42nd Annual Meeting of the American Institute of Professional Geologists

"Geologic Information: Racing into the Digital Age"

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The South-Central Kentucky Karst: Landscapes and Liabilities

Introduction

The South-Central Kentucky Karst, situated between the Green and Barren Rivers of south-central Kentucky, is one of the most well developed karst landscapes on Earth. Mammoth Cave, at a current surveyed length of 365+ miles, is the world's longest known cave. The cave has a vertical extent of less than 500 feet. Besides Mammoth Cave, several other great cave systems are located in the region: Fisher Ridge Cave (110+ miles), the Martin Ridge Cave System (30+ miles), Hicks Cave (20+ miles), and James Cave (13+ miles), as well as hundreds or maybe thousands of shorter ones. On the surface, many classic landforms are developed as well, such as sinkhole plains, deep karst valleys, disappearing streams, and springs.

The South-Central Kentucky Karst lies within the Mississippian Plateaus Region of south-central Kentucky (Fig. 1). It is subdivided into the Pennyroyal Plateau, typified by its vast sinkhole plains, and the Mammoth Cave Plateau, a gently dipping cuesta rising 150 to 200 feet above the Pennyroyal surface. The Mammoth Cave Plateau is capped by a series of mixed carbonate and siliciclastic units that protect the underlying limestone from rapid dissolution. These two roughly horizontal plateau surfaces are separated by the Dripping Springs Escarpment, which defines the northwest boundary of the Pennyroyal in the area we will visit (Fig. 2). The nonkarstic Glasgow Uplands, where rocks of the lower St. Louis Limestone are exposed at the surface, delimit the southeastern boundary of the Pennyroyal. An additional control over much of the hydrogeology, subterranean passage development, and landscape develop-

Figure 1. Physiographic map of Kentucky. From Kentucky Geological Survey.

Figure 2. Oblique aerial view of karst plain, escarpment, and plateau areas. View toward east. Note ponding of water in sinks.

ment in the region is the 300-foot-deep gorge that the Green River has cut into the Mammoth Cave Plateau, establishing the regional base level.

The landscape owes its nature in large part to the sequence of nearly horizontal, very pure limestones of Mississippian age, which have been divided stratigraphically (in ascending order) into the St. Louis, Ste. Genevieve, and Girkin Formations (Fig. 3). Overlying the Girkin is the Big Clifty Sandstone, also of Mississippian age (Chesterian series), which acts as a protective caprock for the Mammoth Cave Plateau. On some areas of the plateau, Pennsylvanian siliciclastics, notably conglomerate and pebbly sandstone of the Caseyville Formation, also occur. The upper boundary for major karst development, in general, is the contact between the Girkin Limestone and the Big Clifty Sandstone. The current lower limit of karst development is set by the Green River, which, in Mammoth Cave National Park, pools at the middle of the St. Louis Limestone at about 400 feet elevation. Some minor cave development also occurs in the Haney Limestone, a 40-foot-thick unit directly overlying the Big Clifty Sandstone.

We will also observe that the geologic structure has had a significant influence on landscape development. The region lies between the Cincinnati Arch to the east and the Illinois Basin to the northwest. Regional bedrock dips are generally 1° or less to the northwest. Local structural flexures also occur, and have been shown to influence the detailed development of groundwater flow in some areas of Mammoth Cave (see, for example, Palmer and Palmer, 1993). The cuesta form of the Mammoth Cave Plateau results from the steep southeast-facing scarp slope (the Dripping Springs Escarpment) and the gentle northwesterly dip of the bedrock along the plateau surface itself (Fig. 4).

Lithologic heterogeneities within the carbonate stratigraphic package, particularly thin-bedded cherts that occur near the contact between the Ste. Genevieve and St. Louis Limestones (Howard, 1968; Woodson, 1981; Groves and Crawford, 1990) have some influence on groundwater flow and cave development (see Palmer, 1991). The most prominent of these is the Lost River Chert, a nodular to bedded unit extending from southern Indiana (type section) through Kentucky and into Tennessee and northern Alabama. A short distance stratigraphically below the Lost River Chert is the Corydon "Ball" Chert, which can also be seen in some areas of Mammoth Cave, but is not exposed at the surface in the area that

