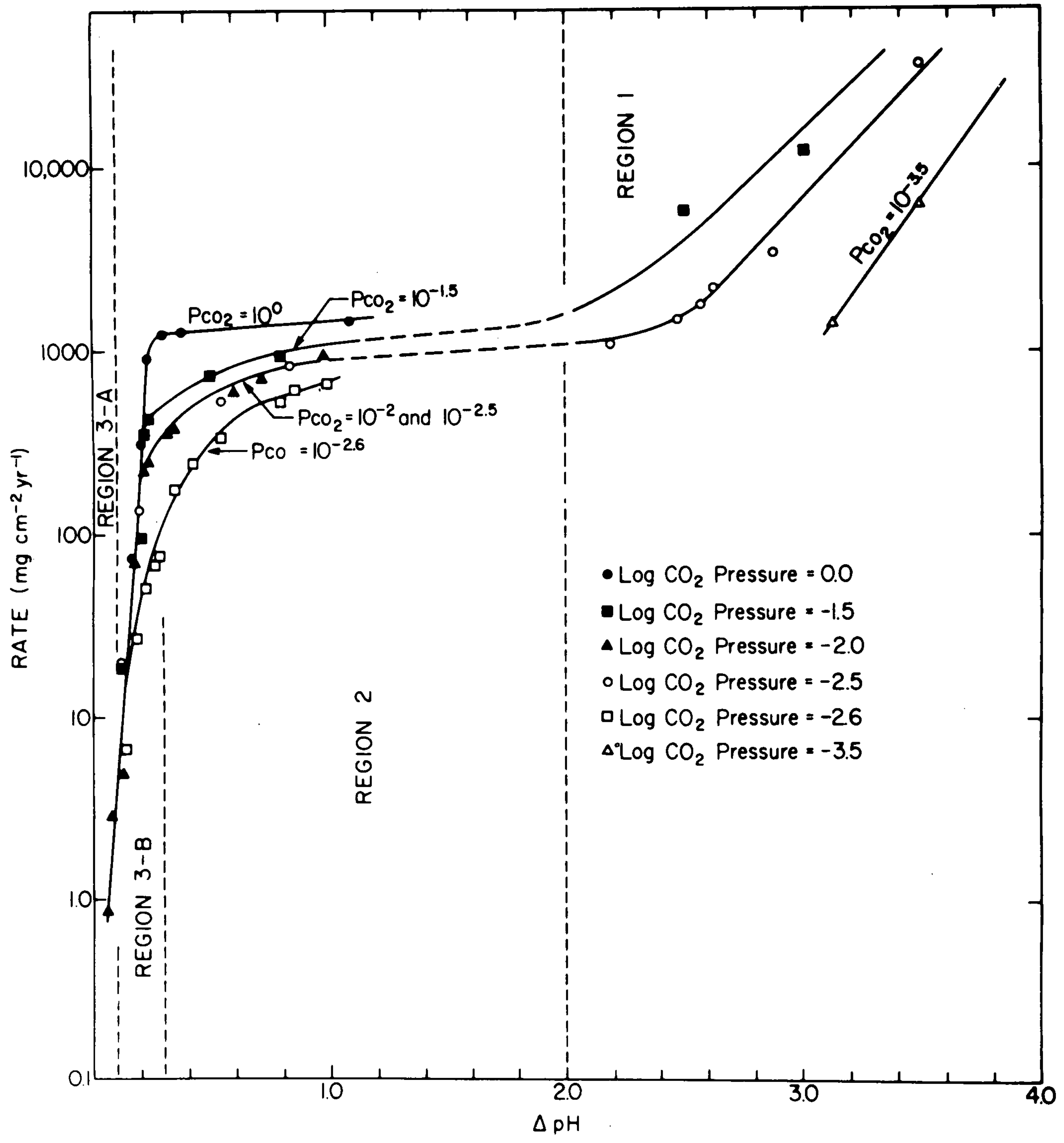


Figure 5. Solution rate experiment data of Berner and Morse (1974) plotted as functions of the deviation of pH from its equilibrium value at the given carbon dioxide partial pressure (from White, 1977).

Second, in the subsurface, large numbers of "soda straw" stalactites form from seeps along cavern ceilings. Frequently, these cavities are only a few meters beneath the surface. These deposits form by crystallization at the perimeter of successive

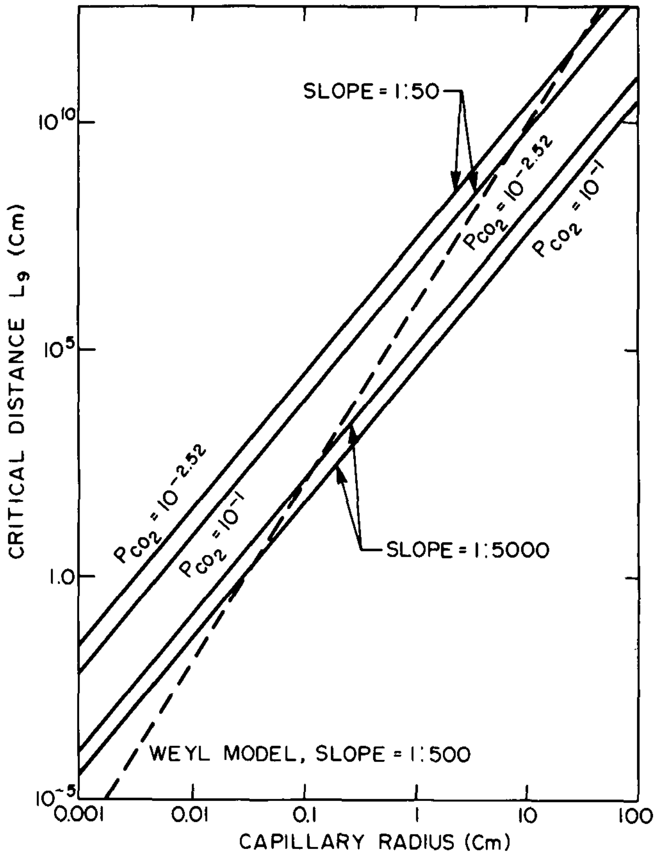


Figure 6. Distance to 90 percent saturation with respect to calcite as a function of conduit diameter. Hydraulic potential surface slopes of 1:50 and 1:5,000 are shown, calculated with the Plummer and Wigley (1978) rate equations. A slope 1:500 is also calculated using the Weyl (1958) model. Carbon dioxide partial pressures of 10E-2.52 and 10E-1 are used, reflecting values typical of spring waters and soil waters, respectively. (Adapted from White, 1977.)

drops of seepage water supplied through a central canal. Typically, soda straws are a few decimeters in length but range to 1 m or more. The shallowness of some of these caverns makes it probable that the drip waters have not travelled far from their initial contact with limestone, yet they have achieved a degree of saturation that not only makes stalactite growth possible but precludes the re-solution of its base from the inside in these slender forms (Ewers, 1982). Finally, White (1977) pointed out that springs in the Appalachians are typically undersaturated at the critical 90 percent level. This undersaturation corresponds to the dramatic decline in the mass transfer rate in region 3 of the Berner and Morse experiments.

Porosity Distribution

Secondary permeability, in the form of joints and bedding planes, should provide the capillary spaces through which the bulk of groundwater movement in limestone will occur. In support of this statement is the widely published data, from many sources, on the low primary permeability of Paleozoic limestones with which this study deals. For example, Davis and DeWiest (1966, p. 348), Choquett and Prey (1970), and Freeze and Cherry (1979, p. 29) listed limestone permeabilities of less than 0.1 millidarcies when fracture porosity is not considered. Early workers such as Martell (1921) and Swinnerton (1932) pointed out the importance of these partings.

Bedding planes have been shown by several authors to be associated with phreatic conduits, and quantitatively more closely associated with these conduits than joints. Ewers (1972), in an analysis of more than 20 km of subsurface conduits in south-central Kentucky, showed that 93 percent of these were apparently related to bedding planes. Deike (1967) found joints of very limited importance in the development of subsurface karst in the Mammoth Cave Region, and by implication, that bedding planes are of great importance. Ford (1971) reported that, in his field experience, the ratio of bedding plane to joint passages commonly ranges from 10:1 to 100:1 in those caves where bedding planes are of any importance at all.

The reasons for the overwhelming importance of bedding planes in this regard is not difficult to understand. Bedding planes are frequently more common than major joints, and their lateral extent is often much greater, often reaching all boundaries of a limestone mass. Joints that do traverse an entire rock mass can carry groundwaters only along a single horizontal vector, which may not coincide with the regional hydraulic potential field. Bedding planes are capable of conducting flow along any horizontal vector. Even in those cases where complementary joint sets may provide a continuous capillary opening to the limestone boundary, it is not clear that it will be enlarged. Ford (1971) pointed out that groundwater flowing through a network of joints is required to make many turns at joint intersections. Such a course is one of high resistance and vulnerable to capture by a straighter, more efficient bedding plane, with which the joint almost certainly intersects.

A THEORETICAL MODEL

Arguing from these stated principles and the generally accepted principles of flow in porous media, five statements logically follow.

1. Because the solution kinetics are quite rapid, the initial solution porosity will propagate from the input toward the resurgence.
2. Because the pore space conducting the groundwater flow, a bedding plane, is a thin three-dimensional space, each input will discharge along a separate vector. Thus, each vector will give rise to a separate network of tubes. Ewers (1982) has shown that these networks should be in the form of distributaries or anastomotic bands (Ford, 1968).
3. The rate and direction of that propagation is related to the pressure field within the bedding plane. This pressure is, in turn, related to the geometry of the inputs and resurgences and their relative fluid potentials.
4. As the networks grow, the pressure field must change, and networks possessing high growth rate will retard the growth of those with slower growth rates.
5. The hydraulic capacity of a tube network changes abruptly when it fully penetrates a bedding plane.

Prior to the establishment of a low-resistance link with the output, the meteoric water catchment for an input is likely to be small, because the network's discharge capacity is small. The discharge capacity is determined by the transmissivity of the remaining unaltered bedding plane through which the growing tube network must discharge, not the network itself. When a network breaches the bedding plane, it may then be capable of conducting all of the water available to it. In such a case, the head throughout the network will approach the level of the resurgence. This will produce a depression in the hydraulic potential field in the region of the network. Surrounding networks will respond to this pressure field change with an increase in their growth rates and a redirection of their growth toward the low-resistance tube. The first of these to link with the initial low-resistance tube will become the dischrge target for some of the remaining networks. These remaining netwoks, in turn, become the targets for additional networks developing from still more distant inputs. Thus, the cave grows in length by the linking of short segments of conduit in a headward direction and a stepwise fashion. The gross pattern is tributary in form, but the individual elements are distributaries. This evolutionary scheme has been called the progressive headloss model (White, 1977). The details of any particular linking system depend upon boundary conditions imposed by topography and geologic structure. Three linking models have been investigated: high-dip, low-dip, and restricted-input (Ewers, 1982). The latter applies most commonly to the Cumberland Escarpment karst and to Cave Creek specifically.

Evolution of the Linking Pattern

Figures 7a-e illustrate the development of the restricted input linking pattern. In this idealized case, three inputs and a single-point resurgence occur along a stream course where an impermeable caprock has been breached. Groundwater is assumed to be conducted to and from the bedding plane by way of joints. Equal driving potentials h_1, h_2, and h_3 are assumed for the inputs. Porous media hydraulics require that input 1 will have the highest throughput, with successively smaller Q values for Inputs 2 and 3. The solution kinetics predict that the growth rates of the tube networks arising from the three inputs will be in proportion to their throughputs. The flow from input 1, the proximal input, is symmetrical about the input-output axis, and the flow envelope will possess an ovoid shape. A tube network should develop along the center of the initial flow envelope. Inputs 2 and 3, however, exhibit a two-lobed flow envelope and initially generate a pair of tube networks that form relatively independently (Fig. 7b).

In Figure 7c the network forming from input 1 has completed a low-resistance connection to the output, and it is assumed to have enlarged to a diameter sufficient to conduct all of the water available at Input 1 under average conditions. Therefore, the head at input 1 will drop to the level of the resurgence, and the network associated with it will function as a sink for groundwaters entrained in the bedding plane. The discharge boundary is thereby altered from a point with limited capacity to one of linear dimension, equal to the perimeter of network 1, with greatly increased capacity. In response to this change and its newly established proximity to an output boundary, network 2 should commence rapid growth. The new growth of this network will take place along a route that combines already existing tubes with the shortest available path to form a link with network 1 (Fig. 7d). Network 3 should show increased growth following the breaching of the bedding plane by network 1. Subsequent to the linking of networks 1 and 2, network 3 should commence growth to complete a low resistance link with network 2, in the manner already described (Fig. 7e).

Laboratory solution experiments verify that there is good reason for such a linking system to be operable in nature: it is simply more efficient. Where the possibility exists to drive a groundwater conduit over a given distance from a single input or from several intermediately spaced inputs in a linking scheme, the multiple input systems will prove more time-efficient (Ewers, 1982).

SUMMARY

The restricted-input linking scheme can be characterized in the following ways:

1. Subsurface drainage basins should be established by the stepwise integration of small distributary sub-units into a tributary system.
2. Similarly, the integration of the system should proceed from the resurgence in a headward direction, the opposite of the direction of the network propagation.

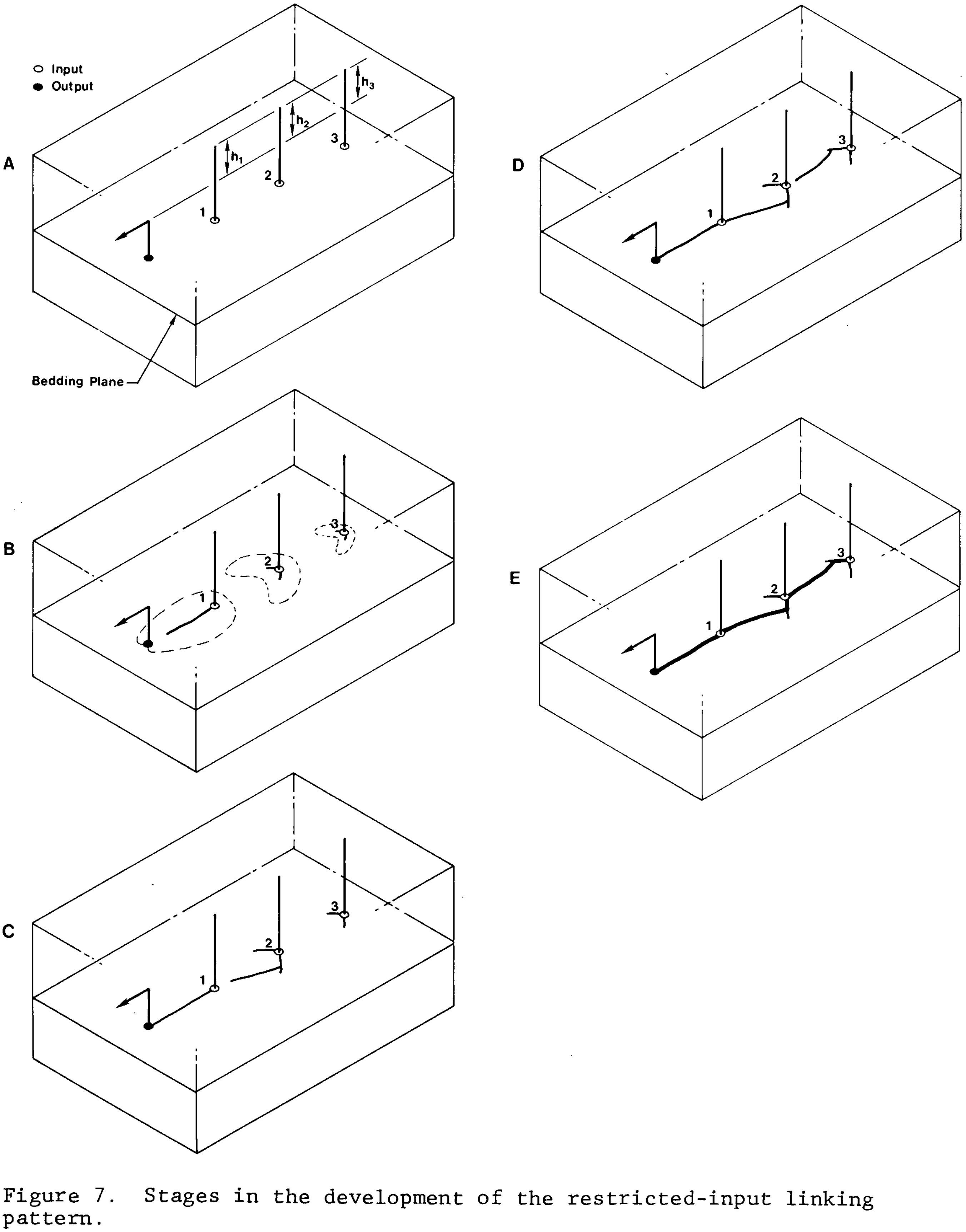


Figure 7. Stages in the development of the restricted-input linking pattern.

3. The plan form of the conduit pattern should be simple, linear, and relatively unbranched and should parallel the stream course from which it originated.

The morphology of the conduits beneath Cave Creek Valley are consistent with their having evolved in the manner described in the restricted-input model. The fact that alternate, but unused, pathways of steeper gradient for discharge of the headwaters of the system exist argues strongly that the theoretical growth advantages of the multiple input system are real. This mode of cavern development is the most common type in the region of the Cumberland Escarpment.

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Chapter 5

CAVES OF NORTHEASTERN KENTUCKY (WITH SPECIAL EMPHASIS ON CARTER CAVES STATE PARK)

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East on Interstate 64 from the heart of the Blue Grass area, the jagged rock outcrops are passed so quickly, it is difficult to appreciate the incomprehensible amount of time that led to their formation. It takes only about 2 1/2 hours to travel the 193 km from Lexington to Ashland, in the northeastern corner of the State. But in that stretch, one passes rocks that took over 400 million years to accumulate.

The Paleozoic Era, 600 to 250 million years ago, was a time when all of Kentucky was under water. Sediments accumulated on the floors of these ancient seas and eventually were compressed to form the rocks we now see. We know it was a time of regression and transgression of these ancient seas. There were times of tranquility, when animal remains could easily be preserved. There were times of turbulence, when the remains were ground up into microscopic bits and pieces. All of these paleoenvironmental fluctuations are readily observed due to the diversity of rock type stacked in layers, one on top of the other, from the oldest to the youngest.

At some point in time after the rocks had been formed, there was a period when these rocks were thrust vertically upward along a line running north-south from northwestern Ohio through Cincinnati to the Nashville, Tennessee area. Had subsequent erosional events not affected this Cincinnati Arch, there would be a high ridge in central Kentucky today, instead of rolling, pastoral farms and fields. As this uplift occurred, erosional forces kept pace, wearing away the arch as it pushed upward. Today, there is no mountain grandeur in central Kentucky--just the core of the arch exposed. In the center of the uplift, the youngest rocks have been eroded away, leaving the older rocks exposed. As one travels from the center of the Blue Grass, progressively younger rocks outcrop like concentric growth rings in the center of a tree trunk.

A caver, traveling east on Interstate 64 from Lexington, would not have much to be enthused about for some distance. One would first pass the thin-bedded, fossiliferous limestones of the Ordovician Period. Not much in the way of caves there. Farther along, one would pass the shales and dolomites of the Silurian and Devonian periods. Nothing there. In this area, a chain of conical-shaped hills can be seen. These are the Knobs. They form a ring around the Blue Grass. The Mississippian and Pennsylvanian rocks are exposed at the tops of these Knobs, and it is within the next 40 km of Interstate highway that one would cross a northeast-southwest trending belt of limestones in which most of the caves of northeastern Kentucky may be found.

The Mississippian limestones exposed in this region have been identified as the same limestones found in similar stratigraphic position in other parts of the State. However, in northeastern Kentucky, the Mississippian and Pennsylvanian periods were times of transgression and regression of inland seas. Water inundated areas for a time and then receded. Barrier islands of sand developed, only to be covered by transgressing seas. Limestones interface with sandstones to show the transitional energies that were occurring at the time. In the region, the maximum thickness of good homogeneous limestone available for solution is 27 m.

Tygart's Creek is a relatively small stream that meanders northeast through Carter and Greenup counties on its way to the Ohio River. Through a 32 km stretch, it crosses the limestones of northeastern Kentucky, and within that section most of the significant cave development of the region occurs. The geologic history of this stream and its tributaries is vitally important to the understanding of the speleogenesis.

Prior to the glacial and interglacial events of the Pleistocene, Tygart's Creek, then a part of what has been called the Teays River drainage system, was eroding downward toward the Mississippian limestones that had been deposited millions of years earlier. As the stream eroded downward, the limestones became more vulnerable to the chemical and mechanical actions of the watershed. Water, seeping into cracks and crevices of the limestone, began the process of solution along joints and bedding planes. During the early glacial events of the Pleistocene, many of the cave passages found in the upper portions of the limestones were being acted upon. With subsequent interglacial periods, Tygart's Creek and its tributaries experienced periods of rapid down cutting. By the end of the last glacial transgression, most of the caves in the area had achieved much of their present size. During the last glacial event, many of the passages in the caves were practically filled with outwash and sediments. Terracing of the slopes in the region can be attributed to glacial events that reduced the erosional energy of the streams in the area. Tygart's Creek is a fine example of a stream that has been rejuvenated. Once it meandered over a wide area, slowly cutting through the rock. Then with glacial melting and a more easily eroded substrate, the stream began a period of entrenchment which is clearly visible in the vicinity of Carter Caves State Resort Park.

Today along the northern Cumberland Plateau, the tops of the hills are usually around 305 to 427 m in elevation, while the valley floors are usually 152 to 213 m in elevation. The cave-forming rock, the Newman limestones, outcrop near the 244 m contour level and extend downward. The erosional progress of Tygart's Creek has taken it through the Newman sequence to the thin, impure limestones correlated to the St. Louis Formation. Below this, the shaly, silty strata of the Borden Formaton are not readily dissolved by surface or subsurface water. Thus, Tygart's Creek itself is no longer a part of the cave-forming process. However, tributaries are still eroding through the Newman, and this is where the subsurface water routes still exist. Within the area, many springs of water emerge at the contact point of the Newman limestones and the less soluble strata beneath it.

Within the northeastern region of Kentucky, Carter Caves State Resort Park is the best known and most intensively visited cave site. The Park is located about 8 km off Interstate 64 in Carter County, Kentucky (the origin of the Park's name). The relief within the Park averages 152 m. At the highest elevations within the Park, the orthoquartzitic sandstones predominate the rock outcrops. The tidal barrier deposits intergrade in other parts of the region with silts and sandy limestones of the Pennington Formation. Of notable interest to the serious visitor is the erosional arches and rock houses found in the sandstones. The more interesting of these are Fern Bridge and Raven Bridge. Fern Bridge is an arch believed to have been formed by a waterfall. The water at some point in time was diverted through a crevice in the outcrops and subsequently undercut the upper rock strata to produce the bridge as it appears today. Raven Bridge is a much smaller arch with well defined openings on both sides of the arch. Water, undercutting the rock, and subsequent collapse of additional strata, has led to the formation of this delicately balanced arch.

Another feature of interest in the sandstones of Carter Caves is a feature called Box Canyon. Located in a remote section of the Cascade Area, the surface feature was produced by collapse along parallel joints that were dissected by a third joint running essentially perpendicular to the others. The result is a feature with two nearly perfect 90 degree corners.

There are approximately 20 caves that are collectively called the Carter Caves. No one cave bears the name. They range from 3.35 km down to those that could barely be called true caves.

Currently, the largest is Bat Cave (Fig. 1). This is an undeveloped cave that is best known as a hibernaculum for the endangered Indiana bat (<u>Myotis sodalis</u>). This is the third largest colony of this bat in the world, and because of the vulnerability of the Indiana bat to wintertime disturbance, the cave is gated. Tours are conducted through the cave by Park staff during the summer months when the

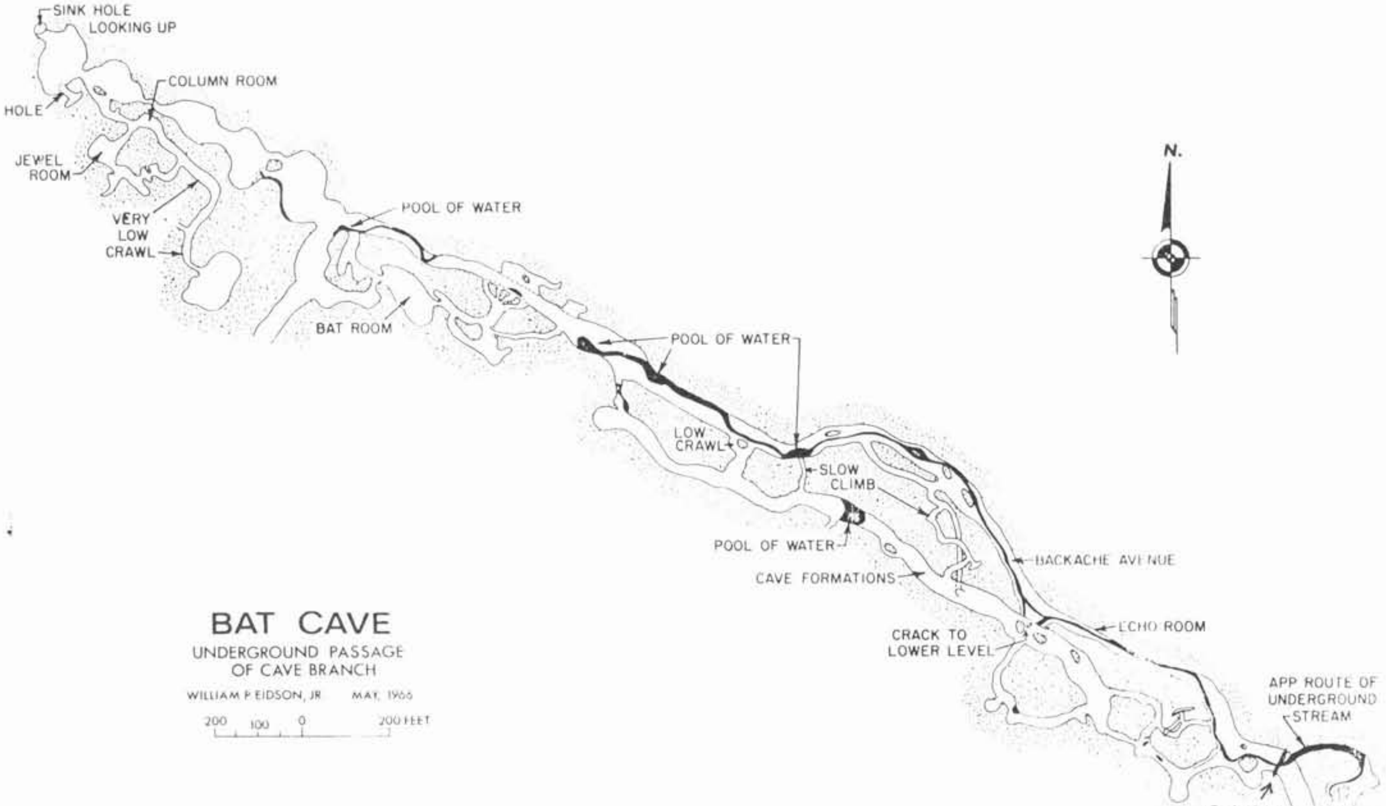

Figure 1. Bat Cave, the longest cave in Carter Caves State Resort Park and a hibernaculum of the Indiana bat, <u>Myotis</u> <u>sodalis</u>.

bats are not in the cave. Bat Cave is made up of two levels of passages running parallel to one another. The main, lower-level passage is a wide, underground conduit that was formed by solution along bedding planes. Large rooms along this passage, where the ceiling reaches 10.7 m above the floor have resulted from the collapse of the thin rock strata that forms the ceiling. A small stream, Cave Branch, flows through this passageway, making it susceptible to flooding during periods of heavy rainfall. Debris, gravel, and mud-caked surfaces attest to this. The upper levels of the cave are drier, and some speleothem growth has occurred. Bat Cave was uncontrolled up to 1974. Before that time, thousands of people roaming through the cave extensively damaged many of the formations. Today, much of the original beauty of the cave is gone because of the thoughtlessness of earlier cave visitors. A surveying project is currently underway, and Bat Cave is likely to be in excess of 3.05 km in total length.

Another cave in Carter Caves State Resort Park is Cascade Cave (Fig. 2). A small stream named James Branch begins inauspiciously alongside Interstate 64 and travels in a northerly direction toward Tygart's Creek. Flowing through the hilly farm country, 3.2 km into its journey, it drops over a waterfall approximately 12.2 m high. The resistant rock that causes the falls is the area's sandstone which sits on top of the Newman limestones. As the water drops over the falls it enters a valley underlain by the limestone, and shortly, the water flow has been diverted into the cracks of the rock and the streambed is dry. Under this valley floor, extensive cave development has occurred. Throughout the remainder of its course, James Branch remains below the surface. The valley above is pitted with sinkholes, and no present-day stream bed exists.

Cascade Cave, formed by James Branch during its subterranean journey, was commercially developed in 1925. It is considered by most to be one of the most scenic caves in the area. The four main passages run parallel at slightly different elevations. The size of the passages along the tourist route makes this bedding plane-controlled cave seem quite large, if not in length, certainly in the volume of the cavity. At main intersections of passageways,

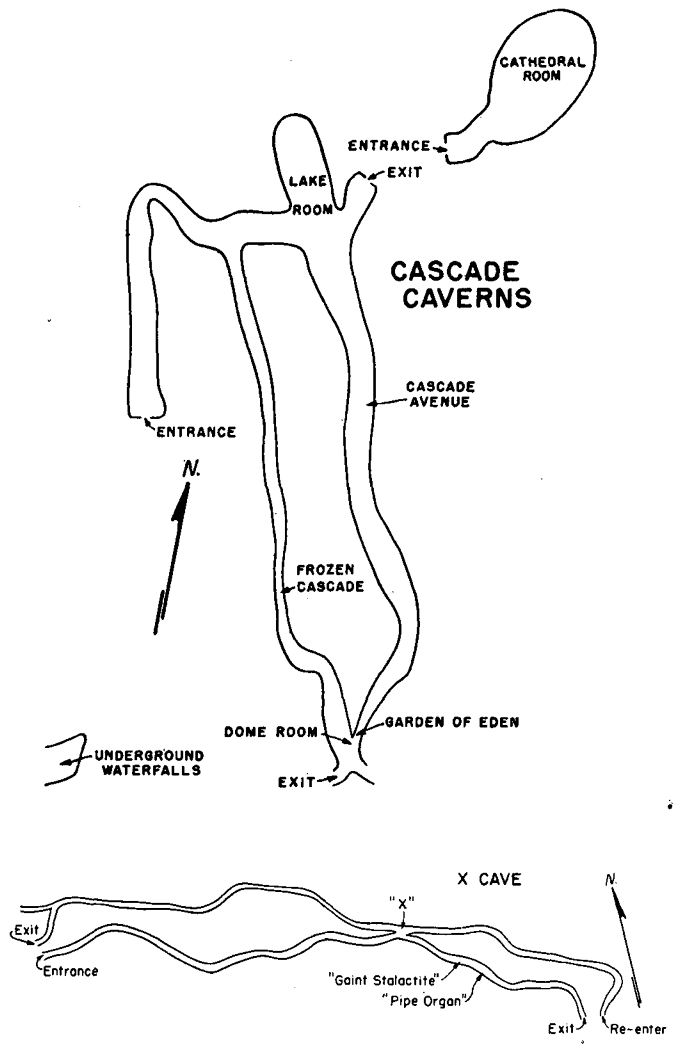

Figure 2. Sketches showing the main passages in the two lighted commercial caves at Carter Caves State Park. (from Geology of Carter Caves State Park)

enlargement has occurred through collapse, and at one of these points called the Lake Room, the visitor can see James Branch exit the cave through a large opening to the outside. The water pools in the opening, and an impressive mirror lake that reflects images of the landscape outside the cave is created. In a disjunct part of the tour, the Cathedral Room can be seen. Underneath a massive system of sinkholes, large amounts of water seep into the cave and deposit a number of formations. Many columns have developed in the room. One of them, resembles a castle or cathedral sitting on a hill, and thus gives rise to the name of that section of the cave (Fig. 3).

Another disjunct part of the commercial tour is the Underground Waterfalls. It is located about 91.4 m west of a sinkhole entrance to Cascade Cave. Access to the waterfalls is through a man-made entrance. This interesting phenomenon is a dome-pit structure like those of many other areas. Water, flowing along a bedding plane, has been diverted downward through a joint to another bedding plane water course. The visitor can view the 11 m plunge from a viewing platform constructed at about the midpoint of the falls. The water eventually reaches James Branch within Cascade Cave, but attempts to physically connect the waterfalls to the main cave have, so far, been unsuccessful. Within the last few years, area cavers working in conjunction with Park officials have surveyed regions of the cave not previously connected to Cascade Cave. They are hopeful that this cave may become the longest in the Park.

The most unusual, and perhaps the most interesting cave of Carter Caves is Saltpetre Cave. Formed along a bedding plane near the top of the Newman Limestone, this cave's broad passages are mostly dry and dusty. The dirt and gravel that nearly fill the passages in many places show that the cave has not always been the way it looks today. The black soot that covers the walls of the cave and the old tools and devices found in the cave suggest that the cave has some historical significance (Fig. 4). No documentation exists concerning the activities that took place in

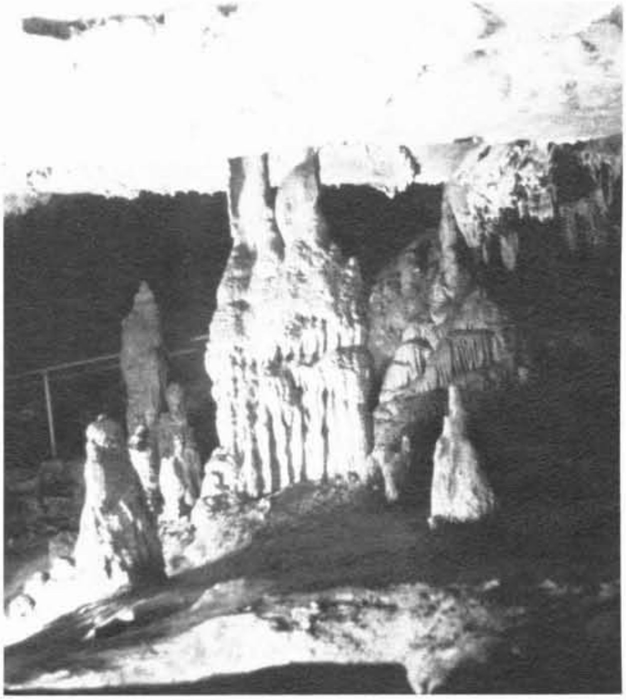

Figure 3. The Castle in Cathedral Room of Cascade Cave.

Figure 4. Signatures of early visitors in Saltpeter Cave.

this cave, but legends told in the area suggest that the dirt on the floors of the cave was mined as early as the War of 1812 for the extraction of sodium nitrate (saltpetre). The extreme dry conditions of the cave are due to the impermeable nature of the sandstone that covers practically the whole cave. Near the main entrance to the cave, where the sandstone does not overlay the cave, dome-pits have developed by the invading water from the surface. In a few places of this part of the cave, mineral-laden waters have been able to deposit some calcite formations. What the visitor sees in Saltpetre Cave, more than anything else, is the dark, dingy color of the walls and formations due to the flames of torches and lanterns used in the cave in earlier days. Recent surveying of this cave has put the length at just under 3.05 km. Lantern-lit tours are conducted daily throughout the year. During the summer, cave guides also conduct frequent spelunking trips through the cave by advanced reservation.

Just across the parking lot from Saltpetre Cave is X Cave. Electrically lighted, it offers an extreme contrast to Saltpetre Cave. X Cave is a cave of narrow, high-ceilinged passages. It has two main passsages formed along vertical joints, tht intersect in the middle of the cave, so that when standing at the intersection, there is an obvious "X" configuration of the passages. Each trunk of the "X" has an outlet. One side of the cave is under the sandstone caprock, which makes it drier and, for the most part, except where dome-pit activity exists, void of formations. The other side is wet and has a great deal of on-going speleothem growth. The more significant formations have been named over the years. A massive collection of columns, stalactites, and stalagmites that collectively form a deposit 9.1 m tall and over 2.2 m in diameter is called the Giant Column. A series of drapery type formations is called the Pipe Organ because of the early custom of tapping the formation to produce musical tones (a custom which is no longer demonstrated).

Two other caves worthy of note at Carter Caves are Laurel Cave and Horn Hollow Cave. Laurel Cave is an undeveloped cave that is formed along a vertical joint. The downstream entrance is located alongside Cave Branch. The upstream end of the main passage is in Horn Hollow, an elevated valley that seldom has water flowing along the valley floor. Instead, the water is underground. Further upstream, Horn Hollow Cave may be seen. Water flows out of the entrance, forming a large pool that necessitates a chilly wade to enter the cave. This is strictly an underground water conduit for Horn Hollow Creek. The volume of water that occasionally flows down this valley makes this a cave to avoid during periods of heavy rainfall.

Within a 40 km radius of Carter Cave there may be as many as 200 named pits and caves. To the northeast of Carter Caves, another cave system of note is what cavers have called The Cow Counterfeiter's Cave System. Around the turn of the century, parts of this cave were developed for tours by private owners. They called it Oliginook Caves. The cave was shown for a brief time, but since then it has become a favorite with local cavers because of the intricate maze of crawlways and climbs. This system has formed along a series of northeast-southwest trending joints. There are three sizeable entrances to the cave. The connecting passages from one joint to the next are small, and crawling and some technical climbs are necessary to visit all parts of the cave. All of the entrances are located near the top of a formidable hill. The walk to the cave from the car weeds out the weaker cave visitors.

Because the limestone thickness is less than in the more significant cave areas of the State, there are few caves which attract the vertical caver to northeastern Kentucky. There are a number of pits in the area, but the deepest of them would not be much deeper than 24.4 m.

Because much of the solution and development of caves has occurred along joints, many of the caves offer some complexity to rock climbing and negotiating through narrow, confining passages. One cave that offers a diversity of challenge is Burchett's Cave (formerly Jarvie Roark's Cave). This is a maze of criss-crossing, joint-controlled passages where solution has also occurred at different levels along the bedding planes. Of particular interest is a narrow passage called Rimstone Avenue, where one can see rimstone dams in excess of 1.5 m in height. Another interesting section of the cave is Heavenly Crawl, a low-ceilinged passage where soda straw stalactites descend up to 46 cm.

Along the gorge of Tygart's Creek from Olive Hill, Kentucky to the Carter-Greenup County line, caves of varying sizes can be found. Most are small, being less than 91.4 m in length. Names given them seem to be sufficient description. Crawlsbad Caverns, Disappointment Cave, H_2O Cave, Impossible Cave, Moonshiner's Cave, Garbage Cave, Rat Cave, and Zig-zag Cave...all seem to offer little incentive to visit except for those masochistic folk that seem to constantly be on the prowl for a "BIG" cave somewhere out there just waiting to be discovered.

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Chapter 6

PINE MOUNTAIN KARST AND CAVES

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Pine Mountain is a long, narrow, straight ridge extending 170 km in a northeast-southwest direction in eastern Kentucky and another 24 km in Tennessee (Fig. 1). This dominant topographic feature represents the northwestern edge of the Pine Mountain Overthrust Block and is bounded on the northeast by Russell Fork Fault near Elkhorn City (Kentucky) and on the southwest by the

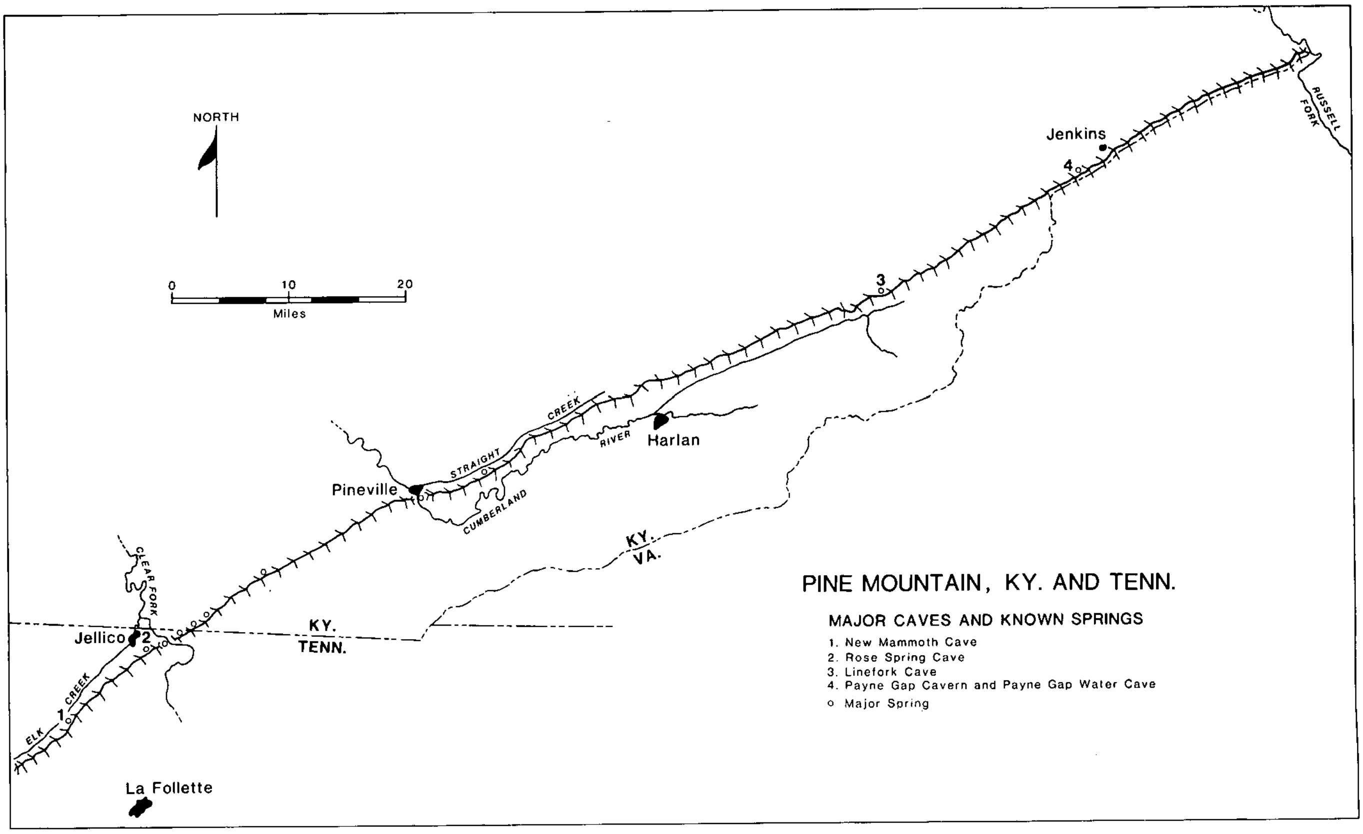

Figure 1. Pine Mountain, a large overthrust block, extends 105 miles in a northeast-southwest direction in eastern Kentucky forming the highest cave region in the State.

Jacksonboro Fault near Lafayette (Tennessee). Pine Mountain encompasses parts of Pike, Letcher, Harlan, Bell and Whitley counties in Kentucky, and Campbell County in Tennessee. In Letcher and Pike counties, Kentucky shares Pine Moutain with Virginia, as the state line lies at the mountain crest.

Pine Mountain is a narrow-crested ridge of the Appalachian Valley and Ridge type, and is the westernmost mountain in this part of the Appalachians. Due to the stratigraphy exposed by the thrust faulting, the coal so abundant and important to the local economy in the Cumberland Plateau to the northwest, as well as the Middlesboro Basin to the southeast, is absent on the outcrop slope of Pine Mountain.

The elevation of Pine Mountain's crest commonly ranges from 640 m to 700 m at the southern end to 792 m to 854 m at the northern end, with relief up to 488 m. The highest point on Pine Mountain is approximately 997 m above sea level and located east of the community of Whitesburg. The mountain is crossed by streams at only two places. The Cumberland River, the master stream in the region, encompassing the southern portion of Pine Mountain, crosses the mountain at Pineville in a narrow water gap at an elevation of 305 m. Near Jellico, 32 km to the west, Clear Fork crosses the mountain. To the east of Pineville, the mountain runs for 130 km unbroken by any surface stream, although minor shallow gaps in the crest occur at several places. Interstate 75 south of Jellico climbs the outcrop slope of Pine Mountain before traveling along the crest for nearly 16 km. The relatively homogeneous topography of Pine Mountain is remarkable on its northern upper slope for its relative homogeneity, with contours running nearly straight and parallel for kilometers. This homogeneity is especially true along the southern reaches of the mountain where the dip into the mountain is greater. Mountainside hollows and ravines are much more prominent on the outcrop slope in the northern reaches of Pine Mountain.

