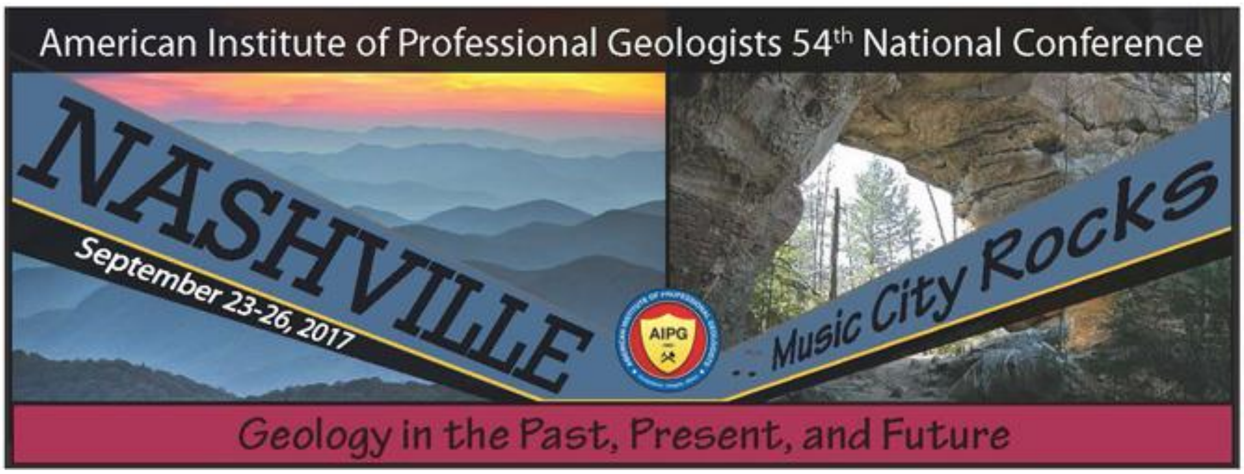
54th Annual Meeting of the
American Institute of Professional Geologists



Karst Geomorphology and Environmental Geology of the Mammoth Cave Region, South Central Kentucky

Field Trip, Sunday, September 24, 2017

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Hosted by
Tennessee Section of the American Institute of Professional Geologists
September 23-26, 2017
Nashville Airport Marriott Hotel
Nashville, Tennessee

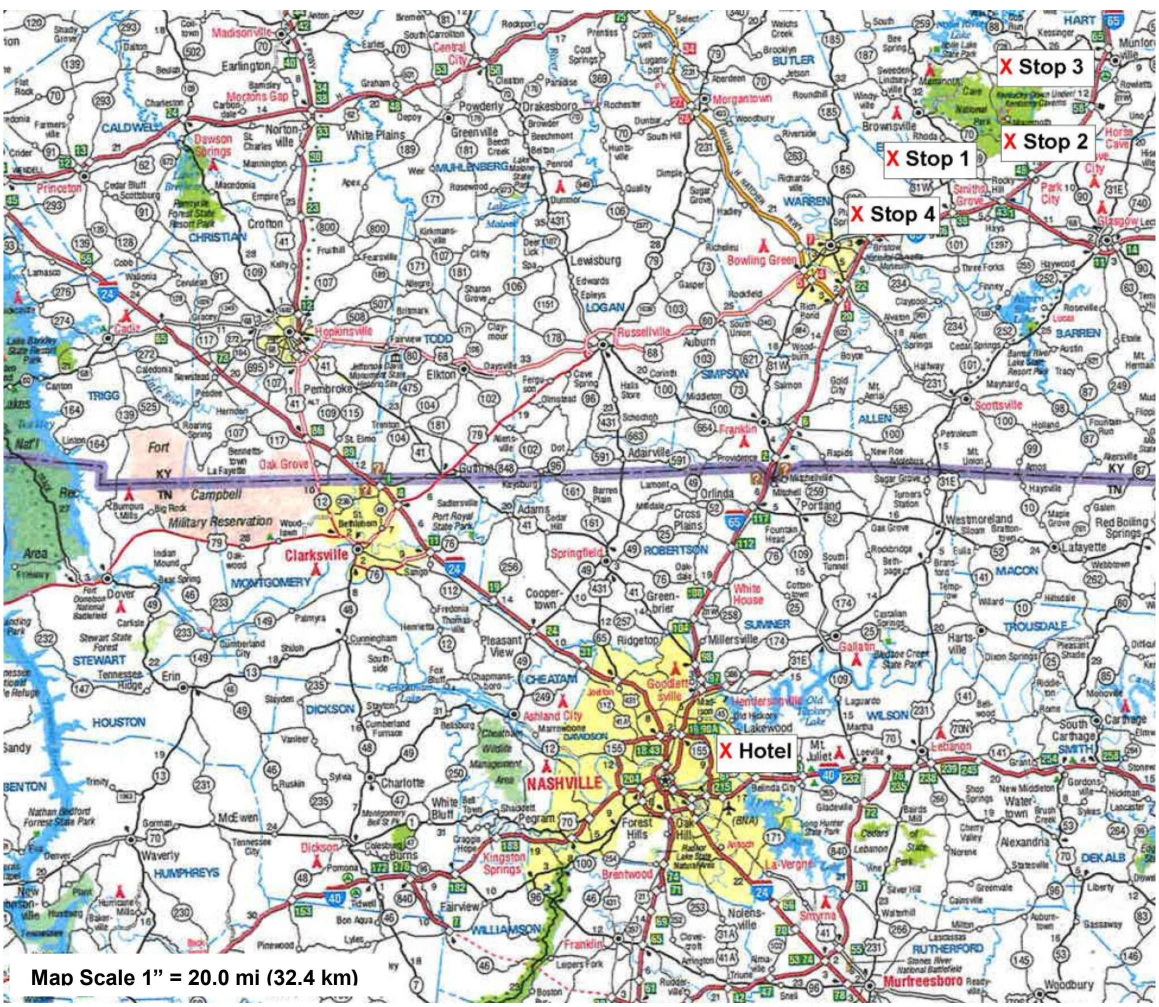
Photographs of Mammoth Cave National Park (Courtesy U.S. National Park Service).