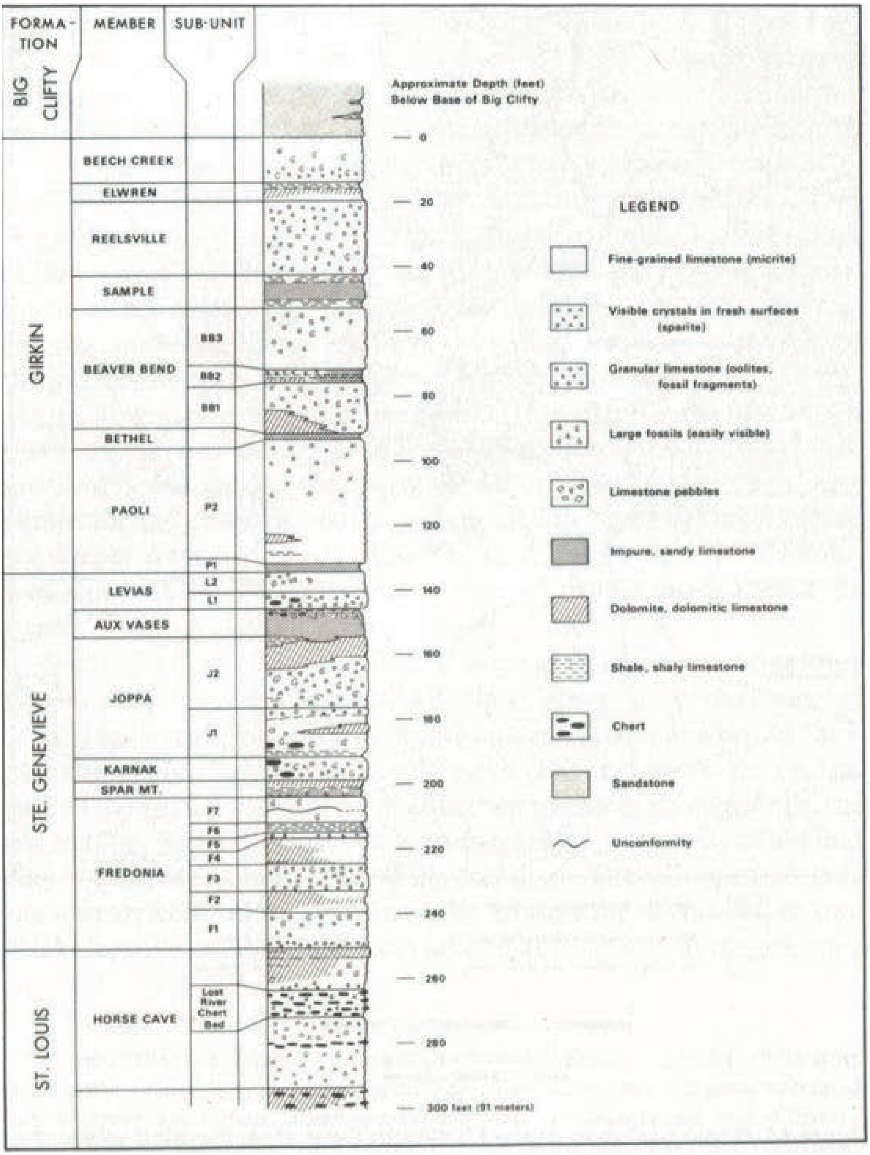

Figure 3. Stratigraphic column for rocks in Mammoth Cave National Park and adjacent area. From Palmer (1981).

we will be visiting. The location of the contact between the Ste. Genevieve and St. Louis Limestone has been identified by some workers based on the position of the Lost River Chert, but this depends on whose stratigraphic section is consulted. Rexroad (2000) suggested that conodont biostratigraphy better defines the bound-

Figure 4. Westward view from Park Mammoth overlook showing principal physiographic features of the South-Central Kentucky Karst.

ary between these two lithologically similar units. We will use the section compiled by Palmer (1981, p. 62) (Fig. 3), which places the Lost River Chert within the Horse Cave Member of the St. Louis Limestone.

Why Has the World's Longest Known Cave Developed Here?

Development of karst landscapes depends on five basic elements, and the nature of any particular karst landscape can be understood by observing the interactions among these elements. What are these elements and how are they expressed in the South-Central Kentucky Karst?

1. **Existence of a suitable body of rock.** Although karst features can develop in a variety of rock types, carbonate rocks are the most common. In this region, high-calcium limestones provide an ideal lithology for karst development because of their high solubilities in carbonic acid, and the kinetics of the resulting fluid/rock interactions. Compositional heterogeneity in the limestones, such as dolomite, clay, and other clastic impurities, is,

however, common in these units. From about the middle of the St. Louis downward (generally below base level here) the rocks contain more clastic impurities, inhibiting dissolution and karst development. The structural attitude of the rocks, as mentioned above, also is an important factor. Their gentle northwesterly dips expose a vast surface recharge area to karst processes.

2. **Existence of a suitable solvent for dissolution.** Limestones are only slightly soluble in the presence of pure water. In solutions of carbonic acid (H_2CO_3), however, the solubility increases dramatically. A basic component of H_2CO_3 is, of course, carbon dioxide. This CO_2 comes in small part from the atmosphere, where CO_2 concentrations are very low, but is primarily derived from contact with soil gas, where root respiration and microbial activity occur. Soil gas can have CO_2 pressures over 100 times that of atmospheric levels (Atkinson, 1977; White, 1988). Karst development is favored in areas of (a) abundant precipitation, (b) organic-rich soils, and (c) relatively warm temperatures supporting both vegetation and microbial communities to enhance soil CO_2. Note that although limestone solubility in carbonic acid increases with decreasing temperatures, this is a relatively minor factor and is generally overshadowed by abundant microbial CO_2 production in warm climates.

   South-central Kentucky receives an average of about 127 cm of precipitation per year, and has an average annual temperature of about 14°C. The organic material within soils provides an abundant supply of carbonic acid for limestone dissolution.

3. **A continuous fracture network within the rock body.** Paleozoic limestones of the southeastern United States, within which many great karst aquifers have formed, generally have relatively low primary (i.e., depositional) porosities. For waters to be able to penetrate the interior of rock masses and begin dissolution, a fracture network must be present. Many of these rocks, including those in south-central Kentucky, are typified by the presence of well-developed bedding planes and vertical joints (Fig. 5). Both of these provide routes that will eventually be enlarged by solutioning, forming conduits and caves. The spatial orientation of the fracture network influences the resulting geometry of the cave systems that develop (see Palmer, 1991, Fig. 16). For this reason, in the South-Central Kentucky Karst, hundreds of miles of cave passages have developed within a stratigraphic

Figure 5. Solutionally enlarged joints in limestone bedrock.

interval of less than 500 vertical feet. Bedding planes, because they tend to be more continuous than fractures, exert a greater influence over groundwater flow and cave development in the region (Deike, 1967).

4. **Hydrogeologic conditions resulting in a sufficient hydraulic gradient.** The nature of the carbonic acid/limestone interaction is such that the time scales over which the solvent typically becomes saturated are on the order of a few days (Rauch and White, 1977; Hess and White, 1988). For this reason, if groundwater cannot move into, through, and out of an incipient carbonate aquifer at a sufficient rate, the waters will quickly reach saturation and karst development will be limited (Groves and Howard, 1994). In order for water to move rapidly through the rock, a sufficient hydraulic gradient must be available. Many of the world's great karst aquifers have formed on escarpments or above river valleys where topographic relief provides a steep hydraulic gradient.

   Regionally, the Green River has incised the Mammoth Cave Plateau, carving downward through the Big Clifty Sandstone and Caseyville Sandstone caprocks, and into the underlying Girkin, Ste. Genevieve, and St. Louis limestones, establishing the base level (Fig. 6). Thus, there is a gradient from the Pennyroyal sinkhole plain through the limestones beneath the Mammoth Cave Plateau surface, downward to the Green River, allowing large subsurface drainage basins to form. These basins collect water over hundreds of square miles of the sinkhole plain and move it downgradient until it rises at a series of large springs along the Green River. Groundwater flow along the regional gradient has thus carved the world's longest cave, by slowly removing many cubic miles of bedrock from the area.

5. **Geologic time.** The development of karst requires sufficient time. Although it has been argued that the regional landscape in south-central Kentucky has reached an overall equilibrium (Hack, 1960; Palmer, 1985), the present appearance of local features must be considered within the context of time. Over time, the Dripping Springs Escarpment and the most intense zones of karst development have gradually retreated toward the northwest. There was an exact moment some millions of years ago when rainwater first touched the uppermost layers

Figure 6. Aerial view of the Green River downcutting through Mammoth Cave Plateau (photo from www.usgs.gov).

of Girkin Limestone, and there will occur a time in the future when that formation will be entirely removed from the region by dissolution. The process of forming a karst landscape is, as White (1988) has expressed, one of decay (Fig. 7). We are lucky to be here (if you consider having the world's longest cave in your back yard as being "lucky") at a time when the caprock is sufficiently dissected to allow water to enter and dissolve the underlying limestone at many locations, but still protect large areas of cave-rich limestone.