GEOLOGY

Caves on Pine Mountain underlie the northern (outcrop) slope of the mountain, the only position on the mountain where limestones outcrop. Strata dip into the mountain at 20 to 40 degrees. The caves are found in the Mississippian Newman Limestone, the local equivalent of the Greenbrier or Glen Dean-Girkin-Ste. Genevieve-St. Louis limestones. Along Pine Mountain the Newman Limestone is between 122 to 183 m thick and is exposed about halfway up the mountain. It is overlain by up to 215 m of sandstone, siltstone, and shale of the Pennington Formation (Fig. 2), including the sandstone mountain crest. Ninety meters of the Grainger Formation, mostly siltstone and shale, lie comfortably below the Newman Limestone. The Chattanooga Shale (upper Devonian and Mississippian) is found beneath the Grainger and up to 183 m of it extends downslope to the Pine Mountain Fault near the foot of the mountain. In places there are secondary faults in proximity to the Pine mountain Fault (e.g., at Jenkins, Kentucky, and Newcomb, Tennessee), and in at least one such case a sliver of Newman Limestone is exposed at the foot of the mountain. (Interestingly, there appears to be a subterranean meander cutoff of Elk Fork in such a situation near Hells Point Ridge, Tennessee.) The Newman itself is divided into a larger lower member of limestone and a smaller upper member consising of shale, limestone, and sandstone. Most, if not all, the known caves are in the lower member, and most appear to be in the low, commonly dolomitic portions of the lower

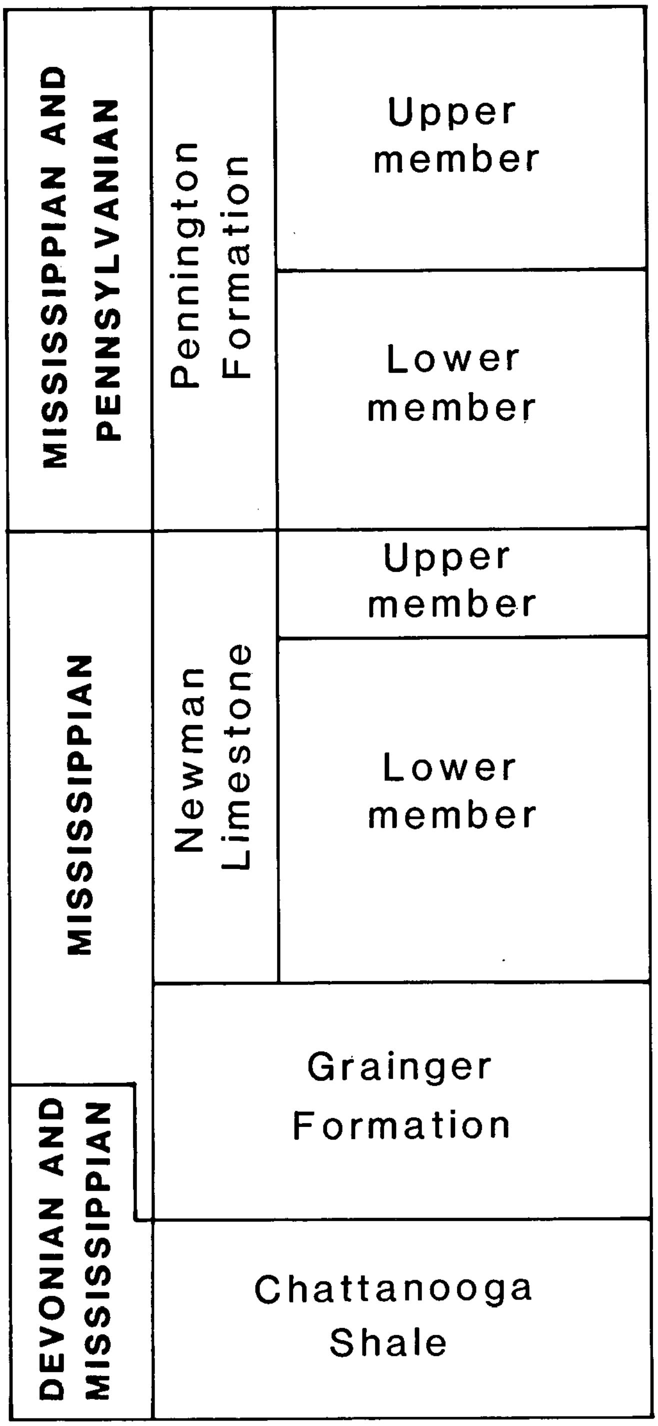

Figure 2. Stratigraphic profile of the outcrops exposed on Pine Mountain.

member, althouh lack of exposure of the basal contact and paucity of detailed stratigraphic study within the Newman preclude an authoritative statement.

The water gaps through the mountain at Pineville and Jellico are associated with faults in the overthrust block. The gap at Pineville is on the Rocky Face Fault and is related in origin to the Cumberland Gap 16 km to the south (Rich, 1933; Froelich and Tazelaar, 1974). An array of faults exists on Pine Mountain just east of the gap at Pineville.

The mountainside overlying the Newman Limestone is steep, and ravines and hollows cut into the limestone commonly have braided rubble streambeds. Solution dolines are few in number. Because of the relatively short distance from the top of the mountain to the base exposures of the limestone, usually 305 to 450 m, stream flow in these small hollows and ravines is intermittent. There is recognized potential for loss of some or all such intermittent flow into the limestone under the rubble. In the case of Payne Gap Cavern (Figs. 3 and 4), the overlying ravine has intersected the cave passage. This intersection has resulted in an entrance that takes some of the intermittent stream flow coming down the ravine. Several pits are known on the mountain, including Colehole (60 to 73 m deep) and a vertical entrance to Linefork Cave. Springs are fairly common in the limestone, presumably near the base. They range from small ones with no cave opening to larger springs with base flow of about 14.2 l/s (liters per second). The limestone springs on Pine Mountain tend to be larger and cleaner compared with springs in the surrounding area, and commonly are employed as domestic or community water sources for people living at the foot of the mountain. Caves are commonly found at or near springs on Pine Mountain, and in some instances access to water supply caves has been difficult. Numerous large vertical faces of limestone are found along the mountain, commonly above the springs.

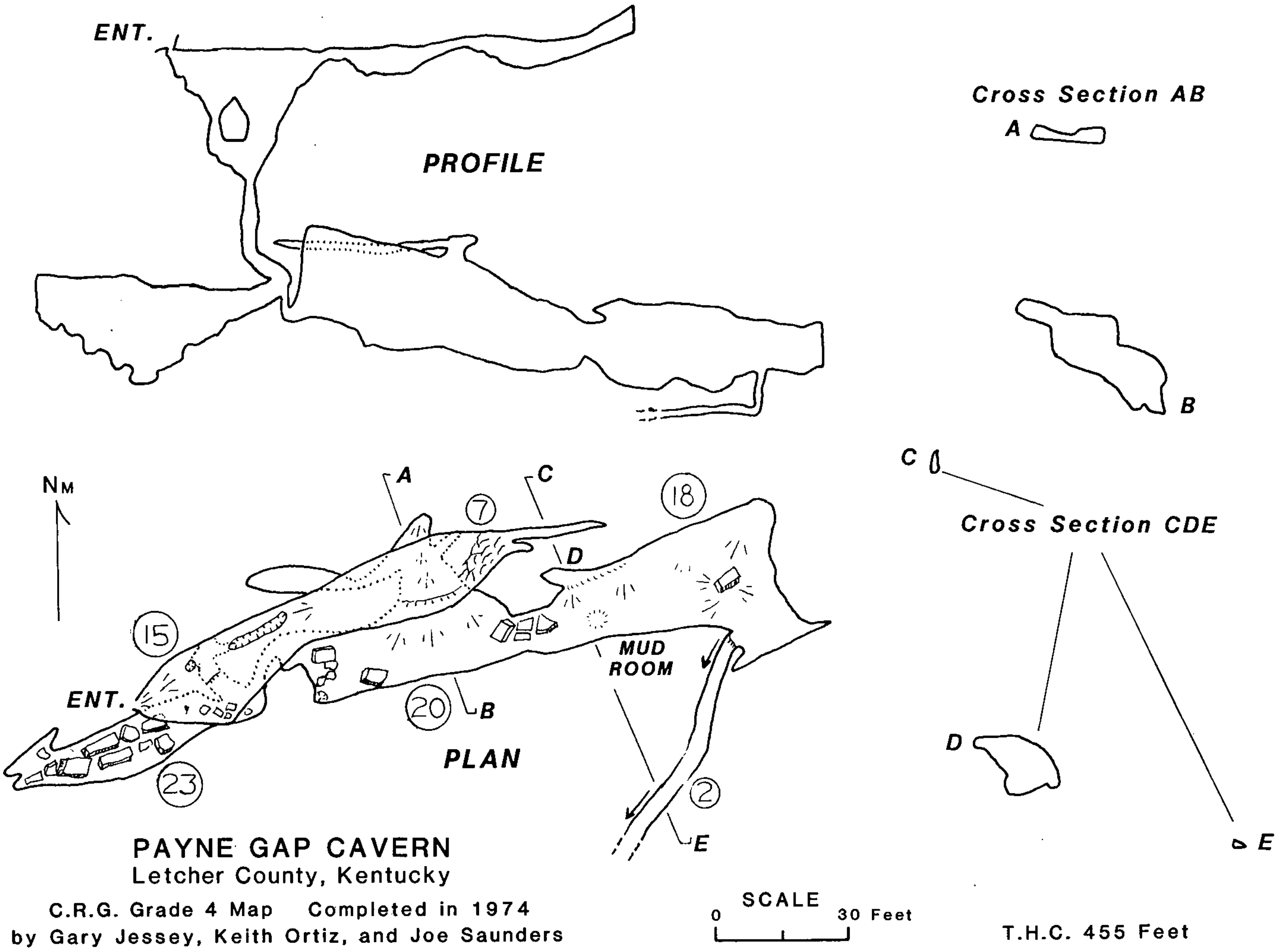

Figure 3. Payne Gap Cavern, Letcher County, Kentucky--a three-level cave containing a base-level streamway.

CAVES

There are nine mapped caves on Pine Mountain, and 15 to 20 known but unmapped caves. The longest known cave is Linefork Cave in Kentucky, where a survey in progress has mapped 2,440 m along the strike (Fig. 5), corresponding to a surface distance of 1,830 m. The cave's main entrance is near a major spring, and five sumps in the main stream are bypassed through higher level passages. A sixth sump has presently halted exploration. There are indications that there has been a terminal sump in this area of the cave for some time, namely the descending ceiling and floor in the upstream direction (Fig. 6). Although the load reduction bank of sand is often found at sumps, it might also have been deposited in a flood event. An examination of the relation of Linefork Cave's passage to the overlying topography reveals that the downstream (western) end of the cave is found where the hillside is steepest. If we assume that the dip into the hillside is relatively uniform in magnitude, then the spring below the main entrance at the western end represents the lowest elevation in the area that the limestone is exposed. One might expect drainage

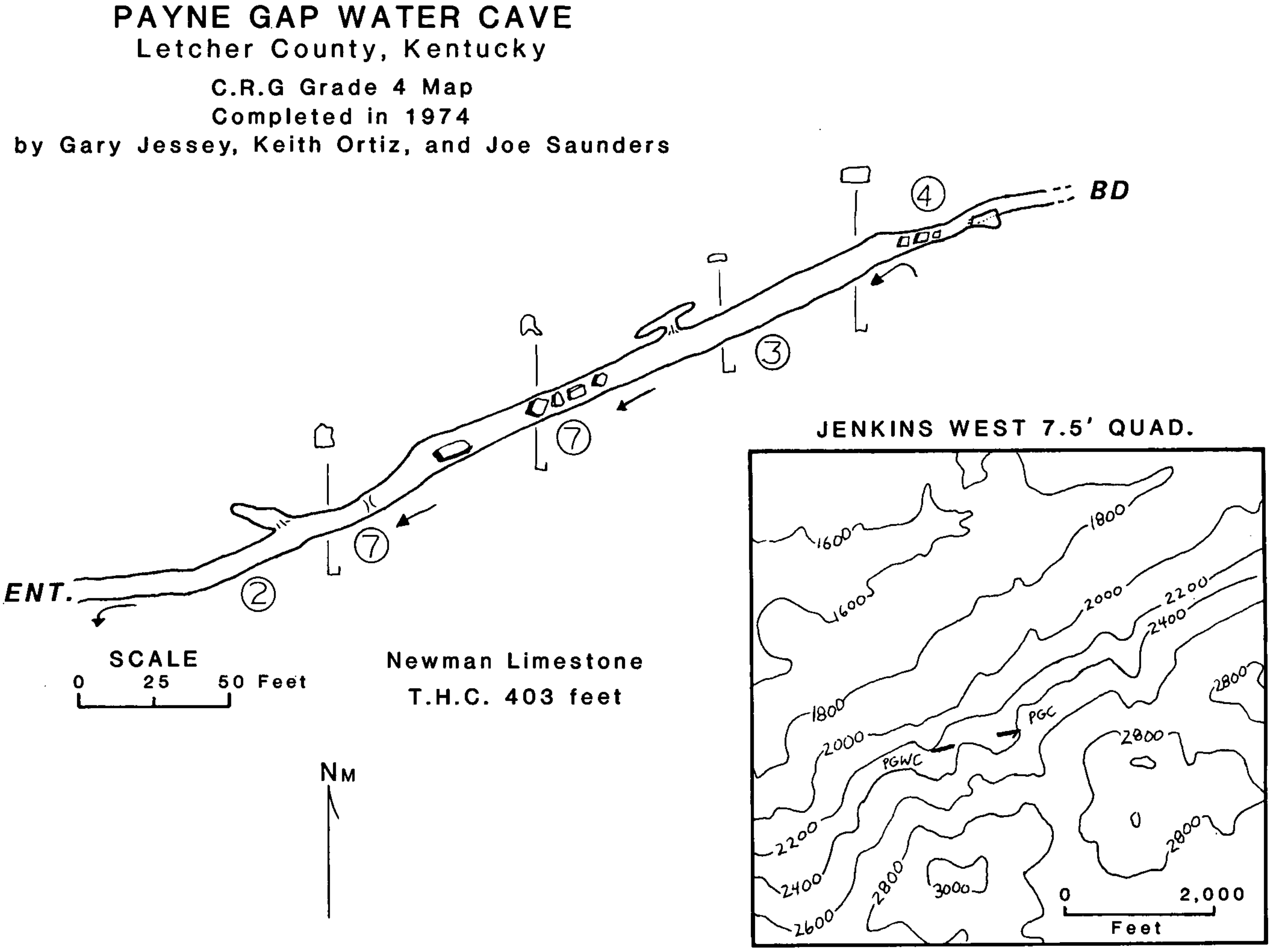

Figure 4. Payne Gap Water Cave, Letcher County, Kentucky--an example of an Appalachian-strike single-passage cave.

within the limestone to be discharged at this lowest possible outlet, although the alternative explanaton of the spring branch being responsible for the topographic situation must also be weighed. Linefork Cave has at times in the past, been referred to as Water Cave. The present survey project in Linefork Cave is reserving the name Water Cave for the 45-m-long spring cave located immediately below the main Linefork entrance and corresponding to the downstream side of sump no. 1 in Linefork Cave.

In addition to Linefork Cave, there are five caves mapped on Pine Mountain in Kentucky, all around 152 m in length. Two of these caves are in the Pound Gap area near Jenkins and have been hydrologically connected with a fluorescein trace (Saunders, 1974). Payne Gap Cavern has three distinct levels including a base level streamway, whereas Payne Gap Water Cave downstream is in some ways the stereotypical Appalachian strike single passage cave (Figs. 3 and 4). Icebox Cave at the water gap at Pineville may be associated with faulting in the mountain there.

The Colehole in Letcher County is the deepest known pit on Pine Mountain. The entrance to the pit

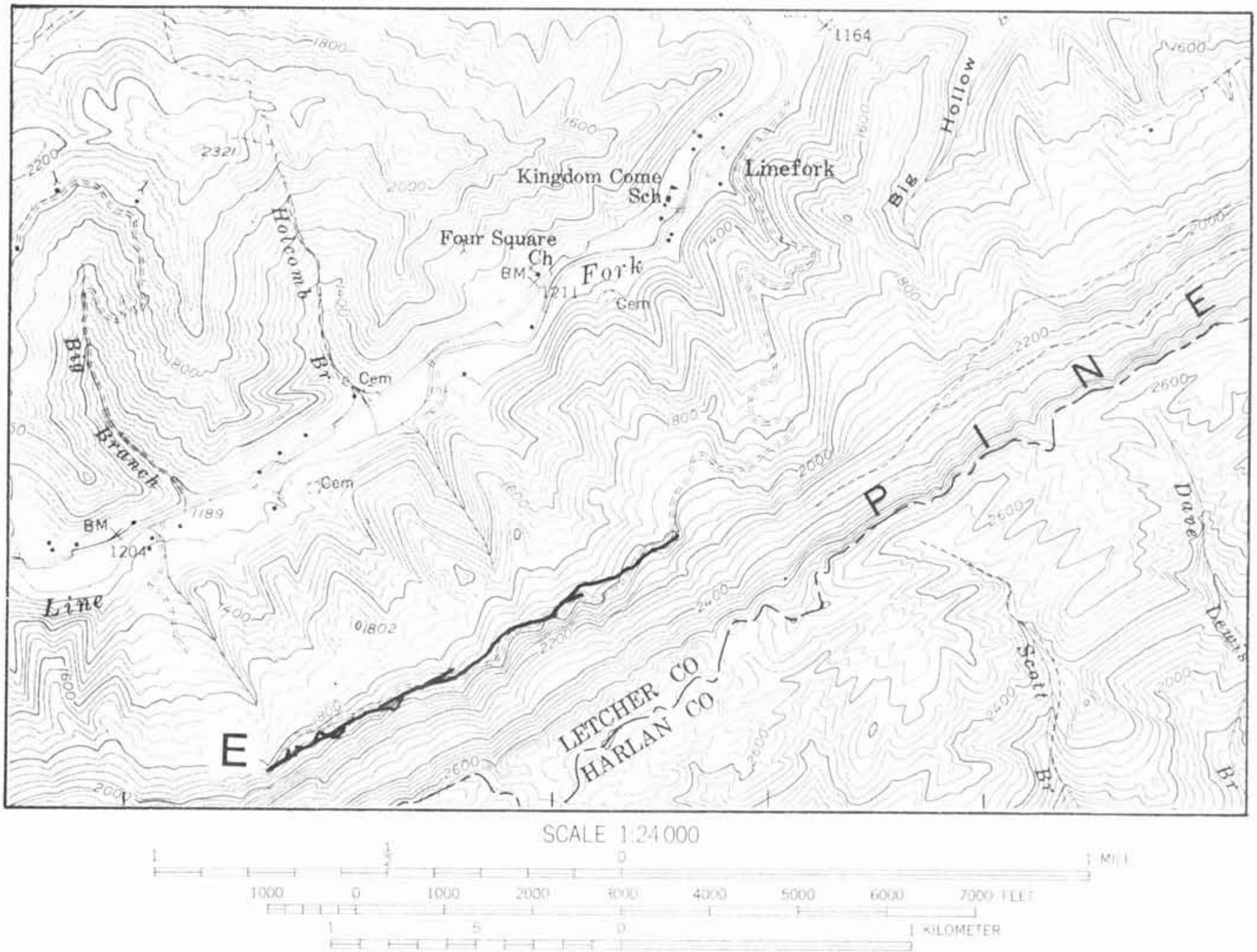

Figure 5. Linefork Cave, the longest mapped cave on Pine Mountain.

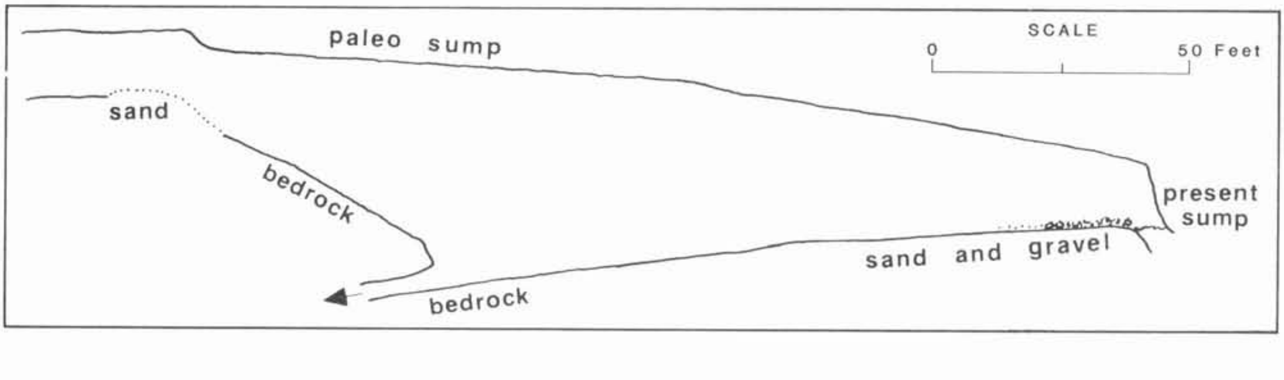

Figure 6. Exploration in Linefork Cave has been stopped by a terminal sump formed from a descending ceiling in the upstream direction.

is a hole 1.5 m in diameter. The geologic structure of the mountain is reflected in the pit by ledges and offset vertical drops. From ground zero at the entrance there is a sheer vertical drop of 27 to 30 m onto a steeply sloping ledge. The largest area in the pit is at this ledge, where the shaft may be 12 to 15 m in diameter. Below the first ledge is another drop onto a second ledge. A third drop immediately folows, descending to a breakdown slope at the bottom of the shaft. Total depth below the entrance has not been accurately determined but is between 61 to 73 m.

Horizontal gallery passage in Pine Mountain caves is relatively irregular in cross section. Pocket and alcove features suggest that phreatic development played a very significant role in passage formation, perhaps similar to the role envisioned by Bretz (1942) in Cudjo's Cave in Cumberland Mountain 16 km south of Pineville, under similar structural and stratigraphic conditions.

A characteristic feature of Pine Mountain caves is that many of the passage cross sections display the effect of the steep dip. Ceilings, ledges, and sometimes floors often slope into the mountain (Fig. 7a-b). The influence of the geological structure on passage trend is fairly consistent as well. Thus, passages usually follow the mountainside, nearly parallel to both the outcrop strip and the mountain crest. Dip tubes (i.e., steeply sloping passages draining from the surface in a downdip direction at right angles into the strike passages) have not been seen by the author in Pine Mountain caves. They are seen in caves in other long mountains in the Appalachians, where they may be associated more with greater mountainside doline frequency.

LONG-MOUNTAIN SETTING

Pine Mountain is one of the long mountains in the central Appalachians of the eastern United States that were discussed by Saunders and others (1977) as the setting for a genre of karst, caves, and subterranean hydrology. Long- mountain karst occurs where limestone or dolomite units crop out in continuous strips along one side of linear sandstone or conglomerate capped mountains, paralleling the strike and the mountain crest, and dipping into the mountain. Whereas the stratigraphy may differ from mountain to mountain, the

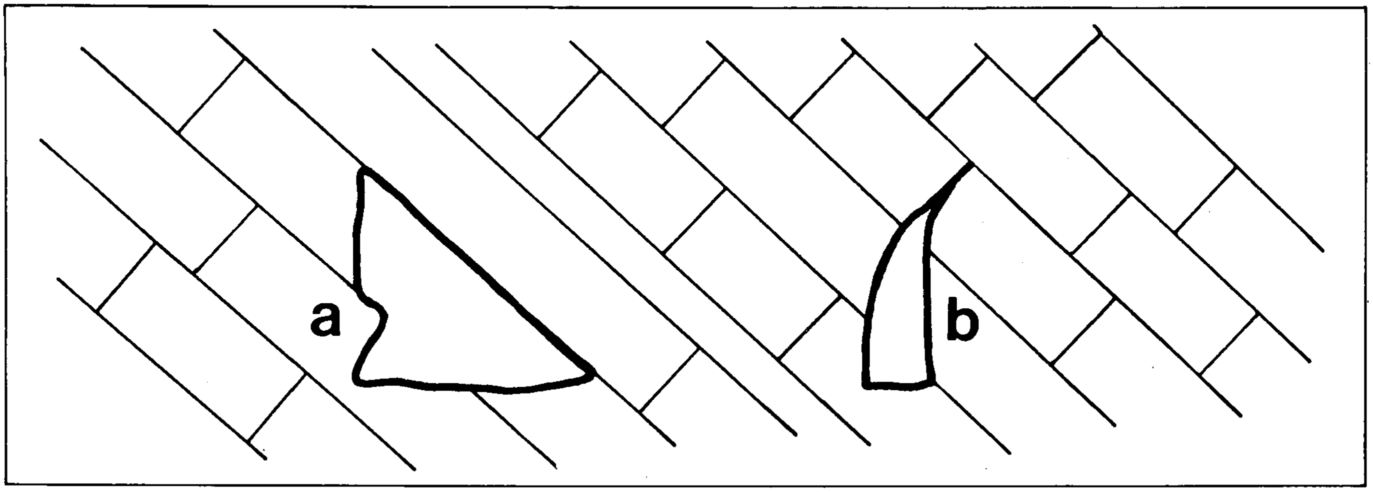

Figure 7. Cross sections of passages in Pine Mountain caves show the effect of the steep dip of the formations.

structural setting is similar and fairly regular, with beds dipping 5 to 40 degrees, depending on the particular area. The relatively uniform relationship between stratigraphy, structure, and topography along each mountain should permit generalizatons about the development of caves and subsurface drainage from the number of examples that arose under seemingly similar circumstances. In the case of Pine Mountain, the cave and spring record is so incomplete that generalizations based on Pine Mountain examples alone are risky. Nevertheless, one can pose questions drawn from other long mountains and try to answer these with available data.

Drainage basins of Pine Mountain springs are long and narrow. With up to 213 m of clastic sediment lying between the Newman Limestone and the crest of the mountain, the widths of the drainage basins are between 245 and 460 m. Distance between springs on Pine Mountain appears from incomplete field work to be up to 5 km. Thus drainage basins are up to 4,575 m long and 460 m wide. They are oriented along the strike, and thus are concordant with most of the adjacent major surface drainage. Drainage under the mountainside to a spring from one direction on the mountainside only is the rule in the limestones in the long mountains. On Pine Mountain, information is available for only three mountainside subterranean drainage systems. Two appear to drain from one direction only (Linefork Cave and Payne Gap Water Cave). Rose Sping Cave in Tennessee is the exception, as it drains from two directons (Fig. 8). There is evidence from the western part of that cave of an abandoned outlet, suggesting the fusion of two drainage systems into one at some time in the past.

Drainage for these basins cannot be considered fully captive because during wetter weather some runoff passes over the limestone band along the steep mountain and continues on down the mountainside surface in the numerous ravines and hollows. It has not been ascertained how many sites in the limestone swallow such intermittent stream flow either partially or wholly (fewer are known on Pine Mountain than on other long mountains), nor to what extent flood pulses are experienced in the downstream portions of the subsurface drainage systems. It is presumed that the range of discharge volumes is relatively narrow for Pine Mountain springs if much of the wetter weather flow goes uncaptured as it flows down the mountainside. A related matter is the degree to which water levels in the caves rise during extreme precipitation events, and the extent to which cavers might be endangered. In the judgement of this author, both are relatively minor.

WATER GAPS

Perhaps the most interesting question pertaining to Pine Mountain caves and subsurface drainage is the comparison between gap and mountainside caves. Most of the springs and caves on Pine Mountain lie on the mountainside several hundred meters above present-day base level surface streams. This is because the limestone is exposed on the mountainside well above the surface streams. Mountainside springs can be viewed as spillover points for water flowing within the limestone, most of which in the mountain lies below the elevation of the spring. As spillover points, most springs can be expected to represent the lowest elevation exposures of limestone along the mountainside. Due to the steep dip into the mountain, incised topographic features in the limestone outcrop such as deep ravines and hollows represent the lowest elevations on the mountainside where discharge

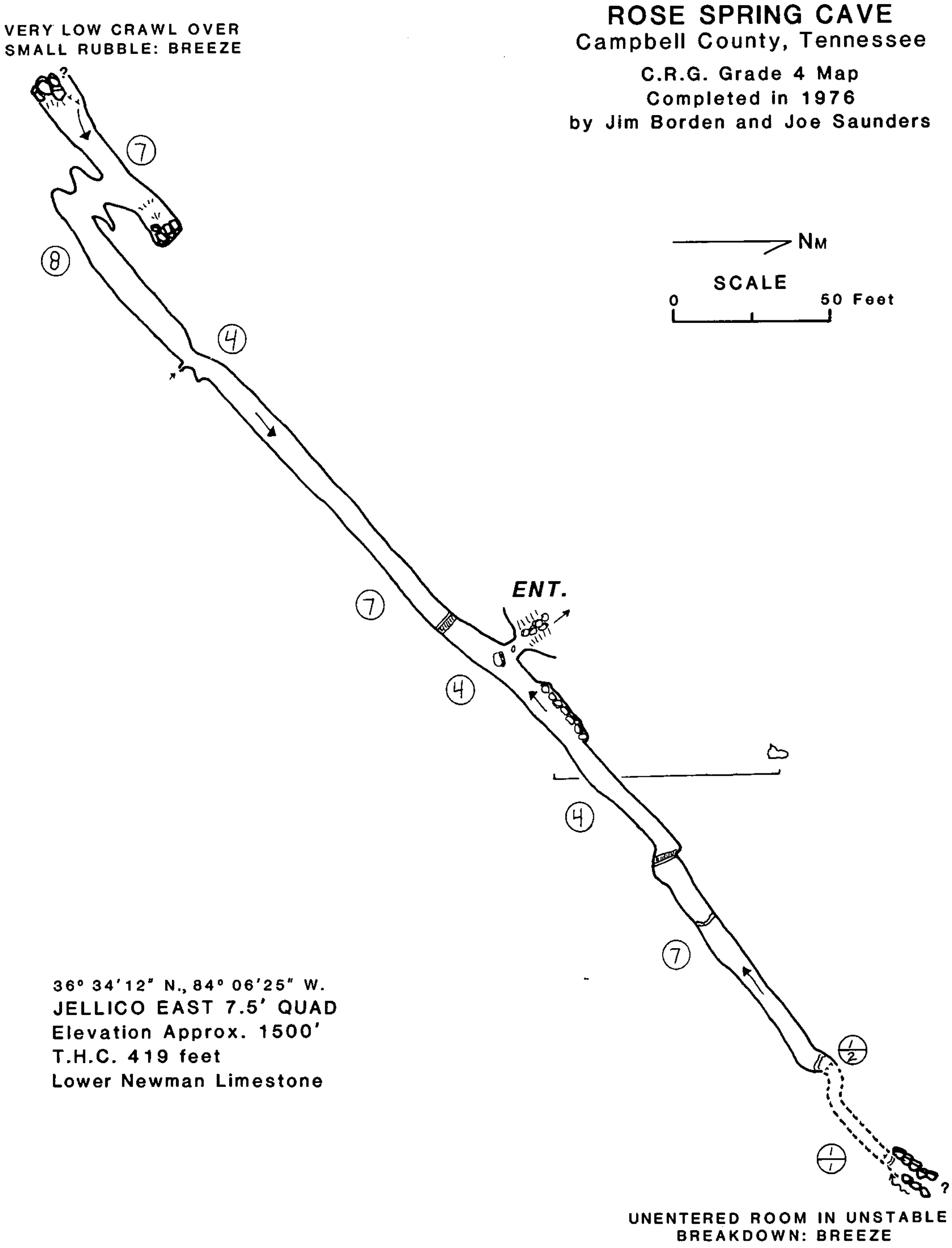

Figure 8. Rose Spring Cave in Campbell County, Tennessee, drains from two directions, an unusual occurrence on Pine Mountain.

from the limestone is possible. Extreme examples of this should be found at water gaps where major base level surface streams cut through the mountain. Here the limestone is found at river level several hundred feet lower than the lowest mountainside limestone exposures a mile or more away (Figs. 9 and 10). Although this exposure at river level would be expected to allow gap springs to compete very well with mountainside springs for drainage

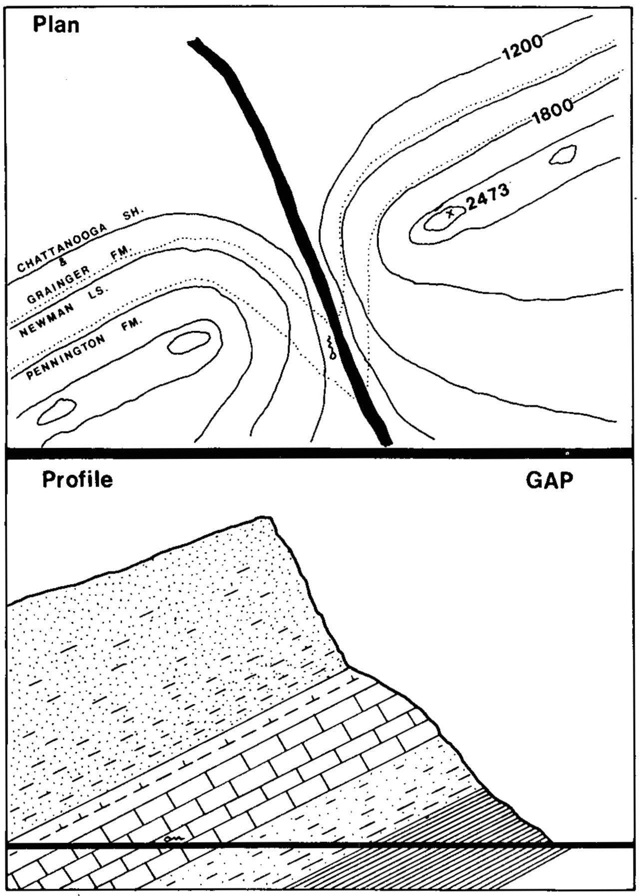

Figure 9. Water-gap exposure of limestone at river base level. Expected cave formation at the gap spring did not materialize.

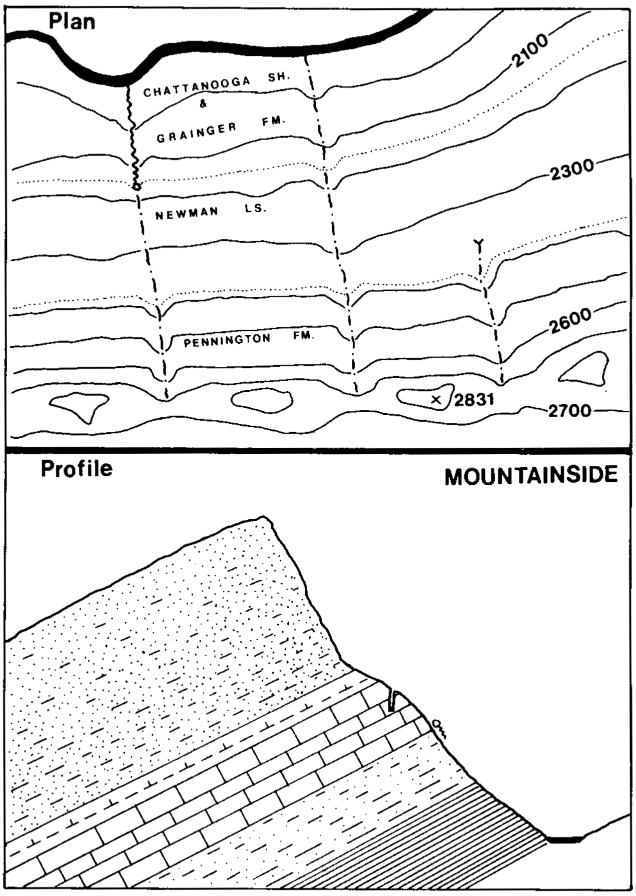

Figure 10. Most springs and caves lie on the mountainside several hundred feet above present base level of surface streams.

area, and to allow discharge sites for the development of long and deep caves, there is little evidence for this at the water gaps at Pineville and Jellico. There are three small caves and a small spring known on the east side of the gap at Pineville. While no spring was noted on the western side of the gap at Pineville, there is a high water outlet in which the owner will not permit exploration. Nothing was found on the eastern side of the gap at Jellico, and a very minor spring was located on the western side. Rose Spring Cave on the mountainside, 2.5 km west of the gap at Jellico and more tha 92 m higher in elevation, drains from the directon of the gap. A kilometer east of the gap there is a spring on the mountainside nearly 92 m higher in elevation than the river gap. No cave was noted there, and no dye tracing was attempted to determine the flow direction to the spring.

It is not clear how to account for the apparent absence of major springs or caves at the Pine Mountain water gaps. One suggestion has been that in cases where the water gap appears to owe its existence to a fault running through the mountain, such as at Pineville and Jellico, joints and bedding partings otherwise available for the development of solution openings and conduits have been adversely affected during development of the fracture zone. An alternative explanation involves recent or rapid changes in regional base level inasmuch as this might relate to time available for gap springs to capture drainage in a headward direction at the expense of mountinside springs. One has only to look 16 km south of Pineville to Cumberland Gap to see the potential for cave development at water gaps. There, with stratigraphy and structure similar to Pine Mountain, Cumberland Gap Saltpetre Cave has a length of several miles and a depth of several hundred feet. A large spring rises at the gap and has been traced by Dr. James F. Quinlan from 15 km away on a mountainside. One difference in the situation there is that Cumberland Gap is an abandoned water gap now several hundred meters above the major surface streams. The abandonment is thought to have involved the piracy of a stream in the Middlesboro Basin west of the gap from the Tennessee River drainage to that of the Cumberland River (Rich, 1933). A possible explanation for the greater cave and hydrosystem development at Cumberland Gap compared to the gaps at Pineville and Jellico is that the postulated water gap stabilized the elevation of the spring, whereas at Pineville and Jellico the spring outlet elevations have been continually dropping as the Cumberland River and Clear Fork downcut, dropping at a rate too fast to permit development of solution channels capable of headward growth.

CONCLUSIONS

Pine Mountain karst and caves are unique with regard to their counterparts in all other areas of Kentucky. They are unique because Pine Mountain lies in the small portion of the State considered to be in the Appalachian Valley and Ridge physiographic province, with its charactristic topography and geologic structure. Formal exploration and study of the caves has been limited. It is recognized that the potential for new discoveries exist, including pits and caves of moderate length (i.e., approximately 2 km).

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Chapter 7

THE MAMMOTH CAVE REGION AND PENNYROYAL PLATEAU

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The Mammoth Cave Region is by far the best known karst area in the United States and is the one most commonly cited in articles on cave origin. Since it has been described in considerable detail in previous works, only a brief summary of the specific karst landscapes and cave systems will be given here. Instead, the main purpose of this chapter is to provide insight into the origin of these features and to determine what makes the area unique.

Only the area in and around Mammoth Cave National Park is considered in detail in this chapter (Fig. 1). Except to the northwest, the karst of this region extends a great distance in all directions, diminishing somewhat in intensity. Although these surrounding areas are not specifically treated here, the general concepts apply to them as well.

REGIONAL SETTING

The area covered by this chapter is located in west-central Kentucky at the southeastern edge of the Illinois Basin and is underlain by limestone of Mississippian age (Fig. 2). These rocks dip gently northwestward toward the center of the basin at 5 to 10 m/km. The total thickness of cavernous limestone in the region is only a few hundred meters--rather thin in comparison to most other karst regions of the world. However, its small angle of dip allows it to be exposed over a wide area, so that extensive karst drainage basins of up to 500 km^2 have developed.

The cavernous limestone is underlain by impure, poorly karsted limestone, also of Mississippian age, and is overlain by sandstone and shale of Mississippian and Pennsylvanian age, which contain thin units of limestone generally no more than 10 m thick. The insoluble rocks form hilly, dissected plateaus in the center of the Illinois Basin, but around the edges of the basin they have been removed by erosion, exposing the limestone at the surface (Fig. 3). The limestone forms a broad, low-relief karst plain, typified by sinkholes and sinking streams, called the Pennyroyal Plateau. The deeply dissected perimeter of the hilly region consists of limestone ridges chapped by insoluble rocks and separated from one another by steep-walled valleys. Many of these are perched karst valleys at the general level of the Pennyroyal Plateau (Fig. 4). This borderland is called the Chester Upland, and the sharp, irregular, 60-m-slope that separates it from the Pennyroyal Plateau is called the Chester Escarpment (Fig. 5). The Pennyroyal is subdivided into two areas: a sinkhole plain, which is located on relatively pure limestones bordering the Chester Upland, and the Glasgow Upland, which is an area of largely surface drainage on silty and shaly limestone lower in the section. Many of the streams on the Glasgow Upland sink into karst depressions where they flow onto the purer limestone.

The Chester Upland and Pennyroyal Plateau form a crescent-shaped band of karst that

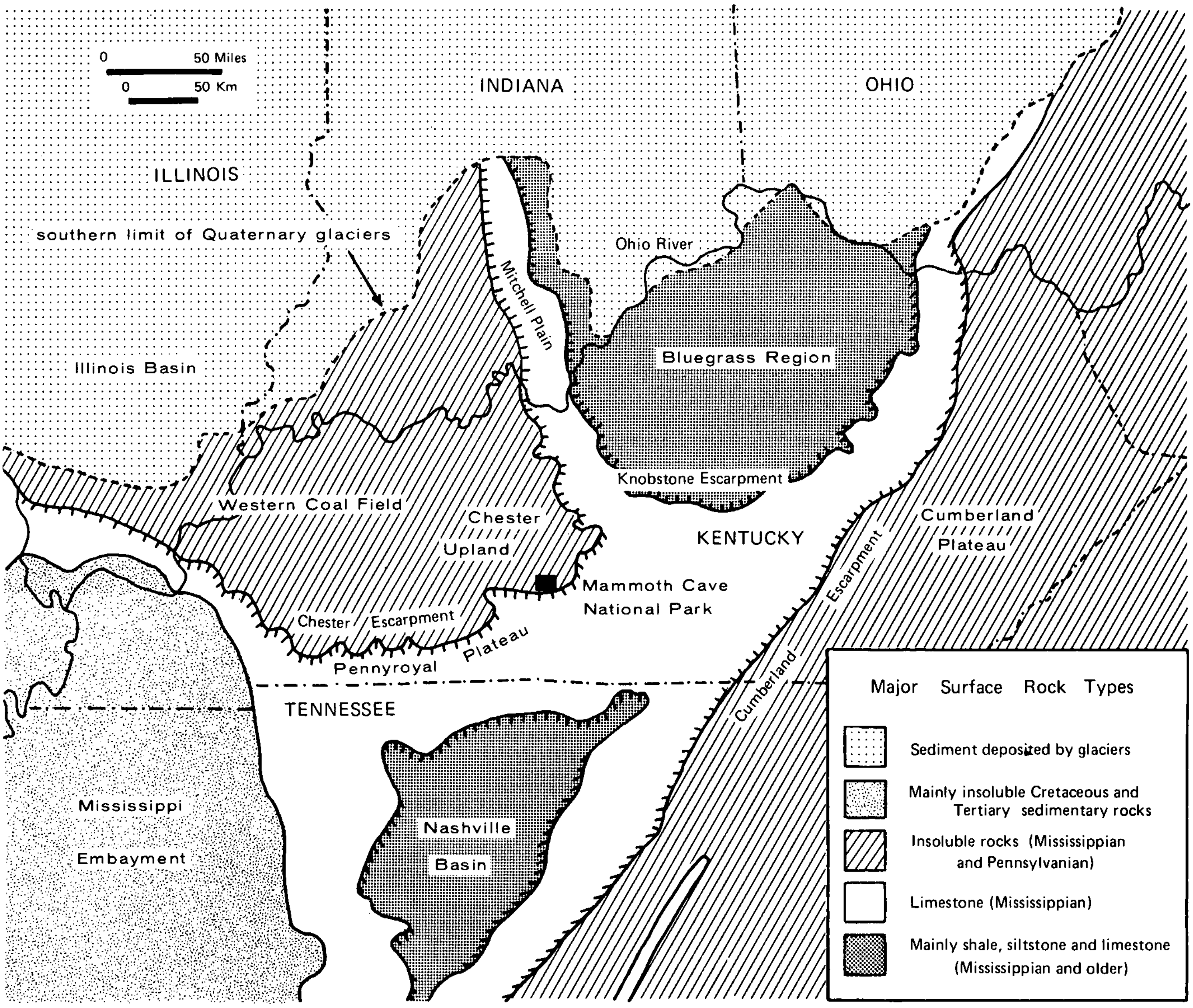

Figure 1. Physiographic map of Kentucky, showing the location of the Mammoth Cave Region.

extends around the southern and eastern edge of the Illinois Basin from southern Illinois, through western Kentucky, into southern Indiana. The karst area diminishes northward because of decreasing limestone thickness and an overburden of glacial deposits. The broad-scale configuration of this karst area is determined primarily by the form of the Illinois Basin, but its local details are controlled by broad open folds.

The region is crossed by several entrenched rivers that serve as outlets for karst groundwater. The largest of these are the Green River and its tributary, the Barren River, at a local altitude of 130 m. Tributary to these are numerous karst basins with mainly subsurface drainage. These basins have been delineated over the past 10 years by James Quinlan of the Uplands Research Laboratory at Mammoth Cave with the aid of dye traces and measurements of static water level in wells. These basins are shown in generalized form in Figure 6. The largest karst basins lie either entirely within the Pennyroyal or have headwaters in

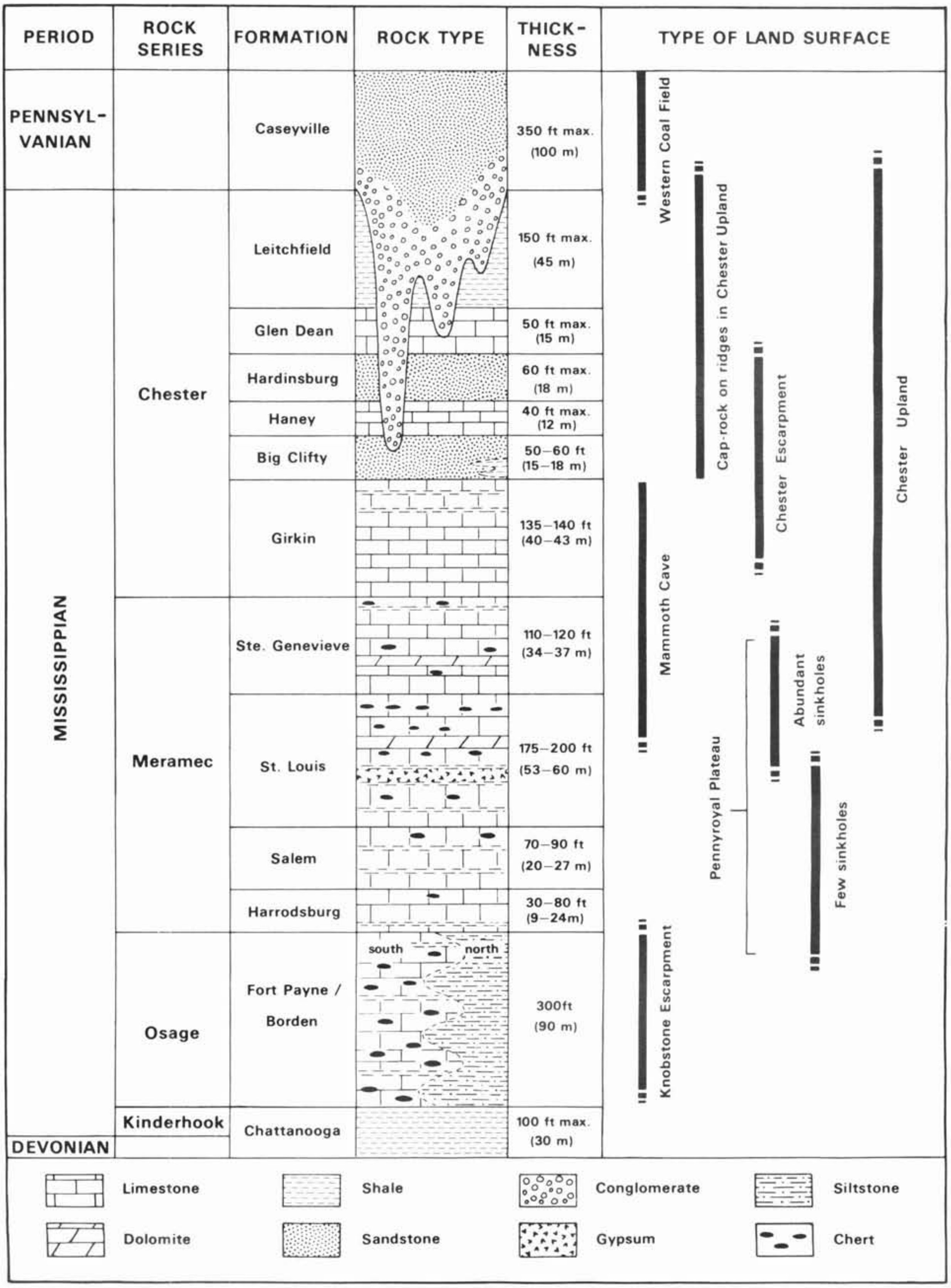

Figure 2. Stratigraphy of the Mammoth Cave area and its relationship to the surrounding landscape.