Photographs of selected area attractions and accommodations for those seeking nostalgia or needing to add to their bucket list.

Field Trip Itinerary (All times Central Daylight Time)
Sunday, September 24, 2017

7:30 a.m. Depart Nashville Airport Marriott Hotel, Nashville, TN
7:30 a.m.-9:00 a.m. En route to Smiths Grove, KY
9:00 a.m. -10:00 a.m. Stop 1. Crumps Cave, Smiths Grove, KY
10:00 a.m.-10:15 a.m. En route to Park City, KY
10:15 a.m.-11:00 a.m. Stop 2. Park Mammoth Resort Overlook, Park City, KY
11:00 a.m.-11:30 a.m. En route to Mammoth Cave, KY
11:30 a.m.-3:00 p.m. Stop 3. Mammoth Cave National Park, Mammoth Cave, KY
- 11:30 a.m.-12:30 p.m. Private Lunch Buffet at Rotunda Dining Room
- 12:30 p.m.-2:30 p.m. Historic Entrance Cave Tour
- 2:30 p.m.-3:00 p.m. Visitor Center Museum and Gift Shop (on your own)

3:00 p.m.-3:45 p.m. En route to Bowling Green, KY
3:45 p.m.-5:00 p.m. Stop 4: National Corvette Museum, Bowling Green, KY
5:00 p.m.-6:00 p.m. En route to Nashville Airport Marriott Hotel, Nashville, TN



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Acknowledgements

The authors gratefully acknowledge the technical contributions by Dr. Jason S. Polk of the Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky. In particular, Dr. Polk provided an electronic copy of his geotechnical report "Cars and Karst: Investigating the National Corvette Museum Sinkhole" published in the 2015 Proceedings of the Fourteenth Multidisciplinary Conference through the National Cave and Karst Institute Symposium, and he also provided written communications regarding the details of geotechnical investigations performed prior to museum construction and during the exploration of the Skydome collapse sinkhole.

Introduction

The term “karst” has traditionally been used to refer generally to regions of exposed soluble bedrock having an abundance of surface landforms, such as sinkholes, sinking streams, and springs, that reflect the presence of subsurface voids or caves (Ford and Williams, 2007). However, during the last few decades, a distinction has been made between karst features that represent surficial (*epigenic*) solutional processes and karst features that reflect deep-seated (*hypogenic*) solutional processes, both of which result in bedrock voids (Palmer, 1991). Consequently, usage of the term “karst” has broadened, as recognition of karst features existing deep in the subsurface in numerous environments has gained greater attention (Klimchouk, 2007).