Several lines of evidence independently suggest that karst development in south-central Kentucky began in the late Tertiary or early Quaternary (Palmer, 1981, 1985; White and White, 1989). Early data documenting this history includes paleomagnetic dating of cave sediments (Schmidt, 1982), radiometric dating of speleothems (Harmon and others, 1978), and consideration of the time scales associated with limestone dissolution kinetics in carbonic acid (Dreybrodt, 1990; Palmer, 1991). Improved precision in the absolute dating of landscape evolution in the Green River Valley, including

Figure 7. Hand sample of Ste. Genevieve Limestone showing complex dissolution in three dimensions.

Mammoth Cave, has resulted from analysis of cosmogenic isotopes (Granger and others, 2001).

Hundreds of Miles of Cave Passages

During the millions of years that Mammoth Cave has been forming, the Green River has been progressively downcutting into the Mammoth Cave Plateau. The rates of downcutting have been highly variable, with relatively stable periods interspersed with rapid events. Periods of valley infilling have occurred as well. Much of this history has been unraveled by Palmer (1981, 1984, 1985) from his observations of passage geometry combined with careful stratigraphic leveling surveys through Mammoth Cave. Granger and others (2001) have added more detail with their analysis of the cosmogenic isotopes contained in cave sediments.

When the base level established by the Green River remained steady at a fixed elevation, significant limestone dissolution occurred at the water table. Over time, these stable periods allowed several distinct, well-developed cave levels to form. We will visit the major levels of the cave during our trip, the lowest being the level of active drainage where the cave is still enlarging. The various levels are well interconnected with vertical shafts and a variety of other passages, including deep, complex canyon systems and shaft drains. This vast three-dimensional network extends over many miles, indeed far beyond the boundaries of the Mammoth Cave National Park itself.

Environmental Issues of the South-Central Kentucky Karst

Groundwater Contamination. Shallow carbonate aquifers in karst areas are vulnerable to groundwater contamination from human and animal wastes, agricultural land use, urban stormwater runoff, leaking underground storage tanks, and other surface activities from industry, transportation, and agriculture. Contaminants can easily run into the aquifer along with stormwater runoff, sinking directly into caves without any filtration through the soil. Contaminants may also percolate through thin soils into the cave drainage system below. Once contaminants reach fast-flowing underground streams, they may be carried for miles through the aquifer in a matter of hours or a few days.

Water that has had contact with human and animal waste is one of the more serious pollutants in underground streams of the

South-Central Kentucky Karst. High fecal coliform bacteria and fecal streptococcus counts indicate this condition. Runoff from heavy rain washes past livestock wastes from farm land into subsurface streams at swallets. Heavy precipitation also flushes septic-tank effluent from the soil downward into underlying conduits in the limestone. In addition to septic tank effluent originating from the suburbs and rural areas, human waste enters karst aquifers from many homes in the older areas of towns and cities that were never connected to city sewers.

A Special Case for EPA's Stormwater Rule. The U.S. Environmental Protection Agency regulates the discharge of runoff from municipal and industrial areas. The general vehicle for regulation is the National Pollutant Discharge Elimination System permit. As an example, the city of Bowling Green, located west of our field trip area, is currently addressing its flooding issues and applying best management practices for improvement of its stormwater quality. The effects of urban stormwater runoff in Bowling Green have been investigated by monitoring the quality of underground streams, swallets, and springs. Contaminants that typify these karst streams include fecal coliform bacteria, gasoline, oil, lubrication grease, chromium, and lead. Other water-quality issues include low levels of dissolved oxygen and high levels of total dissolved solids. Measurements of elevated specific conductance, reflective of high TDS, and measurements of high turbidity unfortunately characterize many streams in the South-Central Kentucky Karst, especially after heavy rains.

The city of Bowling Green (nearly 50,000 population) and smaller cities with standard municipal services such as water and sewer are presently faced with increased costs of stormwater compliance. The EPA is now moving to remedy runoff or stormwater pollution from smaller municipalities classified as Phase II cities. Phase I cities, by comparison, include the large metropolitan areas of the United States, and these were the initial focus of the EPA clean-up effort. EPA's stormwater Phase II Final Rule (EPA, 2000a) focuses on what are known as municipal separate storm sewer systems (designated MS4). Because of its karst terrain, Bowling Green may have to double its current $1 million annual budget for stormwater issues in order to reach compliance under the Phase II Rule. Much of this expenditure is going toward flooding issues (handling high quantities of water), but the city will have to increase its efforts in dealing with water-quality issues as well. This increased expenditure is a conservative estimate in the short term and addresses only a 5-year plan approved by EPA permit in March of 2003.

Long-term issues will also have to be dealt with, and in karst these may prove to be quite expensive. There is the potential for multimillion dollar stormwater and water-quality projects to be managed in the near future. As an example, as of 2003, Bowling Green had 217 miles of city streets and more than 800 injection (dry) wells or swallets/sinks, but only 23 miles of storm sewers. Quick inspection of these numbers suggests that just over 10 percent of the city's streets have engineered storm sewers to handle runoff, while nearly 90 percent of them allow polluted water to flow untreated into the subsurface. The natural subsurface conduit system then carries this contaminated water to springs located at major surface streams such as the Barren River. Thus, the presence of karst complicates the stormwater issue for Bowling Green, where polluted stormwater becomes polluted groundwater and upon rising at springs, these waters pollute surface waters downstream.

Use of best management practices is a possible solution to remedy polluted stormwater drainage and is a starting point for meeting the Phase II small MS4 program requirements. Examples of BMP's include installing grass strips around dry wells and swallets, putting up silt (or sediment) fences at construction sites, and installing filtration systems in discharge areas such as around parking lots or commercial developments. The goal of the program is to reduce the discharge of contaminated water to the maximum extent possible, to protect water quality, and to abide by the Clean Water Act. Another aspect of the Phase II rule is to conduct public education and outreach as a minimal control measure for stormwater (EPA, 2000b) and to communicate to construction companies about controlling runoff from excavated sites (EPA, 2000c). There are additional provisions for the Storm Water Rule, but these will not be discussed here. The education and outreach portion of the program has been challenging for karst areas because of the sensitive nature of aquifers. The public, however, is now beginning to realize that drainage from every residential, commercial, and industrial property or thoroughfare either helps or hinders the goal of compliance with the CWA.