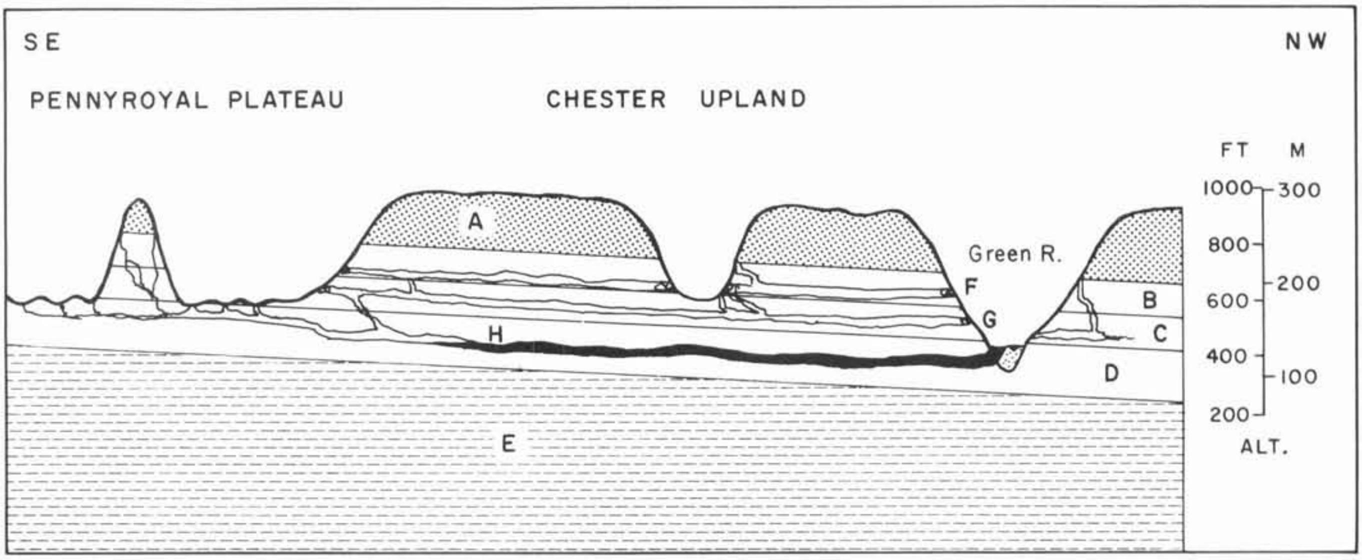

Figure 3. Generalized profile through Mammoth Cave. A = caprock of interbedded sandstone, shale, and limestone (Chesterian Series); B = Girkin Formation; C = Ste. Genevieve Limestone; D = St. Louis Limestone; E = impure limestone and detrital rocks; F = upper cave levels of late Tertiary age; G, H = typical levels of Quaternary age (partial flooding of the lowest is due mostly to late Pleistocene alluviation of the Green River).

Figure 4. A typical sinkhole-floored karst valley in the Chester Upland. The flanking ridges are capped by insoluble rocks of Chesterian age.

Figure 5. View from the Chester Upland (at left) into the Pennyroyal Plateau near Mammoth Cave.

the Pennyroyal and drain to the Green River through the Chester Upland.

The largest karst springs of the area are fed by passages 10 to 15 m below present river level, rising upward through openings in alluvial sediment (Watson, 1966; Hess, 1976). The area lies more than 80 km south of the farthest limit of Pleistocene continental glaciers, so it was spared the direct effect of glaciation. But the Green River is a tributary of the Ohio River, whose base level was greatly affected by glaciation, and the 15-m-thick alluvial deposits of the Mammoth Cave area are the result of aggradation of the Ohio River during the Wisconsinan glacial advance. The major flow routes delineated by dye traces are accessible only in a few scattered cave passages. Most of the large stream conduits are perennially flooded because of alluviation of the river valleys. For example, one of the largest karst basins is the one that feeds Turnhole Spring on the Green River. A few of its upstream branches can be seen as minor sinking streams on the Glasgow Upland. Other tributaries include a lengthy system of river passages in the southern part of Mammoth Cave. The main underground stream appears at the bottom of Mill Hole, an impressive karst window at the southern edge of the Chester Upland, and can also be seen in caves at the base of Cedar Sink, a huge collapse sinkhole in the bottom of Woolsey Valley. However, these scattered fragments give only a crude idea of the exact pattern and nature of the conduits that presently lie below base level.

STRATIGRAPHY

The largest caves of the region are developed within a continuous sequence of Mississippian limestone formations having a total thickness of approximately 150 m (Fig. 2). These include, from bottom to top, the St. Louis Limestone, Ste. Genevieve

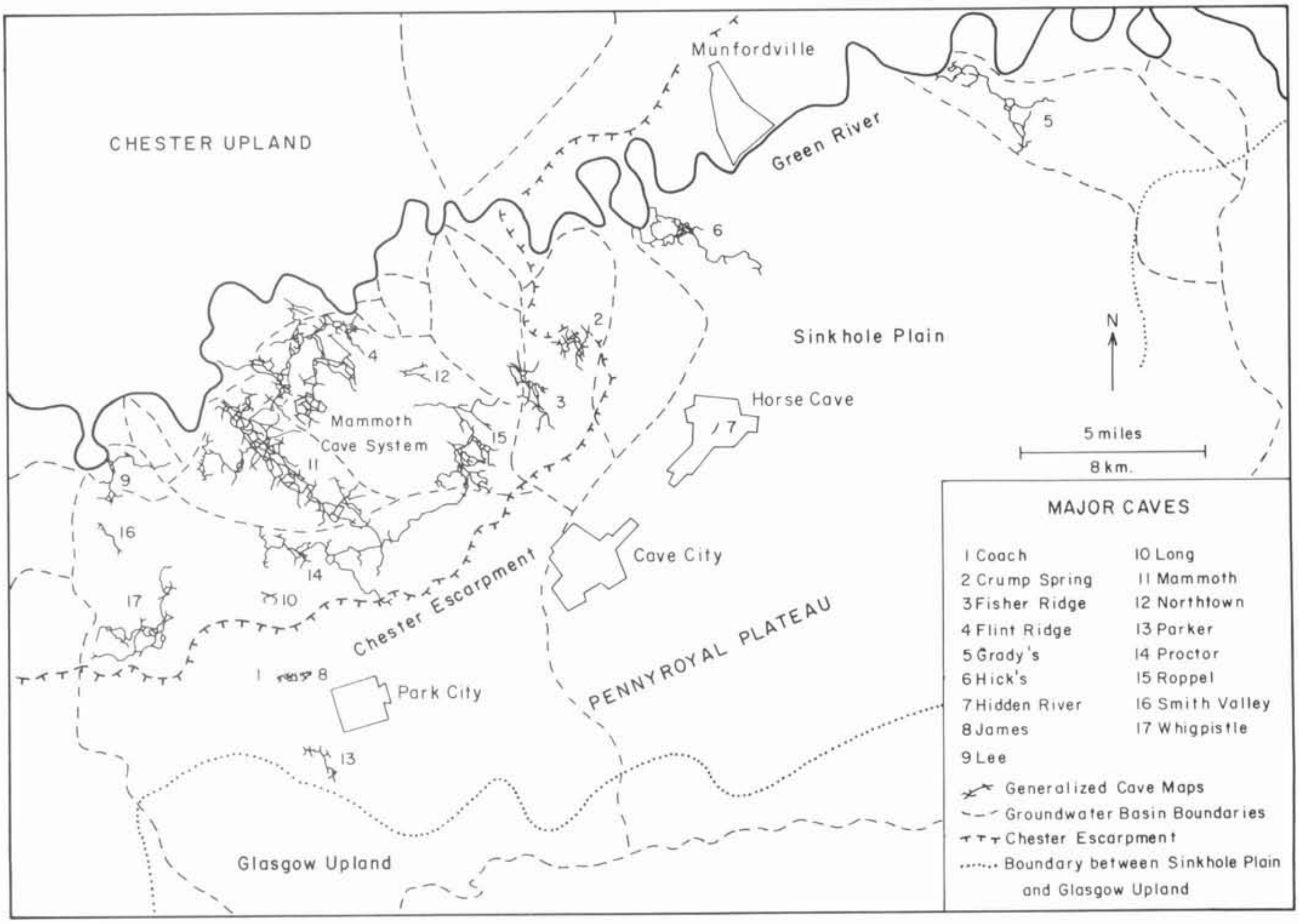

Figure 6. Location map of caves and subsurface drainage basins in the Mammoth Cave area (modified from Quinlan and Ray, 1981).

Limestone, and Girkin Formation. These rocks are laterally very extensive. The St. Louis and underlying rocks maintain their identity over great distances throughout the east-central United States. The Ste. Genevieve and Girkin are less uniform in character, for the upper part of the sequence becomes interbedded with insoluble detrital rocks toward the northwest in Illinois and Indiana. The effective top of the cavernous zone is near the base of the Girkin (Paoli Member) in Indiana and as far down as the middle of the Ste. Genevieve (Spar Mountain Member) in Illinois. Only small caves occur in the thin limestone units sandwiched between the insoluble rocks above these horizons. To the southeast, the Ste. Genevieve and Girkin have been removed by erosion, but they reappear in eastern Kentucky and Tennessee and in northern Alabama and Georgia, where the bottom-most insoluble unit (Hartselle Sandstone) is correlative with the Hardinsburg Formation of the Mammoth Cave area. The major cavernous limestone formations are described in the following paragraphs.

The St. Louis Limestone consists of 50 to 60 m of shaly, silty, and cherty limestone and dolomite. Karst development is greatest in the upper half of the formation, where shaly and silty beds are fewer. At depth below the surface, the St. Louis contains extensive gypsum beds, but they are usually leached out by groundwater long before they have a chance to be exposed in caves or at the surface. Bedded and lenticular chert occurs throughout most of the formation and is particularly abundant near the top. The St. Louis is underlain by the Salem and Harrodsburg formations, which are rather impure shaly limestones with a combined thickness of 30 to 50 m. Karst development is rather poor in these rocks, and caves are mainly small and perched on insoluble beds. The Glasgow Upland is developed on the lower St. Louis and the Salem-Harrodsburg, and the sinkhole plain is developed on the purer upper St. Louis and to a lesser degree on the Ste. Genevieve.

The Ste. Genevieve Limestone is about 35 m thick. It is probably the most cavernous limestone unit in the region and contains most of the Mammoth Cave System and nearby caves. It consists of interbedded limestone and dolomite in the lower half, and limestone interspersed with thin beds of incompetent silty beds in the upper half. Nodular chert is common near the top and in the middle of the formation.

The Girkin Formation, 25 to 40 m thick, consists of limestone with thin interbedded shale and siltstone. It is a favorable rock for cave development where geomorphic conditions are suitable. The insoluble beds are generally less than 1 m thick and do not significantly interrupt the continuity of cave development in the area. The Girkin is overlain by the Big Clifty Formation, the basal sandstone of the chiefly insoluble caprock that forms the ridge crests of the Chester Upland. Thin limestone units between the insoluble rocks contain perched karst drainage, and springs at their basal contacts provide the water supply to Mammoth Cave National Park.

These limestone formations were deposited in a shallow continental sea that extended across most of southern North America during the Mississippian Period. Detrital sediment carried from the adjacent land areas created a broad delta (Michigan River Delta) that extended progressively across the central part of the sea (Swann, 1964). The thin beds of impure limestone in the Girkin and upper Ste. Genevieve are the early precursors of this invasion of detrital sediment, and the thick sandstone and shale of the Chester Series represent the advance of the delta into the area. After a period of fluvial erosion at the end of the Mississippian Period, the region was blanketed again by Pennsylvanian conglomerate, sandstone, and shale, which are exposed in the central parts of the Illinois Basin. The unconformity at the base of the Pennsylvanian rocks has a maximum relief of nearly 100 m. There is little evidence for a Mississippian paleokarst, so prevalent in the western United States, because most of the pre-Pennsylvanian erosion was confined to the insoluble rocks capping the limestone.

Figure 7 shows the stratigraphic changes in the Girkin Formation as it is traced northward and westward from the Mammoth Cave area. In both directions the formation becomes progressively more partitioned by thick shale and sandstone units, breaking the hydrologic continuity of the limestone. This trend might help explain why the Mammoth Cave area is so favorable to cave development. However, very few passages in Mammoth Cave occupy the upper beds of the Girkin, so this explanation alone is inadequate. More importantly, the topographic relief is greatest in the Mammoth Cave area, with 90 to 140 m of continuous limestone exposed above base level. This figure diminishes gradually northward to about 65 m and westward to less than 45 m. Dissection of the Mammoth Cave Region by the Green and Barren rivers was even deeper in the past, because the valleys are now

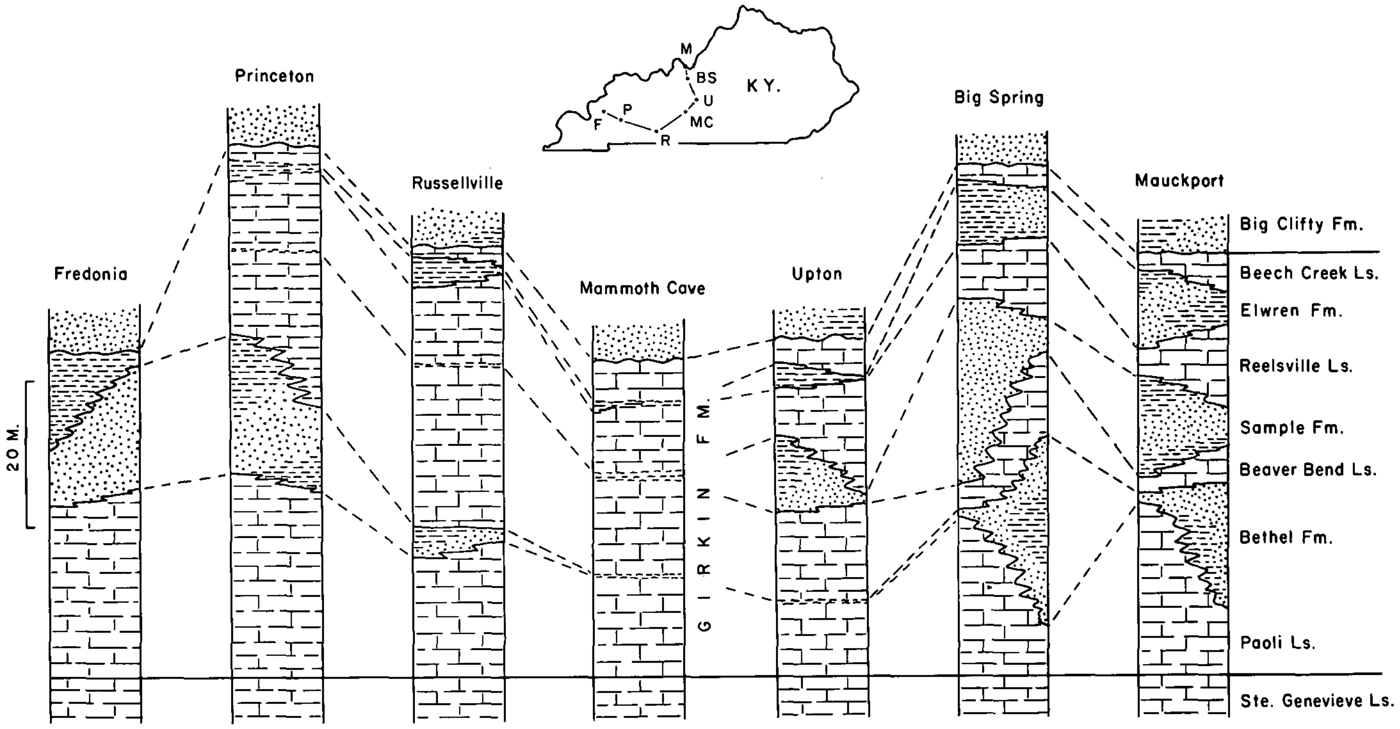

Figure 7. Lateral variation in the Girkin Formation and correlative rock units in western Kentucky. The Girkin consists of uninterrupted limestone in the Mammoth Cave area but is partitioned into separate formations by insoluble rocks to the north and west. (Correlation is based mainly on geologic maps by the U. S. Geological Survey.)

floored by roughly 15 m of late Pleistocene sediment. Furthermore, the position of these deeply entrenched rivers with respect to the broad extent of exposed limestone is ideally suited to the development of underground drainage.

MAJOR CAVE SYSTEMS

The caves of the Mammoth Cave area are notable not so much for the size of their passages, which is matched or exceeded by many caves elsewhere, but for their unusual length and interconnectivity (Fig. 6). Caves once thought to be entirely independent have been linked with such regularity in recent years that it might seem only a matter of time before every cave in the region is interconnected. Although such a feat will probably never be achieved, it is still appropriate from the genetic standpoint to consider nearly all the caves of this region to be part of a single huge system. Generalized maps of the major caves are shown in Figure 3.

Although distinct karst drainage basins have been mapped in the region (Quinlan and Rowe, 1977; Quinlan and Ray, 1981), many of the divides lose their identify during high flow as numerous overflow routes become active. Because the underground divides also shift with time, dry passages connect several caves that are now located in separate basins.

Caves of the Chester Upland

Chief among the caves of the region is of course the Mammoth Cave System, which now includes its connected neighbors Flint Ridge, Proctor-Morrison, and Roppel caves, with a total length of 490 km. Mammoth Cave is the world's longest cave by a factor of more than three. Its sheer size is what has drawn the attention of explorers, writers, and scientists for nearly 200 years. The system extends under at least five different ridges of the Chester Upland and beneath the karst valleys that separate them. It is surrounded by many caves that are enormous in their own right, some of which are hydrologically or genetically related to Mammoth. Mammoth Cave has been formed by drainage from not only the Chester Upland, but also from adjacent areas of the Pennyroyal Plateau. The water emerges at several large springs along the Green River. Mammoth Cave and all others in the Chester Upland are typified by long tubes and canyon passages at many levels, with vertical shafts concentrated around the perimeters of ridges (Figs. 8 and 9). Recharge to the caves comes both from nearby parts of the Pennyroyal and from karst valleys in the upland. Except for active canyons, the upper-level passages are rather dry, particulrly those beneath the nearly impermeable caprock. Lower levels are still active and are subject to backflooding from the Green River to heights of as much as 20 m (Fig. 10).

The system is being explored and mapped by the Cave Research Foundation (CRF), which was organized in 1957 by the explorers and commercial operators of Floyd Collin's Crystal Cave. The earliest history of exploration by this group is described in THE CAVES BEYOND by Lawrence and Brucker (1955). By 1961, CRF explorers had linked most of the caves of Flint Ridge into a single system, which became the world's longest in 1967. In 1972, a connection was found beneath Houchins Valley to Mammoth Cave, creating a single cave 230 km long. The explorational history of the Mammoth Cave System up to this point is told in THE LONGEST CAVE by Brucker and Watson (1976). Since then the cave has been connected to Proctor Cave, Morrison Cave, and Roppel Cave by an extensive series of river passages in th St. Louis Limestone.

Figure 8. Turner Avenue, in the Flint Ridge section of the Mammoth Cave System, is a shallow-phreatic tube of Quaternary age now situated at an altitude of 168 m.

Figure 9. View downward into a 200 m deep vertical shaft in Mammoth Cave.

Roppel Cave, in the northern end of Toohey Ridge east of Mammoth Cave, was discovered in 1976 and has been explored to more than 80 km by the Central Kentucky Karst Coalition (CKKC). In character it is similar to Mammoth Cave, although many passages show evidence of flow reversals and piracy. Most of the larger passages seem to be truncated upstream fragments of passages in Mammoth, although the exact correlation is not yet clear. The single connection with Mammoth Cave was discovered in 1983 by a combined CKKC-CRF team through a long river passage in the St. Louis Limestone (Borden and Crecelius, 1984).

Fisher Ridge Cave is located a short distance northeast of Roppel Cave. It was discovered in 1981 and has been explored and mapped to about 47 km by the Detroit Urban Grotto of the National Speleological Society. Although some of the more promising passages have led to sumps, the potential for additional discovery is great, for streams in the cave receive water from as far away as Cave City.

Crump Spring Cave (19 km long) is located in the northern arm of Fisher Ridge. Since its discovery in 1965 it has been explored by groups from a large geographic area, most recently under the direction of Joseph Saunders of Lansing, Michigan. The cave is a complex of canyons and vertical shafts with active and abandoned drains on many levels.

Whigpistle Cave, to the southwest of Mammoth Cave, was discovered in 1978 by personnel of the Uplands Research Laboratory and has since been mapped to 32.5 km. It is a dangerously wet cave that drains several local karst valleys. Its largest passage, which ends in breakdown at Woolsey Valley southwest of Joppa Ridge, seems to be an upstream fragment of part of New Discovery at the western edge of Mammoth Cave.

All of the caves described above lie south of the Green River. Directly north of the river, as well as farther downstream toward the west, caves are comparatively small because the exposure of limestone is limited by an increasingly thick clastic caprock.

To the south and southeast of Mammoth Cave National Park are many residual limestone knobs presently or formerly capped by outliers of sandstone (Fig. 3). An example is Bald Knob, which contains James and Coach Caves. These are complex, three-dimensional caves consisting of numerous interconnecting canyons and shafts, and with high-level network mazes directly underlying the sandstone cap.

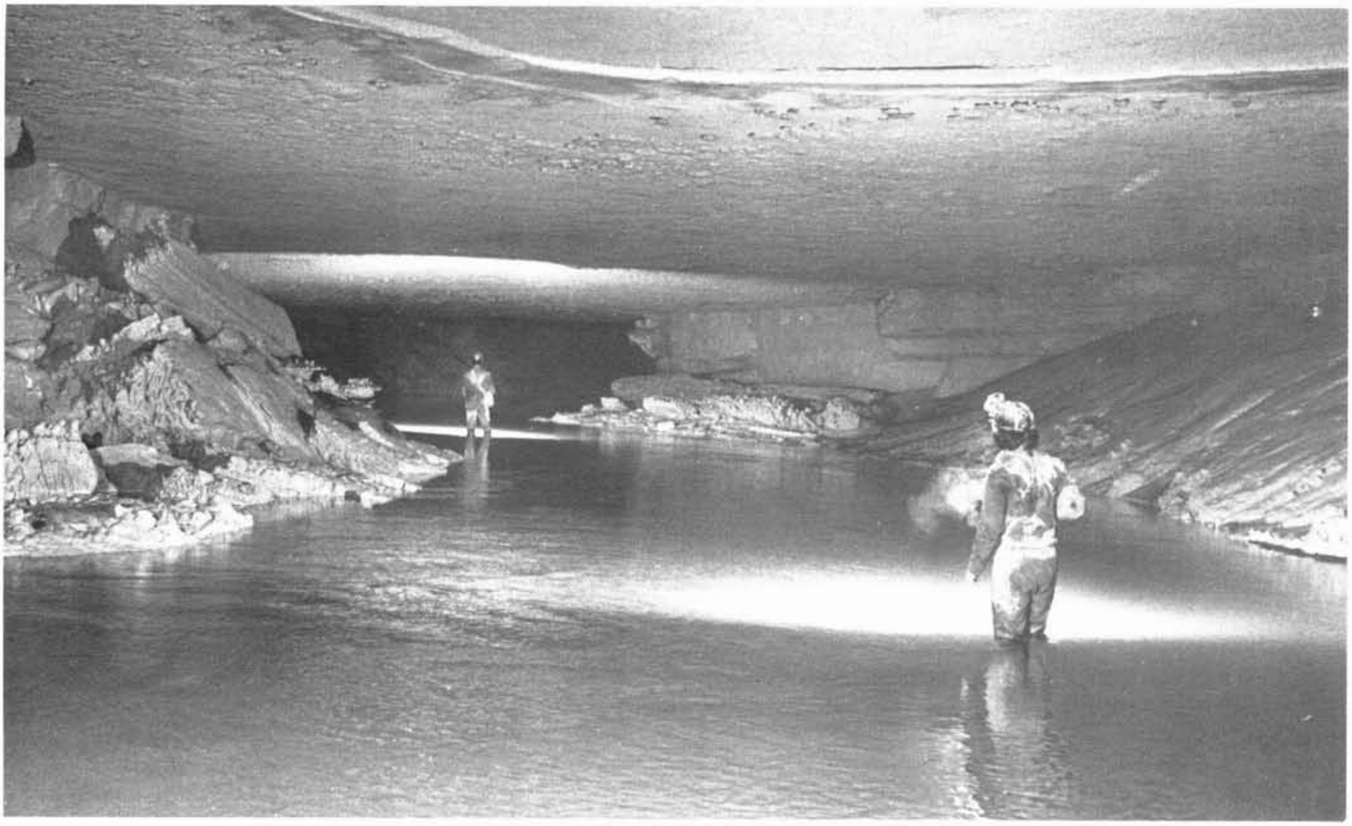

Figure 10. Logsdon River, part of an extensive dendritic system of active passages in the southern end of Mammoth Cave. The upstream end of this passage connects with Roppel Cave.

Caves of the Pennyroyal Plateau

The extent of explorable caves in the sinkhole plain became apparent only in the early 1970's. Although sinkholes are numerous, most are clogged with soil, collapse material, and assorted debris. Caves are wet and dangerous due to the possibility of rapid flooding. Because the sinkhole plain is relatively flat and has a fertile soil, it is more densely populated than the ridges and groundwater pollution is widespread. Despite these drawbacks, recent years have seen a great increase in the number and length of explored caves in the sinkhole plain. Most of these are developed in the St. Louis Limestone.

Hidden River Cave, in the town of Horse Cave, was commercialized in 1916, but by 1943 the pollution from domestic sources and a nearby creamery was so severe that the operation had to shut down. In 1975, 15,000 liters of gasoline were lost in the system from a leaky tank, and gasoline was smelled in local basements. The water from Hidden River Cave divides downstream into numerous distributaries and discharges at 46 springs over an 8-km reach of the Green River. The cave is part of an enormous karst drainage basin of 500 km^2.

Hicks Cave is a major part of this distributary system and takes much of the overflow from the Hidden River System. Hicks Cave is being explored and mapped by Uplands Research Laboratory cavers and now has 31.4 km of surveyed passages, most of which are partly filled with water nearly at the present river level.

Gradys Cave is located in the lower St. Louis Limestone in the far eastern portion of the sinkhole plain. It was first explored in the middle 1960's, but has since been pushed farther and mapped to a length of 19.3 km by a group under the direction of Joseph Saunders. Most of the cave consists of river passages situated at base level, with numerous overflow routes.

Parker Cave, near Park City, is located near the headwater area of the Turnhole Spring drainage basin. It is distinctive in having five independent parallel stream passages connected by a single upgraded overflow route that transmits water in various directions depending on the pattern of flood pulses in the various stream passages. The cave was explored by Uplands Research Laboratory personnel and mapped to a total length of 9 km.

To the southwest of the area shown in Figure 6 is a vast area of sinkhole karst draining westward to the Barren River. The largest karst basin is that feeding Graham Spring, which drains 310 km^2. The city of Bowling Green is located over a similar karst system. The city has occasional problems with industrial and domestic groundwater pollution, drainage problems, and backflooding of sinkholes during wet periods. The work of the Center for Cave and Karst Studies at Western Kentucky Universiy is directed mainly toward understanding and alleviating these problems.

Karst Areas North of Mammoth Cave

The Chester Upland and Pennyroyal Plateau extend northward into southern Indiana (Fig. 1). Althouh topograhic relief diminishes slightly in this direction and the Girkin Formation becomes partitioned by detrital formations, the region between Mammoth Cave and the Ohio River hosts some of the finest karst and caves in the country. The reader is referred to George (1976) for a more complete description.

Although the karst and cave development in this northern area is similar in many ways to the Mammoth Cave Region, there are several features that make it unique. The boundary between the Pennyroyal Plateau and the Chester Upland is not so clearly defined as it is near Mammoth Cave, and the largest cave system, the Sinking Creek System, extends both under ridges and sinkhole plain. The longest single cave in the system is Big Bat Cave, with 20.2 km of mapped passages. The cave is part of a karst drainage basin of 376 km^2 that discharges to Boiling Spring, which has an estimated peak flow of more than 50 m^3 per second (George, 1976). Some caves in the area are very shallow, and there are extensive cave pasages that have been partially unroofed by erosion and exposed as open trenches. These passages generally terminate upstream and downstream in remnant caves that have not yet been unroofed.

RELATIONSHIP OF KARST AND CAVES TO THE GEOLOGICAL SETTING

Stratigraphy exerts the primary control over the karst landscape, as shown in Figure 2. The clearest expression is the contrast between the Chester Upland and Pennyroyal Plateau, determined by the presence or absence of insoluble Chesterian rocks. On a more subtle scale, the relatively small vertical permeability of the Salem, Harrodsburg, and lower St. Louis inhibits karst and promotes surface drainage. The areas of greatest sinkhole and cave development in the Pennyroyal Plateau are formed by the upper St. Louis beds, which are relatively pure except for their chert content. Deep-seated removal of gypsum by solution may account for some of the fracturing and small-scale distortion of these beds, which in turn may foster the extensive sinkhole development. The even purer carbonate rocks of the Ste. Genevieve, on the other hand, develop broad, shallow sinkholes that are fewer than those in the St. Louis. Whether this distribution represents a true stratigraphic control is obscured by the fact that the area of the sinkhole plain where the Ste. Genevieve is exposed lie at the foot of the Chester Escarpment, where insoluble colluvium accumulates from the upland and fills karst depressions.

Caves of the region are affected rather uniformly by the different strata, and the major differences in cave type are imposed more by the local hydrologic and geomorphic setting. The thin but prominent bedding and numerous small joints cause the cave to be more sinuous and concordant to the strata than in most other karst regions (Deike, 1967; Palmer, 1977). The basic pattern of passages is dendritic, but this pattern is usually obscured by the numerous overflow routes in the Pennyroyal caves and by the many superimposed levels and diversions to progressively lower levels of the Chester Upland caves.

The prominent bedding and general lack of tectonic disturbance has allowed cave passages to develop very clearly defined shapes: high, narrow, sinuous canyons; wide, low-gradient tubular passages with elliptical or lenticular cross sections; and vertical shafts up to 60 m deep with almost perfectly vertical walls. Canyons and shafts are far more common in the high-relief Chester Upland than in the Pennyroyal Plateau. Even vertical shafts are strongly influenced by the prominent bedding, because inflowing water is generally perched along bedding-plane partings or on a relatively resistant bed. Growth of a typical shaft takes place downward in stages through time, with the bottom deepening from one major bed to the next, and with successive lateral drains within each bed.

The nature of any given cave passage depends strongly on whether it originated in the vadose zone or in the phreatic zone. Most passages that form in the vadose zone (canyons and perched tubes) have an almost perfectly consistent downdip orientation. Many passages of phreatic origin trend nearly parallel to the local strike, because in these prominently bedded rocks the most efficient path for phreatic water is usually at shallow depth at or just below the water table. Fractures tend to become tighter and fewer with depth, and so few large ones cut across the bedding that deep flow along one bed is usually not able to pass upward into overlying beds. Nevertheless, some passages are discordant to the bedding and show evidence of phreatic water that rose in the downflow direction. The discordance is almost invariably in a competent, thick-bedded limestone, such as that of the Girkin Formation, the middle and lowest beds of the Ste. Genevieve, or certain massive beds in the upper St. Louis. Echo River in Mammoth Cave shows several such jumps from one bed to another.

The sinuosity of both phreatic and vadose passages is strongly controlled by local variations in dip and strike of the controlling bed or bedding plane. The fact that neighboring passages commonly exhibit diverse and seemingly independent trends is due to local variations in structure from bed to bed. Each bed has its own unique structure imposed by depositional irregularites and by variations in thickness. Generalized contour maps of the geologic structure drawn on a single stratigraphic horizon are rarely of use in interpreting the local structure that controls cave passages, however useful they may be in regional studies.

Network mazes are rare in the Mammoth Cave area because of the lack of prominent joints and the concentraton of groundwater recharge into numerous small point sources (mainly sinkholes). Small networks do occur where the upper beds of the Girkin Formation are highly fractured and overlain by thin permeable sandstone, such as in parts of James Cave. In general, the insoluble caprock of the Chester Upland is too thick and impermeable to admit enough water to form caves. Instead, the caprock forms a barrier to all but diffuse capillary water, so underlying upper-level passages no longer occupied by streams are exceptionally dry. The thin limestone units interbedded with the insoluble Chesterian rocks actually reduce the amount of water passing downward to the main limestone below by shunting water laterally to perched springs.

CAVE DEPOSITS

Detrital sediment is the most common type of cave deposit in the region (see Davies and Chao, 1959; Collier and Flint, 1974). Present or former stream passages that have had rapid flow contain sand and sandstone fragments mainly from sandstone in the Chesterian caprock, quartz pebbles from the basal Pennsylvanian rocks (limited almost exclusively to caves in the Chester Upland), and chert fragments from the limestone. Much of this material is second-generation sediment, having collected first at the surface at the base of steep slopes and later carried underground through sinkholes. Silt and clay from heterogeneous sources collect in passages that are flooded by slow-moving water. These include passages abandoned by low-flow streams but which are subject to flooding by slow-moving water overflowing from active passages during high flow, and base-level passages backflooded by nearby rivers. Caves of the Pennyroyal Plateau are particularly rich in silt, clay, and residual chert derived from the local limestone.

Calcium carbonate speleothems such as flowstone and dripstone are most common where abundant but diffuse water passes through soil into limestone along the flanks of ridges and knobs in the Chester Upland. This water picks up a great deal of carbon dioxide from the soil and quickly approaches equilibrium with dissolved limestone at high concentration. The water degasses readily when it enters underlying dry, aerated passages, which have a much lower carbon dioxide content. In the Pennyroyal the frequent flooding of passages is not so conducive to the growth of speleothems, although local areas of travertine occur, especially in dry upper cave levels. Isotopic analysis of carbonate speleothems from the Mammoth Cave System has been useful in interpreting past temperatures of the region (Harmon and others, 1978).

The small amount of water that penetrates the caprock of the Chester Upland generally moves by differences in capillary potential, rather than by gravity. It is drawn toward dry, aerated caves from the surrounding moist limestone and particularly gypsum and epsomite, are deposted in these passages (Pohl and White, 1965). For a complete description of these materials, see Hill (1976).

HYDROLOGIC CONTROLS OF CAVE PATTERNS

Although all the caves of the region share certain broad similarities, there are some striking differences between caves, and commonly between different parts of the same cave system, that are caused by variations in the hydrologic setting. These differences are most easily seen in the Mammoth Cave area, where the great size of the drainage basins and length of the caves have allowed the fullest possible response to variations in local hydrology.

Some caves, or sections of caves, such as the upper levels of Mammoth Cave (Fig. 11), consist of a few major passages that extend for great distances with little change. Some, such as Crump Spring Cave, are complex tangles of narrow canyons and rudimentary tubes. Others, such as Hicks Cave, are complex anastomotic systems with numerous overflow routes. These differences can be attributed mainly to the individual hydrologic setting.

Caves in High-Level Recharge Areas

Vadose flow is drawn downward by gravity along the steepest available path. In the Mammoth Cave area the prominent bedding inhibits the direct vertical descent of water along discordant fractures, and instead water has a strong tendency to perch on relatively insoluble beds or along bedding-plane partings. Vadose cave passages tend to be dip oriented and may extend several kilometers before they merge with present or former phreatic passages. While a vadose passage is forming, it tends to lose water through its floor along fractures or partings that eventually enlarge enough by solution to divert the entire stream flow into a lower-level route. With time, a single input of vadose water can create a system of canyons on many different levels, each in a different bed or series of beds. Variations in dip from one bed to another cause each canyon level to follow a slightly different course from its predecessor.

The higher the input above the local base level, the greater the

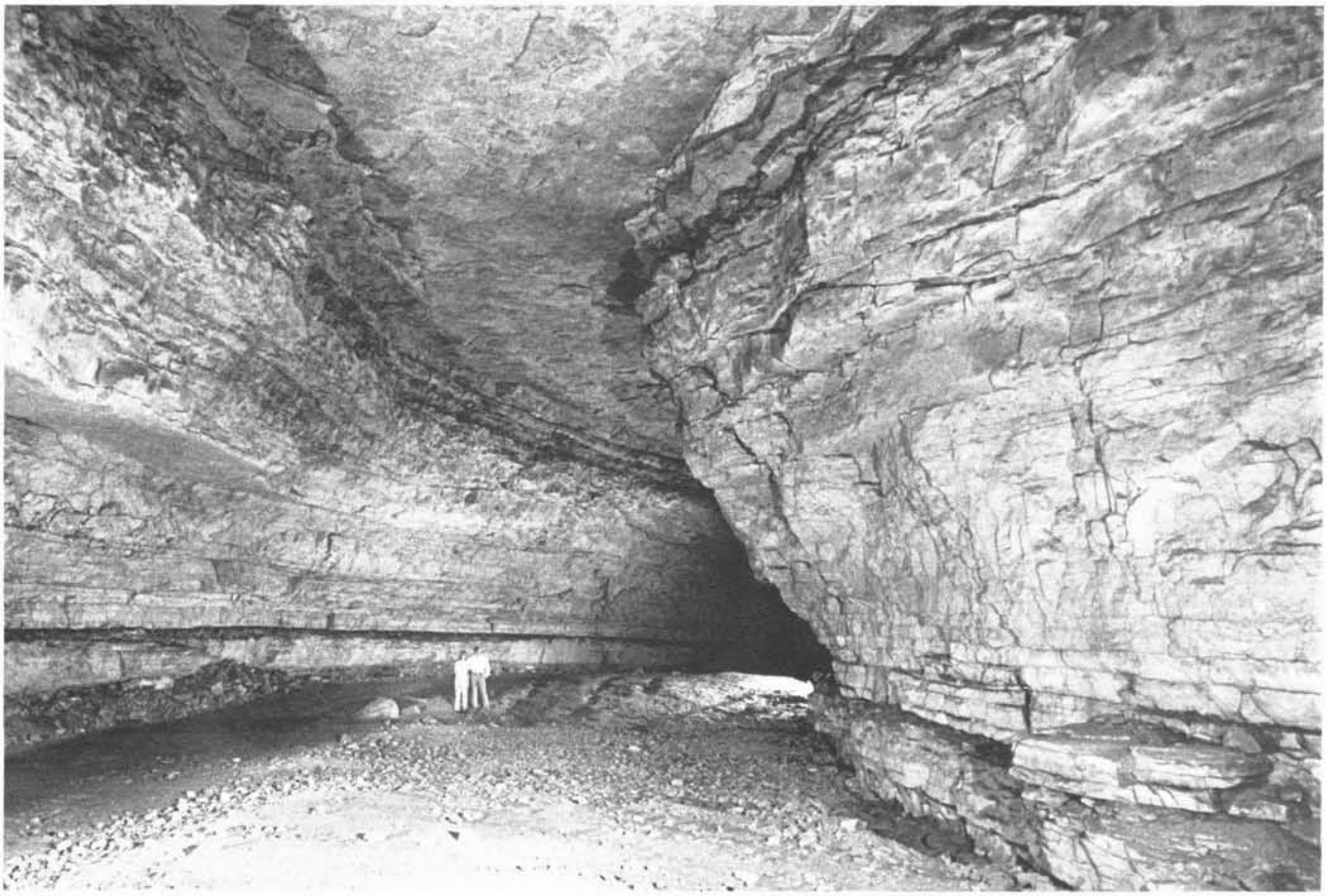

Figure 11. Audubon Avenue in Mammoth Cave is a typical upper-level canyon of late Tertiary or early Quaternary age, partly filled with detrital sediment.

potential for multi-level vadose canyons to develop. The most favorable of such inputs are located in the Chester Upland along the flanks of ridges or in karst valleys, where 50 to 100 m of relief existed above base level while the caves were forming. The Mammoth Cave System, for instance, contains local areas where vadose canyons, shafts, and perched tubes are so densely concentrated that they are almost impossible to portray clearly on a plan-view map. Each of these sections has been formed by only a few concentrated high-level inputs of aggressive vadose water where a stream valley has breached the insoluble caprock. The complexity of the caves is due to the tendency for vadose water to divert to lower routes, and to the many thin beds that provide those routes, rather than to a complicated geomorphic history or to shifts in the pattern of groundwater recharge.

Caves Along Major Phreatic Drainage Lines

Phreatic cave passages form zones of low hydraulic head, toward which the water in surrounding openings is drawn. As a result, water in these passages has little or no tendency to divert to new routes. As long as they are located at or below the local river level, no matter how large they grow or how much flow they acquire, their position remains stable. Such passages usually have a tubular shape and extend for great distances with little change (Fig. 10). They may be located precisely at base level and be filled with water only during periods of high flow, or they may descend into the phreatic zone and be perennially water filled over part or all of their length. The tendency for water to follow shallow paths near the top of the phreatic zone, rather than penetrate to considerable depth, leads to the development of distinct levels of major passages during lengthy periods of stable base level (Fig. 12). Those passages that do loop downward into the phreatic zone remain active and continue to grow long after contemporary passages formed at the water table have been abandoned by a lowering of base level. The large size of the passages in and around Echo River in Mammoth Cave is due partly to the fact that they are contemporaries of passages that lie as much as 25 m higher. Although the higher passages have long been dry, the lower parts of the passage loops are still active today and have grown to a considerably larger size than otherwise would have been the case.

Many caves in the Pennyroyal Plateau have the relatively simple morphology described here. Because of the low relief, vadose feeders reach the water table over rather short distances, in comparison with those in the Chester Upland, so complex systems of canyons and shafts are rare.

Caves at the Downstream Ends of Catchment Areas

An exception to the simplicity of caves in the Pennyroyal Plateau is introduced by flood water overflow. In caves subject to flooding, which is somewhat more common in the Pennyroyal than in the Chester Upland, the main passages fill with high-pressure floodwater much faster than the water table can rise in the surrounding fractured but non-cavernous bedrock. When this happens, the hydraulic gradients around the pasages are reversed, so they are no longer toward the passages but away from them. Water is forced out of the cave passages into fractures in the surrounding limestone, and since this water is solutionally aggressive it tends to form alternate routes of flow. In a rather short time, geologically speaking, this high-gradient aggressive water can form a system of diversion

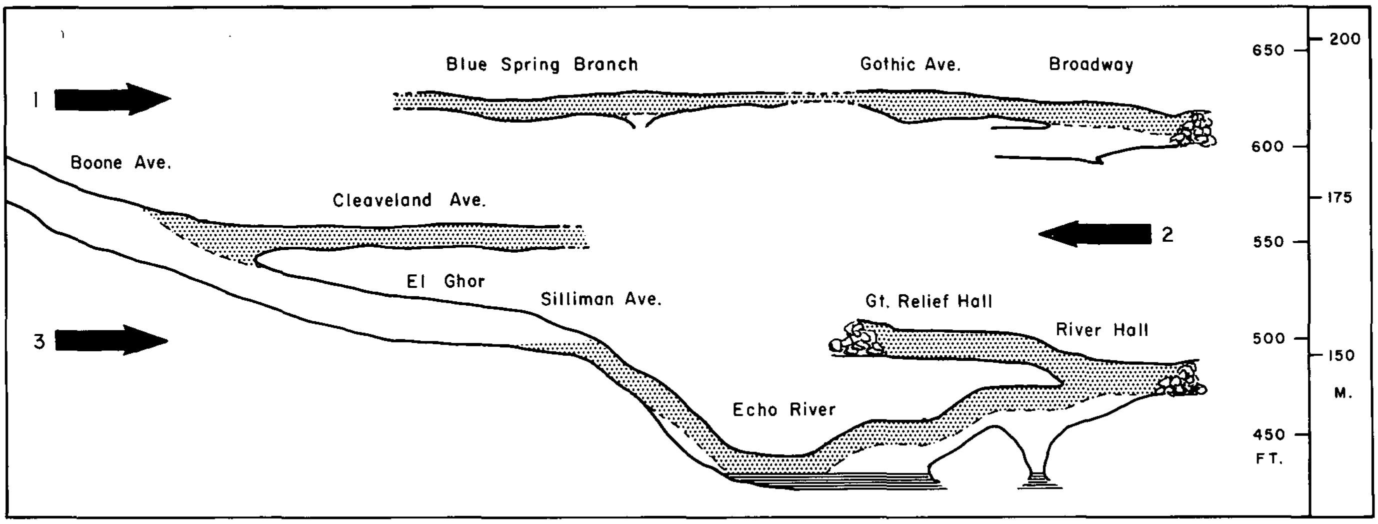

Figure 12. Generalized profile through part of Mammoth Cave, showing the three major levels of passage development (labeled 1, 2, and 3). Shaded areas represent the original tubular portions of each passage. Passages on level 3 were originally adjusted to a static base level at 152 m, but the phreatic sections span a vertical range of 20 m. See text for further details.

passages emanating from the original ones, either connecting different parts of caves (as in Parker Cave) or forming distributaries to the nearest river (as in Hicks Cave). These passages typically form approximately at the same level and along the same limestone beds as the host passages, so the resulting pattern is distinctly anastomotic.