Karst landscapes and processes have a significant worldwide environmental and economic impact. In the U.S., all 50 states contain rocks with potential for karst development, and about 18 percent of their area is underlain by soluble rocks having karst or the potential for development of karst features (Weary and Doctor, 2014). The Interior Low Plateaus Physiographic Province of the east-central United States has a significant land area affected by karst development, predominately on or within Mississippian and Ordovician age limestone (Figure 1). Kentucky is one of the most famous karst areas in the world. Approximately 55 percent of Kentucky is underlain by bedrock that could develop karst terrain. About 38 percent of the Commonwealth has at least some karst development recognizable on topographic maps, and 25 percent of the state is known to have well developed karst features (Figure 2; Pryor and Currens, 2001).

The south central Kentucky karst, situated between the Green and Barren Rivers, is one of the most well developed karst landscapes on Earth. Mammoth Cave, at a current (2017) surveyed length of 405 mi (656 km), is the world’s longest known cave. The cave has a vertical extent of less than 500 ft (152 m). In addition, several other great cave networks are located in the region: Fisher Ridge (125 mi/202 km+), Whigpistle Cave (34 mi/55 km+), Hidden River Cave (21 mi/34 km+), and James Cave (10 mi/16 km+; Guilden, 2017). On the surface, many classic landforms are developed, including sinkhole plains, karst valleys, disappearing streams, and springs (May et al., 2005).

The regional aquifer level is often at a depth of 160 to 200 ft (49 to 61 m) below the surface (Polk et al., 2015). As is well known, shallow carbonate aquifers in karst areas are vulnerable to groundwater contamination from human and animal wastes, agricultural land use, urban storm water runoff, leaking underground storage tanks, and other surface activities from industry, transportation, and agriculture. Once contaminants reach fast-flowing underground streams, they may be carried for miles