Sinkhole Flooding. The flooding of sinkholes in karst regions is a part of the natural hydrologic system (Fig. 8). Flooding, exacer-

Figure 8. Aerial view of sinkhole flooding in Warren County, Ky. Photo courtesy of Dr. Nick Crawford, Center for Cave and Karst Studies at Western Kentucky University.

bated in urban areas, occurs during periods of intense rainfall, usually of short duration: (1) when the quantity of stormwater runoff flowing into sinkholes exceeds their outlet capacities and they cannot drain into underlying caves fast enough to prevent ponding, (2) when the capacity of the cave system to transmit stormwater is exceeded, and the water is retained on the surface in sinkhole basins, and (3) during even a relatively minor storm, if the water table is already high (see Crawford, 1984). Unfortunately, in the South-Central Kentucky Karst, houses have been built in these natural storage areas (sinkholes). The problem has been greatly aggravated by increased runoff resulting from urban development and the filling of sinkholes by developers.

The Problem of Modified Surface Drainage. The city of Bowling Green, as noted above, has installed hundreds of stormwater drainage wells to allow surface water to sink into the ground more easily (Crawford and Groves, 1984). These wells are normally located in sinkhole bottoms, along drainage ditches or ephemeral streams leading to sinkholes, and in stormwater retention basins. These so-called "dry wells" are associated with a number of environmental problems (Crawford and Groves, 1995), including surface collapses. Drilled wells vary in diameter from 6 to 12 inches, and are generally less than 100 feet deep. They are usually cased to bedrock with standard steel well casing, although galvanized culverts are sometimes used. The annular space between the hole and the casing is rarely, if ever, properly grouted and sealed with concrete, and generally no attempt is made to seal the casing at the regolith-bedrock contact. As a result, scores of collapses have occurred adjacent to these wells (Crawford, 1982; Crawford and Groves, 1995); see Figure 9, for example. It is hypothesized that there is often a large void where the casing rests on the irregular bedrock surface, and water flowing from the well saturates the surrounding regolith. The saturated regolith is piped downward, away from the well, causing a large void to develop. This is known as a "regolith arch," and it continues to expand upward during floods until it eventually collapses from the surface (Crawford, 1982). At a larger scale, modifying surface drainage around construction sites can have catastrophic results, as shown by the February 2002 collapse

Figure 9. Surface collapse around dry well in Bowling Green, Ky. Hole is approximately 5 feet deep.

of the Dishman Lane roadway in Bowling Green, which cost about $1 million to repair (Fig. 10).

Large Industrial Site. Another environmental concern in the Mammoth Cave region is the proposed Kentucky Trimodal Transpark, which entails siting a 4,000-acre air-, rail-, and truck-terminal facility and associated industrial park on the karst plain less than 8 miles from Mammoth Cave National Park near Bowling Green. A large automotive parts plant has already been constructed at the site, and more heavy industry is being encouraged to locate there. The siting of such a large facility has been controversial because no geology was considered during the siting process. The location was preselected and ultimately chosen through an inadequate review process largely based on nonscientific criteria.

Key geological issues were ignored or downplayed in the site-selection process for the Transpark. The LawGibb report (2001) included a preliminary environmental assessment that contained fundamental misconceptions about the nature of karst terrain. One misunderstanding was that arrows indicating the general direction of groundwater flow on a topographic map were misinterpreted by the engineers as being actual caves or conduits. In reality, the dye-trace studies upon which these arrows are based (Quinlan and Ray, 1981) are much more generalized and do not indicate specific flow paths or the actual location of well-developed cave systems across

Figure 10. February 25, 2002, collapse of Dishman Lane over State Trooper Cave in Bowling Green, Ky.

the site. Many of these caves are at multiple levels and weave in and out of each other in a wonderful display of complexity.

Another misinterpretation concerns the fact that the Transpark site straddles the contact between the Mississippian St. Louis and Ste. Genevieve limestones. The southern part of the site is riddled with sinkholes in the classic St. Louis style. In the northern part of the site, the Ste. Genevieve is exposed but displays fewer, albeit much larger, coalesced sinkhole basins. These large sinkhole basins in the Ste. Genevieve typically contain numerous small swallets. The engineers, however, counted a large basin only as one sinkhole. Proponents of the Transpark have stated that a lower number of sinkholes per unit area equates to a safer building site relative to engineering costs and groundwater protection. But the key issue here is that the Ste. Genevieve may have fewer sinkholes per unit area compared to the St. Louis, but the catchment areas for these sinkholes are much larger. It is well known that cave systems are well developed within the Ste. Genevieve. By simply counting the number of sinkholes, engineers assembled some numbers for assessing the geohazard risks for the Transpark site. They suggested that karst, which most geologists recognize as a "stealthy" geohazard (see, for example, Cobb and Currens, 2001), is minimized in the Ste. Genevieve because of this. Karst geologists know that this is not true.

Another critical concern regarding water quality is the potential for releases of DNAPL's (dense nonaqueous phase liquids)—organic solvents such as degreasers typical in train, truck, and air terminals—and LNAPL's (light nonaqueous phase liquids)—typically fuels—into the karst aquifer. What has been established for the Transpark site is that groundwater will quickly migrate to surface streams, in this case the Barren River, in which threatened and endangered mollusks and other fauna live.

Air Pollution. Other environmental concerns in the Mammoth Cave area center around air pollution, especially that from coal-fired electric power plants. A major concern is mercury deposition, which has resulted in a statewide fish consumption advisory. Bats in the park have been found with elevated mercury levels as well. Other air issues include acid precipitation, increased particulate matter, and excessive ground-level ozone, particularly during summer months. Ground-level ozone and particulate matter are chiefly responsible for degrading visibility, making Mammoth Cave one of the most affected parks for scenic viewing. The natural visibility, estimated to be 113 miles, is reduced to only 14 miles during these months (Simpson and Simpson, 2004).

Field Trip Log

Part 1: Overlook at Park Mammoth Resort

Stop 1. Here, atop the Dripping Springs Escarpment, we will have a brief discussion of the geomorphic, stratigraphic, and structural features of the field trip area of the South-Central Kentucky Karst. This is an excellent photo stop because it affords a view of regional physiographic and geologic features.

We are standing on the edge of the Dripping Springs Escarpment (Fig. 11) at about 800 feet elevation and looking west-southwest across the Pennyroyal Plateau (or sinkhole plain). The escarpment demarcates the boundary between the sinkhole plain and the Mammoth Cave Plateau. At this location, local topographic relief ranges from 200 to 250 feet. Pilot Knob (6 miles away), at 950 feet elevation, and Little Knob (8 miles away), at 770 feet elevation, are two prominent outliers that tower above the sinkhole plain. An aerial view of the karst plain (Fig. 12) near our present location shows a high density of sinkhole development. The caprock of the plateau, in contrast, has few sinkholes and supports surface-water flow and ponding (for example, Sloans Pond in Mammoth Cave National Park).