The processes described here are most common in the downstream parts of large drainage basins, where the discharge is greatest and where phreatic passages are most numerous. Distributaries around springs are favored by the tendency for blockage of outlets by collapse material and landslide debris. Backflooding of caves from the adjacent river may contribute to the enlargement of a distributary system. Alluviation of local river valleys has caused many passages in the downstream ends of cave systems to be re-flooded. Although they may represent several different stages of cave origin, all passages below present base level are now water filled. Because of the numerous interconnections between passages in the area, dye introduced at a single upstream point not surprisingly will usually emerge at many different springs, especially during high flow.

Further details on the morphology and geology of caves in the region are given by White and others (1970), Ewers and Quinlan (1981), Palmer (1981), and Quinlan and others (1983).

RELATIONSHIP OF KARST TO THE LOCAL GEOMORPHIC HISTORY

Two concepts must be integrated when interpreting the geomorphic evolution of the region. First, in the broadest sense, this evolution can be viewed as a steady-state system of gradual uplift and erosion, in which the mainly clastic Chesterian and Pennsylvanian rocks are gradually stripped from the limestone, causing the locus of karst development to migrate with time toward the northwest in the downdip direction. With this view, the present karst landscape and caves are seen to represent (1) a youthful stage in the northwestern areas where the caprock is just beginning to be breached by erosion, (2) an early-mature stage, as in the Mammoth Cave area, where limestones are exposed with maximum relief and cave development is greatest, (3) a late-mature stage, as in the sinkhole plain, where the caprock has been completely removed, allowing full development of surface karst but a diminishing vertical extent of caves, and (4) an old-age stage in the southeastern areas where the most soluble limestone has been removed by erosion.

Superimposed upon this general and steady-state trend is the influence of relatively short-term changes in climate and base level. The otherwise smooth transition from one geomorphic stage to another is periodically arrested or accelerated, leaving a unique signature on the karst features that form at any given time. Although the steady-state model must be kept in mind as a general backdrop, the secondary aspects of geomorphic history are especially important here. The specific morphology of caves and other karst features tells a far more varied and subtle tale than does the steady-state model, and it is more fruitful in the interpretation of past geomorphic conditions.

During the late Tertiary and early Quaternary periods, the region underwent slow erosional degradation, which alternated with periods of broad-scale aggradation. This alternation between erosion and deposition was probably caused by cyclic changes in climate from humid to arid. As a result, a low-relief landscape was developed on the exposed limestone, close to base level. This landscape was the forerunner of the Pennyroyal Plateau. The area containing the insoluble caprock projected as a resistant hilly region, the forerunner of the Chester Upland, but with far less relief than now.

The uppermost levels in Mammoth Cave and surrounding caves formed at this time. They reflect this slow degradation and aggradation in that they are wide, large tubes and canyons up to 25 m deep, filled with sediment to at least two-thirds of their depth in many places (Fig. 11). These passages are concentrated at altitudes around 182 to 190 m at their downstream ends near the Green River, more or less at grade with nearby parts of the Pennyroyal surface. They are relatively few, because the limestone was sparsely dissected at that time, and underground drainage was fed only by a few large sinking streams in the karst valleys and adjacent Pennyroyal Plateau. The Pennyroyal at this time supported mainly surface drainage, as the slow erosion of the region promoted low relief with only small local karst basins (Miotke and Papenberg, 1972). The landscape was probably not very different from that of the Great Valley of Pennsylvania and Virginia on Cambrian and Ordovician carbonate rocks today.

There has been some debate as to the origin of the flat surface of the Pennyroyal Plateau. Its approximate concordance with the strata and the presence of low-relief areas underlain by cherty horizons has led some authors to interpret the Pennyroyal as a stripped structural plain (e.g., Quinlan, 1970). Another aspect of geologic control is the strong relationship between sinkhole distribution and stratigraphy (Howard, 1968). Others, such as Miotke and Papenberg (1972) and Wells (1976), point to the subtle discordance between the surface and the strata as evidence for base-level control. Both views have merit. It seems likely that the Pennyroyal surface formed close to fluvial base level during the slow Tertiary dissection of the region, but that local areas show the effect of differential resistance of strata.

During the Tertiary Period, most of the surface drainage from the Appalachian Mountains drained through the Teays River, located north of the present Ohio River. Early in the Pleistocene, this drainage was diverted southward into the Ohio River by continental glaciers. The resulting increase in discharge caused the Ohio to entrench rapidly. Consequently, the Green River and other tributaries of the Ohio deepened rapidly as well (Miotke and Palmer, 1972). Deep, steep-walled valleys were produced in the Pennyroyal Plateau and Chester Upland. This entrenchment was periodically interrupted by periods of aggradation, probably coinciding with periods of glaciation. In limestone areas, while major streams such as the Green River became entrenched, minor tributaries remained hanging, and water diverted underground. The purer limestone of the low-relief Pennyroyal surface, especially that closest to the entrenched rivers, developed underground drainage, caves, and sinkholes. Karst valleys formed between ridges in the Chester Upland.

Rapid shifts in base level during the Quaternary caused cave passages to form quickly at many different levels (Figs. 8 and 10). Most prominent are those at 168 m and at 152 m. These levels probably coincide with periods of relatively stable base level, rather than with favorable rock units, because the passages that cluster at uniform elevations occur at different stratigraphic horizons. Paleomagnetic analysis of sediment has shown that the 152 m level is at least 700,000 years old (Schmidt, 1982).

With time, greater dissection and relief caused an increase in the number of recharge points. Although major flow routes from the Pennyroyal Plateau still exist, recharge from the Chester Upland has become divided into many small inputs. In addition to a few large passages that are still forming today, many small ones are being formed by numerous local sources of recharge from karst valleys and ridge flanks.

Interpretation of passage levels in Mammoth Cave is not a simple matter of charting the elevation of the largest passage. Most passages in the system have both an upstream vadose section and a downstream phreatic section formed at or below the water table. The elevation at which this transition takes place is the most reliable indicator of a relatively static base level at the time a given passage was forming. Figure 12 shows the major passage levels in Mammoth Cave and some of the complexities that make their interpretation difficult. The uppermost level 182 to 190 m is best represented by Gothic Avenue and its upstream and downstream extensions. No vadose section is accessible, and the entire passage consists of an undulant tube. Although it is more or less concordant with the bedding of the lower Girkin Formation, it rises and falls imperceptibly along its length. Leveling surveys show that there is virtully no dip on the beds, except for minor local structures. The downstream end (Broadway and Audubon Avenue) is roughly parallel to the local strike, but otherwise the passage shows no systematic relationship to the limestone structure. The persistent narrow elevation range of the passage and its tubular shape (except where vadose entrenchment has taken place in the downstream sections) suggest development very near the water table during a period of nearly static fluvial base level. This data is strengthened by the fact that other major passages in the system reach their maximum width at this same elevaion. These passages include the main passages of Salts Cave and Crystal Cave in the northeastern part of Flint Ridge. They lie in rock units different from those of Gothic

Avenue, so the correspondence of elevation is not caused by favorable strata.

There has been recent speculation that the uppermost levels of Mammoth Cave were formed by paragenesis--this is, as tubes deep in the phreatic zone that were enlarged upward owing to sediment accumulation on their floors (Derek C. Ford, Hamilton, Ontario, personal communications, 1975). Under these conditions a tubular-shaped passage would migrate upward to the water table, forming a high, narrow canyon whose lower parts were filled with sediment. The highest passage in the system, Collins Avenue in Crystal Cave (Flint Ridge), may have formed at least partly in this way, as it has an irregular ceiling and its accessible part rises slightly in the downstream direction. Paragenesis is unlikely in most other passages in the system, however, because of the following evidence: (1) numerous passages are filled entirely to the ceiling with coarse-grained sediment capped by a layer of silt and clay only a few centimeters thick, indicating that rapidly flowing streams deposited the fill but did not cause significant upward solution, (2) canyon ceilings are highly concordant to the bedding, which is unlikely in a tube dissolved upward through the phreatic zone, (3) tubular passages on the upper level, such as Gothic Avenue, are also filled with stream-deposited sediment in places that have not yet been exhumed by later entrenchment, and (4) cut-and-fill structures in the sediment of upper levels in Long Cave, south of Mammoth Cave, show evidence of meandering channels formed by free-surface streams (James Currens, Kentucky Geological Survey, personal communicaton, 1983).

The level at 167 to 170 m is best observed in Cleaveland Avenue. Boone Avenue, its upstream end, is a vadose canyon that extends directly down the dip of the beds. At the transition point representing the former water table, the canyon changes gradually to a tube oriented nearly parallel to the local strike. This pattern is repeated at the same elevation, but in entirely different beds, in Waterfall Trail and Flint Ridge (Miotke and Palmer, 1972). The upstream end of Waterfall Trail still contains an active stream perched on relatively insoluble beds, but its former transition from vadose to phreatic conditions is clearly detected by the transition from dip-oriented canyon to undulant tube crudely oriented along the strike. Turner Avenue in Flint Ridge is another example of a tube at this same level (Fig. 8).

The lowest major level is at 152 m. Further entrenchment below the 167 m level allowed the water in Boone Avenue to bypass Cleaveland Avenue and continue on down the dip as a canyon known as the Pass of El Ghor. At the new static water level of 152 m, the canyon gradually changed to a tube (modified somewhat by later entrenchment) in Silliman Avenue. Instead of maintaining this level, however, the tube extended as much as 20 m beneath the water table, forming the Echo River passage. It rose in the downstream direction into River Hall, where it joined the passage from Great Relief Hall, a major tube at 152 m. The combined passage unfortunately terminates in breakdown at River Hall, so the downstream continuation is obscured. However, the presence of the Great Relief tube at 152 m and the transition from canyon to tube in Silliman Avenue at the same elevation is compelling evidence for a static base level at that elevation. Echo River, the low point in this passage system, has therefore been actively forming ever since the Green River was at 152 m. The large size of the Echo River passage can be accounted for in that way. Other passages at the

152 m level include Floyd's Lost Passage and Swinnerton Avenue in Flint Ridge. Each show a transiion from vadose to shallow-phreatic at the same elevation but in different rock units.

The great extent of caves and karst features in the Mammoth Cave area is clearly not a simple product of the vast exposure of limestone, and the steady-state model of slow denudation is inadequate to explain it. Without the relatively rapid and deep entrenchment resulting from Quaternary changes in the Ohio River drainage, the region would probably contain only a small fraction of the caves and karst topography that it does now.

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Chapter 8

WESTERN KENTUCKY REGION

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The Western Kentucky Region is a major cave area of the United States, but only recently has its potential been appreciated. The area has been somewhat lost between more glamorous areas around it, such as Perry County, Missouri, to the west; Monroe County, Illinois, to the north; the Mammoth Cave Region of Kentucky to the east; and the Cumberland Plateau area of Tennessee to the southeast.

The Western Kentucky Region can be defined as the Mississippian limestone area of Kentucky bordering the Western Kentucky Coal Field and west of the West Fork of Drakes Creek, a tributary of the Barren River; it is part of the Interior Lowlands Province of the eastern United States (Fig. 1). Going east to west, this area includes parts of Warren and Simpson counties, minor areas of Butler and Muhlenburg counties, and large areas of Logan, Todd, Christian, Trigg, Caldwell, Lyon, Crittenden, and Livingston counties. The western Kentucky area is drained in the northeast by tributaries of the Green River and in the northwest by tributaries of the Ohio River; but the majoriy of the area's drainage is into the Cumberland River by tributaries of the Red River and the Little River.

The western Kentucky area has over 200 described and documented caves, with 147 currently surveyed to an aggregate length of almost 100 km. Lisanby Cave, Caldwell

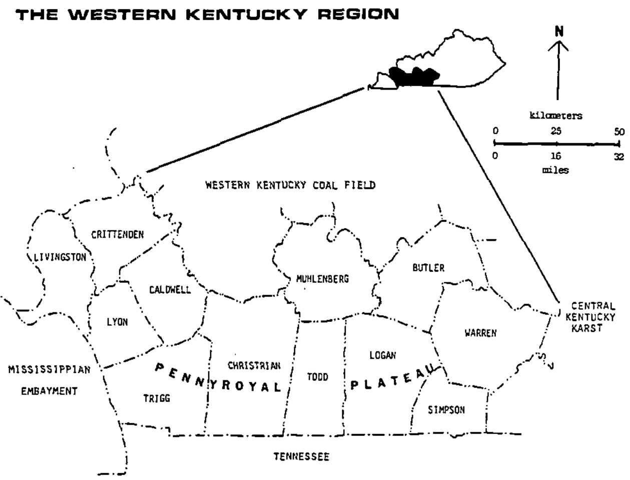

Figure 1a. The Western Kentucky Region.

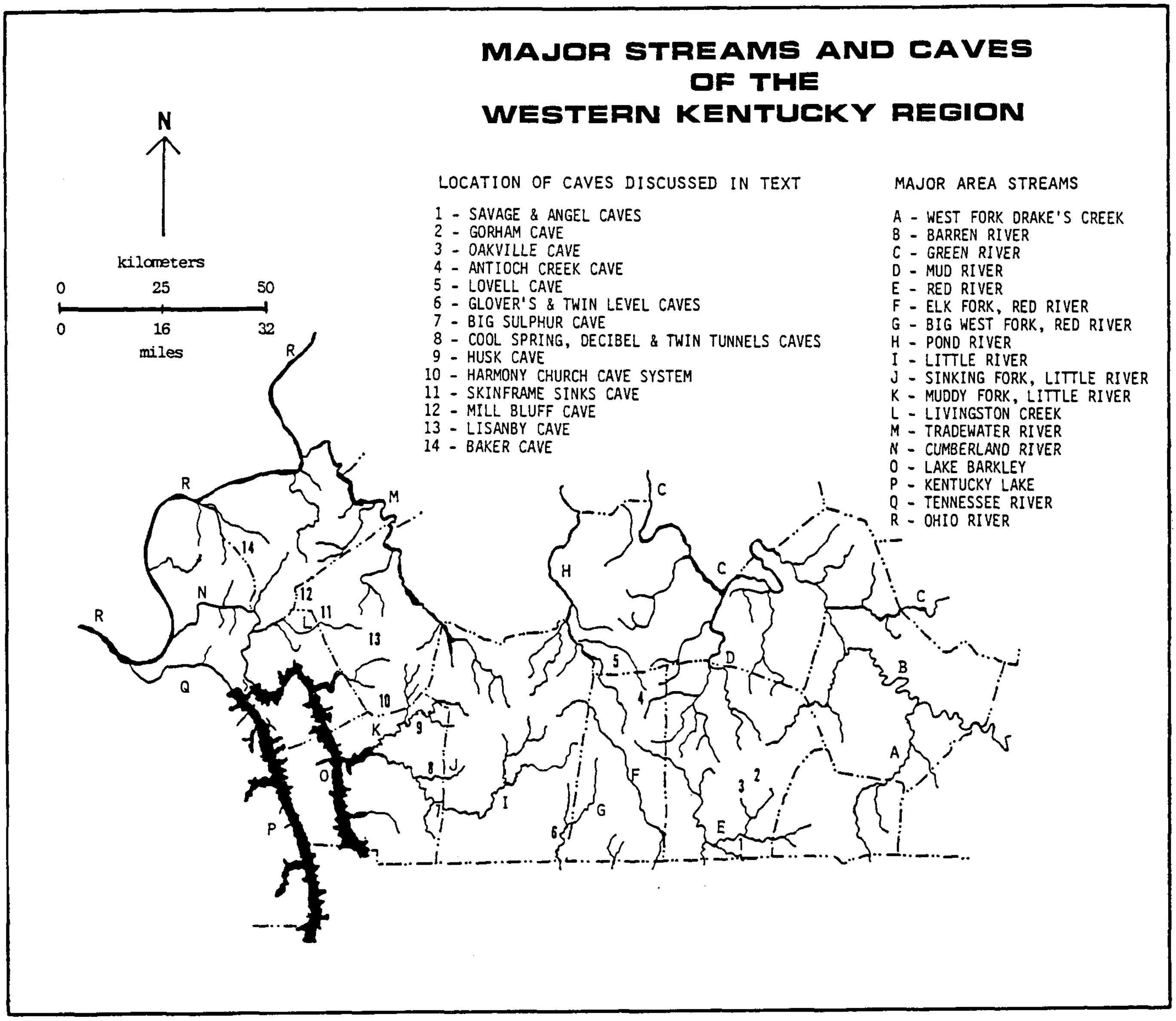

Figure 1b. Major streams and caves of the Western Kentucky Region.

County, at 11.3 km, is the longest cave in the region, and other caves making the 3.0 km limit for inclusion in the International Long Caves List are shown in Table 1.

The known described and surveyed caves are believed to be only a fraction of the caves in existence in the area. Organized caving came to the Western Kentucky Coal Field Region first in the late 1960s as the Southwest Kentucky Student Grotto (SWKSG), which operated out of Murray State University at the western edge of the region. The students explored many caves in the area and produced maps of a few of the major caves, such as Cool Spring Cave and Glover's Cave. The grotto did not survive the graduation of its principal leaders and was dispersed before 1975. Local residents made many discoveries and explorations during the same time period, most notably Mark Caldwell and colleagues out of Paducah, and Herb Scott and others out of Hopkinsville. Some survey and

Table I

INTERNATIONAL LONG* CAVES IN WESTERN KENTUCKY

CAVE	LENGTH (KM)	COUNTY
Lisanby	11.31	Caldwell
Cool Spring	5.30	Trigg
Twin Level	5.00	Christian and Todd
Big Sulphur	4.80	Trigg
Savage	4.28	Logan
Glover's	3.35	Christian and Todd
Gorham	3.21	Logan
Skinframe Sinks (Rice)	3.00	Caldwell

*Caves 3 km or more in length.

documentation were done by these informal groups, but the Western Kentucky Coal Field Region was basically a blank spot within the speleological knowledge of the United States. Some of the best data were in the hands of speleobiologists, such as Tom Barr and John Holsinger, who made forays into the area for specimen collection, and the Evansville Metropolitan Grotto, which did extensive work in the Glover's Cave area of Christian County.

Significant progress in the study and documentation of the caves and karst of western Kentucky began in August of 1977 with the establishment, by the Board of Governors of the National Speleological Society (NSS) of the Western Kentucky Speleological Survey (WKSS). Mike Dyas, a caver with extensive experience in other regions, began caving in western Kentucky in 1975 when his family bought land in Caldwell County. Mike's interest in the region caused him to search for available data from the NSS and elsewhere. It became immediately obvious that there was little published information, yet field work showed a region with considerable potential. In the spring of 1977, John Mylroie, a longtime caver from the Northeast, accepted a position in the geology program at Murray State University, and was recruited into the fledging WKSS. To avoid the problem of lost data and duplication of effort, it was decided to publish an annual report containing descriptions, surveys, and scientific articles on the work done in the WKSS area. Reports covering each year of activity have been published, with a limited and controlled distribution to protect the caves. A compilation of the WKSS activity through January 1985 is shown in Table 2.

GEOLOGY

Western Kentucky may be viewed as a series of cuestas formed by the removal of strata on the southern and western flanks of the Western Kentucky Coal Field. The resulting escarpments define uplands and lowlands of distinct geologic and geographic character. The western Kentucky karst is a sinkhole plain developed on the

Table II

WKSS ACTIVITY THROUGH 1985

COUNTY	NUMBER OF CAVES KNOWN	NUMBER MAPPED	KILOMETERS MAPPED
Butler	2	0	0
Caldwell	36	22	23.42
Christian	20	12	13.24
Crittenden	14	9	2.93
Livingston	14	7	2.19
Logan	52	31	19.53
Lyon	9	1	0.6
Muhlenberg	2	2	1.13
Simpson*	1	1	0.01
Todd	16	11	6.28
Trigg	51	50	24.09
Warren*	1	1	0.33
Total	218	147	93.75

*Portion of the county within the WKSS only.

Pennyroyal Plateau, a long band of Mississippian limestones, extending from eastern Kentucky, arching southward through central and western Kentucky and neighboring Tennessee, to southern Illinois and eastern Missouri. In western Kentucky, the limestones dip approximately 0.5° to the north-northeast but are locally undulatory. The plateau is gently rolling to nearly level, averaging no more than 30 to 40 m in relief, with average elevation around 150 m. While the plateau length is extensive, its width varies considerably. In western Kentucky, the plateau averages 30 km in width. Commonly referred to as the "Sinks" or the "Sinkhole Plain," the plateau is characterized by thousands of shallow sinkholes, occasional blind valleys, and numerous karst windows. Karst pavement has been found in only a few locations, due to the extensive soil development in the region. Stream and river valleys are well alluviated with sands, clays, and chert gravel. Sticky red clay and chert cobbles mantle the ridge tops and plains. Internal drainage is well developed with surface drainage being restricted to several entrenched base level streams.

The limestones of western Kentucky are all Mississippian (Carboniferous), and are similar in many characteristics to other Mississippian limestones of Kentucky and surrounding states. The following geologic description is condensed from Whaley and Black (1978).

The age and general structure of the rocks in Western Kentucky can be seen on the Geological Map of Kentucky (McFarlan and Jones, 1954).

Faults in the southern portion of the area (Logan, Todd, Trigg, and southern Christian counties) are less numerous than faults in northwestern portion (Christian, Lyon, Caldwell, Livingston, and Crittenden counties). In Livingston and Crittenden counties the faults generally strike northeast and are related to similar faults in southern Illinois. The Illinois-Kentucky Fluorspar District has produced fluorite and sphalerite from mineralization associated with these faults. Faults in Caldwell and Christian counties have a northwestly or more westerly trend. To date no significant fluorite mining has taken place along these faults. The gentle regional dip for the rocks in this area changes from northly in the southern portion to northeastly as one moves northwestly around the western flank of the Illinois Basin and the enclosed Western Kentucky Coal Field.

For the most part the rocks in this area are of Mississippian age and belong to the Meramecian and Chesterian stages. In extreme western Trigg County, Cretaceous deposits overlie the Mississippian rocks. Along the shores of Kentucky Lake and Lake Barkley, limestones of older age are present locally. However, the vast majority of the known caves are found in or above the St. Louis Limestone (Fig. 2). Lithologic descriptions and correlation information can be found in the 7.5 minute geologic quadrangle maps of this area. Detailed chemical analyses and lithologic descriptions are also available in Dever and McGrain (1969). Figure 2 and the accompanying lithologic descriptions are a summary of that information.

St. Louis Limestone

The St. Louis Limestone is a light-brown to gray, fine to coarse-grained, argillaceous limestone, 120 to 150 m thick. Dolomitic limestone and beds of oolitic limestone are present. Beds are 2 to 60 cm thick. The unit is divided into upper and lower limestone members. The upper member contains dark gray chert nodules and in part of the area it has been mapped as the lower unit of he Ste. Genevieve Limestone.

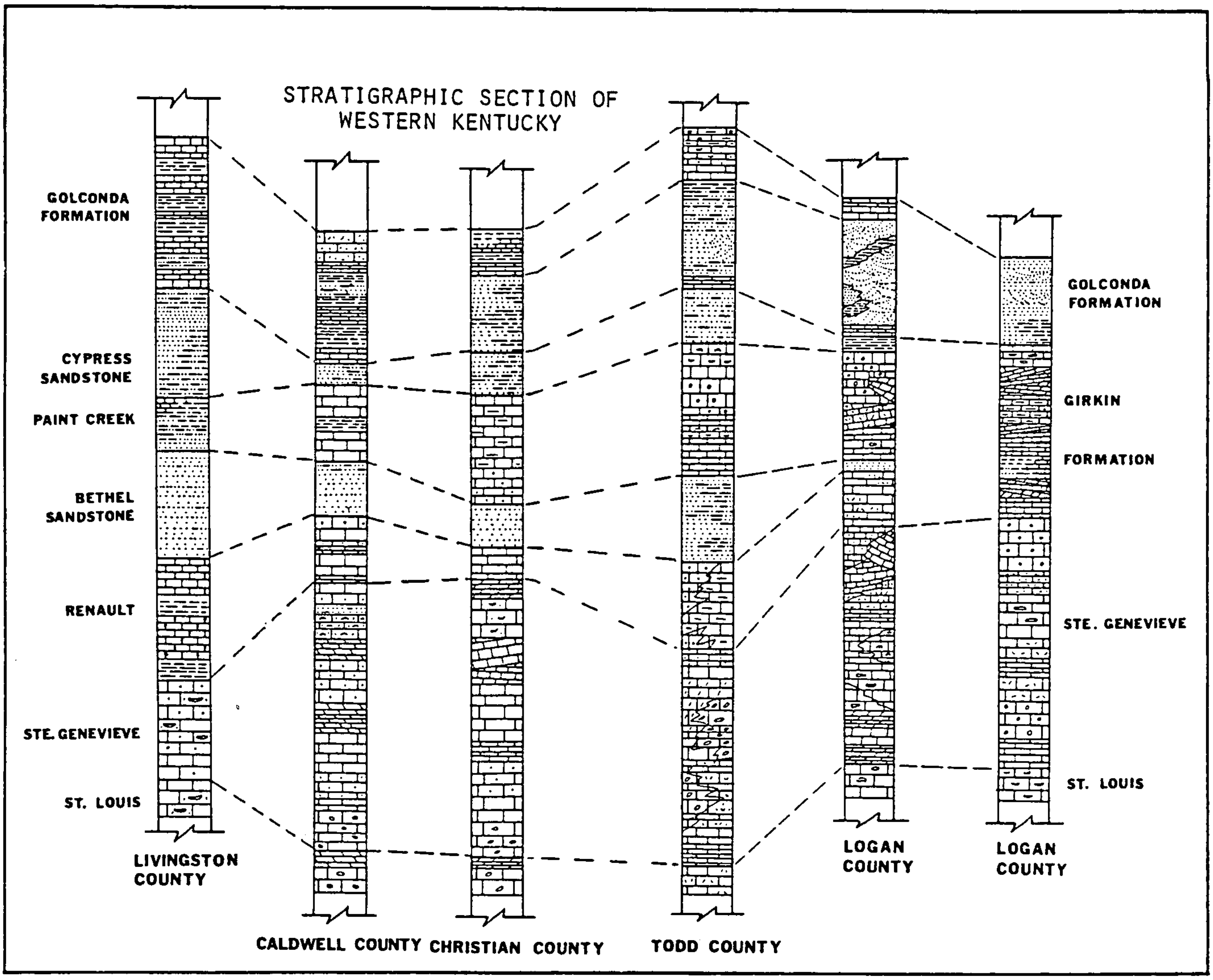

Figure 2. Stratigraphic section of western Kentucky.

Ste. Genevieve Limestone

The Ste. Genevieve Limestone is divided into three members: the lower 60+ m thick Fredonia Limestone, the middle 3+ m-thick Rosiclare Sandstone, and the upper 8+ m-thick Levias Limestone. The variable light gray Fredonia Limestone is predominantly an oolitic limestone with beds of fine crystalline, dolomitic limestone and medium to coarse crystalline, fossiliferous limestone. The Rosiclare Sandstone grades into shale in the southern part of the region. The Levias Limestone is a light gray, oolitic limestone with grayish-green shale laminae. Chert nodules occur in the lower beds.

Renault Limestone

The Renault Limestone is a light to medium-gray, argillaceous, oolitic, fine to medium-grained limestone, that is locally interbedded with shale and siltstone. The formation averages 20 m in thicknrss but thins to 10 m in the central portion of the region. In the eastern portion of the region the Renault Limestone is equivalent to the lower 15 to 18 m of the Girkin Formation.

Bethel Sandstone

The Bethel is light-brownish to gray, fine to medium-grained, thin to thick-bedded sandstone. Siltstone and shale are found in the upper portion of this unit. The Bethel exceeds 35 m in thickness in the west, but gradually thins to the east where it grades into the Girkin Formation.

Paint Creek Limestone

The Paint Creek is a variable unit consisting of limestone, shale, and sandstone. Fine to medium-grained, fossiliferous, oolitic, and argillaceous beds make up the limestone components that dominate in the east. Chert lenses are locally present. Shale and sandstone are dominant in the western part of the area. This unit is part of the Girkin Formation in the eastern part of the region.

Cypress Sandstone

The Cypress Sandstone consists of sandstone and interbedded shale and siltstone. The sandstone is white to light gray in the west, but light-tan to brown in the east. Ripple marks in the thin-bedded deposits and cross-beds in the thicker beds are common throughout the study area. This unit thickens westward from Caldwell County and temporarily thickens eastward where it pinches into the Girkin Formation. Thickness ranges from 1 to 35+ m in the west.

Golconda Formation

The Golconda Formation consists of limestone, sandstone, and shale units which in the eastern portion of the study area have been assigned member status. Its thickness varies from 27 to 45 m. The upper portion of the Golconda, a limestone unit, to the east is equivalent to the Haney Limestone Member while the lower portion, also a limestone, is correlative with the Beech Creek Limestone Member. The intervening sandstones and shales grade eastward into the Big Clifty Sandstone Member. The Beech Creek is a thin, fine to coarse-grained, fossiliferous limestone. The Haney is an argillaceous limestone that yields residual chert upon weathering. The Big Clifty is a fine to very fine-grained, thin to very thick-bedded sandstone. Thin beds tend to be ripple marked while thick beds contain cross beds. Siltstone and shale are interbedded in the sandstone and locally may constitute the major lithology of this member.

The placement of the major rivers has resulted in only a few valleys that cut through both the overlying clastic rocks and deep into the limestones, as the Green River does at Mammoth Cave. Therefore, cave development has progressed poorly in the limestones under the sandstone-capped uplands, with small maze caves and short, simple stream caves being the dominant type. On the adjacent sinkhole plain, large, dendritic, base level cave systems are found. The relief of 30 to 40 m limits the amount of abandoned upper levels above the active cave system, although in many caves, two, three, or four dry, abandoned levels can be found compressed within 10 m of base level. Occasional isolated fragments of upper level passages can be found on the interfluves between major streams, indicating a well-developed subsurface flow before the incision of the current master streams to their present elevation. In the extreme northwestern part of the region, the limestone has been broken up by complex normal faulting and fluorite mineralization. Cave systems are smaller but often complex and highly influenced by structure.

The limestone is covered by a thick residual soil. Agricultural land use has mobilized this soil, and alluviation of sinkholes and cave passages is common. Open

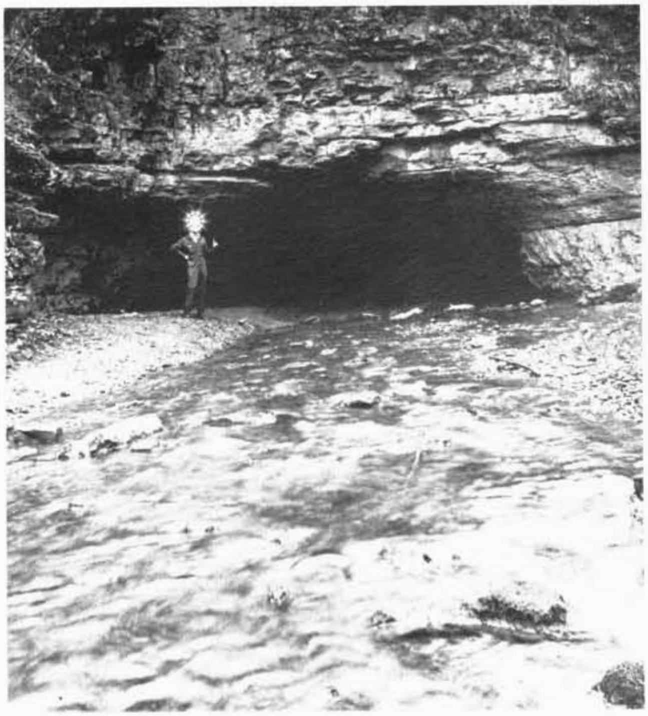

Figure 4. Karst features of the Sinking Fork area, Trigg County, Kentucky.

vertical shafts are relatively rare, and entrances to the caves are of three main types: low gradient entrances at the stream sink points, large collapse sinks and karst windows, and active (Fig. 3) or abandoned resurgences in the bluffs along the master streams of the area.

HYDROLOGY

Other than data collected by direct exploration, little is known about the hydrology of the area. Few dye traces have been run, but where they have, subsurface flow paths of up to 5.5 km have been delineated (Moore and Mylroie, 1979), as in the Sinking Fork basin of Trigg County (Fig. 4). The regional dip, being low and undulatory (except in the northwest), produces cave system orientations controlled by the location of the master surface streams. Occasional normal faults are found throughout the western Kentucky area, and can infuence cave development on a local scale (Fig. 5). The regional joint pattern is a conjugate set approximately northeast to southwest and northwest to southeast in orientation.

The caves of the sinkhole plain are elliptical tubes up to 5 m high an 15 m wide, and the abandoned upper levels, where found, are similar. Tributaries commonly occur as vadose canyons, and in the low gradient of the region they can meander dramatically, producing numerous abandoned sections and areas of substantial complexity (Fig. 6). The canyons are rarely over 10 m high and 3 m wide, and generally break up into impassable inlets at the upstream end. Cross-links between adjacent cave systems occur, such as at the Lisanby-Farless connection (Caldwell County, Figure 7), or at Rimstone Runway Cave (Trigg County), not an unexpected occurrence in a low gradient situation where a minor rise in water level can merge subsurface drainage basins.

Along the meanders of the master streams, piracies or meander cutoffs are common. They have been described from the Sinking Fork of the Little River (Moore and Mylroie, 1979; see Fig. 4), and the West Fork of the Red River (Mason, et al., 1984). Figure 8 shows the relationship between meanders, meander cutoffs, and sinkhole plain caves along the West Fork of the Red River. A complex relationship between river flow and cave development can occur. For example, the efficient and complete flow of surface water through a meander neck can have major consequences for the karst features associated with the meander loop that has been abandoned.

The number of caves located, explored, and surveyed is believed to be only a fraction of the accesible total for the region (Table 2). With such a small data

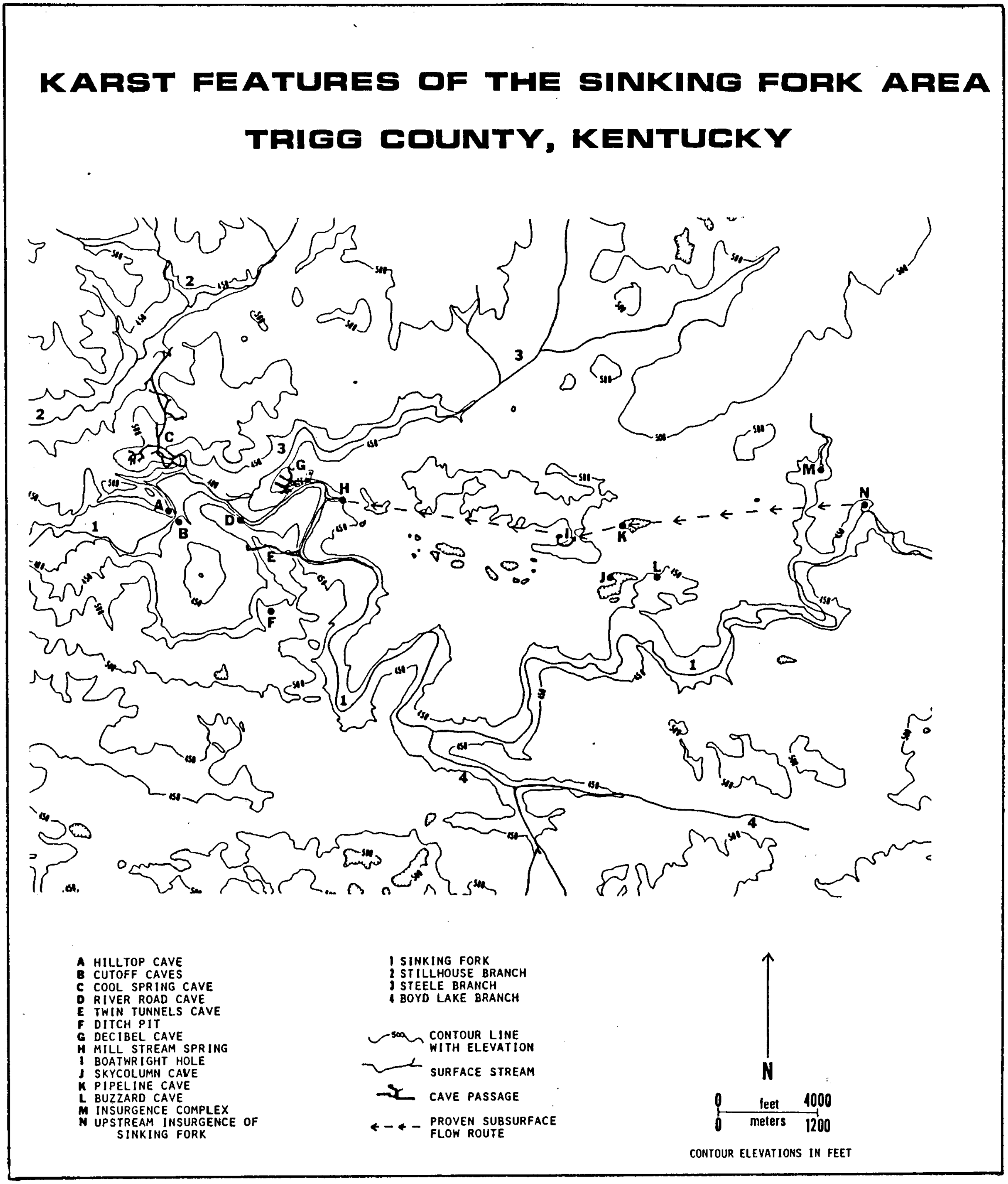

Figure 4. Karst features of the Sinking Fork area, Trigg County, Kentucky.

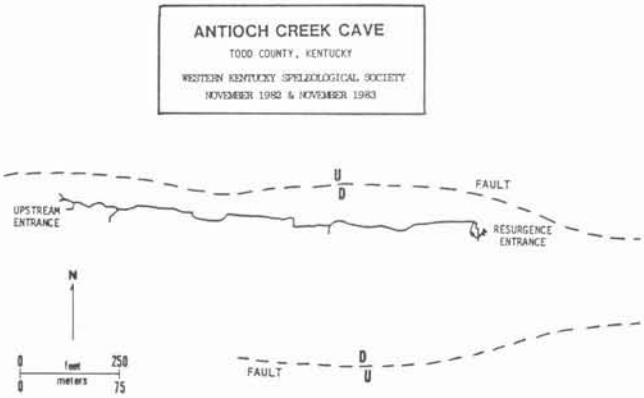

Figure 5. Antioch Creek Cave.

base, any generalizations drawn are going to be necessarily imprecise and vague. The principal significance of the region remains the amount of speleology yet to be done.

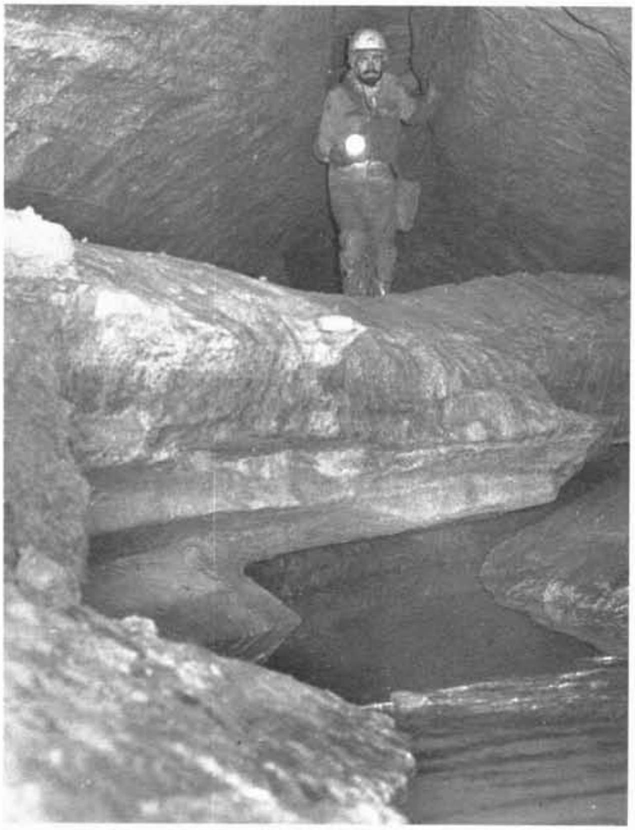

Figure 6. Waterfall Canyon area of Lisanby Cave, Caldwell County, Kentucky.

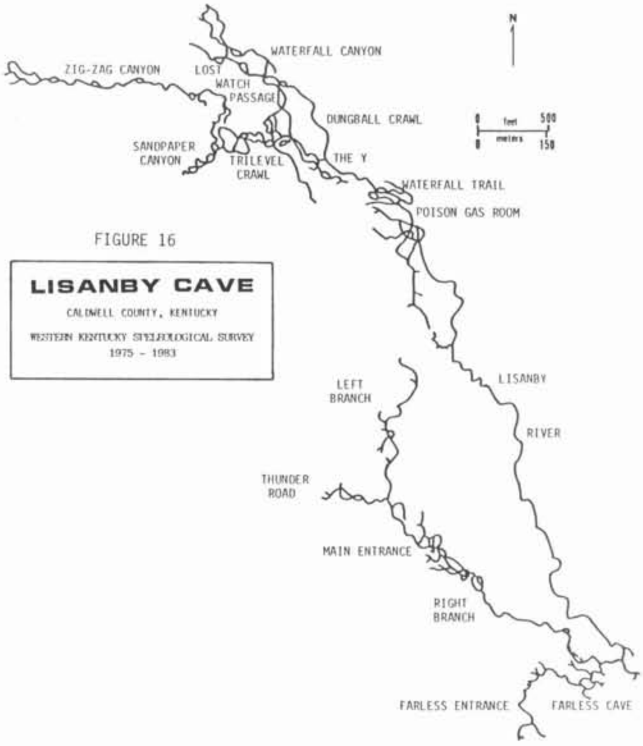

Figure 7. Lisanby Cave.

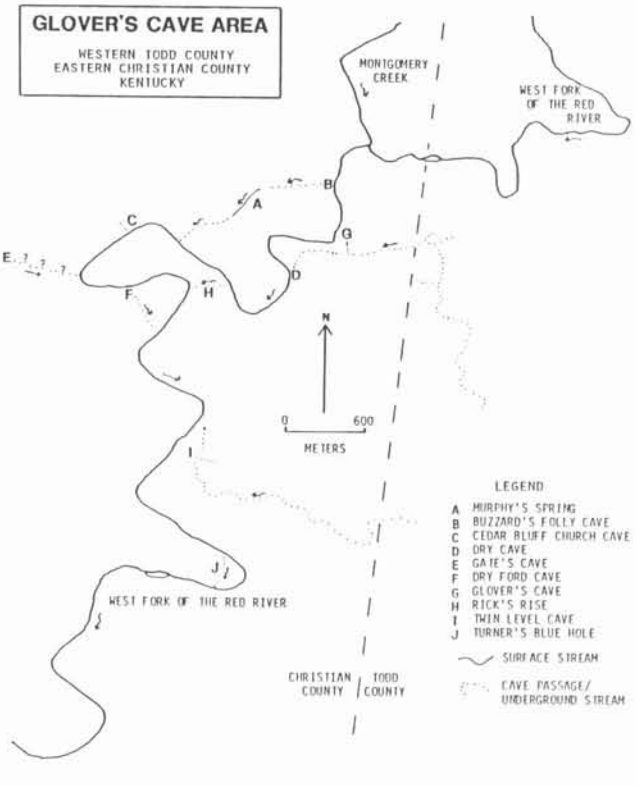

Figure 8. Glover's Cave area.

MAJOR CAVES OF WESTERN KENTUCKY

Tables 1 and 2 give an idea of the size and distribution of caves in western Kentucky. A complete and detailed description of all 200+ caves of the region is not possible, but abbreviated descriptions of the major caves and types of caves can give an impression of cave development over the entire area. The cave descriptions that follow will progress westward from the Logan County area to the Cumberland River. Specific location information is deleted in order to preserve the caves.

The caves to be described include the longest caves in the region, as seen in Table 1, and other caves that show significant features. The descriptions of the Savage/Angel Cave System, Gorham Cave, Glover's Cave, Twin Level Cave, Cool Spring Cave, Big Sulphur Cave, Husk Cave, Harmony Church Cave system, Skinframe Sinks Cave, Mill Bluff Cave, and Lisanby Cave all detail the major known and active sinkhole plain caves of the region.

The other caves show special features. Oakville Cave (Fig. 9) is a phreatic maze with an almost anastomotic nature, further complicated by sediment infill and vadose incision. Decibel Cave (Fig. 4) is a classic backflood maze, located in a hill between a major stream and its principal tributary. The cave shows control and a progressive piracy of the tributary surface stream.

Antioch Creek Cave (Fig. 5) is a cave closely controlled by structure, coincident with or parallel to a set of east-west normal faults over its 1.5 km length, from its upstream sink to its downstream resurgence.

Twin Tunnels Cave (Fig. 4) is a cave demonstrating some important aspects of stream incision and meandering in limestones. The cave is a fossil meander cutoff, formed because its route offered a steeper gradient to the surface stream (same elevation loss in a shorter linear distance). It has become fossil because the section of surface stream it delivered water to has become an abandoned meander loop in response to a meander cutoff cave (the Cutoff Caves) (Fig. 4) downstream. This cave shows the complexities of meanders and the interactions they cause when they are pirated through their meander necks.

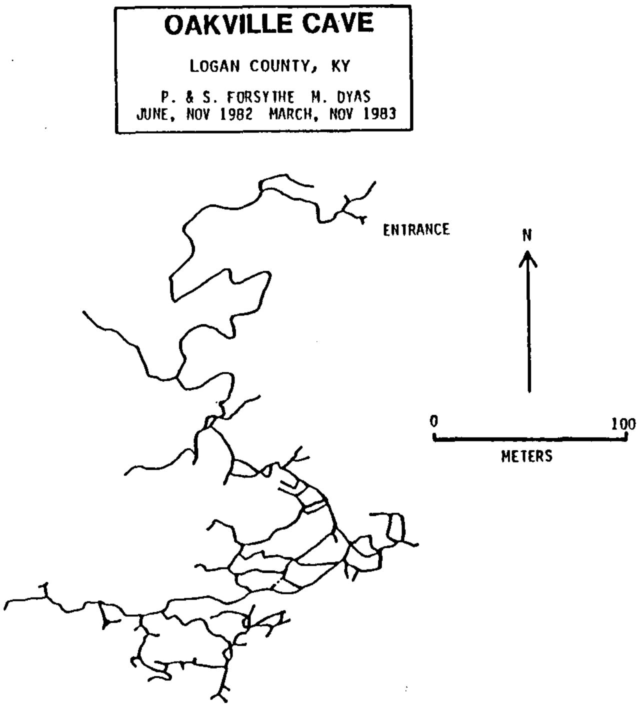

Figure 9. Oakville Cave.