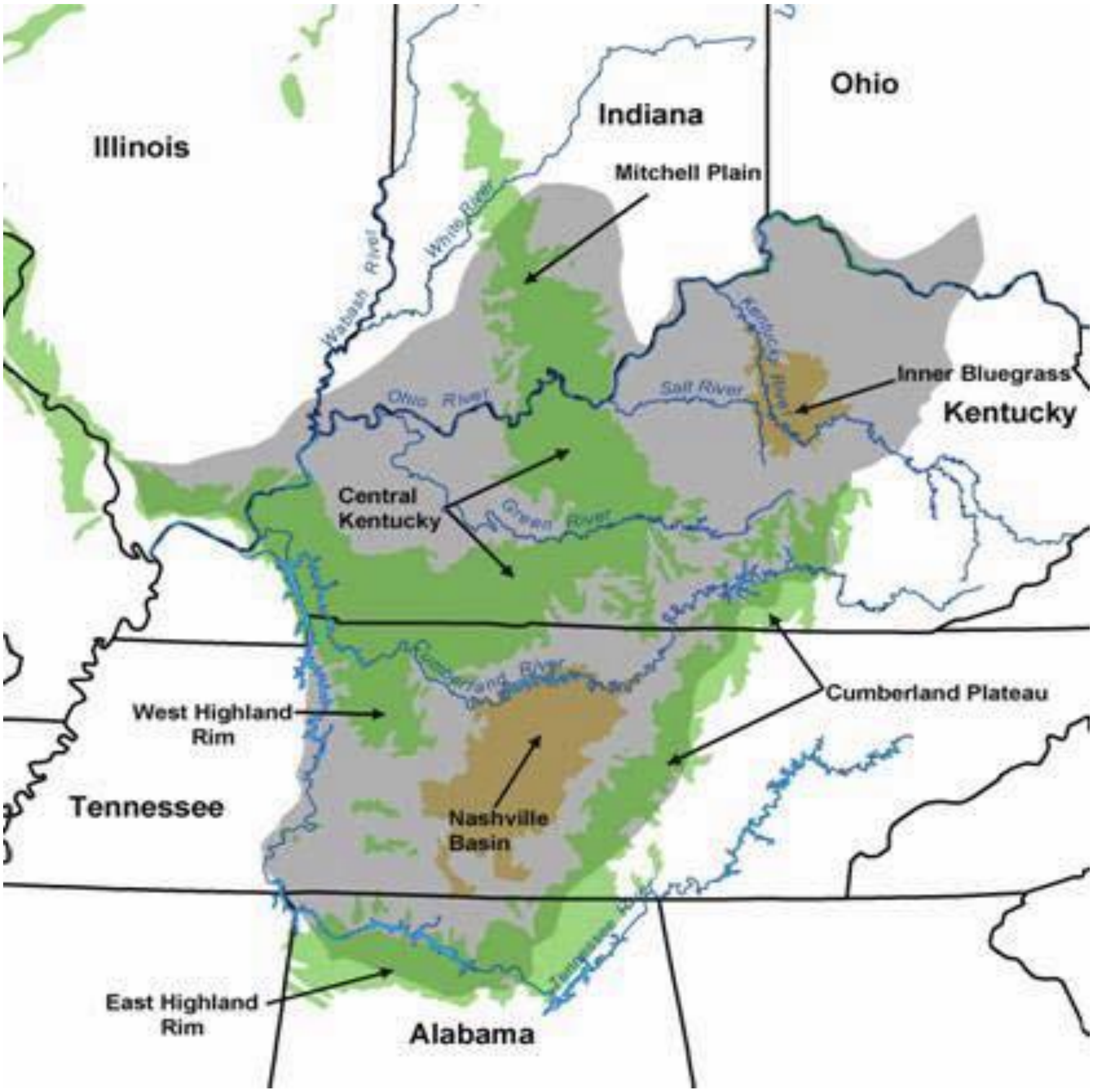

Figure 1. Major karst areas in the Interior Low Plateaus region. Karst areas underlain by Mississippian limestones are shaded green, and karst areas underlain by Ordovician limestones are shaded tan. Gray shading indicates areas with no karst or minor karst. The green shaded area identified as "Central Kentucky" is better known as the Mississippian or "Pennyroyal" Plateau (from USGS, Karst Hydrology Initiative, 2017, https://ky.water.usgs.gov/projects/cjt_karst/index.htm)

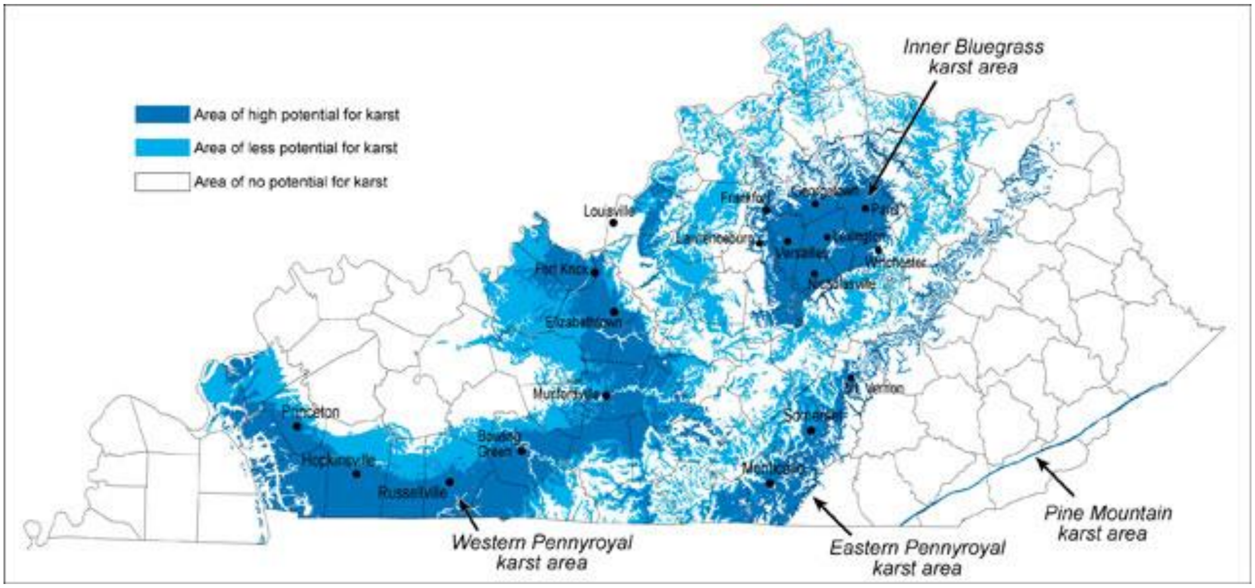

Figure 2. Generalized map of the karst regions of Kentucky. The dark blue colored areas are highly karstic, and the light blue colored areas are less karstic (from Pryor and Currens, 2001).