Regional structural dip of the rock units is to the north, and varies from less than 1° to a few degrees. Our view to the southwest, therefore, is both updip and downsection. The sinkhole plain has

Figure 11. View from Park Mammoth overlook (stop 1) westward along the Dripping Springs Escarpment.

Figure 12. Oblique aerial view of Pennyroyal (sinkhole) Plain near stop 1. View to south. Photo courtesy of the National Park Service.

developed on two carbonate units, the upper St. Louis Limestone and the Ste. Genevieve Limestone (Meramecian-Chesterian series). Exposed almost entirely in the slope of the Dripping Springs Escarpment is the overlying Girkin Formation (Chesterian series). The Girkin is quarried extensively in the area, and some quarry operations can be seen along our traverse. The Big Clifty Sandstone Member of the Golconda Formation and younger units of Chesterian age mainly comprise the caprock of the Mammoth Cave Plateau. Farther north, the plateau is capped by basal Pennsylvanian Caseyville Formation, comprising sandstones and conglomerates.

The surface and subsurface flow of water is to the north, toward the Green River, which serves as regional base level. Flowing toward us then, surface streams will sink as they reach the southeastern edge of the Pennyroyal sinkhole plain. At our location, these streams flow underground, well below the escarpment. The Mammoth Cave Plateau supports surface flow except in places where clastic units have been breached by erosion, exposing the underlying limestones and creating closed, karst valleys.

Part 2: Karst Plain Traverse

We will traverse over the sinkhole plain following the map provided in Figure 13.

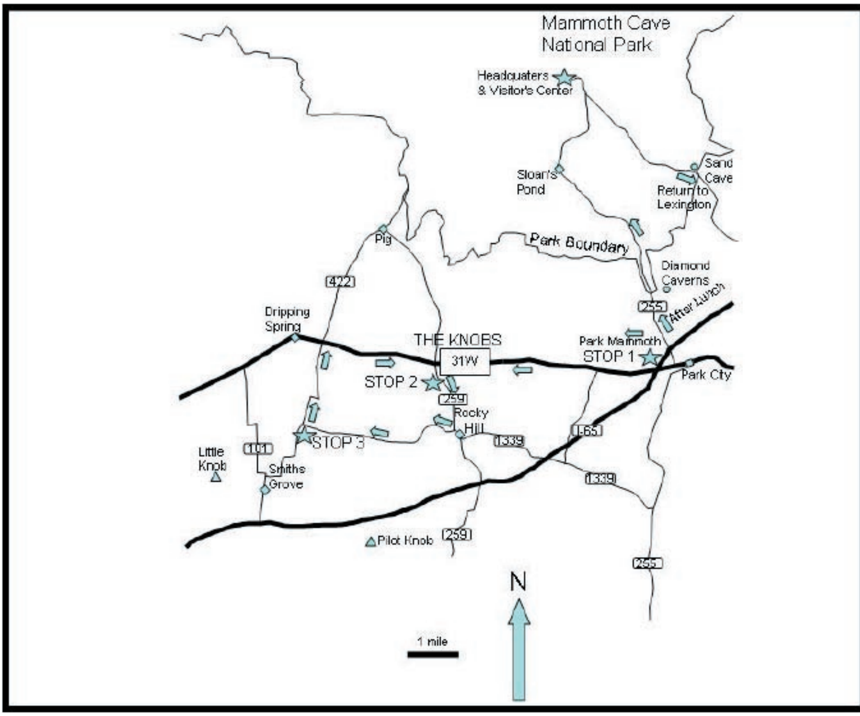

Figure 13. Area map of field trip stops.

Mileage *Interval*	*Total*	
0.0	0.0	Leave Park Mammoth Resort . Turn right (south) onto U.S. 31-W.
4.4	4.4	Turn left onto Ky. 259 south.

Stop 2. Road turns to the left with stop at gravel pullout on right. From this stop we will view karst plain features such as sinkholes and sinkhole ponds (Fig. 14) and the Dripping Springs Escarpment. One thing to discuss at this stop is whether the pond in view down the slope represents the local water table. Past this stop over the next few miles be sure to note the up-and-down nature of the roads, the relief within sinkhole basins, and the width of "divides" between individual sinks. You will see that some sinks have water at great depth (70 or 80 feet) while others

Figure 14. Sinkholes and sinkhole pond visible at stop 2.

		have water up near the ridge crest or the road we will be traversing.
1.6	6.0	Turn right at the Rocky Hill Baptist Church in Rocky Hill, onto Rocky Hill School Road.
2.8	8.8	To the north from Rocky Hill School Road is an excellent view of the escarpment in the distance and the rolling karst plain in the foreground typical of the St. Louis Limestone (Fig. 15).
4.4	13.2	Note on the north side of the road (to your left) the beginning of a uvala (collapsed cave roof forming a valley) that extends for 2,900 feet to stop 3. Here we will take a longitudinal or "down-valley" view of this feature. The uvala has a maximum topographic relief of more than 90 feet on its east end. Also note the general flatness of the topography farther to the east. This is caused by a confining layer near the surface that partially protects the underlying karst features in this locale. This uvala was formed where the

Figure 15. Rolling karst plain developed in the St. Louis Limestone with escarpment and plateau in the background. View to north.

		confining layer was breached, resulting in total dissolution of the cave roof.
0.5	13.7	**Stop 3.** At T-intersection with Upper Smiths Grove Road. Examine the uvala (Fig. 16). Turn right onto Upper Smiths Grove Road
2.0	15.7	T-intersection with U.S. 31-W. Turn right (north). Traverse back to Park Mammoth Resort.
6.5	25.1	Arrive at Park Mammoth Resort for lunch. After lunch we will travel to Mammoth Cave National Park Visitors' Center.
0.0	0.0	Turn left (east) on U.S. 31-W.
0.2	0.2	Barren County line.
0.4	0.6	I-65 underpass.
0.5	1.1	Junction with Ky. 255. Turn left (north) on Ky. 255.
0.3	1.4	I-65 underpass.
0.5	1.9	Entry sign at Mammoth Cave National Park (Fig. 17).
0.8	2.7	Diamond Caverns show cave on right.

Figure 16. View looking down trend of a large uvala at stop 3. View to east.