Baker Cave, although currently unmapped, follows a major fluorite vein for most of its length. It has been worked for some of its fluorite and contains deposits reminiscent of the Derbyshire karst area of Great Britain.

Many caves, such as Baker Cave, Oakville Cave, Glover's Cave, and others not described in this chapter, are major archeological or paleontological sites. While much plundering has gone on, some sites, such as Savage Cave, are currently protected and undergoing intensive study.

Some of the region's caves have been major recreational caves, like Glover's, Cool Spring, and Mill Bluff Cave, while Lovell Cave was once commercialized. Cave management is in its infancy in this region but will become a greater concern in the future.

The Western Kentucky Speleological Survey is the major source of information for caves of the region. As Table 2 shows, 218 caves are known from the region, and 210 have a written description, with 147 mapped as of January, 1985. The respistory for this information is the Western Kentucky Speleological Survey Annual Report Series, published since 1978. Numerous articles on archeology, paleontology, biospeleology, karst hydrology, karst geomorphology, and geochemistry have been published in the Annual Report Series. They are on file with the U. S. Geological Survey, the National Speleological Society and numerous cave groups, or they can be obtained from the authors.

Savage Cave System

The Savage Cave System, in southern Logan County, consists of over 5 km of the active and abandoned underground stream course of Woolsey Creek and its tributaries. Figure 10 shows the location map of the major features of the area, and the cave system components. The features of the Savage Cave System are: Savage Cave, Angel Cave, Barnes Cave, Woolsey Creek Cave, the sink point of Woolsey Creek, and the resurgence on the banks of the South Fork of the Red River (Fig. 10). Portions of Savage Cave and Angel Cave, as well as all of Barnes Cave, are abandoned upper level conduits, indicating a long and varied history for the cave system. Woolsey Creek Cave (located just south of the Woolsey Creek sink point shown in Fig. 10) is a short tributary cave, releasing its water into the Woolsey Creek blind valley. Angel Cave and Savage Cave are separated by about 300 m of sumped passage. From Savage Cave to the suspected resurgence is a distance of over 1 km.

The Savage Entrance to Savage Cave is a large, 25 m wide, 4 m high opening in a broad, gentle sloping sinkhole. The entrance has an apparent collapse origin, and formed at a meeting point of the large upper and middle levels of the cave. Down the entrance talus, a very large (15 m wide by 6 m high) passage leads off (west), and is the middle level; just above it to the left, another large passage, the upper level (10 m by 6 m), parallels the middle level. The left passage, or upper level, continues for 80 m.

The middle level passage, or the main passage, heads west off the entrance room, just to the right and below the upper level. Initially quite large (15 m by 6 m), after 30 m it closes in, averaging 10 m by 3 m. The passage is flat floored and easily traversable, but shows evidence of complete backflooding. It continues in this manner for 350 m westward past breakdown, pools, and flowstone to a complete choke.

To the east at the entrance, a short crawl and stoop over breakdown leads to the majority of the cave and the Eidson Entrance. Over 3.5 km of mostly easy passage leads eastward. The stream sumps in this area, and is not seen again until the resurgence. The main route is the middle level, usually 3 to 6 m wide and 1 to 3 m high, with the stream either in the floor or meandering in its own spacious crawl beneath the middle level. At the upstream end of the cave, a tributary canyon leads to the Eidson entrance, and the main stream sumps shortly thereafter. A canyon complex exists in this area, and the downstream sump of Angel Cave is less than 300 m away to the east.

Angel Cave

The 9 m wide, 2 m high entrance is in a sink midway between the Eidson Entrance to Savage Cave and

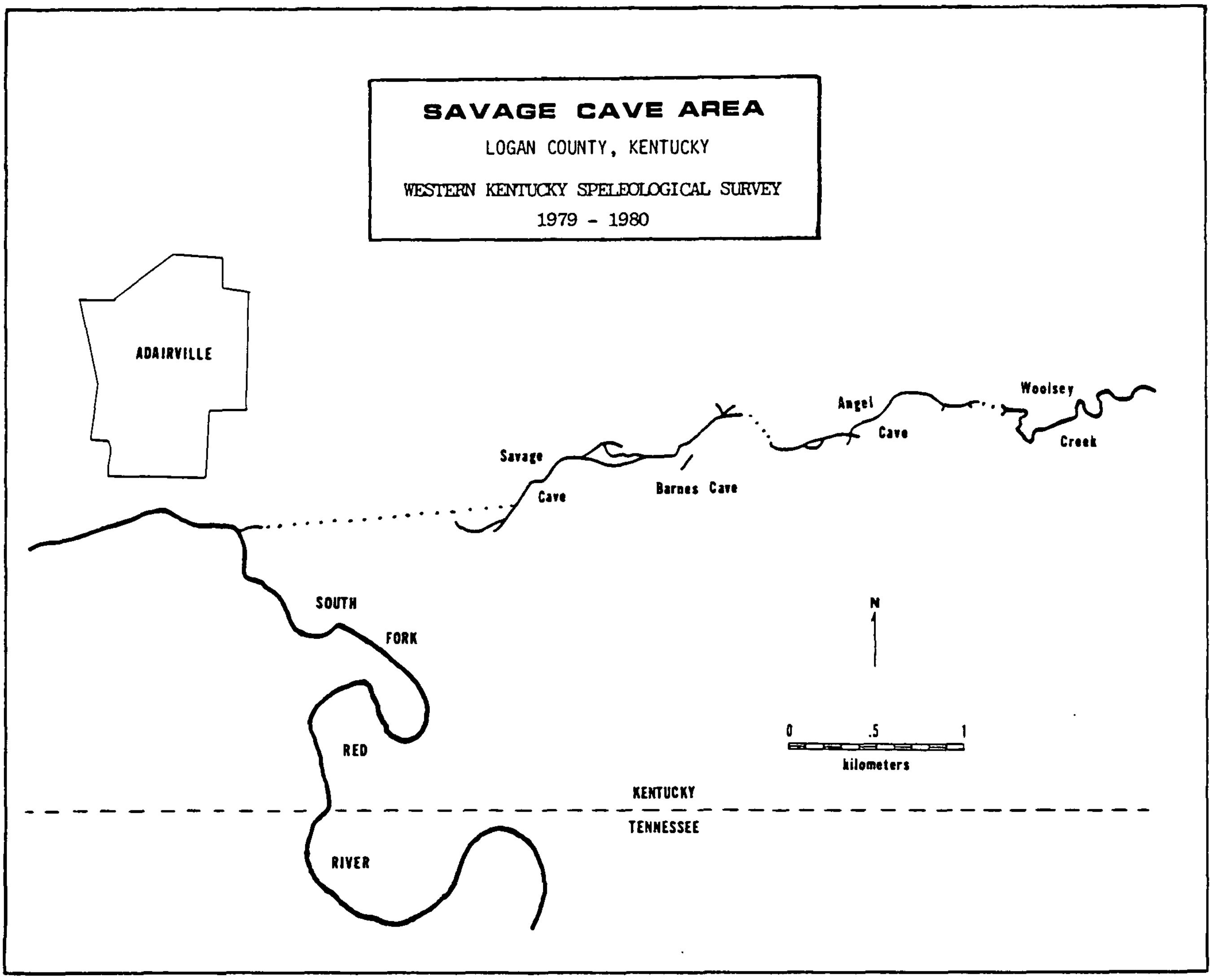

Figure 10. Savage Cave area.

the sink point of Woolsey Creek. Figure 10 shows the cave location and trend. At the left corner of the cave mouth is a dry side passage that goes for 45 m to the southwest to a breakdown choke. The entrance slope opens to a breakdown littered, cobble floored, west-southwest trending trunk, initially 9 to 15 m wide and 2 to 3 m high. The main cave stream is not seen at the entrance under normal conditions, being under the breakdown. On the right, 36 m from the entrance, is the rather inconspicuous connection to the upstream portion of the cave. Forty-five meters beyond to the west, the stream emerges from breakdown; this is the underground course of Woolsey Creek, the same large stream seen in parts of Savage Creek. The passage continues 150 m, partly on two levels, emerging into one end of a breakdown room in excess of 90 m long, 6 to 9 m high, and not less than 18 m wide--at one point over 45 m wide. This impressive chamber, comprised of large breakdown on a gravel base on the right and a sprawling silt bank on the left, is the largest known room in any western Kentucky cave. It is succeeded by another sizable breakdown room, 45 m long, 23 m wide, and 3 to 4 m high. At the end of the second major room, the passage, with ponded water, continues 90 m to the terminal sump.

The lead to the upstream portion of the cave is a clean flood route, soon reaching the main stream. One can continue in a passage varying from crouchway sewer to spacious breakdown trunk to wet crawlway. This extension skirts a broad, flat-bottomed sink and is heavily fractured. At the end, 600 m from the entrance, is a back entrance and another 300 m of passage nearing the sinks of Woolsey Creek.

The Savage Cave entrance area, both surface and subsurface, is an extremely important archeological site (Carstens, 1980). The Archeological Conservancy worked with the WKSS, the landowner, and Murray State University to preserve the cave. The property has been transferred to Murray State University, and access to the cave is strictly controlled. Archeological study of the cave is continuing.

Gorham Cave

This cave is named after J. H. Gorham, whose farm included the entrance. Although locally well known, the 3.2 km cave has suffered surprisingly little vandalism. Gorham Cave is situated in east-central Logan County, about 8 km from Russellville. The entrance, a 3 m climb-down, is in a small sink at the contact of the lower member of the Girkin Formation and the Ste. Genevieve Limestone (Fig. 11). The entrance room, littered by massive breakdown, intersects a trunk carrying a stream. The downstream section trends northwest, averaging 10 m in width and 3 to 8 m in height, for 180 m to a sump. This section reportedly connects with a resurgence cave at Spring Acres, a recreation park a short distance west-northwest of the Gorham entrance. Thirty meters before the sump, a 6-m-wide by 2-m-high side passage with two beautiful pools extends west for 200 m.

From the entrance, the upstream section extends to most of the cave. It trends southwest, carrying the stream, which averages 10-m-wide by 6-m-high, with large breakdown blocks and flowstone at intervals. One kilometer from the entrance, the stream forks. The right branch continues west, past more large boulders, for another 300 m; the ceiling height gradually lowers to a periodic sump, pushable another 300 m to a sinkhole entrance, and a final sump 140 m further. There appears to be one or two additional segments of cave in a karst window adjoining this point.

At the mainstream fork, the left branch goes southwest for 800 m, intersecting a number of side passages of appreciable extent, to a 10 m wide, 60 m long room with several large columns. Just before its end the stream emerges from a 40-m-duck-walk to terminal breakdown. This breakdown plots to be within a few meters of a logjam in a nearby karst window.

Oakville Cave

The location is a deep, brushy sink surrounded by cultivated fields south-southwest of Oakville, Logan County. The entrance, which takes runoff from heavy precipitation, is 3 m wide and 1 m high, and the cave initially trends west-northwest. The cave swings south (see Fig. 9) and becomes a very confusing maze of small vadose passages, phreatic tubes, and abandoned trunk fragments. An active stream is seen in places, only heard in other locations. Air flow is noted in many places. The largest trunk fragments are up to 5 m wide and 3 m high. There is abundant mud, and several bone sites. Digging at a few promising places could easily extend the cave.

A total of 1.66 km has been surveyed in Oakville Cave, with a small amount of unmapped passage.

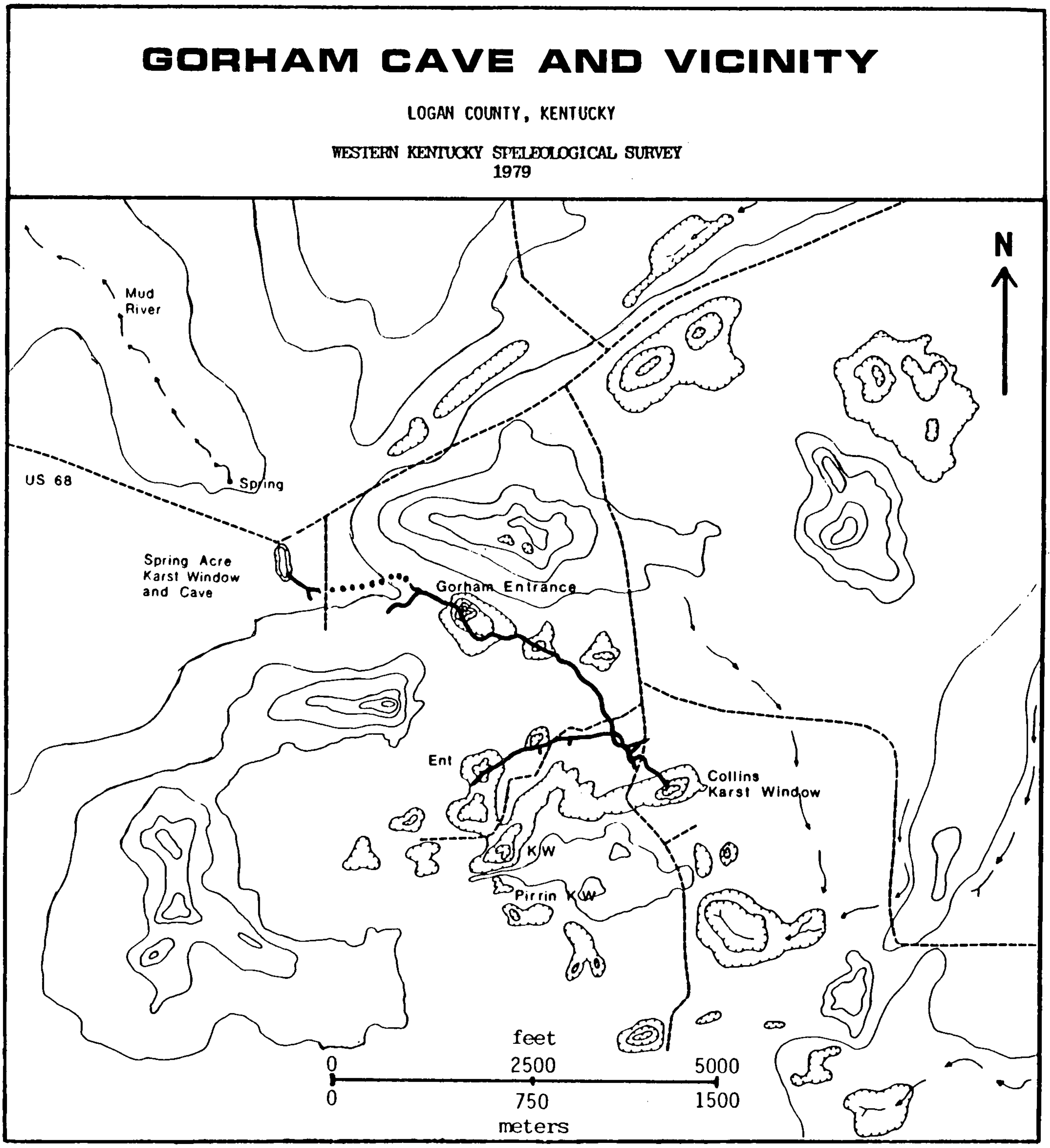

Figure 11. Gorham Cave and vicinity.

Oakville Cave is believed to be part of an extensive underground drainage net. The big stream briefly seen at the northwestern "end" of the cave is apparently the master drainage from the Oakville neighborhood. This is likely the same stream that passes through a series of karst windows at Spring Valley Church, some 1.5

km southwest. The ultimate resurgence is another kilometer southwest, at the former site of the Pleasant Grove Church.

By western Kentucky standards, Oakville Cave is regarded as dry and unlikely to flood. However, large quantities of fresh mud were encountered in the cave in May 1983, after a period of unusually heavy rain, so it appears that most of the cave can flood infrequently.

A large amount of flint (chert) material is evident in the field adjoining the entrance sink. Local residents have collected many arrowheads and other Indian artifacts from this site, which must have been a large camp. Several Indian points have been found in parts of the cave itself far from the present entrance.

Antioch Creek Cave

The location of this cave is roughly 4 km northeast of Sharon Grove, Todd County. One entrance, a resurgence, is at the head of a branch of Antioch Creek, 1.6 km southwest of Antioch Church. The other entrance is a sink (karst window), 1.1 km almost due west of the spring mouth. A stream emerges from the western side of this sink and runs into the cave via the back entrance. The cave has 1.49 km of passage and runs almost straight west to east (Fig. 5), parallel to prominent east-west normal faults in the area.

The resurgence entrance opens in a headwall at the western end of a ravine and is 12 m wide by 3 m high. A walking passage with ponded water trends initially southwest for about 30 m. Here it doubles back to the north as a narrow walkway, with waist-deep pools, for 45 m, emerging over breaddown into the main part of the cave. The entrance streamway may be partially bypassed through a dry upper level crawlway. At the room where these levels rejoin, the stream strunk assumes a nearly due-west trend, which it maintains for approximately 1 km, nearly to the back entrance.

The west-trending trunk is initially of nice proportions--3.5 to 4.5 m wide and 2.5 to 3.5 m high--with broad ledges on one or the other side, the stream flowing shallowly over gravel, and a number of speleothems. The passage gradually lowers, however, becoming a cobble-strewn crawlway with ponded water about 275 m from the entrance; passing several significant leads, it continues west to link with the upstream entrance. The upstream entrance, like the resurgence, is quite spacious--9.5 m wide and 3 m high. The main passage assumes the nearly straight east-west bearing of the downstream cave, starting off as a walking trunk for some 200 m, then becoming a low crawl connecting to the rest of the cave.

Lovell Cave

Located south of Weir in Muhlenburg County, Lovell Cave represents what is probably the largest cave in the county. It is as rich in history and local legend as it is in passage. During the 1920s, a man named Clark ran Lovell Cave as a local tourist attraction. Tours through the walking passages of the cave averaged 50 cents. On warm spring Sundays when the cave was open for business, hundreds of people camped on the ridge above the entrance. By 1928, the commercialization of Lovell Cave had ceased.

Actually, the cave's history dates from much earlier. Indian artifacts have been found both around the entrance and within the cave. The walls of the cave carry several smoked dates in the 1800s including "J. K. East 1833" and a dubious "Jessie James 1868." Local legend also fills the cave with runaway slaves and an improbable number of bankrobbers. The most unlikely story told about the cave is the story of the discovery of several "Egyptian mummies" that were supposedly viewed by Floyd Collins himself. The interior of the cave has suffered from tourism to the extent that even 10-m-high ceilings bear only the stumps of broken stalactites. In many places smoked or painted names obscure the walls.

Lovell Cave (Fig. 12) opens through a 5 m wide, 2 m high entrance in the southern side of a ridge. A passage with a typical arched shape leads down a fairly steep slope into the entrance chamber of the cave. The entrance chamber is in the sandstone caprock of the cave, with a floor composed mostly of large breakdown blocks. Two passages lead from the left (western) side of the entrance room and continue west until they meet Tourist Canyon, a long canyon passage going north-south. The southern end of Tourist Canyon terminates in breakdown, but a narrow stoopway branches west and enters a wide crawlway that contains an intermittent stream, flowing southeast to northwest. As are all water features of Lovell Cave, this stream is extremely variable. A series of small interconnecting passages exists in this area. Back at Tourist Canyon, moving north, passages frequently meet at nearly right angles. With the exception of White Bat Passage on the eastern side of the cave, all these passages are tied together. A moderately large chamber on the western side of the passage is tied to the other passages only by the extremely tight Hard Way Tube. As Tourist Avenue continues north, the side passages intermesh in a more and more complicated system. Several passgeways are yet to be pushed to their fullest extent. Over 1 km of passage has been surveyed.

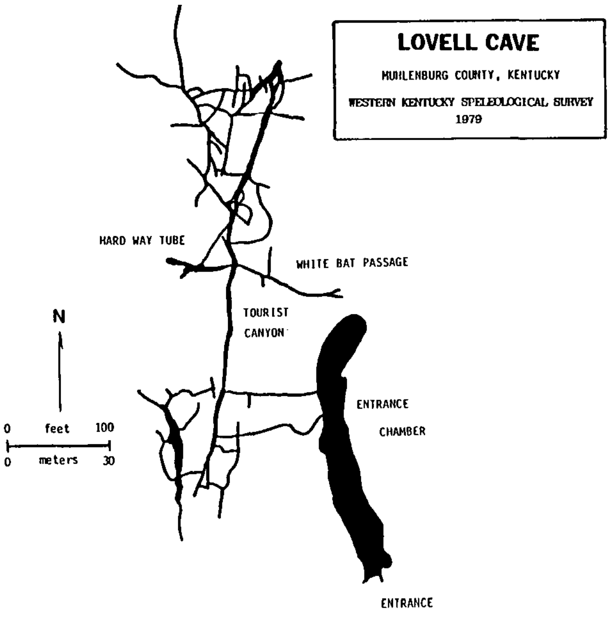

Figure 12. Lovell Cave.

Glover's Cave

The cave entrance is located on the eastern bank of the western fork of the Red River in southeastern Christian County (Fig. 8). From the Primary (or Main) Entrance, the cave proceeds north and east. The northern branch begins as a wide tube 12 m by 3 m, and 45 m from the entrance runs into a cross passage trending east-west. To the west, the cross passage, an oval tube 8 m wide and 1 to 2 m high, ends in sediment and collapse. To the east, the tube runs 110 m, with much mud, to a terminus. At the junction with the cross passage, the northern branch changes to dimensions of 3 to 4 m wide and 4 to 8 m high. This branch runs to the north for 75 m to a chamber with a covered 10-m pit in the ceiling (with water pipes coming down) and a short walkway to the surface through the door at the Secondary Entrance. North beyond this chamber is a complex area of entrances, pools, and siphons. This area is used as a water supply.

Trending east from the Primary Entrance is the main passage of the cave, called the Lincoln Tunnel. This passage runs for 600 m with remarkably uniform ceilings. At many localities in the passage are rimstone dams. After 600 m, the passage forks. The left fork trends northeast for 90 m as a sediment and breakdown floored passage 3 to 6 m wide and

1 to 3 m high. This Lake Passage ends in a deep lake in a room 18 m long, 10 m wide, and 9 m high. The Lake has a definite water flow from the southeast to the northeast and may be part of the water seen at the resurgence. The pool has abundant cave life plus many leaves, sticks, etc., embedded in its shore. From the incoming passage to the lake is a downward 6 m slide.

The right fork is a continuation of the main passage. Thirty meters from the fork, a stream is met that cuts to the northeast under the passage wall into a short side passage leading to a domepit in a decorated chamber called the Grotto (Fig. 13). The stream sinks here, and is believed to go to the Lake, only 60 m to the north. Just beyond the passage leading to the Grotto is another side passage that leads east 210 m as a walk, crawl, stoop-walk, and terminates just beyond a small dome in the ceiling. This passage was recently extended.

The main passage, now carrying a stream, meanders south 200 m as a large tube up to 13-m-wide and 8-m-high. At the Dining Room, collapse blocks the passage. A side lead at this point, the Winder, trends 200 m west. The main passage collapse can be forced to regain the major trend and a short passage, the Ballroom. The next 750 m alternates between solution tube, breakdown passage, and breakdown crawls, averaging 3 to 6 m high and 8 to 15 m wide, passing the Eagle, the Guillotine, and the Cliff Hanger. The main passage ends in a formation area, the Beauty Parlor. A further low, wet, and muddy passage can be followed to an apparent end at a siphon, domes, and sediment blockage. Over 3 km has been surveyed.

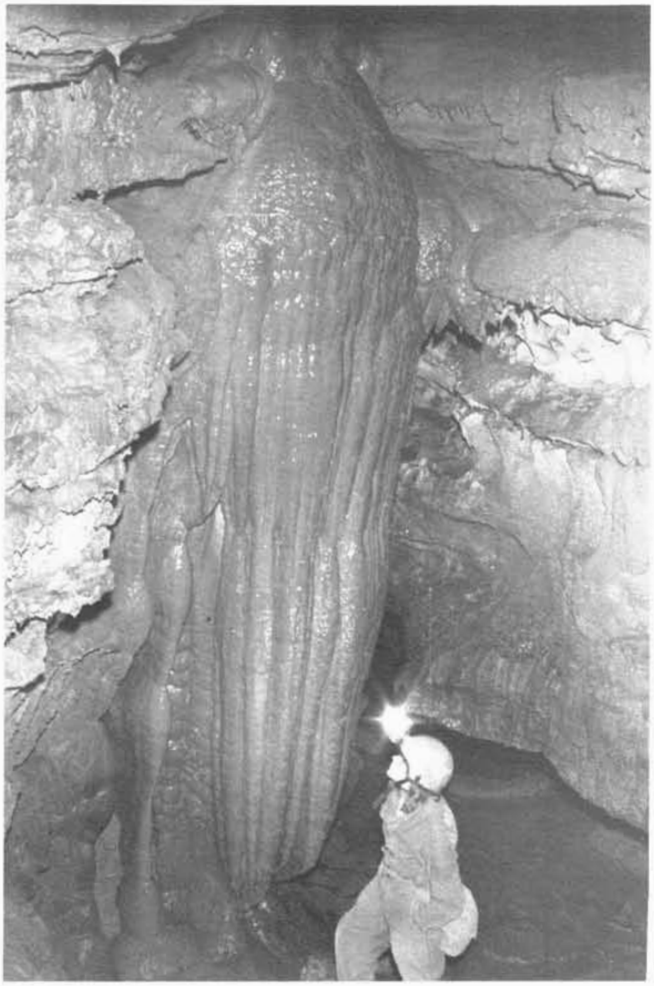

Figure 13. Formations in the Grotto, Glover's Cave, Christrian County, Kentucky.

Twin Level Cave

Twin Level Cave is located on the eastern bank of the West Fork of the Red River in southeastern Christian County (Fig. 8). Over 5 km of passage has been mapped, and survey work continues. The Main Entrance to the cave is a spectacular double level entrance. The upper part is a large shelter that becomes a small passage ending after 60 m. Two passages lead off from each side of the entrance. The northern passage is an overflow tube of mostly walking size, with some ponded water. It lowers to a crawl then reaches the surface on the banks of the river 160 m upstream of the Main Entrance.

The major portion of the cave leads south from the right side of the Main Entrance. An easterly crawl of 100 m leads to a junction with the main stream. Downstream to the left, the main stream passage sumps immediately, but upstream to the right it continues 2 to 3 m high and 2 to 5 m wide for 350 m to a collapse sinkhole entrance, Turner's Window. Pushing upstream the passage continues as before, with some breakdown and low crawls, for a further 1,500 m to another entrance at Carneal's (Watt's) Cave. The cave continues upstream another 1,000 m to an additional entrance, Hamlet's Well, a drilled well 1.2 m in diameter. Total survey to date is 5 km, with leads still remaining.

Big Sulphur Cave

Big Sulphur Cave, 4.8 km long, is situated in southeastern Trigg County on the bank of Little River at the apex of a sharp meander. A distinct, though not overpowering, sulphurous smell is noticed at the entrance (Fig. 14).

The first few meters of passage is a stoopway over small breakdown. Thereafter, one follows a south-southeast-trending stream channel of mostly rectangular cross section, averaging 4 to 7 m width and 2 m height (a few short stretches require easy crawling). The stream generally occupies the whole floor but is usually no more than ankle deep. The first lead on the right is 75 m from the entrance, a 20 m crawl with a trickle tributary emitting the sulphur smell. A more important junction is 30 m past the "sulphur crawl," also on the right. This junction is a climb-up to an upper level section, the Bat Passage, which parallels the main stream passage for over 200 m. It averages 5 m wide by 2 m high.

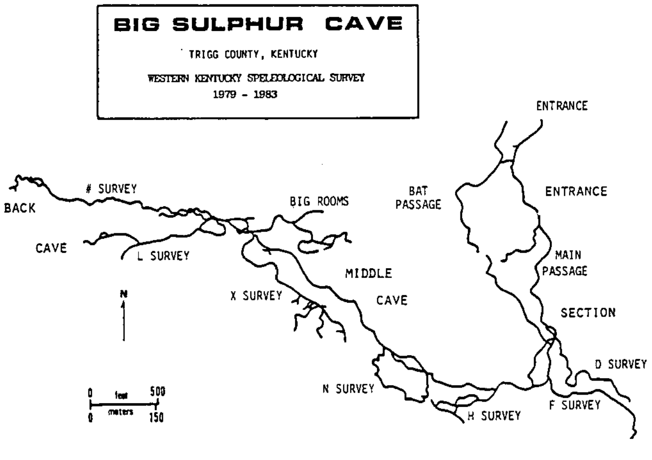

Figure 14. Big Sulphur Cave.

At a point 680 m from the entrance, the stream forks into segments of about equal volume. The right branch continues to most of the known cave as the Middle Cave section. At the fork straight ahead (southeast) is a narrow walkway with ponded water. This walkway appears to aburptly end after 30 m, but beyond a low near-sump, this passage, the D Survey, continues 150 m southeast to where a large block halts progress despite airflow. Right from the major fork is the way to the Middle Cave and most of Big Sulphur. The initial trend remains southward but the main passage soon assumes a sharply different direction than the entrance trunk; west or northwest, roughly paralleling the surface course of Little River, but with an opposing streamflow direction. This section averages 5 to 10 m in width and 1.2 to 4.5 m in height, with two or three slightly offset levels in most places.

Only 25 m past the mainstream fork to D Survey is another significant intersection; on the right, several meters above stream level and not obvious at first glance, is a junction of an upper level. This is a truncated segment of the Bat Passage described above. It begins as a wide but low crawlway, changes to a sizable breakdown route similar to the Bat Passage, trends northwest for 185 m, and ends in collapse very close to the southern end of Bat Passage.

After another 35 m south, the F Survey trends southeast for 225 m, averaging 1.5 m wide and 0.5 to 1 m high. It "ends" by breaking up into several small components that are not negotiable. The F Survey passage closely parallels the D Survey at a slightly higher level; it probably carried the same water at one time. Both these passages are close to a nearby short cave, Little Big Sulphur Cave.

The cave swings west, and just over 100 m past the F Survey intersection is a wide but somewhat low junction of another left branch, the H Survey. This semi-maze, broken-down area trends west-southwest, varying from walking to easy crawling size and totals about 200 m. The N Survey, is also on the left, 120 m after the H Survey. This section, a 270 m loop, is surmised to be a portion of the cave's principal but intermittent upper level. It begins as a south-trending walkway for 50 m, then a tight crawlway continues, doubling around to the northwest and rejoining the main trunk 80 m beyond the initial N Survey junction.

There are no more significant leads off the main passage for the succeeding 320 m after the second N Survey junction, until a breakdown zone is encountered. One can stay low and right, with the stream, skirting the breakdown into the mainstream continuation to the west. A slightly more obvious choice is to crawl straight ahead into the breakdown. By doing so one pops up after 20 m into the Big Rooms area. The first room in the Big Rooms area is roughly rectangular in cross sections, approximately 20 m on each side and 5 m high. Thre are three principal directions from this room.

Near where the L Survey departs the Big Rooms section are two interconnecting and inconspicuous but significant side passages on two levels, the lower with a small stream. A meandering crawl only 1 m wide and 0.5 m high trends west for 325 m, ending in several mud slumps. This is the fartherest point from the entrance in Big Sulphur Cave, a little over 1,500 m.

Cool Spring Cave

Cool Spring Cave is located on the Caledonia 7.5+ minute topographic map, on the northern bank of Sinking Fork in central Trigg County. The cave is complex and the second largest known in western Kentucky. Unusual for the area, Cool Spring Cave has extensive upper level development, with three distinct horizons. Some good leads remain and it is hoped the cave will yield more virgin passage in the future. Over 5 km of passage has been surveyed (Figs. 4 and 15).

Cool Spring Cave has three known entrances, all grouped around the resurgence. The Main Entrance, carrying the cave stream, leads north and then west 145 m as a broad oval tube 8 to 10 m wide and 1.5 to 3 m high. The sinkhole entrance enters through the ceiling of an alcove of this passage just in and to the west of the entrance. At 145 m, the stream

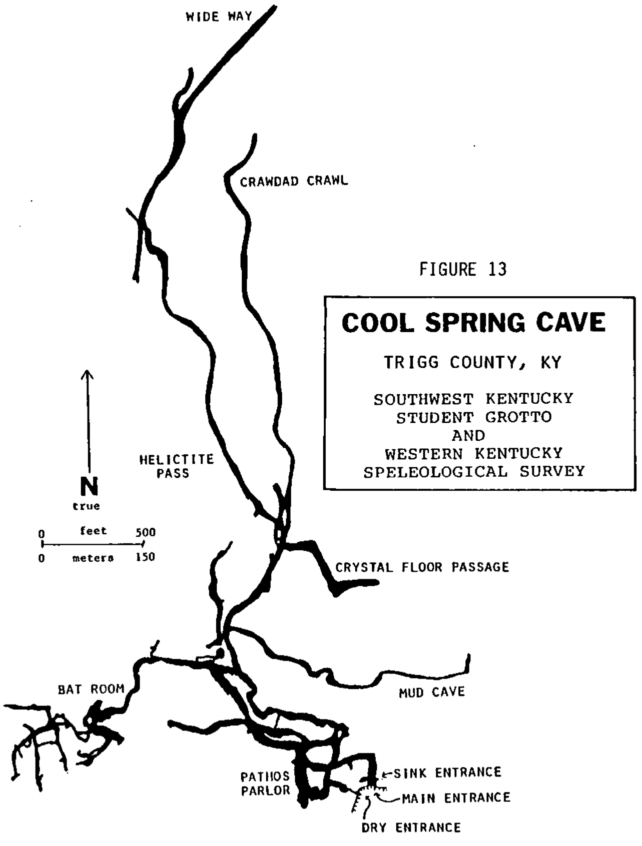

Figure 15. Cool Spring Cave.

passage opens into a large chamber, Pathos Parlor, 90 m long, 15 m wide, formed by the intersection of the three levels of the cave. To the left (south), it proceeds to a passage that ends in a mud, flowstone, and breakdown choke in the upper level. Just before the choke, a passage leads down and east as a low, wide stoop and crawl to the Dry Entrance, as a segment of the middle level of the cave.

From the northern end of the Pathos Parlor, passages leave at all three levels. The upper level leads west as a tube 4 to 8 m wide that starts out 2 m high but diminishes, finally ending in sediment fill after 210 m. Leaving the northern end of Pathos Parlor, the stream or lower level trends northwest for 200 m to a sump as a tube 1 to 2 m high and 6 to 9 m wide. Sixty meters from Pathos Parlor, a large breakdown occurs. Up and to the south through the breakdown is a connection to the upper level. Just before the sump the lower level crosses under the middle level to form a large room. To the east this middle level leads past an important side passage at Breathing Junction and continues over 300 m, connecting into Pathos Parlor from the east and into the Dry Entrance area.

To the west from the siphon area of the main stream, the middle level runs 240 m to the southwest, as an oval tube 3 to 4.5 m wide and 1 to 2.5 m high ending in the Bat Room, a large chamber complex formed by intersection with the upper level. For the next 300 m the middle level is criss-crossed by the upper level many times, resulting in considerable passage complexity and over 900 m of passage. Ample wind and many small domes indicate a possible entrance nearby. These passages end in sediment fill, flowstone, or collapse. No active streams are seen in this section of the cave.

The major portion of the cave lies north of the Breathing Junction. From this point, the middle level extends north 60 m as a tube 3 to 6 m wide and 1 to 2 m high to Guano Junction, where the lower level stream passage is rejoined. The middle level continues north across the stream as a walking passage, gradually diminishing to a crawl and ending after 120 m. The stream passage siphons downstream to the southwest, but continues north as Crawdad Crawl for over 600 m, gradually lowering from a walkway to a stoop to a crawl. It continues, upstream from Guano Junction, and the middle level is intersected again. It proceeds east 180 m as a wide, low tube, Crystal Floor Passage, and north over 1,100 m also as a wide, low tube, Helectite Pass. Its end has not been reached, as it degenerates into a very low crawl, Wide Way. A sharp right from the base of the Guano Junction leads as a diminishing tributary passage, Mud Cave, for 500 m to the east.

Cool Spring Cave is a very complex cave, and good potential exists for significant extension of the cave. The source of the water in the cave is not known, and the major tributary passages have not been reached within the cave. The plan of the cave suggests that it developed initially by gathering water from the Stillhouse Branch tributary of Sinking fork. Much of the current water flow in the cave is believed to originate from further upstream in Stillhouse Branch rather than in past stages of the cave's development (Fig. 4).

Decibel Cave

Decibel Cave, containing almost 2 km of passage, is located on the northern bank of Sinking Fork west of Mill Stream Spring (Fig. 4). The entrance is at river level in a low limestone bluff, and is 1 m high and 2 m wide, with a stream flowing out. This passage leads north into a junction room. To the east, a dry crawl at roof level or a wet crawl at floor level unite after 15 m in a low, wide stream passage, continuing west 20 m before opening out into a large breakdown chamber over 30 m across and up to 6 m high. The stream comes out of impenetrable breakdown at the extreme northern point of the room.

From the junction room near the entrance, a low, muddy crawl can be followed north into a large corridor. The main corridor swings southwest from these side passages and the cave suddenly becomes very complex. From the broad, low room with several bedrock pillars, a short crawlway leads north to a dome. To the west a series of tubes lead, after a short jog south, to a large chamber with many bedrock partitions. Short side passages lead east-southeast from this room, but to the west-northwest a group of parallel passages open into a very large chamber floored with breakdown. Passages radiate in all directions, and the room seems to have gained its breakdown and broad expanse due to the collapse of many bedrock pillars. Leading north out of this room is a low (1 m), wide (3 to 6 m) tube that winds for 150 m north, west, north, east, and then north again ending in a breakdown choke. Some high rooms are passed along the way, and numerous vadose dome pits exist. The walls of this tube show well developed scalloping, demonstrating past flow to the south and southwest.

From the large central chamber, passages lead both west and south. To the west, a series of parallel tubes run for 80 m before ending in dome pits, mud plugs, and breakdown. These passages have scalloping that shows past flow to the east. To the south, a series of low arches trending south-southeast intersect large tubes oriented along joints and trending west-northwest and east-southeast. These cross passages end in mud, dirt, breakdown, and flowstone plugs. The most easterly of the passages has a short tube 20 cm in diameter that leads to the surface, but it is not negotiable.

The cave is isolated in a low hill that extends to the southwest between Sinking Fork and Steele Branch (Fig. 4). The cave apparently conducted water from Steele Branch through the hill to Sinking Fork, as evidenced by scalloping in the passages in the western and northern portions of the cave. The water seen in the eastern portion of the cave is believed to be derived from Steele Branch, but this has not been proven.

Twin Tunnels Cave

Twin Tunnels Cave is located on the southern bank of Sinking fork in Trigg County (Fig. 4). Steep bluffs line the southern bank of the stream at this point, and in this bluff, 3 m above stream level, are the two entrances to Twin Tunnels Cave and some other minor associated cvaes.

The two entrances are 30 m apart, and lead to passages 1 to 2 m high and 4 to 8 m wide. The passages join 80 m into the hill. From the junction, the passage continues west as an oval tube 4 to 8 m wide and 1 m high, with a mud floor continuing a meandering trench 1 to 2 m deep for 300 m, where a very low and wide side passage winds northeast for 30 m. This passage is believed to be a tributary passage associated with some large, blocked entrances on the bank of the Sinking Fork, 60 m downstream of the main entrances to the cave.

The cave jogs briefly south before continuing west, encountering a complex junction area 450 m from the entrance. Very wide, but very low passages lead north and south out of the room. Like the previous side passage, a thin person could perhaps gain more cave here. The meandering trench cut in th floor continues west 60 m, emerging after a short climb, into a large room 50 m long, oriented north-south, with its western wall composed of massive breakdown. This room plots out as being under a large, closed-contour depression, the cave having penetrated a ridge between the active Sinking Fork and an abandoned meander.

Ancient and present day flow markings show waterflow into the 580-m-long cave. The cave apparently functioned as a meander cutoff cave, and was abandoned when its point of discharge became a sediment-filled oxbow of Sinking fork (Moore and Mylroie, 1979).

Husk (Lawrence) Cave

Husk (Lawrence) Cave is located in northern Trigg County. The main entrance is at the eastern end of the prominent 300 m long karst window in a broad sinkhole plain. The mouth, 18 m wide and 8 m high, drops down a mud slope to a trunk carrying a stream. Downstream, the water immediately vanishes into an apparently impenetrable breakdown choke, emerging from a secondary entrance in the middle of the sink, and flowing underground again at the western end of the sink.

Upstream from the main entrance is a borehole passage, 6 to 12 m wide and 3 to 10 m high. Large silt banks continually line the stream on one or both sides. The trunk trends predominantly east-southeast, with a couple of major meanders, for an estimated 1,200 m to a deep pool. Beyond, the character of the cave changes, becoming much lower, with the stream occupying the entire floor. Seventy-five meters beyond the pool, it becomes necessary to stoop, with only a few centimeters of air space. The cave may well continue for a substantial distance, however.

Harmony Church Cave System

The Harmony Church Cave System consists of three major segments totalling over 4 km of passage. Two major streams, Millwood Creek and Battle Creek, sink close to their confluence in southeastern Caldwell County. The water is next seen in Harmony Spring Cave, a complex 1,404 m system that has four entrances to a major river passage with overflow routes and tributaries. It sumps upstream and downstream at major karst window entrances. Harmony Church Cave can be entered 200 m south of the Harmony Springs downstream entrance. Upstream it sumps very close to the downstream sump in Harmony Spring Cave. It continues downstream past a collapse sinkhole entrance to 2.5 km of passage, mostly very wet stream passage or oval flood-overflow routes. The water is next seen 2 km to the southeast at the upstream sump of Perkins Spring Cave; then it flows through a very deep river passage for 300 m to the first Perkins Spring Cave entrance at a karst window. Continuing downstream, nine more entrances are located before the water resurges 150 m south-southwest in a karst window. The water crosses the window and sinks again, reappearing at Martin's Spring on the eastern bank of Kenady Creek less than 1 km south--a classic sinkhole plain cave with almost no abandoned upper levels.

Skinframe Sinks (Rice) Cave

The main entrances are located in west central Caldwell County in an almost vertical-sided, elliptical collapse sink, approximately 30 m long by 15 m wide and 4 m deep at the terminus of Skinframe Creek's normally dry bed (Fig. 16).

From its entrance, the main upstream passage has been mapped for 1.6 km south and east, with a major branch to the southwest. At 225 m upstream from the entrance, the stream forks, the lesser flow coming from a major right branch, the Brewster Creek section. Beyond, the main upstream passage continues, now predominantly east-southeast. At 590 m from the entrance, the stream is lost at a

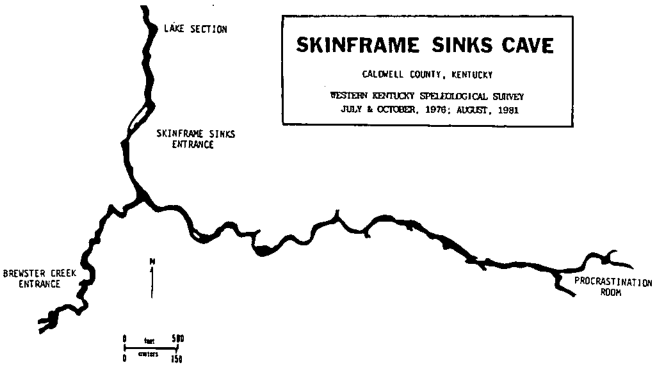

Figure 16. Skinframe Sinks Cave.

sump, and further progress is by way of an overflow route. At 650 m the only relatively large room is seen in this branch (about 15 m long, 8 m wide, and 2.5 m high); a small stream is seen here but can not be followed in either direction. The continuing passage, an overflow route the entire distance, is chracteristic of the previously explored cave: a generally damp-dry gravel/cobble-floored elliptical tube subject to complete flooding, averaging 3 to 5 m wide and 0.5 to 1 m high, with one brief stretch of walking passage and a few other stand-up spots.

Although a small tributary stream occupies the extension passage for 100 m, the main Skinframe Creek is not seen. At Procrastination Room, 1,500 m from the entrance, is a fork; the right branch, of standing height and occupied by knee-deep, stagnant, debris-laden water, goes 60 m to an apparent sump. The other way, a rather low crawl over silt beds, goes 140 m to a low room and branches, both ending within 50 m.

The south-southwest-trending Brewster Creek branch of the upstream cave has been surveyed over 700 m from its intersection with the main stream. Passage dimensions average 3 to 4 m wide and 1 m high. At 425 m from the junction is a room 15 m long, 11 m wide, and 3.5 m high, with three openings to the surface. This entrance complex is in a small sink just northwest of the main Brewster Creek sinks.

The downstream main entrance passage opens to a 8 m wide, 1 m high overflow trending north-northeast. At 80 m, the main stream joins from the upstream portion of the cave. The passage beyond was explored 250 m, trending north and averaging 6 to 10 m wide and 1 to 2 m high to an apparent sump. The stream throughout this branch is ponded into one large "lake," averaging 1 m deep, and usually occupying the entire floor.

Cross sections of Skinframe passages are typical of western Kentucky sinkhole plain systems: uniformly arched, 3 to 5 times wider than high. Survey data indicates portions of the cave near the entrances to be generally 10 m or less beneath the surface, although the stream extension may have 15 m or so of overburden. A few unremarkable speleothems in the Brewster Creek branch were the only formations observed. Large crayfish, conspicuous in overflow pools, are common. The total surveyed extent is 3 km.

Mill Bluff Cave

The locally well-known opening to Mill Bluff Cave is 2.6 km south-southwest of the town of Fredonia. The entrance, in an overhanging cliff of Ste. Genevieve limestone, is likely the largest and most striking of any cave in western Kentucky, being 50 m wide and 18 m high.

Three spacious passages lead back southeast from the entrance, two of them are flood-overflows, and all unite within 200 m of the entrance. A major stream passage, 8 to 14 m wide and 3 m high (1 m of water) continues a further 200 m to a complex junction area. North is a large passage with deep water sumping after trending north-northwest for 160 m. Continuing east and then northeast is a major stream passage, sumping after more than 550 m of additional passage. A series of overflow routes parallel the stream passage to the south, joining both at the junction complex and near the terminal sump. These passages alternate between wide, roomy tubes and muddly crawls. The cave, believed to drain a large area of Caldwell County to the east, penetrates over 1 km eastward and contains 2.4 km of passage.