1.1	3.8	T-intersection with Ky. 70. Turn left (north).
2.4	6.2	Sloans Pond on left—evidence of confining layers atop the Mammoth Cave Plateau. Pond is within siliciclastic units forming the caprock for the extensive Mammoth Cave and Flint Ridge Systems.
0.3	6.5	Fresh roadcut of crossbedded Big Clifty Sandstone on left. Descend below caprock through first limestone exposures of the Girkin in the Park. Continue to Visitors' Center.
3.0	9.5	Mammoth Cave National Park Visitors' Center (Fig. 18).

Part 3: Walking Tour of Mammoth Cave

After we arrive at the Mammoth Cave National Park Visitors' Center, we will spend a few minutes to examine maps and literature, and to prepare to enter the cave. Our geological tour of Mam-

Figure 17. Entry sign to Mammoth Cave National Park.

Figure 18. Visitors' Center at Mammoth Cave National Park.

moth Cave will be led by Joe Meiman, Park Hydrologist. Refer to the detailed guide that follows.

Egress from Mammoth Cave Visitors' Center to I-65 northbound.

Mileage Interval	*Total*	
0.0	0.0	Depart Visitors' Center and continue to the second intersection. This is marked by a flashing yellow light.
1.5	1.5	Turn left at the intersection toward Cave City. This is East Entrance Road.
2.8	4.3	Pass Sand Cave on left. This cave became famous because of Floyd Collins being trapped there in the mid 1920's. Floyd's unfortunate situation was chronicled by the national media, including his eventual death after failed rescue attempts.
0.1	4.4	Park boundary.
1.3	5.7	Ky. 255 junction with Ky. 70—continue straight ahead.
3.5	9.2	Junction with I-65 North—turn left onto ramp, merge, and continue back to Elizabethtown and then east on the Bluegrass Parkway to Lexington for the icebreaker.
		End of roadlog.

Guide to the Historic Tour Area of Mammoth Cave

The Cave's Original Entrance

Much of the geological interpretation in the cave, especially the detailed stratigraphy we will discuss, comes from the extensive work of Art and Peg Palmer, and Art's book, *A Geological Guide to Mammoth Cave National Park* (1981), is highly recommended to anyone interested in pursuing the subject further.

We will enter the cave through the original, or Historic Entrance. A map of our route through the cave appears as Figure 19. Although the cave was reputed to have been discovered by a local hunter named Houchens in the late 1700's (either while chasing or being chased by a wounded bear, depending on who tells the story), it is clear that ancient residents of Kentucky used the cave as early

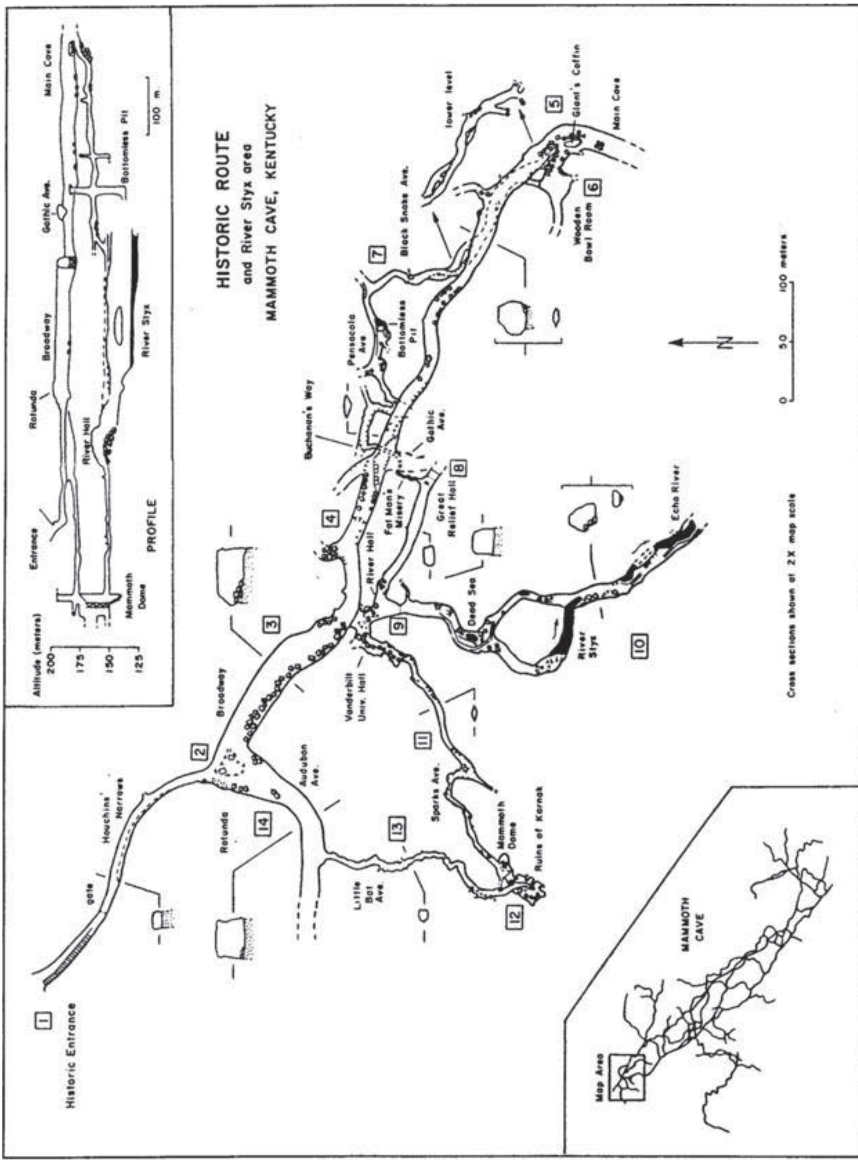

Figure 19. Map of Historic Tour portion of Mammoth Cave (from Palmer, 1981).

as 4,000 years ago. This interpretation is based on ages determined for artifacts retrieved from the cave system (Watson, 1969). These early visitors entered the cave for a variety of reasons, including the mining of sulfate minerals such as gypsum ($CaSO_4 \bullet 2H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), and mirabilite ($Na_2SO_4 \cdot 10(H_2O)$); the use of the cave for shelter or sport; or perhaps they were spurred by the same curiosity that motivates present-day cave explorers.

Mammoth Cave was first shown commercially in 1816, and since then has been open for tourists on a continual basis. Sporadic exploration of the cave system occurred throughout the 1800's and early 1900's. The cave passages we will visit were known by about the 1870's. Those passages beyond the Bottomless Pit were discovered about that time by the famous guide (and slave) Steven Bishop. Steven reportedly crossed over the gaping chasm on a cedar pole with a paying customer who had wanted to go where "no man had gone before." He went on to make a number of discoveries along this route, including Echo River with its blind fish, Great Relief Hall, and the area he was to call his greatest find, Mammoth Dome.

The modern era of exploration in the park began in the late 1940's with a small group of cavers who started a systematic exploration of the caves on Flint Ridge, just to the east of Mammoth Cave. As time went on, these caves became integrated one by one and it was revealed that another great cave system, rivaling Mammoth Cave in extent, lay under that ridge. A growing group of cavers formed the Cave Research Foundation, an organization devoted to the exploration and scientific study of the area's caves, which was able to cooperate with the National Park Service, who up to that time had not supported significant cave exploration. By the late 1960's, the Flint Ridge Cave System reached a surveyed length of more than 90 miles, and a new challenge loomed before the explorers: if a connection could be made beneath the large karst valley that separates these two great cave systems, the two would be joined, making a cave system that would for all time be unrivalled as the world's longest.

Following a great deal of effort and difficult exploration by a number of dedicated cavers, a group of seven entered Flint Ridge on the morning of September 8, 1972. After a long, grueling trip through several miles of low, wet passages beneath Houchens Valley, they emerged early the next morning from a low passage into Echo River and onto the tourist trail in Mammoth Cave. The "Everest" of speleology had been conquered! Since that day, the Flint Ridge–Mammoth Cave System has held its place in the record books as the world's longest. At the time of the connection, the known length of the cave was 144 miles, but today the cave encompasses more than 365 surveyed miles. Borden and Brucker (2000) suggested that there may be hundreds of additional miles to map in the system. Other large caves nearby are currently being explored and surveyed, and will possibly be integrated into the main system as time goes on. How long will the Mammoth Cave System ultimately prove to be? No one can say for certain, but the notion of a 500-mile-long cave system is plausible.

As we descend the hill toward the Historic Entrance we will pass the contact between the Big Clifty Sandstone and the underlying Girkin Limestone. It is within the lower Girkin that we enter the cave, but parts of the cave are developed within the Ste. Genevieve and St. Louis Limestones. A detailed stratigraphic section of these units (Palmer, 1981) is shown in Figure 3.

Rotunda

After passing through the entrance area known as Houchen's Narrows, the Rotunda is the first large room encountered in the cave, and is in fact one of the larger rooms in the system. In the stratigraphic sense, this is one of the higher passages in the cave. The walls here are carved primarily from the Paoli Member of the Girkin Limestone (Fig. 3). The recessed niche of silty gray limestone near the floor toward Audubon Avenue (the large passage winding away to the right) is the P1 unit of the Paoli, which forms the base of the Girkin.

The excavated area in the center of the room is the remains of a large saltpeter mining operation that was active in the cave during the War of 1812. The dirt in the cave was leached for the compound calcium nitrate, which was then mixed with wood ashes to form potassium nitrate. This saltpeter was used in the manufacture of gunpowder. Although mining ended here just after the War of 1812, other caves in the southeastern United States were used as a major source of saltpeter during the Civil War when the Confederate Army was unable to get gunpowder from Europe. Artifacts here are completely original; the cave has been preserved just as it was at the end of the mining activities.

What a horrifying experience it must have been for the miners in the cave during the New Madrid earthquakes of 1811–12! George and O'Dell (1992) have collected a series of stories handed down about the event, and although no deaths were reported, there was considerable concern as the miners went running from the cave, screaming for their lives. The manager of the mining operation was unfortunately fired not long after the earthquake because he was not willing to set foot back in the cave. There is also evidence that the mining works were substantially damaged in the event.

In January 1994, during the extreme cold snap that gripped the central United States, a large slab of the cave roof crashed down on the tourist trail and crushed part of the saltpeter works (Fig. 20). The slab was about 70 feet long by 20 feet wide, and about 1 foot thick, with an estimated weight of approximately 100 tons. Fortunately, the cave was closed at the time because of the winter storm outside, which had closed the entire park as well as Kentucky's highway system. The cause of the roof fall seems to be related to the cold weather, which reached a low of –16°F during the period; temperatures in the Rotunda fell well below 0, and a strong wind was blowing in through the cave passages. This is the only known large rockfall within the developed part of the cave during its 189 years of operation.

Booth's Amphitheater

As we wind down Main Cave to the left of the Rotunda, we begin to move stratigraphically down into the Ste. Genevieve Limestone, walking in the paleo-upstream direction (Fig. 21). Note that we are only seeing the highest parts of these passages, which are filled with up to 80 feet of sediment in places (Palmer, 1981). Booth's Amphitheater (Fig. 22) has formed at the intersection of Main Cave with Gothic Avenue above. Gothic Avenue is the oldest known passage in Mammoth Cave Ridge. It began to form some time prior to 1 million years before the present, by draining water from the ancestral Houchens Valley toward the Green River (Palmer, 1981).

The localized, black, sooty deposits near the ceiling have resulted from years of "torch throwing," where guides would fling tied bundles of kerosene-soaked rags onto high ledges to create an unusual illumination. This practice was discontinued in 1991 for environmental reasons. The walls in this part of the cave, in fact, are dark in general, which may be the result of soot from thousands of years of cane-reed torches used by the aboriginal visitors who mined sulfate minerals in this area (Watson, 1969). Organic acids are present in the mineral coatings (Quinlan and Traverse, 1967), and the dark material seems to preferentially occur on gypsum crusts.

Figure 20. Damage to saltpeter mining artifacts from rockfall in January 1994.

Giant's Coffin

At this point on the trip we will turn into a smaller passage on the right at Dante's Gateway, descending down through the Fredonia Member of the Ste. Genevieve Limestone. Giant's Coffin is the very large breakdown block behind which we will begin our

Figure 21. View in the paleo-upstream direction, Main Cave.

Figure 22. Booth's Amphitheater, at the intersection of Gothic Avenue and Main Cave.

descent. As we make our way down, we will pass through a more complex configuration of smaller passages, which formed during the early or middle Quaternary (Palmer, 1981).

The elliptical passage through which we will travel is Black Snake Avenue (Fig. 23), and its shape suggests that it was formed mostly during phreatic conditions. As the Green River went through a relatively stable period during this time, such passages are very common in the cave system at this level. Some of these passages stretch continuously for miles.