Lisanby Cave

The main entrance to Lisanby Cave (the only one verified prior to 1983) is located on the southwestern outskirts of the town of Princeton, county seat of Caldwell County. The cave is locally famous and no doubt has been famous for a century and a half. However, to date only sketchy information on the cave's history has been gathered. The current owner, Mrs. Alvin Lisanby, indicates that it was previously referred to as the "Saltpeter Cave"; it may also have been known in the early 20th Century as "Hollingsworth Cave" after Mrs. Lisanby's father, who was a Confederate soldier. Although heavy contemporary traffic through the main part of the cave seems to have obliterated most if not all evidence of saltpeter mining activities, there is a good chance that the cave was mined during the Civil War period. The relatively dry passages near the entrance (especially the right branch) superficially appear conducive to nitre production. Entrenchment in a passage between the entrance and first room in the right branch may have been the work of miners. According to Mrs. Lisanby, deserters (from which army?) hid in the cave during the War Between the States. Signatures dating to the 1870s may be seen in Lisanby Cave but most historic inscriptions have probably been obscured by the great volume of modern defacement in the parts of the cave near the entrance. The owner also recollects dances held in the cave when she was young. The property was acquired in 1900 by Mrs. Lisanby's father, James W. Hollingsworth, who died in 1915. The owner married the late Alvin Lisanby, an attorney, in 1921, and they remained on the Hollingsworth farm. There may have been no reference to this cave in speleological literature prior to 1962-63.

The main entrance (6.5 m wide and 1.8 m high) to Lisanby Cave is in a collapse sink that intersects a fossil trunk passage. From the entrance, one can go either left (upstream) or right (downstream) (Fig. 7). The main Left Branch passage is a paleo-conduit, now dry, with thick clay fills. It meanders upstream in a generally northwest to north direction and is characteristically 4.5 to 12 m wide and 0.6 to 3 m high. In places, a small stream is accessible in a lower-level crevice passage, sometimes unroofed by an overlying passage. On the left, 200 m from the entrance, is a rather obscure junction of a significant side passage, Thunder Road, which continues west for 180 m, ending in breakdown. Its stream may come from Watson Cave, 1.5 km to the west. The main passage continues north, with a few minor side passages, for 550 m as a gradually lowering trunk passage, ending in collapse.

The Right Branch route is similar to the Left Branch described above: it is a generally dry, clay-filled paleo-trunk. It extends southeast for abut 435 m to apparently terminal breakdown. It consists of a chain of walking height rooms connected by easy crawlways. Among the often multiple options, the small stream from Thunder Road in the Left Branch can be reached in places. Besides being the most probable site of saltpeter mining in Lisanby Cave, the Right Branch is also the most heavily visited portion of the cave, with many hundreds of inscriptions and usually a good deal of litter in evidence.

Just before the dry trunk seemingly ends in breakdown, the way onward is a 4.5 m climbdown to a stream passage, i.e., the water first seen in Thunder Road. This route trends southeast as a walk and scramble, often on two levels. Only 30 m from the climb-down is a keyhole or which discourages nearly all "flashlight cavers" (judging by the lack of vandalism beyond). Just over 200 m from the climb-down is an easily unnoticed lead at a slightly higher level. This is the beginning of the Farless Extension described in the following section. In the next 100 m is a side passage containing a segment of the Farless Cave stream, and a second keyhole or is encountered, on the other side of which is the rather surprising intersection with the cave's main stream, Lisanby River, at a point 785 m from the entrance.

From the obscure connection to main Lisanby noted in the preceding section, the Farless Extension begins as a tight, dry, twisting crawl trending south then west; at 50 m, a paleo trunk passage is intersected. This passage averages 4 or 5 m wide and 1 m high. One direction is west-northwest for about 100 m before ending. The other way is southeast, rather wide, low, and dry; it leads to a series of upper level fragments and lower level stream crawls. Over 700 m of variable passage leads to the climbable entrance drop of Farless Cave.

Exactly who discovered the Lisanby River, a very significant part of Lisanby Cave--and when--is uncertain. The Lisanby River trunk is remarkably uniform in cross section and nature, varying from 3.5 to 6 m in width and 2 to 3.5 m in height. This conduit in massive Ste. Genevieve limestone has few features to speak of, besides modest-size silt banks and scattered solutional oddities. The stream carries about 0.03 m^3 per second of water in normal flow and has just enough gradient that water more than ankle deep is encountered only in a few pools. The passage meanders considerably but the basic trend is north-northwest for over 1.5 km. Until almost the very upstream end of this segment, there is only a single minor side passage, a tight, 100-m-long tributary from the left at a point 1.1 km upstream from the sump.

An abrupt change takes place 1.48 km upstream from the sump as several connections occur with a rather extensive complex of dry upper levels. Just beyond is the Poison Gas Room, a breakdown chamber 6 m wide and high with three ways on: a connection to the dry upper levels; the low continuation of the "river", and a 117 m long tributary entering over a small rimstone cascade on the right (north), called Waterfall Trail.

Something of a maze of dry passages is developed above Lisanby River around where it reaches the Poison Gas Room. These passages are on two sligtly offset levels, 3 to 6 m above the stream and vary from easy crawlways to barely walkable dimensions. In all likelihood, the upper levels above the Poison Gas Room--as well as those farther upcave--were originally integrated with the Left Branch section complex but now are interrupted by collapses. The various upper level segments in the Poison Gas Room area comprise some 838 m of passage.

Upstream (west-northwest) of the Poison Gas Room, the main Lisanby River conduit is reduced to a rather unappealing crawlway, referred to as the Canal or Elbow Runway (the latter name referring to grooves in the little mudbanks on one or the other side that cavers wear while traversing the crawl). This crawlway is 3 to 4 m wide and somewhat under 1 m high, with ponded water, for a distance of some 125 m. Midway is a distinctly lower ceiling point, normally no problem but which could be closed after high runoff.

On the upstream side of the Canal, the streamway opens back up to barely walking or stooping size, not quite as spacious as before the Poison Gas Room. One hundred forty meters farther, a significant fork of the stream is reached, The Y. About two-thirds of the flow is from the left (western) branch and one-third from the right (northern) branch. The northern branch leads to a series of stream passages, first Dungball Crawl and then Waterfall Canyon, trending to the northwest over 500 m before becoming extremely low and wet. The stream passage intersects at two widely separated points along its southern wall, a dry upper level complex, Lost Watch Passage. This passage trends northwest-southeast, becoming extremely low at its northwestern end, but in the southeast direction it swings south over the left branch of The Y, connecting with further upper levels that continue both south and southeast. Interconnected upper levels, the Trilevel Crawls, join the Lost Watch Passage and wander over the left branch stream to where it in turn branches. The southwestern branch contains a small stream in a multilevel canyon complex called Sandpaper Canyon that becomes too small in less than 200 m. North from the Sandpaper Canyon junction overflow passages reach Zig Zag Canyon, a stream canyon that leads west with over 1 km of passage before ending in mud plugs and sumps. The upper level passages associated with the Lost Watch Passage and Trilevel Crawl total over 2.5 km of passage.

The gross morphology of the cave would suggest that it began as a major stream passage carrying water from the upper (northwestern) end of the Lost Watch Passage southeast past the current position of The Y to the upper levels off the Poison Gas Room and on through the Left and Right Branches of the main entrance series to a resurgence on the banks of Eddy Creek. Along the way it picked up tributaries from the west and southwest at Trilevel Crawl, Thunder Road, and Farless Cave. The lower levels of these three tributaries provide water to the Lisanby River today.

Total passage length is 11.3 km, with some possibilities for extension. This makes it more than twice as long as any other known Western Kentucky cave.

Baker Cave

Baker Cave is located 4 km north-northeast of the village of Salem in Crittenden County. The cave is developed in the Renault Limestone, following joints, faults, and veins striking north-northeast that are related to the nearby Babb and Levias fault systems. The cave has been mined for fluorite, and shot holes, a collapsed shaft to the surface, and various mining paraphernalia can be found in the cave.

The cave has two entrances, situated close to each other. One is a crawlway off a small sink on a hillside that goes west about 7 m then intersects a shaft to the surface (the second entrance) about halfway down its 8 m depth. A climbdown reaches the base of the shaft which slopes immediately into the main stream passage.

Upstream, to the north, the stream passage starts out 3 to 5 m wide and 1.5 to 3 m high. A fault or joint is prominent along the eastern wall. After about 50 m, the passage becomes less than 1 m high, half full of water, but still 3 m wide. The passage has not been pushed beyond this point, although it appears to continue.

Downstream, to the south, the passage is initially easy walking and scrambling for about 40 m, 2 or 3 m high, 3 to 5 m wide. The passage then degenerates, with the major upper level being blocked by sediment fill or collapse, and progress is restricted to a 0.5 m high crawl in the stream. This crawl opens up after 25 m into a large chamber filled with mining debris, and containing a collapsed mine shaft on the western side.

From this point downstream the passage becomes extremely pleasant, being mostly walking height in a fine tube up to 6 m wide and 4 m high. After crawling over and around an occasional breakdown pile, a massive terminal collapse is met an estimated 500 m from the entrance. One short 20 m side passage was noted.

CONCLUSIONS

The Western Kentucky Coal Field Region is a poorly explored but extensively cavernous, low relief sinkhole plain. With almost 100 km of passage surveyed in less than 10 years, the continuing potential of the area is exciting. Because of the region's relative obscurity in speleology, it has provided an opportunity for a conservation-oriented, scientific, and comprehensive survey organization, the Western Kentucky Speleological Survey, to explore, study, map, and compile cave data free from complication and politics. A number of diverse groups and individuals work together in cooperation with the WKSS to maximize both the study and use of the region's caves. Extreme efforts have been made to maintain excellent landowner relations and to preserve the caves (Fig. 13).

All caves are valuable and priceless. The value of the western Kentucky caves depends on the observer's point of view. Cavers interested in deep pits, endless spacious galleries, and fantastic mineral displays will be disappointed. Cavers from areas with small caves, from cold climates, or areas with vandalized and heavily traveled caves will be pleased with most western Kentucky caves. The authors of this chapter, as representatives of the WKSS, welcome interested, conservation-minded cavers to come, locate, explore, and map caves with the WKSS.

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Chapter 9

CAVE LIFE OF KENTUCKY

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The unusually rich life of Kentucky caves reflects the fact that large segments of the two major Mississippian limestone plateaus of the eastern United States are found within the Commonwealth. Although significant but limited cave faunas occur in the Blue Grass and in isolated karst islands along the Rough River Fault Zone and the northwestern face of Pine Mountain, the Mississippian Plateau caves harbor the diverse troglobite faunas for which Kentucky is best known. These faunas are as rich as those of any other karst region in the world.

Historically, Kentucky biospeleology began when Stephen Bishop crossed Mammoth Cave's Bottomless Pit on a crude cedar ladder and discovered Echo River and its blind cavefishes. When James DeKay (1842) described _Amblyopsis spelaea_ in a footnote in his "Zoology of New York", a german physician, Theodor Tellkampf, visited Mammoth Cave in search of specimens of this, the world's first known blind cavefish. He also collected and described blind beetles, a blind harvestman, a blind spider, and a blind crayfish (Tellkampf, 1844a, 1844b, 1845). Constantine Rafinesque (1832) had visited Mammoth Cave almost two decades earlier and observed large hibernating bat colonies, but described nothing else. The eminent Russian coleopterist, Baron T. Victor von Motschulsky, attracted by Tellkampf's descriptons of blind beetles, visited Mammoth Cave in 1854--no small achievement in those days--and described additional species he found there. A few years later Alphaeus Spring Packard, Jr., taking advantage of a free trip to Mammoth Cave offered to participants at an Indianapolis meeting of the American Associaion for the Advancement of Science by the L & N Railroad, collected still further cave inhabitants. Dissatisfied with Darwin's theory of natural selection because he believed it did not entirely explain evolutionary phenomena, Packard subsequently visited Mammoth and other caves, including the Carter Caves in northeastern Kentucky, as well as Wyandotte Cave, Indiana, and Nickajack Cave, Tennessee. He mistakenly believed that life in caves exerted a direct effect on the evolutionary loss of eyes and pigment and was for a time a champion of the Neolamarckian school of thought (_see_ Packard, 1890; Barr, 1968a). Packard's contributions, though leaving much to be desired in the way of accuracy and heavily laden with his Neolamarckian philosophy, at least publicized the rather rich fauna of

Kentucky caves (see Packard, 1888).

When Horace Carter Hovey explored Mammoth Cave he was at times accompanied by R. E. Call, who wrote a chapter on cave life in Hovey's famous guidebooks to Mammoth Cave, published in several editions around the turn of the century. Northwestern University's Professor Orlando Park (a native of Elizabethtown, Kentucky) took his ecology classes to Mammoth Cave in the 1930's and actually published a key to Mammoth Cave animal species as an exercise in his laboratory manual on animal ecology and taxonomy (Park, 1939). The key is now considerably outdated, but it includes the species described by Call, DeKay, Motschulsky, Packard, Tellkampf, and others, as well as observations and redescriptions made when the European biospeleologists Rene Jeannel (France) and Candido Bolivar y Pieltain (Spain) visited Mammoth Cave, Carter Caves, and other caves in 1929 (Bolivar and Jeannel, 1931).

The bulk of our present knowledge of Kentucky cave life is based on widespread collections made by T. C. Barr, J. R. Holsinger, T. G. Marsh, R. M. Norton, and S. B. Peck in the 1960's. This material is still being inventoried and described. Important contributions to cave beetle taxonomy were made by J. M. Valentine (1952) who discovered the three endemic genera Darlingtonea, Ameroduvalius, and Nelsonites in the Somerset-Mount Vernon area, and by C. H. Krekeler (1973), who collected Pseudanophthalmus species in the Blue Grass. The richer and better known fauna of the Mammoth Cave Region attracted ecologists and other biologists who were dependent on pre-existence of a taxonomic data base. These biologists included T. C. Barr, T. C. Kane, R. A. Kuehne, T. McKinney, R. M. Norton, T. L. Poulson, and others. Some of the history of cave biology in the United states was sketched by Barr (1966). The inventory stage is still going on; additional troglobite species are being discovered and described, but at a slower rate than previously.

Studies of bats in Kentucky caves reached a peak in the 1960's and early 1970's with the work of R. W. Barbour, W. H. Davis, and their students at the University of Kentucky. This research centered primarily on hibernating colonies in Mammoth Cave National Park, Carter Caves State Resort Park, and a small number of caves in Lee County (Davis and Barbour, 1965; Hassell and Harvey, 1965).

For consideration of cave faunas, a regional classification slightly different from that used elsewhere in this book has been employed, and reasons for organizing discussion around this scheme will become apparent in this chapter:

1. Western Mississippian Plateau (MP-I)--Pennyroyal + Cumberland Saddle
2. Eastern Mississippian Plateau (MP-II)--Cumberland Plateau Margin
3. Blue Grass
4. Karst Islands
    a) Pine Mountain
    b) Rough River Fault Zone and other isolated caves along the outer margin of the Western Kentucky Coal Field

KINDS OF CAVERNICOLES

The taxonomic groups of animals in Kentucky caves will be considered in a subsequent section. First, we have to consider various classifications of the ecological or evolutionary status of cavernicoles. Any animal that lives in a cave is a cavernicole. If we wish to emphasize degree of restriction to caves and other subterranean habitats (phreatic groundwater, "microcaverns" around tree roots and in talus slopes, and so forth), we can divide cavernicoles into:

A) troglobites--obligate cavernicoles (e.g., blind cavefishes)
B) troglophiles--facultative cavernicoles that can live out their entire lives in caves but are also found in non-cave microhabitats (springs, deep soil)
C) trogloxenes--cavernicoles that roost or remain in caves by day but depend on feeding outside at night; "threshold" trogloxenes are bats, cave rats, and cave crickets
D) accidentals--occasional wanderers and animals that wash or fall into caves

Flatworms and small crustaceans that disperse through groundwater in non-karst regions (and thus have wider geographic ranges than species unable to do this) are sometimes called phreatobites or stygobionts, which are more general terms than "troglobite," but they are, of course, troglobites, too.

Troglobites are relict species that can no longer exist outside of caves or other subterranean microhabitats of the sort discussed; typically, their non-cave ancestors are extinct in the cave areas, because surface conditions hundreds of thousands or millions of years ago were different. Troglobites often show loss or rudimentation of eyes, pigment, circadian rhythms, and other characteristics associated with life above ground. The longer they remain in caves, the more successfully they have become adapted to a cave environment, showing such features as slender bodies, long and stiltlike legs, longer antennae, hypertrophied sensory systems, and so forth. Troglobites that have such adaptations are sometimes said to be highly "troglomorphic," a term that emphasizes evolutionary, rather than ecolgical status. (For further discussion of terms applied to cavernicles, see Barr, 1968a; Barr and Holsinger, in press).

SPECIATION IN CAVES

Speciation in cave faunas was recently reviewed by Barr and Holsinger (in press). For Kentucky troglobites, the most common pattern has been multiple invasions of different cave systems by widely distributed non-cave ancestors; with gradual extinction of the ancestral population outside caves, the cave populations became isolated and underwent genetic divergence to varying degrees. The descendant cave species now occupy one to many caves, depending on (a) their mobility, (b) their capacity to disperse through non-karst terranes or not, and, if not, (c) whether the caves they initially occupied are located in small, very local karst islands, or broadly contiguous MP karst with subterranean connections between caves, or some intermedite karst area such as part of the Blue Grass.

Even in MP areas there are occasional dispersal barriers. In MP-I these barriers are the Ohio River, the Hart County Ridge and fault zone just north of Munfordville, the Barren River at Bowling Green, stratigraphic barriers northwest of Hopkinsville and between the karst regions of Caldwell and Crittenden counties, and once again, the Ohio River. In MP-II the Mississippian limestone outcrops are patchy and isolated northeast of Red River, creating several barriers. To the southwest there are river barriers, notably the deep gorge of Kentucky River some 150 m below cave levels at Irvine, Cumberland River near Burnside, and South Fork as far as the mouth of Little South Fork. River barriers rarely affect dispersal of aquatic troglobites, but they effectively prevent dispersal of many terrestrial troglobites. Smaller, youthful rivers with a meander frequency higher than 1.0/km are rarely barriers, apparently because blind beetles and other troglobites can be washed out of caves on one side and manage to enter crevices in limestone bluffs on the opposite side (Barr, in press).

Different groups of troglobites may show very small ranges--often single caves--on the one hand, and quite large geographic ranges on the other. Pseudoscorpions of the genus *Kleptochtonius,* for example, are rarely known from more than one or two caves, and distinct species are reported from Mammoth Cave and nearby White Cave. Smaller cave carabid bettles (trechines) such as *Pseudanophthalmus inexpectatus* may be limited to Mammoth, White, and Great Onyx caves, but large, active beetles such as *Neaphaenops tellkampfi* and its close relatives in MP-I and *Darlingtonea kentuckensis* in MP-II have very large ranges.

The process of becoming a troglobite (or whole series of troglobitic species descended from a common ancestor that colonized different caves) seems to be in different stages at the present time in different groups of Kentucky troglobites. For example, carabid bettles include about 60 to 70 discrete species in Kentucky that probably became isolated in caves by changing climates during Pleistocene time. No ancestral species exist anywhere in eastern United States, although one *Pseudanophthalmus* species (closely related to Greenbrier Valley cave species nearby) is known from deep soil in the Yew Mountains, Pocahontas County, West Virginia (Barr, 1967a). Many deep soil species of trechine carabids are known in mountains of Europe and eastern Asia. The widely distributed troglomorphic collembolan *Pseudosinella hirsuta* (MP-I and MP-II, Kentucky and Tennessee) probably consists of populations descended from at least four separate cave invasions in different parts of its present day range. These four groups have independently acquired troglomorphic characters at different evolutionary rates and may eventually become four biological species (Christiansen and Culver, 1968). Compared to trechine beetles, *P. hirsuta* has either evolved more slowly or entered caves more recently. Three species of blind crayfishes, *Orconectes pellucidus* (MP-I south of the Hart County Ridge (Fig. 1)), *O. inermis* (MP-I north of the Hart County Ridge), and *O. australis* (MP-II from Rockcastle County southwest to Alabama), are believed to be descendents of a common epigean ancestor related to *O. limosus,* a non-cave species of the eastern Atlantic Coastal Plain that lives in slowly moving, sluggish streams. In early Pleistocene time, stream gradients steepened, and flow was faster, creating unsuitable habitats for the ancestral crayfishes, which retreated into small tributaries and ultimately springs and caves. Hobbs and Barr (1972) postulated survival of this ancestral species in three river systems--the Green, the Cumberland, and the preglacial Teays River; the three colonies gave rise to *O. pellucidus, O. australis,* and *O. inermis,* respectively. These large troglobites are limited to the MP regions, for the most part (*O. australis* has penetrated the eastern edge of the Central Basin in Tennessee in two places, one such colony evolving into the isolated species *O. incomptus*), because of numerous solutional openings permitting dispersal.

Some "species" of troglobites are probably clusters of sibling species--species difficult to differentiate morphologically but belonging to entirely different gene pools. The likelihood that *Typhlichthys subterraneus* a species of blind cavefish whose range includes southern Kentucky (MP-I and MP-II), central Tennessee, northern Alabama, and the southern Ozark Plateau, is actually a cluster of genetically differing sibling species is quite high (Barr and Holsinger, in press;

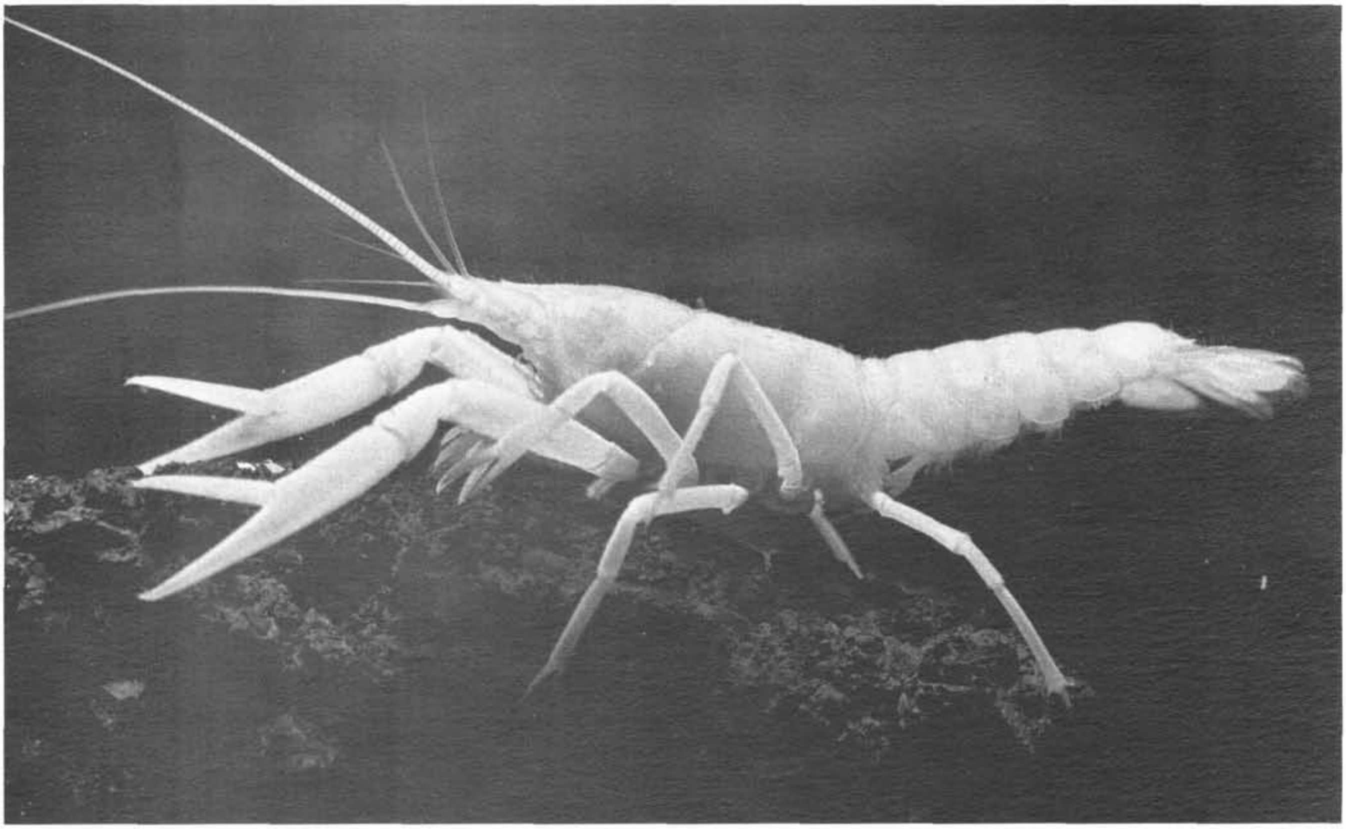

Figure 1. Orconectes pellucides (Tellkampf), the troglobitic crayfish of the Western Mississippian Plateau.

Swofford and others, 1980). This morphological species probably now consists of surviving relict populations of a widely distributed ancestor that has become extinct; troglomorphic features have been acquired, as in Pseudosinella hirsuta, by parallel evolution. Phanetta subterranea, a tiny troglobitic spider originally described from Carter Caves, Kentucky, is perhaps the most widely distributed troglobite in the eastern United States. Even if it is capable of dispersing readily through microcaverns in nonkarst terranes, it is inconceivable that gene flow is maintained throughout this whole complex of populations. Most likely, P. subterranea is a relatively recent cave colonizer, and it has been extremely successful in colonizing a large number of caves over what must have been the range of its extinct, non-cave ancestor. In time, if this interpretation is correct, one might anticipate that the end result will be a large number of local, more discrete, and morphologically more distict species.

CAVE ECOLOGY

Physical aspects of the cave environment have been fairly well described (for Kentucky, see Barr and Kuehne, 1971): the deep cave is characterized by absence of light, constant temperature equivalent to the regional mean surface temperature, low vapor pressure deficit, slightly alkaline pH of cave waters, and so forth. Seasonal fluctuations, however, may be profound. Cold, dry, winter air flowing into entrances expands to cave temperatures and soaks up moisture from the walls and speleothems, so that the rate of evaporation may be as much as 200 times that of the same part of the cave in summer. Most terrestrial troglobites cannot tolerate low relative humidities and disappear from entrance zones in winter. Aquatic cave microhabitats are subject to seasonal differences in water levels in pools or to heavy flooding in streams.

Ultimately, all food utilized by a cave ecosystem comes from the surface. There are two ways in which food gets into caves: (1) transport by vadose water, and (2) transport or direct contribution (feces, dead bodies) by trogloxenes such as bats and cave crickets. Cave rats (*Neotoma magister*) contributes leaves, twigs, and feces to the deep cave community; such food is usually limited to shelves or the floor below shelf runways or nest sites. Hibernating bats contribute very little, but summer bat residents contribute large amounts of guano. Only the gray bat, *Myotis grisescens*, is a significant contributor of guano in Kentucky caves, principally in the southern part of the Commonwealth. Bat guano decomposes slowly, often with toxic byproducts, and seems more significant as food when it is widely dispersed on a wet floor, under flight paths, or when it falls in small quantities into rimstone pools, than when it accumuates in large mounds. Far more important for Kentucky cave communities are cave crickets of the genus *Hadenoecus*, *H. subterraneus* in MP-I and *H. cumberlandicus* in MP-II. Unlike the common cellar and camel crickets (*Ceuthophilus* spp.), which rarely penetrate deeply into caves, these two species (along with three similar species in MP-II of Tennessee and Alabama) roost in large numbers in favored sites on cave ceilings, emerging at intervals of 2 or 3 days to feed outside. Beneath the roosts a thin, humus-like layer of guano accumulates, providing food for many detritus-feeding troglobites (snails, collembolans, bristletails, *Ptomaphagus* beetles, etc.). The detritivores are in turn eaten by predatoy troglobites (spiders, pseudoscorpions, carabid beetles). Two groups of carabid beetles, *Neaphaenops* in MP-I and *Darlingtonea* in MP-II, have independently "learned" to dig and eat eggs of these two *Hadenoecus* species (Hubbell and Norton, 1978). *Hadenoecus cumberlandicus* has evolved parthenogenetic populations (females only) in MP-II northeast of the Red River Gorge (Lamb and Willey, 1975; *see also* Glesener and Tilman, 1978).

Larger streams sinking underground may carry leaves and twigs that are deposited along cave stream banks and eventually decompose through bacterial and fungal action. Vadose water entering caves vertically along joints and through dome pits may leach out organic compounds from humus in the overlying soil mantle, at the same time carrying with it soil bacteria, protozoans, and other microorganisms. Vadose water samples in Mammoth Cave measured at different seasons of the year have a total organic carbon content ranging from 2 to 14 ppm (Barr, unpublished). These organic compounds-hexoses, amino acids, humic and fulvic acids, and so forth--are apparently adsorbed onto clay micceles in the mud of cave pools. Small troglobitic crustaceans--amphipods and isopods--that eat their way through the mud in pools can probably release the organic compounds by altering the pH in their digestive tracts. A wide range of soil microorganisms enter caves in dripping water, but relatively few survive for more than a few weeks. Most cave protozoans, for example, belong to a small number of ciliate species that are repeatedly encountered in various cave waters (Gittleson, 1969). Although there are no photosynthetic producers in cave communities, bacteria and fungi, through decompositon of organic material washed into caves, act as secondary producers, transforming the material into a form that can be utilized by troglobites. In the "Shrimp

Pools" in the Roaring River Passage in Mammoth Cave, bacterial counts on a wide spectum agar are lowest in spring, following annual floods. As the summer wears on, counts rise and coninue to rise, reaching their maximum just prior to the first flood of winter (Barr and Kuehne, 1971). The Mammoth Cave blind shrimp, Palaemonias ganteri, (Fig. 2) feeds on microorganisms by straining bottom muds through their mouthparts.

Bacterial and fungal decomposition of stream-borne detritus provides food that can be utilized by small, threadlike segmented worms (enchytraeids and tubificids, possibly undescribed troglobitic species) that burrow through the mud of stream banks. These worms, in turn, provide food for predatory carabid beetles, many species of which occur--particularly in the western part of MP-I--in great abundance along the banks of cave streams. A few species of carabid beetles feed principally in upper levels of caves, where they occur in the wet, rotting debris of old cave rat nests, picking through the debris and eating the small invertebrate detritivores found there.

Several striking ecological differences have been noted between caves of the MP regions and caves of the Appalachian Valley (AV) (Barr, 1967b). Extensive folding and faulting has produced patchy, quite local karst areas in

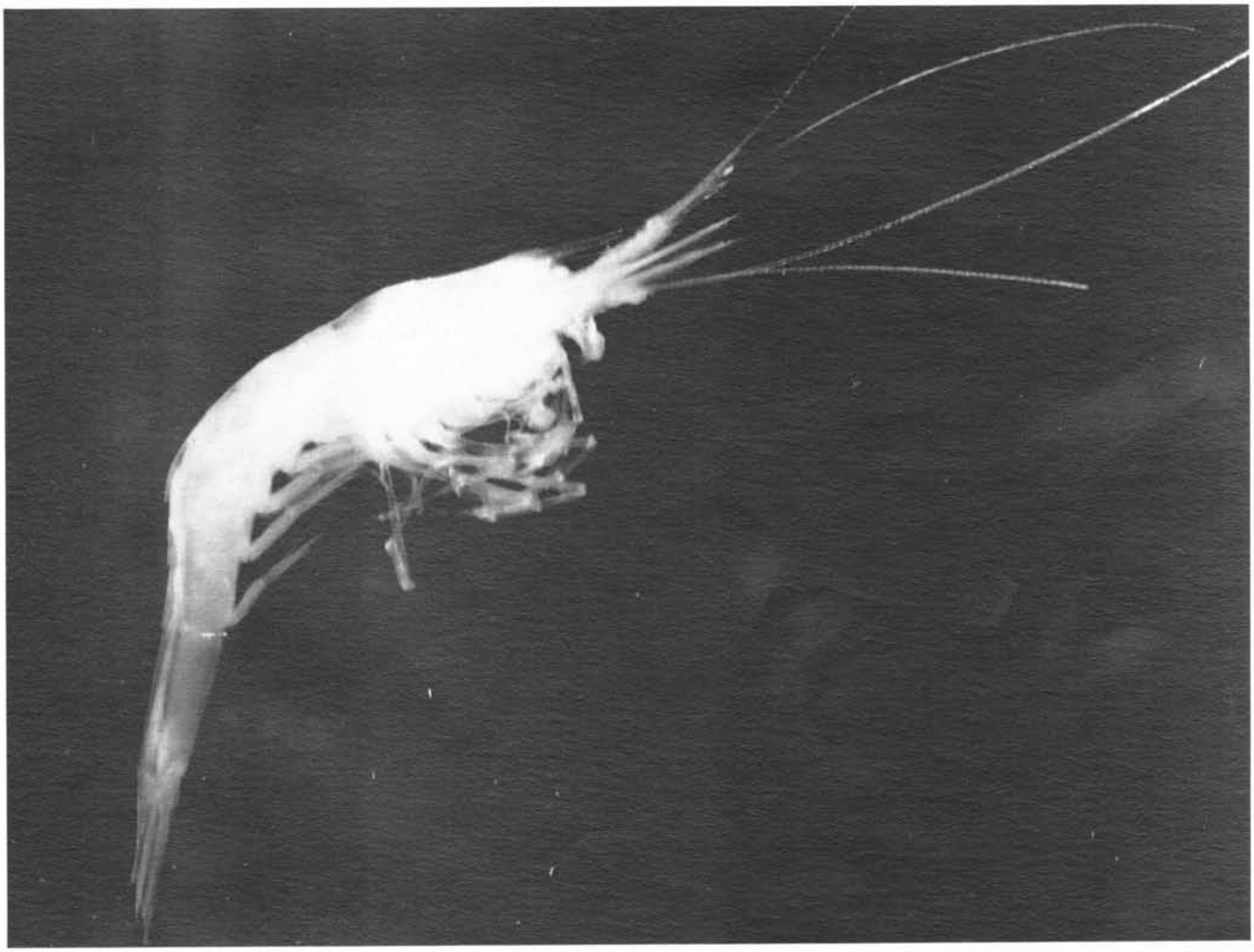

Figure 2. Palaemonias ganteri Hay, a troglobitic shrimp known only from the Mammoth Cave system.

the AV. Although the AV does not extend into Kentucky, similarly local and stratigraphically isolated karst islands in Pine Mountain, the Rough River Fault Zone, and patchy exposures of Glen Dean Limestone around the edge of the Western Kentucky Coal Field are ecologically and biogeographically similar to AV caves. In the MP regions the dispersal potential of a troglobite is much greater: it can move from cave to cave by subterranean solutional openings in broadly contiguous karst. In contrast to AV or karst island caves, troglobite species in MP caves have larger geographic ranges, exhibit fewer species per unit area of exposed karst, and are more commonly sympatric (i.e., two or more species coexist in the same caves). A typical troglobitic community in the MP regions may include 15 to 30 species, while only 5 to 10 species are found in AV or karst island caves. MP troglobites are often larger than those of AV or karst island caves, a phenomenon possibly attributable--at least for predators--to a wider variety of prey species, consequently a more predicatable supply of food. In a small, isolated cave system there may be only one or two prey species, and a carabid beetle predator dependent on these will suffer a decline in number if the prey species decline. In MP caves, factors that affect one prey species may not necessarily affect all of them, consequently carabid beetle populations are often not only unusually large but much more stable (Barr, 1967b, 1968, in press).

The opportunities for evolution of complex communities of troglobites are much more favorable in MP areas. Different ancestors may have colonized different caves at different times in the past, but because there are extensive connections between MP caves, subterranean dispersal may permit many species to eventually occupy the same caves. Coexisting species must be mutually compatible, not competing for the same environmental resources. Several series of closely similar species of cave carabid beetles are known that are parapatric, (i.e., their ranges are contiguous but non-overlapping). Following colonization of two or more different cave systems by the same ancestor, genetic divergence has occurred. As the different beetle populations dispersed outward from their points of origin by subterranean routes, they eventually came into contact with each other. Because of gnetic differences, hybrids between the two populations were inferior; consequently, natural selection favored in-group breeding. Ecological niches of the two populatons had not diverged enough so that they could coexist in the same caves. As a result of genetic incompatibility and niche similarity, the two populations established a range boundary that neither could cross. Much of the western part of MP-I is inhabited by species of the _pubescens_ group of _Pseudanophthalmus;_ most show parapatric ranges. The sole exception is a distinctly smaller species with different feeding habits, _P. loganensis_ (Barr, 1979). While most species of the _pubescens_ group are larger and cruise mud banks in search of prey, _P. loganensis_ hides in detritus piles and between clay laminae, feeding on small arthropods that it finds there. In various caves _P. loganensis_ coexists with _P. ciliaris_ and _P. princeps,_ both larger species of the _pubescens_ group. The mean lengths of most _loganensis_ populations are close to 4.5 mm, while _ciliaris_ is normally close to 5.0 mm mean length. Perhaps it is significant that all _ciliaris_ coexisting wih _loganensis_ belong to the distinctly larger subspecies _P. c. orlindae,_ with a mean length close to 6.0 mm, thus exacerbating the size difference (Barr, 1979, and in press).

The evolution of cave communities in the Kentucky karst appears to be conditioned by three circumstances: (1) which groups were present to colonize caves in the first place, an historical factor; (2) the extent of contiguous karst, which affords troglobites the opportunity to eventually reach the same caves, and (3) niche compatibility of component species. By the principle of competitive exclusion, two species with essentially identical niches cannot coexist in the same cave community.

The Mammoth Cave community has been studied more often than any other cave community in North America. Although more than 200 species have been recorded from the system, only about 30 are components of the deep cave, troglobitic community. As an extremely large cave system with many different microhabitats, Mammoth Cave can accommodate a variety of species with different environmental requirements. Furthermore, it lies at the edge of the Pennyroyal Plateau, a major avenue of troglobite dispersal because of its network of interconnected caves; consequently, its fauna is composed of species with both northern and southern origins. In addition, the Mammoth Cave community has elements that have perhaps dispersed into the area from the southeast, across the Cumberland Saddle (Barr, 1968b). More trechine carabid beetles occur in Mammoth Cave than in any other North American cave-- Neaphaenops tellkampfi (Fig. 3), and five species of Pseudanophthalmus. The largest species, N. tellkampfi, feeds heavily on eggs of Hadenoecus subterraneus, and its own reproductive cycle usually tracks that of the cave crickets, supposedly because availability of abundant food (cricket eggs) permits egg production in the beetles (Norton

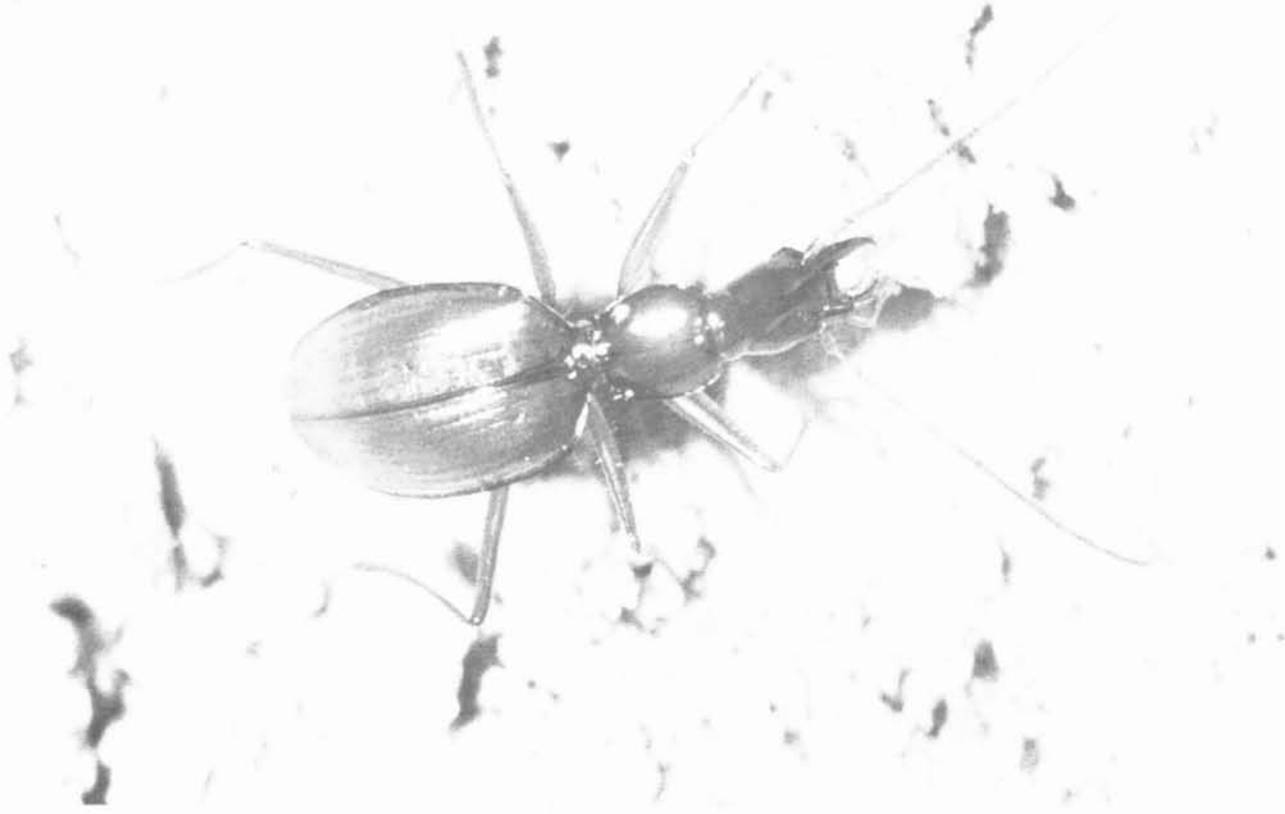

Figure 3. Neaphaenops tellkampfi (Erichson), a 7 mm trechine beetle from the Mammoth Cave area.

and others, 1975). Two smaller species, *P. inexpectatus* and *P. audax*, appear in wet weather and unusually dry weather, respectively, suggesting restriction to quite different niches (Barr, 1966-67). The flattened form of *P. audax* and its great rarity in caves suggests that its normal microhabitat could be microcaverns at the interface between bedrock and soil mantle. The three other species are subequal in size (about 5.5mm)-- *P. menetriesi*, *P. striatus*, and *P. pubescens*. Both *menetriesi* and *striatus* belong to the *menetriesi* group, and thus have higher taxonomic affinity to each other than either has to *pubescens*, which belong to the *pubescens* group (Barr, 1979). While *P. striatus* is almost exclusively a riparian species, found along stream banks in the lower levels of caves, *P. menetriesi's* normal habitat is piles of debris in upper levels. *Pseudanophthalmus pubescens*, like *P. striatus*, is a riparian feeder, although it can appear in considerable numbers in upper levels during periods of unusually wet weather, suggesting that its normal microhabitat has been flooded out (Barr, 1966-67; McKinney, 1975).

Cave communities in karst islands of the Western Kentucky Coal Field or Pine Mountain are much less complex, comprising only 5 to 10 troglobitic species. Cave communities of the Blue Grass are more or less intermediate in ecological characteristics between the two extremes of the MP and AV, having a rather small number of component troglobite species, but some of these species have geographic ranges that are moderately extensive, depending on contiguity of karst.

A BRIEF SUMMARY OF MAJOR GROUPS OF CAVERNICOLES

Emphasis in this section is on more conspicuous faunal groups, especially troglobites.

Protozoans and Other Microfauna

Most protozoans found in caves are small ciliates (Gittleson, 1969). They are morphologically similar to non-cave species. Nematodes, harpacticoid copepods, and creeping rotifers occur in cave pools and streams but have not been studied in detail.

Flatworms

Most cave flatworms belong to the genus *Sphalloplana*, whose species are widely distributed in Kentucky (Kent, 1977). *Geocentrophora cavernicola*, however, is known only from a single MP-II cave (Carpenter, 1970).

Snails

Carychium stygium is a minute, troglobitic land snail only 2 mm high (Fig. 4); it feeds principally on cave-cricket guano and is limited to MP-I from Hart County to the Tennessee line (Hubricht, 1960). Several other snails from Kentucky caves were described by Hubricht (1962, 1963, 1964, 1965, 1966, 1968a, 1968b); their status --troglobites or not--is uncertain, but some appear to be limited to caves. *Antroselates spiralis* is an aquatic troglobite known from Echo River in Mammoth Cave (Hubricht, 1963).

Pseudoscorpions

About a dozen troglobitic pseudoscorpions are known from Kentucky caves, but there are undoubtedly many more, especially in the genus *Kleptochthonius* (Muchmore, 1963, 1965), most species of which appear restricted to one or two caves (Fig. 5).

Harvestmen

Phalangodes armata is an eyeless, pale harvestman, or opilionid found in the Mammoth Cave and Bowling Green areas (Fig. 6). Troglobitic species of this group are very limited in Kentucky; the status of *Erebomaster flavescens coecum* in Carter Caves is uncertain, but it is usually thought of as a troglophile race of a more

Figure 4. *Carychium stygium* Call, from the Mammoth Cave area, retains vestigial eyespots but is a troglobite that feeds on cave cricket guano.

widely distributed Ohio Valley species. The large grayish-brown harvestmen that gregariously hibernate in caves are usually *Leiobenum longipes.*

Spiders

The most abundant spider in Kentucky caves is *Meta menardi,* the cave orb weaver; it is normally a threshold trogloxene. Four widely distributed morphospecies of tiny cave spiders in the family Linyphiidae occur in Kentucky -- *Phanetta subterranea* (type locality, Carter Caves, Kentucky), *Porhomma cavicolum, Bathyphantes weyeri,* and *Anthrobia monmouthia* (type locality, Mammoth Cave, but also found in Tennessee, Virginia, and West Virginia). *Nesticus carteri* is common in MP-II caves; it is a troglophile. A handful of other spiders are commonly found in the twilight zone; they are not troglobites (Barr, 1968b).

Mites

Little is known about cave mites. *Rhagidia cavernarum,* from Mammoth Cave, is rather widely distributed (Holsinger, 1965). Several other genera and families are represented in caves but appear to occur erratically and may not be troglobites.

Amphipods

Two groups of troglobitic (stygobiont) amphipods occur in Kentucky caves. The species of *Stygobromus* are believed to be much older in terms of residence in subterranean waters; they occur in quiet pools, usually in food-poor microhabitats. *Crangonyx packardi,* on the other hand, is the central Kentucky (MP-I to MP-II) representative of 5 cave species that are relatively recent cave invaders; it is most likely to occur in food-rich streams and pools (Holsinger, 1978, in press).