Black Snake Avenue eventually winds close to the edge of Mammoth Cave Ridge, and in this area we will pass a number of dome-pit complexes. On the surface, at points along the edge of the Big Clifty Sandstone, water can make its way into the subsurface. This water is typically undersaturated with respect to calcium carbonate, so it can easily dissolve the limestone and form these shafts. The vertical shafts only coincidentally intersect the horizontal passage along which we are moving. If the conditions are relatively wet, water can be seen at the bottom of Bottomless Pit. We are getting lower in the cave—the water at the bottom of this shaft is level with the Green River, thus representing the local base level.

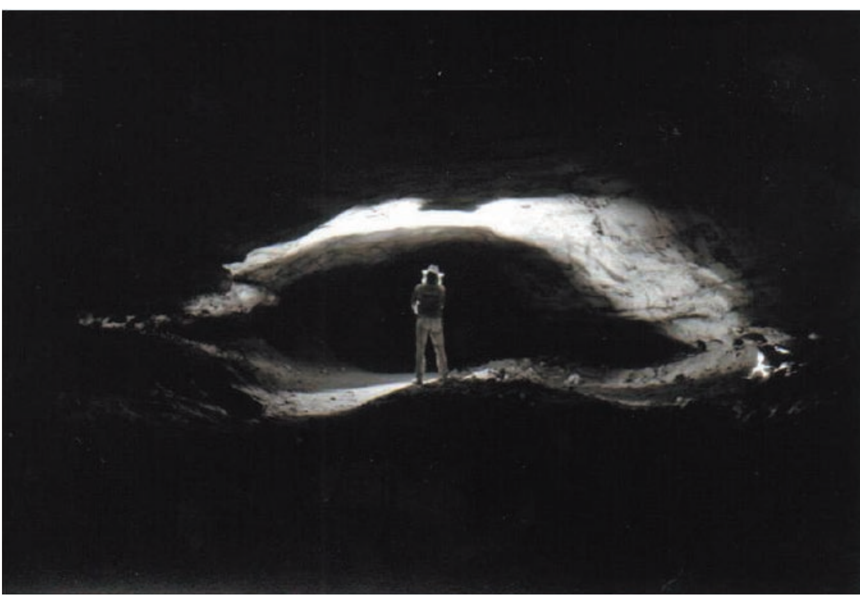

Figure 23. Black Snake Avenue, an elliptical passage whose shape suggests it was filled with water during its formation.

Great Relief Hall

After passing through Fat Man's Misery (Fig. 24) we reach Great Relief Hall, where we will take a break. Emerging from Fat Man's Misery, we enter the passage that Steven Bishop called "Relief Hall." Since the addition of restrooms by the National Park Service, it has been known as Great Relief Hall.

We are moving lower within the Ste. Genevieve, and as we walk toward River Hall we eventually come into the top of the St. Louis. Great Relief Hall is formed within the Fredonia Member of the Ste. Genevieve.

River Hall

At this point, we reach the lowest major level of the Mammoth Cave system, where the cave is actively developing. At River Hall, we will rest and then take a trip down the passage toward the left, which leads to Echo River. This trail is not currently maintained for tourists by the National Park Service because the passage is prone to flooding.

In River Hall, the contact between the Ste. Genevieve and the underlying St. Louis is visible at the top of a prominent ledge near the ceiling (Palmer, 1981). Throughout the passage to Echo River

Figure 24. Fat Man's Misery, a small, keyhole-shaped passage.

we will be at this contact, but sediment on the walls obscures much of the lithologic detail.

Dead Sea

The Dead Sea represents the present base level of the Mammoth Cave system (Fig. 25). It continues as a pipe-full canyon passage to Echo River Spring. At a slightly higher elevation, the River Styx flows to the Dead Sea and finally to Styx Spring. Prior to rapid downcutting of the Green River during the Pleistocene, all flow was through the River Styx. Following the entrenchment of the Green River, flow was diverted to Echo River Spring, and thereafter flow reached the River Styx only during floods. Post-Pleistocene backfilling of the Green River channel caused an elevation of the regional base level, approximating that prior to the Pleistocene. Today the pre-Pleistocene route of the River Styx and the Pleistocene route of Echo River are both active as flow distributaries.

Mammoth Dome

This dome is among the largest of the hundreds known in the cave system. The associated vertical shafts provide routes connect-

Figure 25. View of the Dead Sea, which represents the lowest level within Mammoth Cave. Water levels here closely match those of the Green River.

ing different stratigraphic levels of the cave system. Explorers and surveyors working in the cave must become proficient at moving up and down ropes in order to negotiate these places. Sometimes the drains at the bottom of these shafts can be explored to lower levels, but quite often they are wet and contain breakdown or sediment.

Upon reaching the top of the dome via the fire-tower steps, we pass through Little Bat Avenue (which was once the drain for water flowing from the upper level to Mammoth Dome) and eventually rise into the Girkin Limestone at Audubon Avenue. A short hike to the right brings us back to the Rotunda, where we began our trip.

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Dr. Kenneth W. Kuehn is a professor of geology at Western Kentucky University, where he has been employed since 1984. He earned his Ph.D. from Penn State University in 1981, specializing in regional stratigraphy, fossil fuels, and geostatistics. Over the past 25 years he has consulted widely for government and industry. Active in research and publication, Dr. Kuehn endeavors to integrate classroom, laboratory, and field experiences. In 2002 he was honored as a University Distinguished Professor for his long-term contributions to teaching, research, public service, and the geology profession.

Dr. Chris Groves is a professor of geography and director of the Hoffman Environmental Research Institute at Western Kentucky University. As a recipient of the Phillip Francis DuPont Fellowship at the University of Virginia, he earned a Ph.D. in environmental sciences there in 1993. With his students and colleagues he has since developed an active research program in the geochemistry and hydrogeology of karst landscape/aquifer systems, as well as in global issues of water supply and environmental health. Dr. Groves has collaborative water research projects under way in California, Alaska, China, and Vietnam. He is a member of the China Environmental Forum at the Woodrow Wilson International Center for Scholars in Washington D.C., and serves as project leader for the United Nations scientific program, Global Study of Karst Aquifers and Water Resources, coordinating communication in related research activities of colleagues from 35 countries. In 2004 he was elected, and currently serves as, president of the Cave Research Foundation.

Mr. Joe Meiman is the hydrologist at Mammoth Cave National Park and an adjunct faculty member in the Department of Geography and Geology at Western Kentucky University. Since earning B.S. and M.S. degrees in geology from Eastern Kentucky University he has had more than 20 years of experience designing and implementing specialized systems for monitoring karst groundwater flow, cave atmospheres, and troglophilic fauna. He has developed hydrologic monitoring systems throughout the United States, concentrating recently on water quality within the Mammoth Cave International Biosphere Reserve.

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