Isopods

Troglobitic (stygobiont) isopods of the genus *Caecidotea* are common in a majority of Kentucky caves. These include species, such as *C. stygia* in Mammoth Cve, with very wide distributions, but also species that are rare and quite local in distribution. The group

Figure 5. Kleptochthonius sp. is typical of many troglobitic species in this genus that are seldom found in more than one or two caves each.

was recently reviewed by Lewis (1984).

Crayfishes

As noted in the section on "Speciation" above, three troglobitic species of Orconectes occur in Kentucky, O. pellucidus and O. inermis in MP-I, and O. australis in MP-II (Hobbs and Barr, 1972). Cambarus tenebrosus is a troglophile crayfish that occurs frequently in most cave regions in Kentucky; it often attains unusually large size.

Shrimps

Palaemonias ganteri, restricted to river levels in the Mammoth Cave system, is an isolated relict species; its closest relative lives in Shelta Cave, Alabama (Barr 1968a, 1968b; Hobbs and others, 1977).

Centipedes

No troglobitic centipedes are known in Kentucky caves, and the occasional species that appear seem to be accidentals.

Millipedes

In contrast to centipedes, the millipedes are quite well represented. Species of Pseudotremia are found in many caves; some of them are very pale troglobites, while others--more widely distributed--are troglophiles. Six are recorded from Kentucky, but there are undoubtedly more (Shear, 1972). Scoterpes occur in many caves in the southern MP-I and MP-II; all of its species are

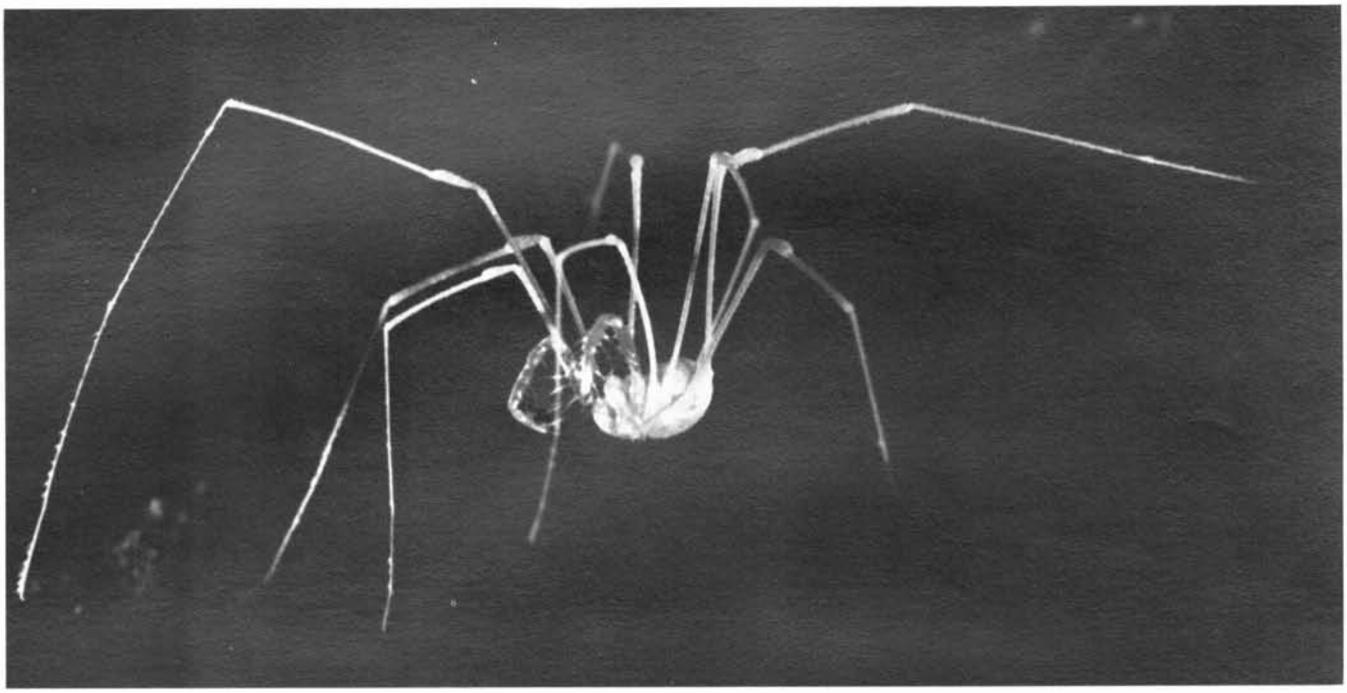

Figure 6. Phalangodes armata Tellkampf, the troglobitic harvestman of the Mammoth Cave and Bowling Green areas, is a predator.

troglobites. The genus has not been systematically studied, and the Mammoth Cave area S. copei is the only one of several Kentucky species that has been described.

Collembolans

Several "springtails" inhabit Kentucky caves, including the widely distributed morphospecies Pseudosinella hirsuta, the highly troglomorphic P. christianseni and Sinella krekeleri (MP-II), and other troglobitic and troglophilic species (Christiansen, 1960a, 1960b, 1966; Christiansen and Culver, 1968).

Diplurans

These silverfish-like "bristletails" belong to the genus Litocampa and have been recently studied by Ferguson (1981). Ranges of the species recognized by him are relatively extensive, suggesting either microcavern dispersal or groups of closely similar biological species (Fig. 7).

Cave Crickets

These are not true crickets, instead belong to an entirely different family, Rhaphidophoridae. Species of Ceuthophilus are shiny, banded cave crickets (in Kentucky) that are often abundant near entrances. Hadenoecus subterraneus (MP-I) and H. cumberlandicus (MP-II) are ecologically more important because they are restricted to regions with numerous caves and deposit much guano beneath their roosting sites. Both are trogloxenes, not shiny, not banded, extremely long-legged, with long antennae. They are absent from the Cumberland Saddle region of MP-I (Hubbell and Norton, 1978).

Trechine Beetles

About 65 species of these small, predatory carabids occur in Kentucky. Most belong to Pseudanophthalmus, but there are 1 to 5 species each in Neaphaenops (MP-I), Nelsonites (MP-IIO, Darlingtonea (MP-II), and Ameroduvalius (MP-II). The related troglophile Trechus cumberlandus also occurs in caves and sinkholes in MP-II, though it is not ancestral to the cave species. Eleven of the 26 species groups of

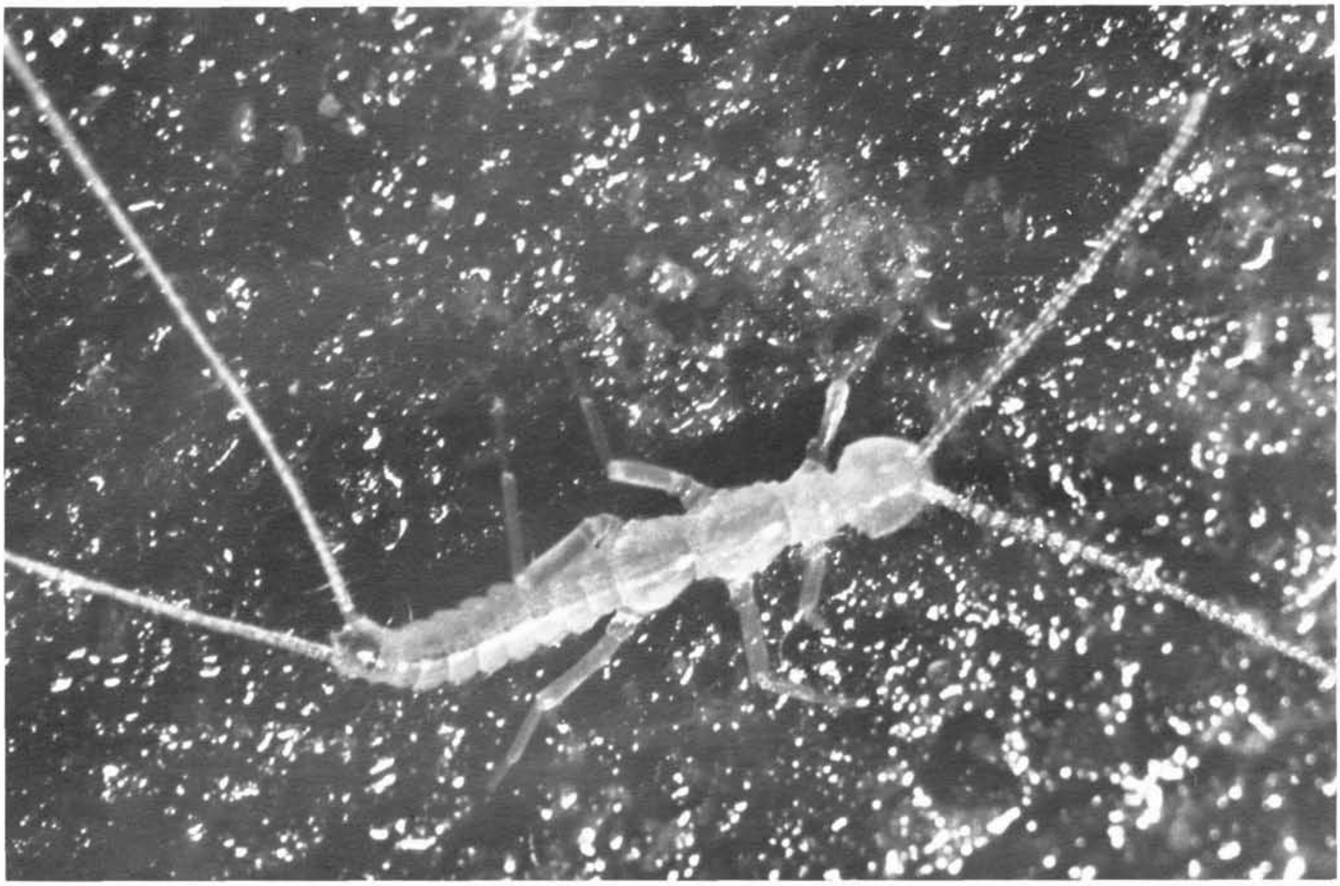

Figure 7. Litocampa cookei (Packard), widely distributed in Kentucky caves, is a detritus feeder eaten by beetles, pseudo-scorpions, and other predatory troglobites.

Pseudanophthalmus, which has about 240 species in 10 eastern states, are represented in Kentucky, and both Neaphaenops and Ameroduvalius are limited to Kentucky. Descriptions of most of the Kentucky species are in press or in preparaton (Valentine, 1952; Barr, 1979a, 1979b, 1981, 1985, in press).

Other Beetles

Pselaphid beetles are small predators that superficially resemble ants because of their shortened elytra. Kentucky cave pselaphids are less troglomorphic than some genera and species in Tennessee and Alabama; they include a few species of Batrisodes 2 species of Bythinopsis, and the widely distributed troglophile Batriasymmodes quisnamus (south-central Kentucky and more common in Tennessee) (Park, 1960, 1965). Ptomaphagus (Adelops)hirtus (Leiodidae) is a detritus-feeding troglobite in the Mammoth Cave area, where it may be locally quite abundant; another 17 troglobitic Ptomaphagus spp. occur farther south in Tennessee and Alabama (Peck 1973, 1984).

Fishes

A variety of fish species may be washed accidentally into caves, and sculpins actively swim upstream into caves, but the only troglobitic species in Kentucky belong to the Amblyopsidae. Amblyopsis spelaea, described from Mammoth Cave in 1842, ranges northward in MP-I into southern Indiana. Typhlichthys subterraneus also occurs in Mammoth Cave, but nowhere else does its range overlap that of

Amblyopsis spelaea. In Kentucky it is reported from MP-I south and west of Mammoth Cave, including caves in Glasgow and Bowling Green and from the Sloans Valley System in MP-II (Cooper and Beiter, 1972). Chologaster agassizi is a troglophilic amblyopsid found in caves and springs of southwestern MP-I and elsewhere (Woods and Inger, 1957; Poulson, 1963).

Salamanders

No troglobitic salamanders occur in Kentucky, but the "cave salamander" Eurycea lucifuga is widely distributed; it is more common in entrance areas where food is more readily available. Pseudotriton ruber, Eurycea longicauda, and Plethodon dorsalis are reported from occasional caves in MP-I and also in the Rough River region.

Cave Rats

Neutoma magister is the common "cave rat" of Kentucky caves, although N. floridanus, common in Tennessee, may occur along the State border.

Bats

Ecologically, the most important bat species for Kentucky troglobites is the gray bat, Myotis grisescens, which lives in caves in summer and is thus a guano bat. Most of its colonies are in the southern part of MP-I, and there is evidence that many older colonies have been abandoned. The largest populations of hibernating bats are Myotis sodalis, the "social," or Indiana bat; this species migrates to northern, non-cave roosting sites in summer; it has been extensively studied in the Carter Caves and Mammoth Cave areas as well as a few other widely scattered caves, mostly in MP-I and MP-II. Smaller colonies of the little brown bat, Myotis lucifugus, hibernate in a number of Kentucky caves. The pipistrelle, Pipistrellus subflavus, and the big brown bat, Eptesicus fuscus, are more solitary bats, rarely occurring in large hibernating groups. Pipistrelles are perhaps the most common bat in Kentucky caves, but E. fuscus hibernates in colder sites, often near entrances in the fall and early winter. Both the eastern and western species of long-eared bats are found (usually uncommonly) in Kentucky caves: Plecotus rafinesquei from the Mammoth Cave Region and Jackson, Pulaski, and Wayne counties; and P. townsendi virginianus from a small number of caves in Lee County (MP-II), where it is in need of protection.

REGIONAL CAVE FAUNAS IN KENTUCKY

Western Mississippian Plateau (MP-1) and Cumberland Saddle

The Mammoth Cave faunas is one of the richest in the world (Barr, 1968b), including troglobitic species of flatworms, snails, pseudoscorpions, harvestmen, spiders, mites, amphipods, isopods, crayfishes, shrimps, millipedes, collembolans, diplurans, beetles, and cave fishes. A majority of the species in Mammoth Cave itself range northward toward Munfordville and southwest to Barren River along the Pennyroyal, but to the southeast, across the Cumberland Saddle, the composition of the fauna changes rapidly--most beetle species disappear or are replaced by others; and crayfishes, cavefishes, and even Hadenoecus subterraneus disappear.

To the north, few terrestrial species cross the Hart County Ridge and fault zone (Barr 1968b, 1979a, in press). A somewhat diverse fauna continues on to the Ohio River, characterized by Orconectes inermis, Amblyopsis spelaea (Barr and Kuehne, 1962), a few species of Pseudotremia, Neaphaenops henroti, and Pseudanophthalmus of different species than occur south of the Hart County barrier. Hadenoecus subterraneus is abundant.

To the southwest, across Barren River, *Typhlichthys subterraneus* is present but not *Amblyopsis spelaea;* all trechine beetle species are different, and even *H. subterraneus* varies geographically. *Orconectes pellucidus* is present.

Farther west in the Pennyroyal, *Neaphaenops* disappears at the eastern edge of Logan County, and *Hadenoecus* is no longer present west of Russellville. *Scoterpes copei* is replaced by one or more undescribed species of the same genus, and the prevalent trechine beetles are wide-ranging, polytypic species (such as *P. ciliaris;* (see Barr, 1979a) whose ranges do not overlap. Both *O. pellucidus* and *T. subterraneus* continue at least to Trigg County. Distinct trechine species with discrete ranges occupy the Princeton-Freonia and Salem-Marion cave regions, respectively.

Southeast across the Cumberland Saddle from Mammoth Cave there is a moderate fauna of trechine beetles, some millipedes, amphipods and isopods, but *Orconectes, Neaphaenops, Hadenoecus,* and *Typhlichthys* are not present. The upper reef limestone member of the Fort Payne Formation contains a number of caves that support a northward extension of this fauna to the Columbia and Greensburg area. The eastern extent of *Neaphaenops, Hadenoecus,* and *Orconectes* is the vicinity of Greensburg, itself.

Eastern Mississippian Plateau

North of Red River the Newman Limestone thins and is confined to local lenses thick enough to support caves; much of this area has only dry, rockhouse-like remnants of former caves on top of the ridges. However, local faunas including some troglobites are known for the Carter Caves area in Carter and Elliott counties, Murder Cave in Menifee County, and one or two additional such karst islands. *Hadenoecus cumberlandicus* is all parthenogenetic here.

A small fauna (2 species of *Pseudanophthalmus, Sinella, Kleptochthonius, Pseudotremia, Crangonyx, Caeciodotea,* bisexual *H. cumberlandicus,* etc.) occupies upland caves between Red and Kentucky rivers in Powell, Estill, and the edge of Lee counties. The Kentucky gorge forms a major barrier to terrestrial troglobites; south of the Kentucky River, three endemic genera of trechine beetles appear-- *Darlingtonea, Ameroduvalius,* and *Nelsonites.* *Scoterpes* sp., *Orconectes australis packardi* (from Rockcastle County southeastward), and *Typhlichthys* (in Sloan Valley System) augment the fauna farther to the southwest. *Pseudanophthalmus* species in the range of *Ameroduvalius* species are all small, less than 4 mm long, but south of the Cumberland River there are several larger *Pseudanophthalmus* of the *robustus* group. Wayne County, Kentucky, with 12 species and 5 genera of trechine beetles, has the most diverse trechine fauna of any comparable area in North America. There is a partial dispersal barrier near the Kentucky-Tennessee border in MP-II, because westward flowing tributaries of the Cumberland do not join until they have cut down into non-cavernIferous Osagian rocks. The Cumberland River near Burnside constitutes a triple barrier near Burnside, Pulaski County: the lower Cumberland River below the mouth of South Fork is a complete barrier for terrestrial beetles, as is the lower South Fork below the mouth of Little South Fork. The upper Cumberland acts as though it were a partial barrier, permitting but reducing gene flow; the upper South Fork is no barrier at all.

Blue Grass

Caves of the Inner Blue Grass are developed in more or less continuous patches of Ordovician limestones. Various species of spiders, isopods, and millipedes are known from single cave systems, but some of the *Pseudanophthalmus* species are moderately widespread, notably between Clifton and Camp Nelson along the right bank of the Kentucky River. A population of parthenogenetic *Hadenoecus cumberlandicus* is known in small caves around Camp Nelson; it is geographiclly isolated from bisexual populations of the species to the east. Trechines include species of the *inexpectatus* group, related to *P. inexpectatus* in Mammoth Cave, and also species of the *horni* group, which is distributed not along present drainage basins but along the preglacial Teays Valley and includes species in southwestern Ohio and southeastern Indiana. These beetles are smaller (3-4 m) than those of the MP region. *Pseudanophthalmus barri* near Clarksville, Indiana, and *P. troglodytes* are sister species that were probably separated by development of the modern Ohio River during early Kansan time (Krekeler, 1973). In MP-I farther west, *P. tenuis* (Indiana) and *P. barberi* (Kentucky) bear the same relationship to each other (Jeannel, 1949).

Karst Islands

Small, island-like patches of karst occur on the northwestern face of Pine Mountain in southeastern Kentucky and also downdip from MP-I, toward the center of the Western Kentucky Coal Field. These patches are characterized by small assemblages of isolated species. For example, the endemic *hypolithos* group of *Pseudanophthalmus* is represented by species in Pike, Harlan, Bell, and Whitley counties, Kentucky, and a fifth species just south of the Allegheny Front in Virginia. One species of the *jonesi* group is described from a Harlan County cave; the remainder of the group occurs in southwestern Virginia and in Pine Mountain (Campbell County, Tennessee), and Grassy Cove (Cumberland County, Tennessee). *Pseudotremia*, *Pseudosinella hirsuta*, *Litocampa*, *Caecidotea*, *Stygobromus*, and *Sphaloplana* are also found in Pine Mountain caves.

Karst islands also occur around the margin of the Western Kentucky Coal Field near the edge of MP-I; almost all significant caves in these areas are developed in Glen Dean Limestone, stratigraphically isolated from the thicker and more cavernous limestones of the Pennyroyal. Most of the troglobitic species are wide-ranging ones with means of dispersal through microcaverns or phreatic water, but at least 9 isolated species of *Pseudanophthalmus* are known (five from the Rough River Fault Zone in Grayson County; others in Hart, Warren, Butler, and Todd counties). The beetle species are closely similar to species of the Pennyroyal surface caves and are presumably derived from the same common ancestors. *Hadenoecus subterraneus* occurs in all of these marginal karst island caves. A small cave in Madisonville Limestone (Pennsylvanian) near Equality, Ohio County, contains *Sphalloplana*, *Crangonyx packardi*, *Sinella*, and *Phanetta*, as well as numerous troglophiles and trogloxenes.

CONSERVATION OF CAVE LIFE

Much attention has been devoted to conservation and preservation of bat species, with emphasis on avoiding disturbance during hibernation. Growth of urban areas in karst regions, with accompanying closure of caves and pollution of underground streams, notably at Somerset and Bowling Green, poses a threat to fish and invertebrate troglobites. Leakage from oil wells and pumping out wells with brine has polluted many Kentucky caves in rural areas. The evolution of Hidden River Cave into a gigantic sewer for the town of Horse Cave or the construction of a garbage landfill above Sloans Valley Cave are tragedies that should never have been allowed.

The larger troglobites of cave streams-- *Oroconectes* crayfishes and the amblyopsid cavefishes--face a long-term danger from even very low levels of heavy metals. These species grow extremely slowly and may require 25 to 50 years to attain sexual maturity. When troglobitic and non-troglobitic crayfishes from the same cave in Tennessee were analyzed for heavy metal concentrations in their tissues, the troglobitic species were shown to have hundreds of times the concentration of several metals that were found in the non-troglobitic crayfishes (which reach sexual maturity in about 2 years). Similar very high levels were found in *Orconectes pellucidus* from Parkers Cave, Barren County, Kentucky. These species live so long that minute concentrations of heavy metals acquired each year may ultimately reach toxic levels. Consider the cavefishes and crayfishes of Echo River in Mammoth Cave, fortunately spared the Hidden River pollution. What about the minute amounts of cadmium generated from wear of vulcanized tires and of lead from leaded gasoline combusion along Interstate 65? There is a very real possibility that the world-famous fauna of Echo River could become extinct, not from a disastrous pollution accident, but slowly and insidiously from low levels of toxic metals. The fauna would disappear not with a bang, but with a whimper. This is a potential danger that is seriously in need of further study.

There is not much hard evidence that heavy caving pressure, other than the dumping of spent carbide, which is fortunately becoming a thing of the past, seriously reduces population levels of troglobites. Disturbance of hibernating bats during winter or disturbance of maternity colonies of bats are probably the greatest damage cavers are likely to inflict on Kentucky cave life, but this can be avoided by education, gating, and restriction of entry to major hibernacula caves at critical times of the year.

Finally, permanent closure of caves, either by bulldozers in an urban area or by landowners who have been pestered by inconsiderate cavers, may or may not mean extinction for the fauna of these caves. Closure does mean that the fauna of those caves is no longer available for study, by anybody. Krekeler (1973) described two unusual species of cave beetles on opposite sides of th Ohio River near Louisville, *Pseudanophthalmus barri* in Indiana and *P. troglodytes* in Kentucky. The only cave where *P. troglodytes* has been collected is now under Oxmoor Shopping Center.

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Chapter 10

VERTEBRATE REMAINS IN KENTUCKY CAVES

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One of the earliest vertebrate fossils to be recognized in North America (preceded only by those at Big Bone Lick, Boone County, Kentucky) came from a Kentucky cave. A skull of a flat-headed peccary (Platygonus compressus) was collected by Dr. Samuel Brown, about 1804, from Great Saltpeter Cave, Rockcastle County. The specimen is still in the collection of the Philadelphia Academy of Science. Despite this early interest in the vertebrate paleontology of Kentucky caves, the area has received little study since. During the nineteenth and early twentieth centuries, only the spectacular finds (e.g., complete skulls, mammoth or mastodon bones, etc.) were likely to be recorded. These early discoveries, however, were likely to be lost or forgotten before any scientific study unless the material went to the large museums in the East. Most modern scientific studies in the vertebrate paleontology of Kentucky were accomplished under the directon of the late John E. Guilday (Carnegie Museum of Natural History) during the 1960's and early 1970's. As his student, I express my gratitude to John for his training and encouragement.

Analysis of bones from several recently excavated sites is still in progress. Some of the new finds are reported here for the first time. The potential of paleontological work in Kentucky caves has hardly been scratched.

WHY STUDY BONES?

Cave bone deposits preserve a record of past animal communities spanning a range of at least several tens of thousands of years. These deposits represent an opportunity to study the paleoecology of many extinct species. By inference from known geographic ranges and ecological tolerances of living species preserved in cave deposits, it is possible to reconstruct the evolution of changing climates and environments in the Ohio Valley. Occasionally, well preserved archeological/paleontological sites permit reconstruction of the activities of prehistoric man and other predators of the distant past. Perhaps most importantly, the kinds of information preserved in cave bone deposits are frequently not preserved in any other paleontological context. If bone deposits are destroyed or disturbed by natural or human processes, part of the prehistory of an entire region is lost forever.

HOW DO BONES GET INTO CAVES?

Cavers are frequently surprised to learn that remains of large animals are found deep inside caves, many kilometers and hours from the nearest entrance. Recovery of the bones of giant short-faced bear *(Arctodus simus)*, flat-headed peccary *(Platygonus compressus)*, and American mastodon *(Mammut americanum)* or mammoth *(Mammuthus)* from Proctor Cave in 1979, for example, required 24-hour cave trips. The mastodon or mammoth bones were found in the talus of a terminal breakdown while the remains of the other species were scattered along an active cave stream. They had evidently been washed to that side by floods after being eroded from the site of original deposition farther upstream.

Most bones are deposited near present or past entrances. Exceptions to this general statement may include bones that wash in, or skeletons of animals that wandered far from the entrance before dying. Vertical shafts act as pit-fall traps and they are responsible for innumerable cave bone deposits. Other common means of bone accumulation include the activities of woodrats, carnivores, and raptors (predatory birds such as hawks and owls). Man has been an agent in the accumulation of bones in Kentucky caves for at least the last 10,000 years. Detailed analysis is often required to determine the mode of accumulation, and many bone deposits are the composite of several processes.

During the thousands of years that an entrance may be open for animals to enter, geolgic processes may have significant effects on the resulting bone deposits. Rockfalls and sedimentation may seal layers of bones from contamination by more recent accumulations. Erosion may expose older layers as drainage patterns shift, and redeposition of the fossils may occur. Fluctuations in the water table affect not only sedimentation patterns, but also animal utilization and the degree of mineralizaton of the bones present. Travertine or gypsum may encrust fossil bones. Entrances may collapse or fill in, altering or ending their accessibility to various kinds of animal activity. These processes may produce extremely complex stratigraphy and require careful excavation and record keeping to decipher. Gnawing and digging by animals such as woodrats, woodchucks, and carnivores may further confuse the record. In Kentucky, those deposits not buried soon after deposition are often so completely gnawed that the accumulation is reduced to very small bones such as mouse and shrew parts, and the harder crowns of large mammal teeth. Complete and articulated skeletons are extremely rare in Kentucky caves.

WHAT HAS BEEN FOUND?

Most caves contain bones. Some contain extensive deposits, representing thousands of individual animals and dozens of species, while others may contain only an occasional scrap of bone. The significance of any particular bone deposit depends on a variety of factors including the age, number, diversity of species represented, quality of preservation, presence and number of extinct or extralimital (no longer living in the local region) species, and the taphonomy (history of accumulation and subsequent alteration) of the deposit.

Species represented in cave bone deposits are either extinct, still living in the area of the cave, or extralimital. Those species still living in the vicinity of the cave seldom provide dramatic insights into changing environments, but they can serve as reminders of the relative adaptability of some species. They may also provide information on when additions to the local fauna first arrived in a particular region.

Indications of how climates and environments change may be inferred from interpretation of fossils of extralimital species. A few examples will serve to indicate the significant changes in the Kentucky mammalian fauna. Northern species like porcupine (*Erethizon dorsatum*), red squirrel (*Tamiasciurus hudsonicus*), heather or spruce vole (*Phenacomys*), yellow-cheeked vole (*Microtus xanthognathus*), snowshoe hare (*Lepus americanus*), wolverine (*Gulo gulo*), pine marten (*Martes americana*) and least weasel (*Mustela nivalis*) have been found in Kentucky caves. A 1920s report by a University of Kentucky graduate student of a polar bear (*Thalarctos maritimus*) is almost certainly based on a misidentification. Unfortunately, the specimen has been lost.

Western species recovered from Kentucky caves include 13 lined ground squirrels (*Spermophilus tridecemlineatus*), plains pocket gopher (*Geomys bursarius*), Mexican free-tailed bat (*Tadarida brasiliensis*), badger (*Taxidea taxus*), and grizzly bear (*Ursus acrtos*). Kentucky caves also contain evidence of the former presence of many species that have disappeared (or nearly so) from the local fauna during the historic period. These include elk or wapiti (*Cervus elaphus*), gray wolf (*Canis lupus*), red wolf (*C. niger*), mountin lion (*Felis concolor*), black bear (*Ursus americanus*), otter (*lutra canadensis*), prairie chicken (*Tympanuchus cupido*), and whooping crane (*Grus americana*).

Extinct species reveal the limits of environmental flexibility and are perhaps the most intriguing of Kentucky vertebrate fossils. The extinct species that have been found in Kentucky caves are listed in Table 1. The most common species is the flat-headed peccary, having been found in at least 8 Kentucky caves. In the case of Welsh Cave, Woodford County (Carbon-14 date: 12,950 ± 550 years before present) and Toolshed Cave, Bullitt County, numerous individuals were recovered that may represent herds. At least 31 individuals were recovered from the Welsh Cave deposits and at least two dozen from Toolshed Cave. Flat-headed peccaries are common in Kentucky caves because they traveled in herds and, like living peccary species, they often used caves as shelter. Typically, the fossil herds are composed of young animals only a few weeks old at the time of death as well as young adults and aged individuals identifiable by their worn teeth and advanced arthritis.

Platygonus vetus, a larger species that preceded *P. compressus* evolutionarily, has been found in Lisanby Cave, Caldwell County. Discovered by cavers who were mapping the cave, this may be the oldest Kentucky bone deposit discovered to date. Although precise dating is not possible, these bones are probably more than 250,000 years old. A third species, the long nosed peccary, *Mylohyus nasutus*, has been recovered in Savage Cave, Logan County, and Icebox Cave, Bell County. *Mylohyus* traveled alone or in small family groups and it preferred more wooded areas than *Platygonus*.

Horses evolved in North America, but became extinct at the end of the Pleistocene (Ice Age) about 10,000 years ago. A related European species was introduced by Spanish explorers in the sixteenth century. Bones or teeth of an extinct horse species have been found in several caves in the Blue Grass Region of the State. Two species of tapirs, small relatives of the horse, with long flexible snouts, have also been preserved in Kentucky caves. The smaller *Tapirus veroensis* was found in the late 1970's in Proctor and Bowman Saltpeter caves. The larger *Tapirus haysii* was recovred early in this century from a sinkhole in Scott County.

Table 1. Extinct mammals recovered from Kentucky caves.

SCIENTIFIC NAME	COMMON NAME	SITE NAME
Order Edentata		
Dasypus bellus	beautiful armadillo	*A-maze-in Cave, Bullitt Co.
Megalonyx jeffersonii	Jefferson's ground sloth	Glass Cave, Franklin Co. Gillenwater Cave, Barren Co.
Order Carnivora		
Canis dirus	dire wolf	Welsh Cave, Woodford Co.
Arctodus simus	giant short-faced bear	Glass Cave, Franklin Co. Proctor Cave, Edmonson Co.
Felis onca augusta	jaguar	A-maze-in Cave, Bullitt Co.
Order Rodentia		
Castoroides ohioensis	giant beaver	Cutoff Caves, Trigg Co.
Order Perissodactyla		
Equus complicatus	complex-toothed horse	fissure at Mundy's Landing, Mercer Co.
Equus sp.	horse	Glass Cave, Franklin Co. Welsh Cave, Woodford Co.
Tapirus haysii	Hay's tapir	sinkhole, Scott Co.
Tapirus veroensis	Vero Tapir	Bowman Saltpeter Cave, Rockcastle Co. Proctor Cave, Edmonson Co.
Order Artiodactyla		
Mulohyus nasutus	long-nosed peccary	Icebox Cave, Bell Co. Savage Cave, Logan co.

Table 1. (Continued)

Platygonus vetus	Leidy's peccary	Lisanby Cave, Caldwell Co. Granny Puckett Cave Hart Co. Great Saltpeter Cave, Rockcastle Co. Lone Star Peccary Cave, Hart Co. Proctor Cave Edmonson Co. Savage Cave, Logan Co. *Toolshed Cave, Bullitt Co. Welsh Cave, Woodford Co. unknown, Wayne Co. Wells Cave, Boyle Co.
Platygonus compressus	flat-headed peccary	
Order Proboscidea		
Mammut americanum	American mastodon	*Hall's Cave, Bullitt Co. Toolshed Cave, Bullitt Co. Turner Cave, Barren Co. Walnut Hill Farm Cave, Fayette Co.
Mammuthus sp.	mammoth	Welsh Cave, Woodford Co.

*Investigation of A-maze-in, Hall's, and Toolshed caves during 1984 was supported by a grant from the Kentucky Heritage Council to Philip J. DiBlasi and Ronald C. Wilson.

Other unusual species that are represented by fossils in Kentucky caves include *Castoroides ohioensis* (Cutoff Caves, Trigg County), a giant beaver that approached the size of a black bear; *Dasypus bellus* (A-maze-in Cave, Bullitt County), a giant armadillo about twice the size of the living North American species; and *Megalonyx jeffersonii* (Glass Cave, Franklin County and Gillenwater Cave, Barren County), a giant ground sloth larger than a black bear.

Several extinct large carnivores are also among the species recovered from Kentucky caves. The largest is the giant short-faced bear, *Arctodus simus.* Larger than a grizzly bear, this giant carnivore has been recovered

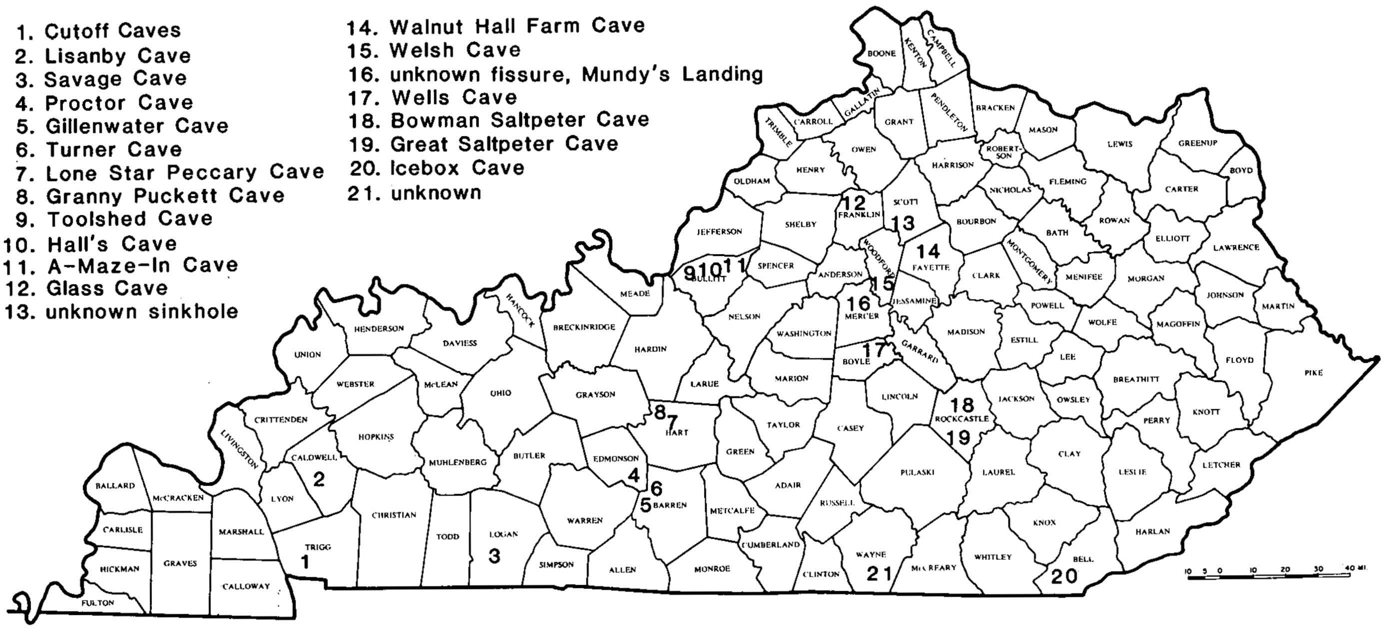

Figure 1. Locations of Kentucky caves where remains of extinct species have been collected.

from Glass Cave, Franklin County and Proctor Cave, Edmonson County. Other extinct carnivores include the dire wolf, *Canis dirus* (Welsh Cave, Woodford County) and the jaguar, *Felis onca augusta* (A-maze-in Cave, Bullitt County).

Discovery of the jaguar in 1984 was bittersweet. The first extinct large cat to be recorded in Kentucky, the bone preservation was better than in any previous find of the species in the eastern United States. The large mature cat was crippled by an injured toe when it sought the dry shelter of A-maze-in Cave. It died curled up in a small dry alcove and lay there undisturbed for more than 10,000 years. When found, however, all that was left were foot bones, ribs, sternum, one vertebra, and a knee cap. These were found scattered among the back dirt piles of a looter's pit. Had it been recovered intact, it would have provided the first exhibit quality specimen for museum display as well as biological data on the species. Instead, the skull, jaws, vertebrae, and all major limb bones are lost to science and are probably disintegrating from lack of care in someone's basement or closet.

THE CAVER'S ROLE

The value of vertebrate fossils lies in the opportunities they provide for interpretations of paleobiology and past climates. As in the case of archeology, stratigraphic relationships are important clues to the accurate interpretation of any fossil assemblages. Excavation by untrained individuals should never be attempted unless they are working under the guidance of a professional.

Cavers are responsible for many significant bone discoveries. Fossil bone deposits in Welsh, Toolshed, Icebox, Lone Star Peccary, Cutoff, Lisanby, Granny Puckett, Proctor, and Bowman Saltpeter caves are all first reported by cavers with no paleontological experience. Discovery of such deposits requires good observation skills. Most deposits first reveal themselves by a few small fragments of bones or teeth on the surface of the cave floor. Bones are more likely to be old if they are stained brown or black by minerals, brittle from loss of organic matter due to leaching, preserved in orange, yellow or light brown seiments or beneath flowstone. The major bone deposit in Toolshed Cave, for example, was beneath four layers of flowstone, but was exposed by erosion of a stream channel. Bones are probably very recent if they are in an active den or nest, if they are in dark brown sediments, or if they still contain grease.

If bones are to be collected for evaluation by a specialist, the initial sample should be small and select. It should include those elements that have the highest probability of being identifiable: jaws, teeth, major limb bones, pelvis or large ankle bones. Bones should not be collected unless they can be packed well enough to survive the trip out of the cave. If bones are very distinctive or too fragile to collect, they may be identified from a photograph or detailed sketch. The *Arctodus* manible from Proctor Cave was first identified from a detailed sketch in the notebook of a Cave Research Foundaton survey party.

Whether the initial collection of data is a sketch, photograph, or representative collection of bones, it must be labeled immediately. The label should include the name and location of the cave (and of the site within the cave if the cave is a large one), the name of the collector(s), and the date. Once out of the cave, the bones should be repacked for shipment to a competent faunal analyst or vertebrate paleontologist. *The bones should not be washed.* If breaks occur, be sure to save all the pieces and wrap them so they do not rub against each other during shipment.

Bones can be reliably identified only by professionals with extensive training, experience and access to appropriate comparative material. Once identified, bone collections belong in repository institutions where they will be available to future researchers and where they can be maintained with all accompanying information. Since no Kentucky institution at present employs a vertebrate paleontologist and no collection of vertebrate fossils in Kentucky institutions are being actively curated, Kentucky cavers are forced to look elsewhere to insure the proper long term management of their discoveries. The institution with the largest Kentucky collections, and a good track record for professional management of collections, is Carnegie Museum of Natural History, Pittsburgh, Pennsylvania. However, other midwest state museums (Illinois, Indiana, etc.) also have trained personnel. Further guidance on dealing with bone discoveries can be obtained by contacting the author of this chapter or the NSS Vertebrate Paleontology Section.

The fossil bones in Kentucky caves have just begun to reveal their secrets. Based on recent discoveries in neighboring states, exciting finds can be expected at any time. Among the discoveries to be expected are sabertooth cats, camel, cheetah, better preserved material of other extinct species discussed in this report, and additions to the list of extralimital species from the State. These discoveries await informed cavers who are aware of the possibiliies and who have sharp eyes.

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Chapter 11

ARCHEOLOGY

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The best cavers in the world--until about A.D. 1950--were some of the people who lived in the area of Mammoth Cave between 2,000 B.C. and 0 B.C./A.D. Barefooted, or shod with thin woven-fiber moccasins, and very lightly clad otherwise, prehistoric Indians used dry weedstalk or cane torches to light their way through the main trunk to lower-lying canyon passages and crawlways several kilometers from the cave entrance (Fig. 1). They explored and mined cave minerals extensively in several parts of the Mammoth Cave System, especially Salts Cave and Mammoth Cave. At least two of them died in the cave; one was a boy no more than 9 years old, the other a man of about 45 (Pond, 1937; Neumann, 1938; Meloy and Watson, 1969; Robbins, 1971, 1974; Meloy, 1984). What we know about their lives and their caving activites is summarized in a number of publications (Watson and others, 1969; Watson, 1974, 1984; Stein and others, 1981).

For several years it was thought that the archeological remains in the Mammoth Cave System were unique, but we now know that to be false. It appears that throughout the entire mid-continental karst region of the United States, wherever there were relatively accessible natural entrances, the aboriginal human inhabitants entered caves in search of exploitable resources, to contact supernatural forces, or just to satisfy their curiosity. This chapter is a brief summary of what is known about the archeology of Mammoth Cave and of several other Kentucky caves and karst features, making comparative reference to archeological remains in Wyandotte Cave in Indiana and in some Tennessee caves.

Figure 1. Salts Cave. Imitation aborigine. CRF photo.

THE MAMMOTH CAVE SYSTEM

The first comprehensive attempt to assess Mammoth Cave area prehistory was made by the archeologist Doughas Schwartz in the late 1950's when he was on the faculty at the University of Kentucky (Schwartz 1960, 1965). Schwartz's work was preceded by that of N. C. Wilson (1917) and Alonzo Pond (1937), and has been succeeded by that of the Cave Research Foundation Archeological Project beginning in 1962 (Benington and others, 1962; Stein and others, 1981; Watson and others, 1969; Watson and Yarnell, 1966; Watson, 1974; see also CRF Annual Reports from 1977 to the current year).

On the basis of that body of research, one can suggest the following interpretation of Mammoth Cave prehistory. The inhabitants of the region now comprising Mammoth Cave National Park began exploring at least the upper trunk passages in Mammoth Cave about 4,000 years ago (ca. 2,000 B.C.). Between that period and 0 B.C./A.D. they freely explored several kilometers of cave passages of all sorts, including some very low crawlways (for example, Wilson's Way off Ganter Avenue in upper Mammoth Cave).

Nature of the Archeological Remains

In spite of 175 years of recent traffic in the dry, upper levels of this great cave, abundant--if scattered and highly fragmented--aboriginal materials remain as testimony to the wide-ranging and persistent aboriginal presence. For the most part, these are fragments of torch and campfire fuel: cane, dried weed stalks, twigs, and branches (Fig. 2). But there are also pieces of cordage, portions of vegetable-fiber moccasins, broken bowls made of gourds or of thick-walled gourd-like squashes, and dozens of prehistoric human fecal deposits (paleofeces) that contain invaluable dietary information (Figs. 3 and 4). A

Figure 2. Marshall Avenue, Lee Cave (Joppa Ridge, Mammoth Cave National Park). Torch canes. CRF photo, Pete Lindsley.

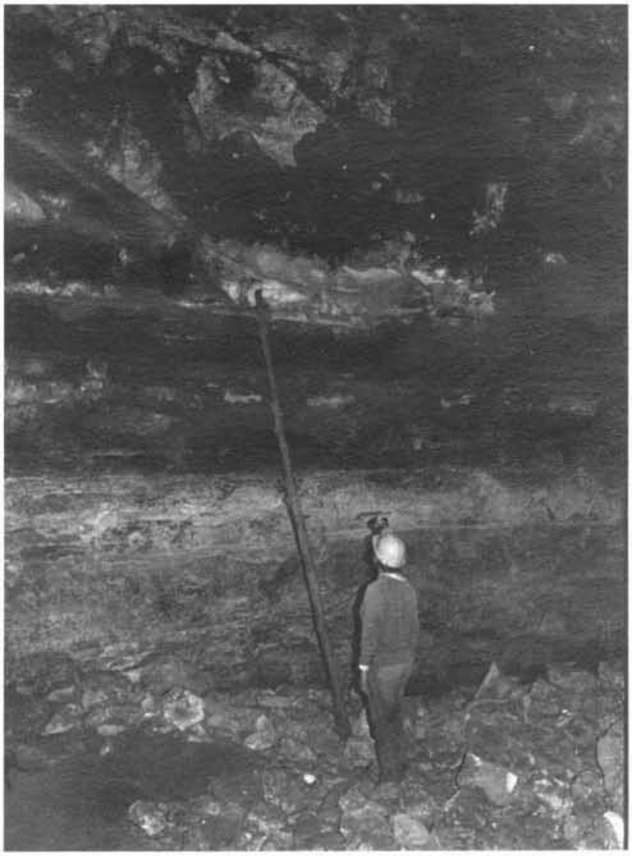

Figure 3. Climbing pole, possibly prehistoric, in the Upper Trunk Passage, Mammoth Cave. CRF photo, William McCuddy.

Figure 4. Ganter Avenue, Mammoth Cave. Basket, probably prehistoric. CRF photo, Roger Brucker.

summary of radiocarbon dates on many of the materials is shown in Table 1.

Other indications of prehistoric exploration are charcoal smudges on walls, ceilings, and breakdown blocks, as well as batter marks where the gypsum crust was hammered off passage walls (Fig. 5), perhaps to be used in making white paint. There are also many places, especially in upper Mammoth and upper Salts, where sediments have been dug away in search of other crystalline forms of gypsum (satinspar and selenite).

Although the evidence is difficult to interpret, most work parties were probably small. A very efficient size would be 6 people, with 2 serving as more or less full-time torch bearers when the group was moving and fire-tenders when they were working in one place. Experiments with cane torches (Ehman, 1966; Watson and others, 1969, p. 60-62) have shown that they are a very satisfactory form of cave light, and that it is quite possible to carry enough dry cane to last many hours (10 or 12, or even more if several people carry spare fuel. Torch fuel may also have been stored or cached in the cave on a temporary basis) (Fig. 6). The author believes these prehistoric cavers were as comfortable in the cave as are contemporary cavers, and--given the limitations of their equipment --were just as competent at subterranean navigating, climbing, and hiking.

Figure 5. Salts Cave. Gypsum crust battered off wall (top), mirabilite and gypsum crystals on ceiling of a little ledge (center), and torch smudges on wall below ledge (bottom). CRF photo.

Of course, we cannot be sure we know everything about why these prehistoric people went underground because some of their activities may not have left any material remains. But it is clear that they frequently sought and obtained the various forms of

Table 1

MAMMOTH CAVE NATIONAL PARK Prehistory: Summary of Available Radiocarbon Dates (Libby half-life, uncalibrated)

PROVENIENCE	MATERIAL	DATE
<u>Salts Cave Vestibule</u>		
Test II, F. 2A	Charcoal	1540 B.C. ± 110 (GaK 2767)
Test E, Level 5	Charcoal	1410 B.C. ± 220 (GaK 2764)
Test G, Level 6	Charcoal	1460 B.c. ± 220 (GaK 2766)
Test E, Level 7b	Charcoal	710 B.C. ± 100 (GaK 2622)
Test E, Level 7b	Charcoal	990 B.C. ± 120 (Gak 2765)
Test JIV, Level 4	Charcoal	520 B.C. ± 60
Test JIV, Level 6	Charcoal	390 B.C. ± 50
Test JIV, Level 8	Charcoal	480 B.C. ± 50
Test JIV, Level 11	Charcoal	560 B.c. ± 60
Test KII, Level 4	Charcoal	570 B.C. ± 70
Test KII, Level 6	Charcoal	250 B.C. ± 60
Test KII, Level 11	Charcoal	430 B.C. ± 60
Test KII, Level 14	Charcoal	460 B.C. ± 60
<u>Salts Cave Interior</u>		
Upper Salts, P54	Paleofecal specimen with squash seeds	290 B.C. ± 200 (M 1573)
Upper Salts, P38	Paleofecal specimen	320 B.C. ± 140 (M 1777)
Upper Salts, P63-64	Paleofecal specimen with gourd seeds	620 B.C. ± 140 (M 1574)
Upper Salts, P54	Soot	1125 B.C. ± 140 (I 256)
Upper Salts, Test A		
0-10 cm	Cane	560 B.C. ± 140 (M 1584)
30-40 cm	Cane	480 B.C. ± 130 (M 1585)
70-80 cm	Cane	890 B.C. ± 150 (M 1586)
140 cm	Wood	570 B.C. ± 140 (M 1587)
Middle Salts, Blue Arrow Passage. A60	Paleofecal specimen with squash pollen	400 B.C. ± 140 (M 1577)
A42	Paleofecal specimen with sunflower achenes	710 B.C. ± 140 (M 1770)
Lower Salts, Indian Avenue, I76	Wood	770 B.C. ± 140 (M 1588)
I67	Wood and bark	1190 B.C. ± 150 (M 1589)

Table 1. (Continued)

PROVENIENCE	MATERIAL	DATE
Salts Cave Mummy	Internal tissue	A.D. 30 ± 160 (M 2258)
	Internal tissue	10 B.C. ± 160 (M 2258)
Mammoth Cave Interior		
Upper Mammoth	Slipper	280 B.C. ± 40 (X 8)
	Cane	420 B.C. ± 60 (X 9)
Lower Mammoth		
Ganter Avenue, B10	Wood	1050 B.C. ± 70 (UCLA 1730B)
Jessup Avenue, C7	Twigs	2170 B.C. ± 70 (UCLA 1730A)
Mammoth Cave Mummy	Matting	445 B.C. ± 75 (SI 3007A)
	Internal tissue	15 B.C. ± 65 (SI 3007C)
Lee Cave Interior		
Marshall Avenue, K83	Cane	2250 B.C. ± 65 (UCLA 1729A)

gypsum noted above. Medicinal sulfate salts (most commonly epsomite and mirabilite) also occur naturally in the caves, and it is very likely that these were also of interest. Both epsomite and mirabilite are excellent cathartics, and mirabilite (being a form of sodium sulfate) is also salty, so both were probably mined as well as the gypsum.

Figure 6. Salts Cave. Bundle of twigs and sticks, apparently cached in the breakdown and lost or forgotton (note torch smudges on rock above the bundle). CRF photo, Robert Hall.

Aboriginal Caving Techniques

Techniques were simple but effective insofar as one can tell from the evidence remaining. No special clothing was worn, and in fact there are several well-preserved footprints in dust or mud (Watson and others 1969, p. 63, Plate 14) that indicate the Indians at least sometimes went barefoot in the cave (Fig. 7). It is quite possible to negotiate crawlways and breakdown climbs while holding a torch in one hand. Chimneying and canyon straddling would have been a greater challenge but by no means impossible, especially with cooperation among torch-bearers

Figure 7. Lower Salts Cave. Canyon passage explored by the Indians. CRF photo, Mark Elliott.

and non-torch-bearers (Fig. 8). Two or three cane torches will light the largest rooms and passages much better than carbide lamps or even battery-powered headlamps (because the light is more evenly diffused). Hence, a party of 8 or 10 could move about with ease, as long as they kept fairly close together, using the light from only 2 or 3 torches. Several people would then have their hands free to carry food, water, collecting bags or other containers, and spare fuel.

The torches themselves were several pieces (3 to 5 seems optimum) of cane 2 to 3 feet long, or several weed stalks of similar convenient length. These torches were sometimes loosely bound together with strands of inner bark fiber. The techniques for making fire are not known, but could have included various systems involving applied friction. Twirling a hardwood stick against another, flatter piece of wood with punk of timber placed to catch fire from the friction is one such possibility.

Figure 8. Mummy Valley, Salts Cave, with imitation aboriginal explorers. CRF photo, James Dyer.

Prehistoric Subsistence

One of the most productive avenues of inquiry stemming from the archeological remains of the Mammoth Cave System is that of how the Indians made a living. Traces of their food are very well preserved in the dried excrement that is still present in many places. We know they were growing some plant foods such as sunflower, and were harvesting the nuts and fruits from several forest species such as hickory, oak, blackberry, and strawberry. They were also growing gourds and squashes, both of which were probably used as containers (these people did not make pottery), although they did sometimes eat the seeds of both plants (Fig. 9). Squash and gourd are of special interest because they are tropical plants that were first domesticated in Mexico or somewhere even farther south.

Figure 9. Warty squash bowl and torch canes in Indian Avenue of Lower Salts Cave. CRF photo, Robert Keller.

However, by 5,000 B.C. they had been traded as far north as the lower Illinois River Valley (Conrad and others, 1984), so it is not surprising to find them in the Mammoth Cave part of the Ohio River drainage (the Green River, which runs past Mammoth Cave, is one of the tributaries of the Ohio). Nevertheless, the abundance and excellent preservation of botanical remains in the cavern passages makes them a unique and extremely valuable storehouse of information on plant use and early cultivaton in the Eastern Woodlands.

Animal bones--cracked, cut, broken, and sometimes charred--are present in midden deposits once abundant in the entry areas of both Salts Cave and Mammoth Cave. These bones, together with the much less readily identifiable animal remains in the fecal deposits, indicate that deer, turkey, raccoon, opossum, squirrel, rabbit, and other animals, including birds and fish, were hunted and eaten.

ARCHEOLOGICAL REMAINS IN OTHER CAVE AND KARST FEATURES NEAR MAMMOTH CAVE NATIONAL PARK

Both inside the Park and outside it, prehistoric materials were once present in sandstone and limestone rock shelters. Nearly all of these materials have been badly disturbed by vandals and relic collectors, many of the sites being so completely ransacked that virtually no contextual information is left. These shelters once provided seasonal homes for small groups of prehistoric people, families or extended families, and temporary campsites for parties of hunters and gatherers. The fragmentary remains in those shelters that have been examined by archeologists indicate intermittent occupation from several thousand years ago to a few hundred years ago in various of them.

The ancient Kentuckians also camped near natural features like Mill Hole, a karst window or resurgence point south of Mammoth Cave National Park, where they quarried chert from outcrops in the limestone to be made into projectile points and other tools. Crump's Cave, which opens off a sink near Smith's Grove, is another nearby, karst-related prehistoric campsite (now badly disturbed). In Short Cave, a number of burials--probably late prehistoric--were dug up in the early 1800s by saltpeter miners. On Prewitts Knob near the highway between Cave City and Glasgow, prehistoric people quarried chert and also disposed of some of their dead in pits in vertical shafts occurring at the edge of the sandstone capping the knob. A few footprints and torch remains have been found in Fisher Ridge Cave near the town of Horse Cave; on the basis of two radiocarbon determinations on the torch remains, these footprints date to about 3,000 years ago. The karst window entrance of a cave near

Bowling Green (48 km south of Cave City) was a long-term campsite and chert quarry like Mill Hole; unfortunately it has been severely vandalized in the past 2 years. Another archeological site in a cave opening off a sinkhole (Savage Cave, in south-central Kentucky) has been recently purchased by the Archeological Conservancy, and is being managed by Murray State University so that what remains of the cultural deposit will be protected.

Finally, recent work in the vicinity of Louisville by paleontologist/zoologist Ron Wilson (University Museum, University of Northern Iowa, Cedar Falls) and archeologist Phil DiBlasi (Archeological Survey, University of Louisville) has resulted in the locating of several caves containing historic and prehistoric cultural remains (Fig. 10).

CAVE ARCHEOLOGY ELSEWHERE IN THE MIDWEST AND MIDSOUTH

Archeological remains deep in caves, and thus somewhat comparable to the Mammoth Cave situation, are known from Wyandotte Cave in southern Indiana and from several Tennessee caves. Middle Woodland Indians explored Wyandotte Cave and mined chert and aragonite there, which was rather widely traded throughout the Midwest. In Zarathustra (Saltpeter) Cave in northern Tennessee, chert was also mined in some quantity, and Jaguar Cave (northern Tennessee) (see Robbins and others, 1981) (Fig. 11), and Big Bone Cave (central Tennessee) were both rather thoroughly explored prehistorically. The most unusual archeological remains from any cave are probably those in Mud Glyph Cave in eastern Tennessee, where drawings in the mud that

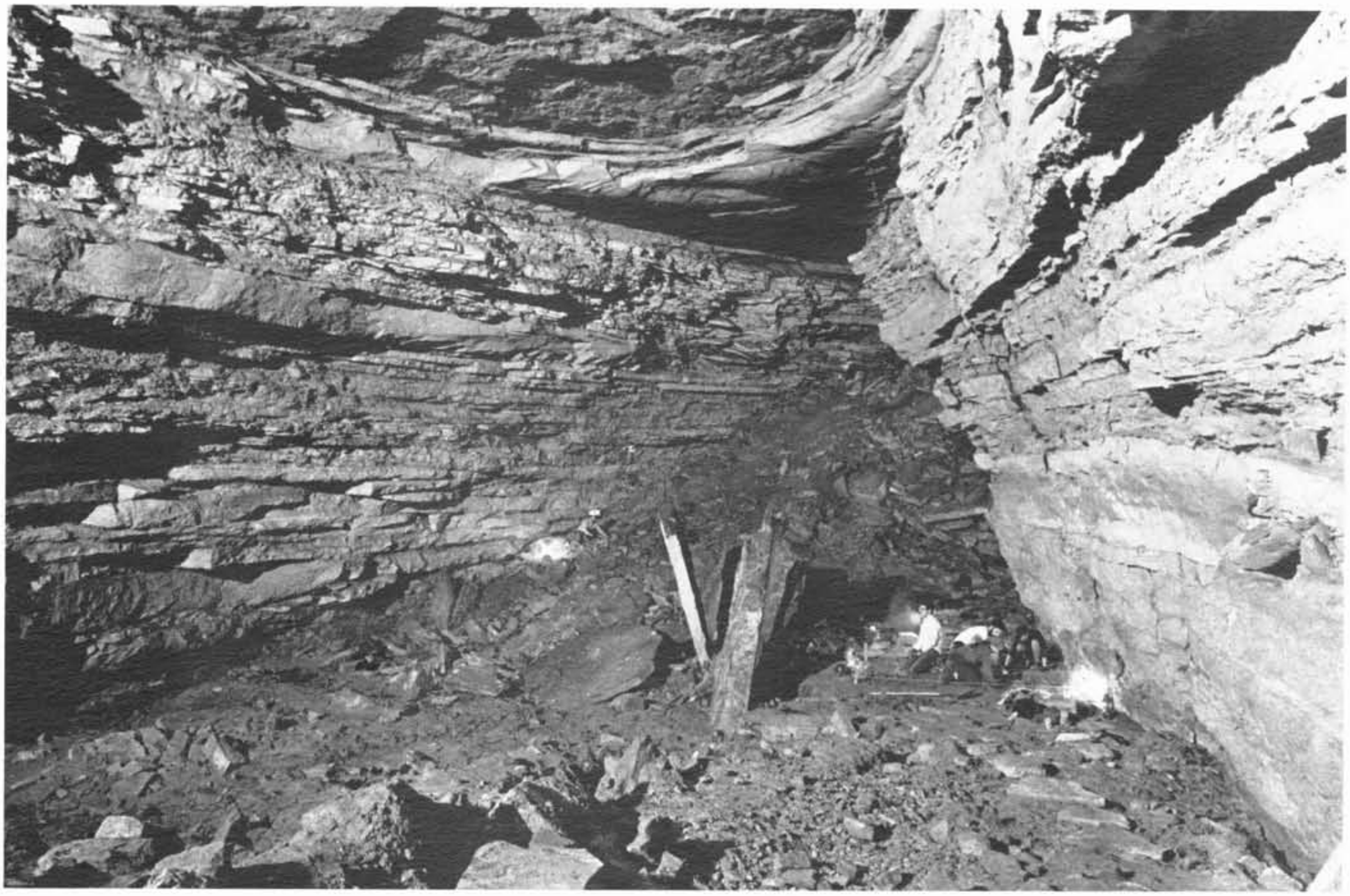

Figure 10. Salts Cave vestibule excavations. CRF photo.

Figure 11. Jaguar Cave, near the Tennessee/Kentucky border. CRF photo, William McCuddy.

covers walls of a 100 m long passage have been dated to the last prehistoric period a few hundred years ago (Faulkner and others, 1984).

Mud Glyph is the best known representative of what seems to be ritual or ceremonial caves. Very few of these are known at present, but this kind of cave-related activity seems to be later in time than use of caves and rock shelters for habitation purposes, and the exploring and mining of Mammoth Cave. Little is known about the specific ceremonies that might have taken place in Mud Glyph Cave, but it is apparent that creatures known from historic southeastern Indian mythology are represented, as are motifs of the so-called Southern Cult that spread through the eastern part of North America in the late prehistoric-protohistoric period.

SUMMARY

Prehistoric people throughout the Midwest and Midsouth made use of rock shelters and cave entrances as habitations for thousands of years. It is now abundantly clear that as long ago as 2,000 B.C. they also frequently entered caves to extract natural resources that were of interest to them. They went deep into the interior of the longest cave in the world, and at least part of the time some of them were simply reconnoitering, or just plain caving. During the latter part of the prehistoric period, some caves apparently became sacred places where ceremonies were held, possibly as a means of communicating with the subterranean world of the supernatural.

Archeological remains in caves, whatever their nature, are extremely valuable and extremely fragile. Should you find anything in a cave that appears to be evidence for historic and prehistoric activity there, do not touch it or disturb it. Record as much information about it as you can and report it to the State Archeologist. Most of the recent evidence of prehistoric deep-cave utilization has been discovered by cavers rather than archeologists. Only if cavers maintain this exemplary tradition can our mutual knowledge of the world underground continue to increase.

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Chapter 12

CAVES AND THE SALTPETER INDUSTRY IN KENTUCKY

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Cave exploration in the pioneer days of the State of Kentucky was not for recreation, commercial tourism, or scientific study, but rather for the mining of minerals necessary for survival. Common salt, sodium chloride, was almost the only preservative early settlers had to pickle or cure their beef or pork, and preserve their game. Natural brines from salt licks were so important that Congress encouraged development of salt springs wherever they were found.

Also important as a chemical to pioneer survival was potassium nitrate, or saltpeter. The name "saltpeter," with its various spellings, meant "salt of earth" or "salt of rock," in contrast to common salt, which came from water. Calcium nitrate deposits in caves and rock shelters were eagerly sought, and an industry was developed to convert the raw mineral to purified saltpeter. Saltpeter is an important chemical for the preservation of meat. Medicinally, it is used as a diuretic. Saltpeter is also a necessary component, with sulfur and charcoal, for the manufacture of gunpowder for firearms, fuses, and blasting.

Histories of saltpeter mining in Kentucky dazzle readers with stories of cave saltpeter playing a major role in concluding the War of 1812. Unfortunately, this may not be correct. Its use in gunpowder made supply and demand for saltpeter vary greatly in times of war. This war-related inflation of value led to intensive exploration of the caves of Kentucky, for they were an important economic resource. The early interest in the caves, nearly 200 years ago, has left a rich history for modern-day historians and speleologists.

There are important parallels between the development of the saltworks of Kentucky, and the saltpeterworks. The technology of making salt from brines and making saltpeter from calcium nitrate leached from earth was similar. Prominent salt merchants also sold saltpeter. Without these chemical industries, the settlement of Kentucky might have occurred differently.

SALTPETER AND EARLY KENTUCKY HISTORY

Daniel Boone first settled in Kentucky in 1769, a period of exploration and settlement of the Blue Grass Region which left the pioneers far from sources of chemicals in Virginia. To the west of Kentucky, settlements in what are today Missouri and Illinois were established to mine lead and to obtain animal furs. In 1770, "Long Hunters" explored the middle and southern regions of Kentucky. They would have been the first to find the caves later mined for saltpeter production.

The Treaty of 1763, ending the French and Indian War, gave England the land between the Appalachian Mountains and the Mississippi River plus Canada. The British discouraged any settlement of their "Northwest Territory," which was north of the Ohio River. The Commonwealth of Virginia, which included Kentucky, began surveying its land south of the Ohio River in 1773. As the movement toward independence from British rule increased, more settlers moved into the Blue Grass Region, despite frequent Indian attacks. In the spring of 1774, James Harrod built the first cabin in Kentucky, at the town of Harrodsburg.

In October, 1774, the British prohibited the export of gunpowder to the rebellious colonies, and confiscated stores of gunpowder in Massachusetts. Hostilities increased, and the Revolutionary War began when British Regulars fired on the Minutemen at Lexington, Massachusetts, on April 19, 1775.

At a time when settlers in Kentucky needed saltpeter for gunpowder to insure their safety, and salt for food, the eastern communities could not provide it. The British blockade required the colonists to produce their own essential chemicals. On June 10, 1775, the Continental Congress decreed that all saltpeter the colonists possessed had to be delivered to the nearest factory for gunpowder producton. One month later, Congress adopted a resolution to promote the production of saltpeter within the colonies. The resolution was written by Dr. Benjamin Rush of Philadelphia, a famed physician and signer of the Declaration of Independence. Rush described the methods of production of saltpeter from calcium nitrate found in caves, rock shelters, and the dry soil under buildings.

With the Declaration of Independence in 1776, France began supporting the cause of the 13 colonies. Arms and supplies for war were bought from France. Large quantities of gunpowder were imported despite the British blockade. The pivotal victory of Saratoga in 1777 was made possible by gunpowder received from the French. The Continental Congress appointed a committee to promote the manufacture of saltpeter. District committees would purchase a pound of pure saltpeter for 20 cents. Numerous caves east of the Appalachian Mountains were mined for saltpeter during and after the War of Independence. When some of the miners moved west, they took their knowledge of saltpeter production technology with them.

The War of Independence ended with the defeat of Cornwallis on October 19, 1781. The immediate result of the cessation of hostilities was a surge of immigrants into Kentucky. The Treaty of Paris in 1783 formally ended the war, but did not halt bitter feelings toward the British. England maintained outposts in Indiana and Michigan, and supported Indian attacks against the immigrants.

Saltpeter production remained a commercial venture in Virginia after the Revolutionary War. Local gunpowder mills produced the explosive for firearms, and to use in blasting for land clearing and construction. Transport of the explosive over rough roads for long distances was dangerous. Kentucky settlers searched for caves to produce saltpeter for their own personal needs. Early records do not outline evidence of a commercial saltpeter industry in Kentucky after the end of the Revolutionary War; by 1800, however, 28 saltpeter caves and rock houses were reported to have produced 100,000 pounds of saltpeter.

Kentucky achieved statehood on June 1, 1792. Saltpeter production was still a local cottage industry requiring only calcium nitrate-containing earth, ashes, water, digging tools, lumber for a leaching vat, and a boiling kettle. By this time, the saltworks in the State employed hundreds of men as carpenters, wood choppers, boiling kettle tenders, and waggoners. Salt production began shortly after the first settlers entered the State, and saltworks were developed despite the hazard of Indian attack. Daniel Boone was captured by Indians in 1778 while making salt for Boonesboro. The first commercial saltworks was erected at Bullitt's Lick, near the present-day town of Shepherdsville, in 1779. Three thousand gallons of water were boiled down to yield four bushels of salt. Immigrant demand for salt was so great that at the end of the War of Independence, the price of salt was inflated to over $500 per bushel. Numerous salt licks were developed in the vicinity of Bullitt's Lick and timber for fires was cut from a large area. Wells were dug to find salt brine. The brine was transported to the boiling kettles by miles of hollow wooden pipes made from logs that were bored by augers, with the ends held together by iron bands. By the turn of the century, the price of a bushel of salt fell to $1.00. Figures 1 and 2 show some of the equipment used in the salt and saltpeter industry.

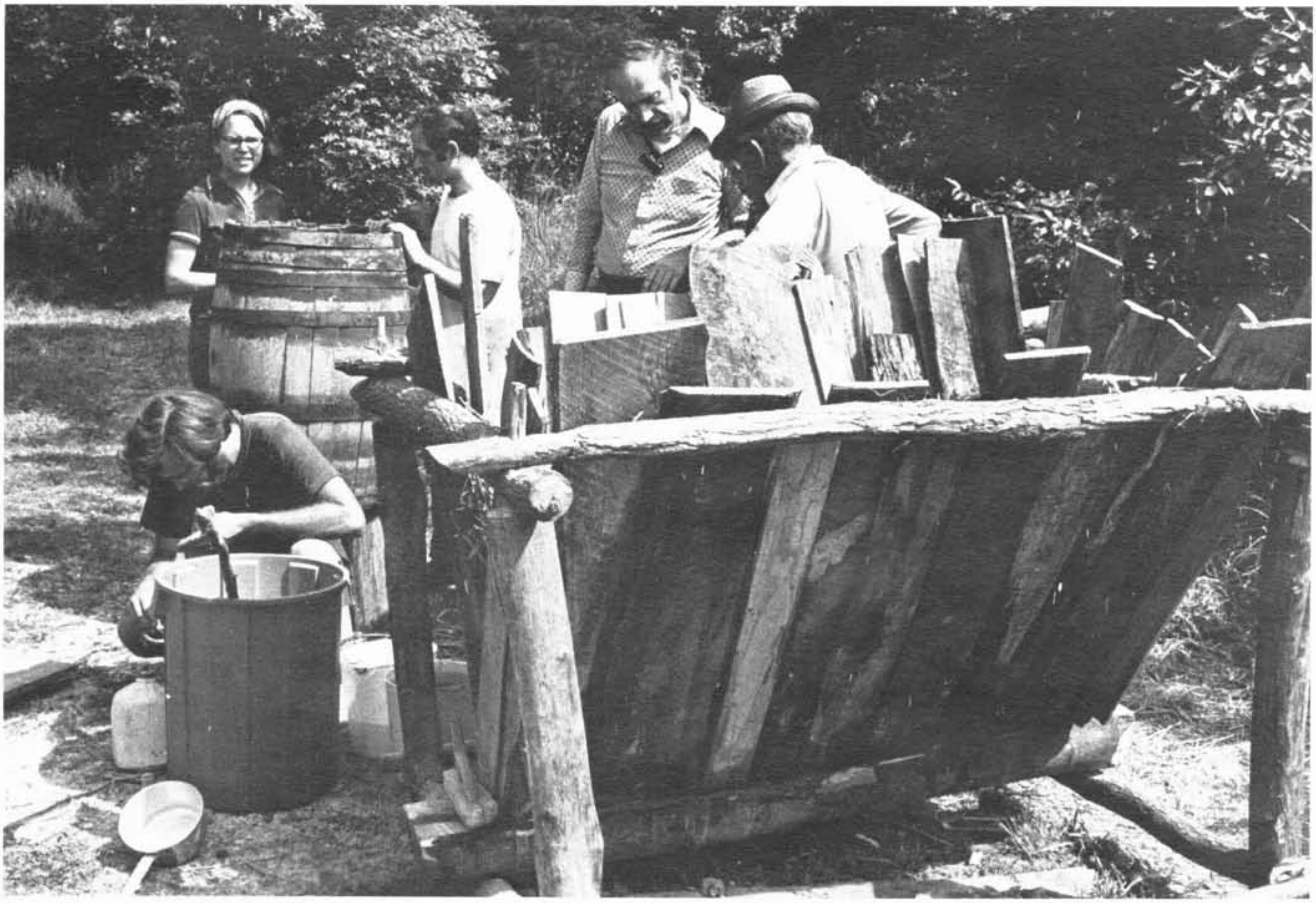

Figure 1. V-leaching vats used in the entrance of Mammoth Cave. From Mammoth Cave Saltpeter Action History Experiment, July 1974. CRF photo, R. Pete Lindsley.

Figure 2. One of the original saltpeter furnace bioling kettles from Mammoth Cave, recently located near Brownsville, Kentucky. CRF photo, R. Peter Lindsley.

SAMUEL BROWN, M.D., AND THE COMMERCIAL SALTPETER INDUSTRY

Dr. Samuel Brown was the first scientist to describe the process of saltpeter production in early Kentucky. Born in Rockbridge County, Virginia, in 1769, the son of a Presbyterian minister, he was raised in the town of Rockbridge. Nearby was Saltpeter Cave of Rockbridge County, close to Natural Bridge. Brown attended medical school in Philadelphia, and became a private pupil of Dr. Benjamin Rush, Chairman of the Department of Chemistry, as well as a physician of great fame. Undoubtedly, Brown learned of Dr. Rush's interest in saltpeter mining during the Revolutionary War.

Dr. Brown studied under Dr. Rush 3 years. In 1792, he went abroad to study medicine in Edinburgh, Scotland, receiving his Doctor of Medicine degree in 1797. Upon returning to the United States, he ventured to Lexingon, Kentucky, and was appointed Head of the Department of Chemistry at Transylvania University Medical School in 1799. In 1800, through the influence of Thomas Jefferson and Dr. Rush, he became a member of the prestigious American Philosophical Society.

Brown demonstrated a special interest in industrial chemistry and its application to agriculture. At this time, Lexington had one gunpowder mill which received its saltpeter from nearby caves. In 1801, he visited Kinkaid's Cave (Great Saltpeter Cave), located 50 miles southeast of Lexington. The cave had been discovered only 2 years earlier by John Baker, but it already supplied much of the saltpeter for the Lexington mill. Dr. Brown's interest in the commercial production of saltpeter at this cave resulted in the most important contemporary article published on the subject, "A Description of a Cave on Crooked Creek, with Remarks and Observations on Nitre and Gunpowder." He read his paper before the American Philosophical Society at Philadelphia on February 7, 1806.

Dr. Brown described the process of prospecting for the presence of "petre dirt" by taste, or the effacement of foot and handprints imprinted on the surface of the cave soil. He outlined the process by which calcium nitrate in the cave dirt was leached with water to yield "mother liquor." Wood ashes, contining high concentrations of potassium, were leached with water to yield potassium hydroxide or potash. The potassium hydroxide solution was added to the "mother liquor," yielding potassium nitrate in soluton. This solution was filtered and concentrated by boiling to make crystalline saltpeter. Dr. Brown, like Dr. Rush, understood the process by which the raw material in the cave soil became a purified chemical, but could not have understood the underlying chemical reactions. The element potassium was not isolated as a metal until 1807.

Dr. Brown observed that the workmen routinely returned the leached dirt back to the cave floor. Saltpeter production had occurred long enough in the cave for the workers to observe that leached soil would again develop significant concentrations of calcium nitrate after 3 to 5 years. Brown thought the process could be continued indefinitely, making the supply of saltpeter from a good saltpeter cave inexhaustible.

George Montgomery purchased Great Saltpeter Cave in 1802 and continued saltpeter mining on a limited scale. In 1804, Dr. Brown and Thomas Hart purchased the cave and increased saltpeter production, their venture being extremely successful. In 1805, they widened the scope of their enterprise and began producing common salt from local springs. In 1806, an anonymous article was published in the "Medical Repository," the most popular medical publication of its day. Entitled "Caverns in Virginia, Kentucky, and Tennessee, which Afford an Inexhaustible Supply of Salt-Petre," it undoubtedly was written by Dr. Brown. With his brief career as a salt and saltpeter producer a success, Brown moved to New Orleans in April, 1806. He did not return to Lexington until 1819 to resume teaching at Transylvania University.

Figure 3. Saltpeter miners moved large quantities of floor breakdown to excavate the saltpeter earth. Leaching hoppers were in the cave passage above the breakdown slabs in the center of the photograph. Dixon Cave, Mammoth Cave National Park. CRF Photo, R. Pete Lindsley.

Great Saltpeter Cave became the second greatest source of saltpeter in Kentucky during the War of 1812. As many as 60 to 70 men worked at the cave. Each bushel of cave dirt, about 220 pounds, yielded slightly more than 1 pound of saltpeter (Fig. 3). In 1805, about 150 bushels of cave dirt were processed daily. With improvements on the saltpeter works, it was reported that up to 1,000 pounds of saltpeter were expected to be produced daily.

MAMMOTH CAVE AND THE WAR OF 1812

Modern records do not identify the earliest settlers of the Mammoth Cave Region, but James Sturgeon, a Revolutionary War soldier, filed a military claim on 200 acres east of Mammoth Cave in the fall of 1790. He was probably one of the first settlers on the ridges along the south bank of the Green River. Some of these early settlers were involved in mineral exploitation as noted by Imlay, who wrote of Kentucky in 1792: "Sulphur is found in several places in abundance; and nitre is made from earth which is collected from caves and other places to which wet has not penetrated. The making of this salt, in this country, is so common, that many settlers manufacture their own gunpowder. This earth is discovered in greater plenty on the waters of Green River, than it is in any other part of Kentucky."

Today, there is no record of the earliest saltpeter production at Mammoth Cave and the Dixon Cave; however, it is likely that these were among the first caves mined in the State. On September 14, 1798, Valentine Simons purchased 200 acres for $80, making a down payment of about $10. In 1799, the property was surveyed and it included "two saltpeter caves." Simons assigned rights of the caves to John Flatt, and in 1808 Mammoth Cave was known as Flatt's Cave. Common V-leaching vats were used in the entrance of Mammoth Cave (Fig. 1). The extent of the production of saltpeter from the caves in this period is unknown.

Persisting hostilities with Great Britain were soon to have a profound effect on nitrate mining and saltpeter production in Kentucky. On October 21, 1805, Great Britain defeated the French and Spanish in the Battle of Trafalgar and gained control of the seas. Several weeks later, however, Napolean gained supremacy on land in Europe. The United States was the world's second-greatest maritime nation at this time, and was uninvolved directly in the European war. American ships supplied war materials to Napoleon, prompting Great Britain to blockade American ports. Congress responded with passage of the Embargo and Non-Intercourse Act to deprive both France and Great Britain of American Goods. This action harmed United States' trade and sources of saltpeter from Spain and India became less accessible.

In Kentucky, it was felt that the British were inciting the Indians to attack frontier settlements, and were supplying them with gunpowder and arms. The net result of mounting conflict with Great Britain was congressional Declaration of War on June 18, 1812.

Prior to 1808, Valentine Simons sold the 200 acres including Dixon Cave and "Big Cave" to John Flatt for at least $116.67. Also prior to 1808, Flatt assigned the property to brothers John, Leonard, and George McLean for an unknown sum, but at least $400. In January, 1808, 44 acres including Dixon Cave were sold to Charles Morton for $600. Prior to 1810, the McLeans sold the remaining 156 acres including Mammoth Cave to a "saltpeter company" owned by Fleming Gatewood and Charles Wilkins for $3,000.

Charles Wilkins was a prominent Lexington, Kentucky salt and saltpeter merchant. Records document that in 1808 he was selling Kentucky saltpeter via Philadelphia saltpeter merchant Archibald McCall to E.I. du Pont Company of Wilmington, Delaware. Wilkins purchased saltpeter made at Great Saltpeter Cave, and must have known of Dr. Brown's ownership and interest in the cave. As the British blockade tightened prior to the War of 1812, sources of saltpeter near Lexington could not meet the demand of the large manufacturers of gunpowder such as du Pont. Wilkins found his needed sources of saltpeter in the caves of the Mammoth Cave Region. In 1812, wealthy Philadelphia merchant and saltpeter dealer Hyman Gratz purchased Fleming Gatewood's interest for $10,000. The combined business acumen of Wilkins and Gratz resulted in spectacular saltpeter production from Mammoth Cave between 1812 and 1815.

As the price of saltpeter rose prior to the War of 1812, the value of caves containing saltpeter also increased. Saltpeter sold for 17 cents a pound in 1808 with land at Mammoth Cave selling for $14 per acre (Table 1). When war was declared

Table 1.--Economic Cycle - Mammoth Cave Land and Commodities, 1775-1984.

Year	Land (acre)	KNO_3 (pound)	Gunpowder (pound)	Corn (bushel)
1775		$.20		
1798	$.40			
1800	.58	.15	$.25	$.20
1806	2.00	.166	.375	
1808	14.00	.17		
1810	19.23	.17		
1812	128.00	.70		
1813	100.00	.75	1.69	
1814		1.00		
181		.15		.125
1828	.15			
1838	3.11			
1839	6.21			
1984	450.00	8.90	6.95	2.79

in 1812, saltpeter sold for 70 cents a pound. Hyman Gratz purchased his half-interest in Mammoth Cave for $128 per acre. This represented an 800% increase in the value of the land and cave in 4 years!

Speculation in Mammoth Cave and its valuable resource led to a fascinating array of maps outlining the cave's extensive saltpeter deposits. Charles Wilkins' brother-in-law, Doctor Frederick Ridgley, sent one of the maps to Philadelphia to Dr. Samuel Brown's famous mentor, Dr. Benjamin Rush. Despite lack of a survey base and the distortion of distances on these maps, they have proven an important source of information on the early history of the cave.

In 1812, Kentucky supplied over 300,000 pounds of saltpeter from 35 saltpeter caves and rock shelters, with a value of approximately $2 million. Even though this represents the bulk of saltpeter produced in the United States that year, there is no evidence that this and subsequent production was vital in concluding the War of 1812. The war had no prolonged battles requiring large stores of munitions. Neither Great Britain nor the United States gained any clear-cut military advantage over the other.

The British were exhasted by the Napoleonic struggle; American export trade was paralyzed. The British influence over the Indians was lost, and the tide of American settlement in the west could not be stopped. A truce, not surrender, was reached by the Treaty of Ghent on December 14, 1814. The large quantities of saltpeter produced in Kentucky did not "win the war", but probably helped to stabilize the war-related inflation in its value. Had the value of saltpeter continued to climb due to scarcity, undoubtedly other sources of the chemical would have been exploited.

ECONOMIC AFTERMATH OF THE WAR OF 1812

After the war, the value of saltpeter plummeted. The price of a pound of saltpeter fell to 15 cents or less with cessation of the blockade and resumption of foreign imports. Demand for saltpeter declined due to its limited usefulness as an industrial chemical, and the lack of demand for gunpowder. Transport of cave saltpeter from the interior of Kentucky to Philadelphia was too difficult and expensive to continue cave production. As late as 1840, only a single land road led to Mammoth Cave. When the road was wet, wagons could not reach the cave and visitors traveled by horseback. E. I. du Pont continued to dominate gunpowder manufacture, utilizing foreign sources of saltpeter.

Economic stagnation and depression worsened steadily after the war, resulting in the Panic of 1819. The inflated value of Mammoth Cave land collapsed (see Table 1). All of the saltpeter caves except Mammoth Cave and Great Saltpeter Cave fell into disuse. Great Saltpeter Cave was reportedly mined commercially for saltpeter during the Mexican War, beginning in 1844.

Stories of aboriginal remains found by saltpeter miners in Short Cave and Mammoth Cave resulted in renewed interest in Mammoth Cave. Nahum Ward, of Shrewsbury, Massachusetts, visited the cave in October, 1815. On his return to Massachusetts, he took with him one of the "mummies" found in Short Cave and displayed in Mammoth Cave. He wrote a newspaper article on his cave trip that was widely reprinted here and abroad for many years. A map of the cave accompanied his article (Fig. 4). Nahum Ward´s account made the cave famous, and was crucial to the early commercial tourist activity at Mammoth Cave.

Immediately after saltpeter production ceased at Mammoth Cave in the Spring of 1815, the cave became a commercial tourist attraction. This commercialization led to preservation of the saltpeter works in the cave, although surface works were destroyed by cave development and

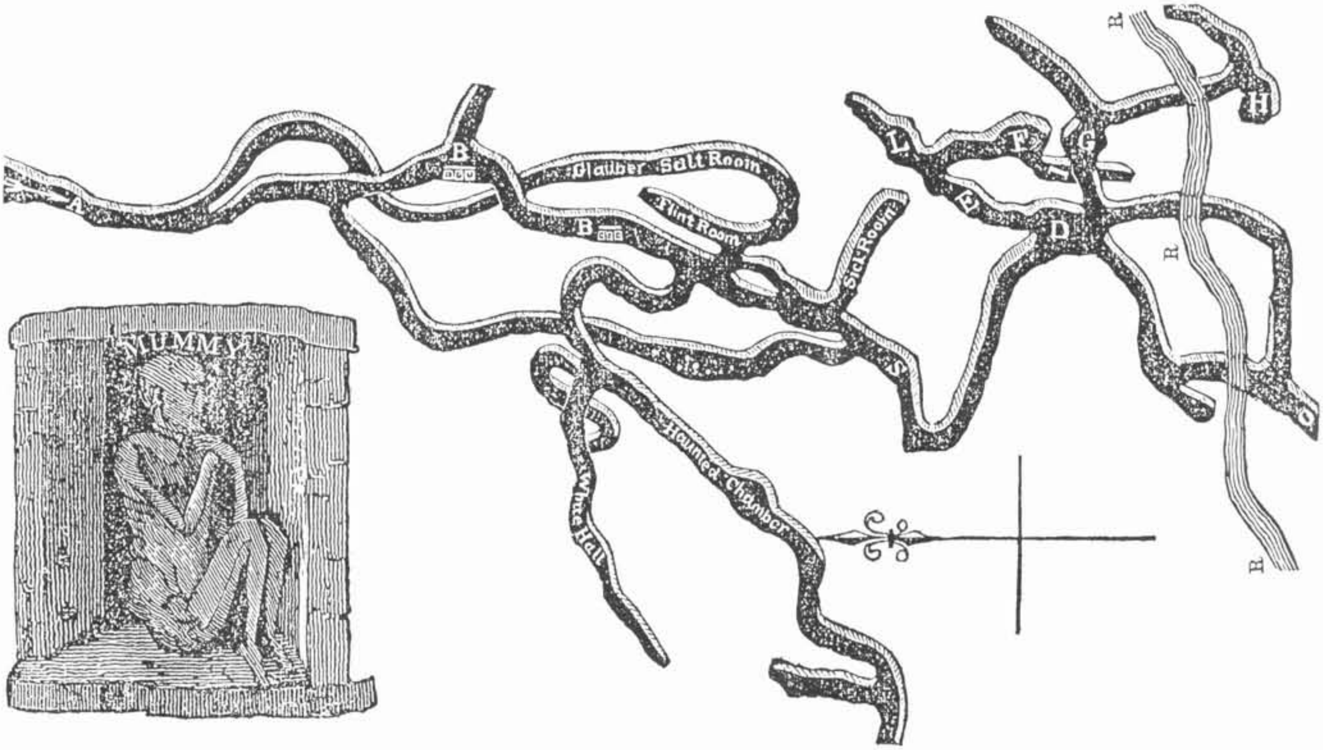

Figure 4. One of the several versions of Nahum Ward's "Map of Mammoth Cave." The Green River is shown over the cave far to the south of its true location. From Sears (1850).

natural elements (Fig. 5). The other saltpeter caves were not so fortunate, and their saltpeter works decayed or were destroyed. Small numbers of workers were used for saltpeter production, so no towns or villages were built near the caves. Salt production fluorished after the war, however, with producton of up to 500,000 bushels annually. Towns built near salt licks still exist today.

Mammoth Cave and surrounding land including 1,614 acres was purchased for $10,000 by Doctor John Croghan in 1839. He was an enterprising businessman, physician, and farmer, and in addition produced salt from land he owned in southern Kentucky. He developed an intense interest in Mammoth Cave, that led to the cave becoming a world wide tourist attraction. Dr. Croghan died in 1849, leaving a will detailing future management of the cave. His estate maintained a controlling interest in the cave until 1929, when the Mammoth Cave National Parks Associaton purchased a two-thirds interest of the estate.

Mammoth Cave National Park today protects Mammoth Cave, Dixon Cave, and three smaller saltpeter caves, Martin Cave, Jim cave, and Long Cave (Grand Avenue Cavern). Coach Cave and Short Cave, outside the park boundary, were mined for

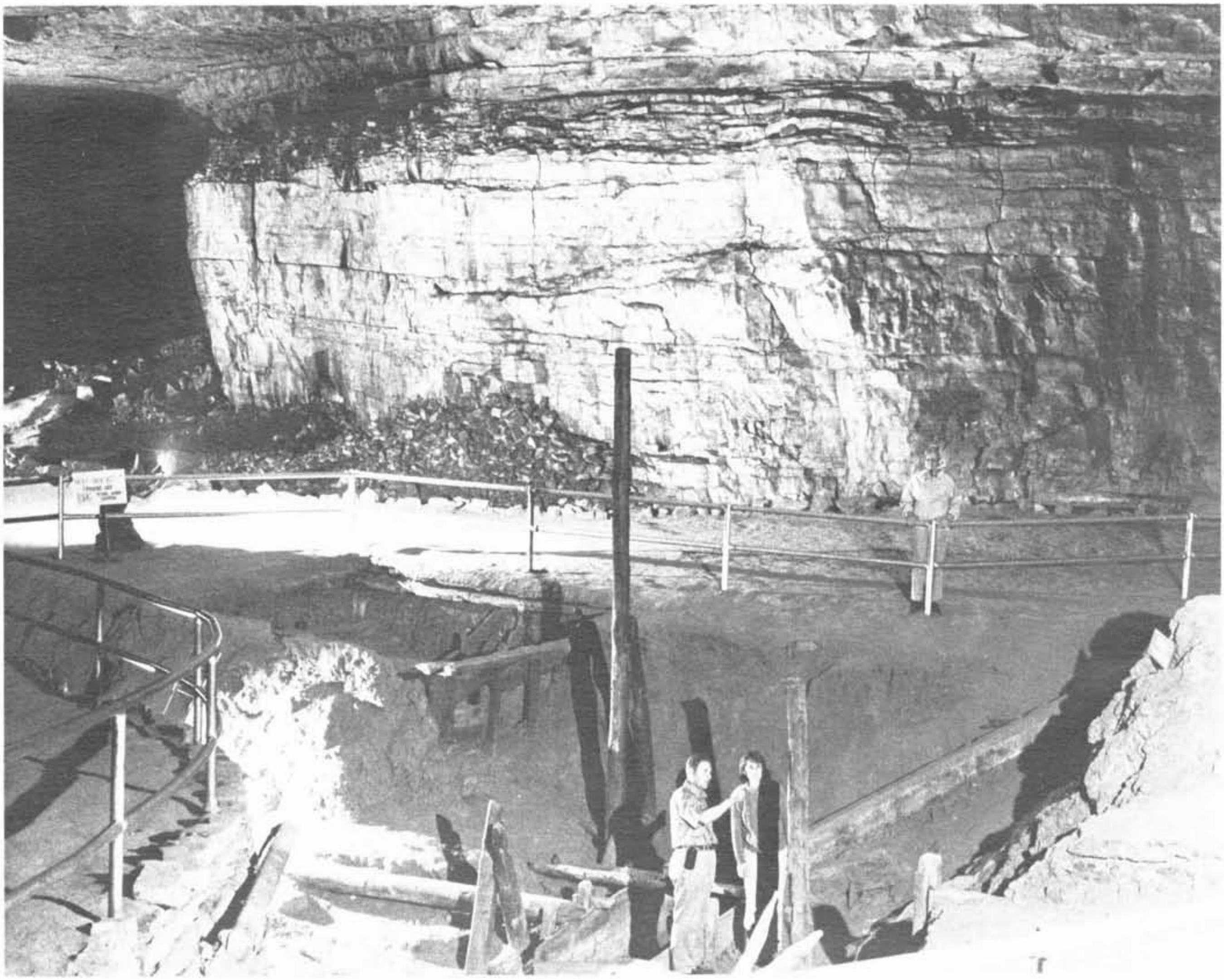

Figure 5. Rotunda saltpeterworks at Mammoth Cave. CRF Photo, R. Pete Lindsley.

saltpeter, and are intermittently shown on a commercial basis. Other caves that had limited saltpeter production exist in the Mammoth Cave Region. Only Pruett Saltpeter Cave near Bowling Green had a large-scale operation that would compare with that of Mammoth Cave and Great Saltpeter Cave. Saltpeter Cave in Carter Caves State Park, and Great Saltpeter Cave also have underground saltpeter works preserved, and are open to the public.

In 1973, the Saltpeter Group of the Cave Research Foundation addressed the challenges of the science and history of cave nitrate formation and saltpeter production. Under the leadership of Carol A. Hill and Duane DePaepe, the results of their studies were published in the "Bulletin of the National Speleological Society in October, 1981. This remains the definitive study of the scientific aspects of cave saltpeter.

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