through the aquifer in a matter of hours or a few days (May et al., 2005). In south central Kentucky, water influenced by human and animal waste is one of the more serious pollutants in underground streams. Runoff from heavy rainfall events washes past livestock wastes from farm land, and also flushes septic-tank effluent from the soil downward into underlying conduits in the limestone. Small towns and urban areas, such as Bowling Green (2016 population 65,234), home to the General Motors Corvette Assembly Plant, contribute storm water contaminants including gasoline, oil, lubrication grease, chromium and lead (May et al., 2005). The mitigation of storm water runoff and water quality is thus a significant environmental and economic issue for industries and municipalities faced with compliance to Environmental Protection Agency regulations. Moreover, the effective management and control of surface water contaminants in south central Kentucky directly effects groundwater quality and preservation of cave ecosystems and is a very significant consideration for sustainability.

The purpose of this field trip is to provide an overview of the karst geomorphology and environmental geology of the Mammoth Cave region, south central Kentucky. The overriding question to ask is, “Why is the world’s longest cave located here?” To answer this question, we must first define the specific set of physical elements that are required to form a karst landscape and aquifer system. Between the Green and Barren Rivers of southcentral Kentucky, a proverbial “perfect storm” of these elements has conspired to form a great range of surface and subsurface landforms. What are the landscape forming elements, and how are they expressed here? They are as follows:

The ***lithologic*** element. Especially soluble rocks must be present, and here the thick (400 ft/122 m) succession of Chesterian (Upper Mississippian) Girkin and Ste. Genevieve Limestones and the Merimecan (Upper Mississippian) St. Louis Limestone consist of relatively pure calcium carbonate. These units are locally capped by a thinner section of less soluble, resistant Big Clifty Sandstone (Chesterian) and other mixed carbonate and siliciclastic rocks, which effectively protect the soluble bedrock from subaerial erosion and cave collapse.

The ***climatic*** element. There must be a solvent, and the area receives about 52.2 in (132.6 cm) of mean annual precipitation. Climatically, south central Kentucky, like most of the Southeastern U.S., is classified as having a temperate, humid subtropical climate, with the Koeppen Classification *Cfa*. The *Cfa* classification denotes a hot summer and a cool winter, and the mean annual temperature near Mammoth Cave is approximately 57°F (14° C). More importantly, there is no significant precipitation difference between seasons, and no dry season. Given this climate and middle latitude location, the deeper interior passages of Mammoth Cave average approximately 54°F (12°C) year-round.

The ***structural*** element. There must be a system of fractures that allows the solvent to get into, move through, and remove dissolved limestone from the aquifer framework. Here, the limestone dips approximately 30 feet per mile to the northwest on the flank of the Cincinnati Arch, and the bedrock has well developed vertical joints. Bedding planes, because they tend to be more continuous than fractures, exert a greater influence over groundwater flow and cave development in the region (Dieke, 1967).

The ***topographic*** element. Water flows downhill, so the water getting into the karst system must do so at an elevation higher than where it will ultimately drain out of it. Thus, there must be relief in the landscape, and there is approximately 400 ft (122 m) of local relief within the National Park boundary. Most recharge enters the extensive Pennyroyal Plateau in the area immediately south of the National Park boundary (550 to 650 ft MSL), and emerges at springs along a gorge of the Green River (440 ft MSL), a meandering stream that has down cut into the plateau.

The ***geologic time*** element. Once these other requirements are satisfied, karst landscapes do not suddenly appear. Down cutting of the Green River began during the Late Pliocene Epoch (Granger et al., 2014), lowering the water table, and producing erosive voids in the soluble bedrock, particularly along the bedding planes. Continued downcutting during the Pleistocene Epoch produced new underground drains, abandoning the higher conduits as caves. Thus, the oldest cave passages are closer to the surface, and the youngest horizontal passages are deepest underground.

Mammoth Cave records a 3.5 million-year erosive history that preserves records of biological, climatic, and even human activities that have shaped southcentral Kentucky.

Regional Geologic Setting and Physiography

Middle Tennessee and south central Kentucky are located along the north-northeast to south-southwest trending axis of the Cincinnati Arch, a broad structural upwarp, which exposes late Middle Ordovician to Late Mississippian strata along strike (Figure 3).

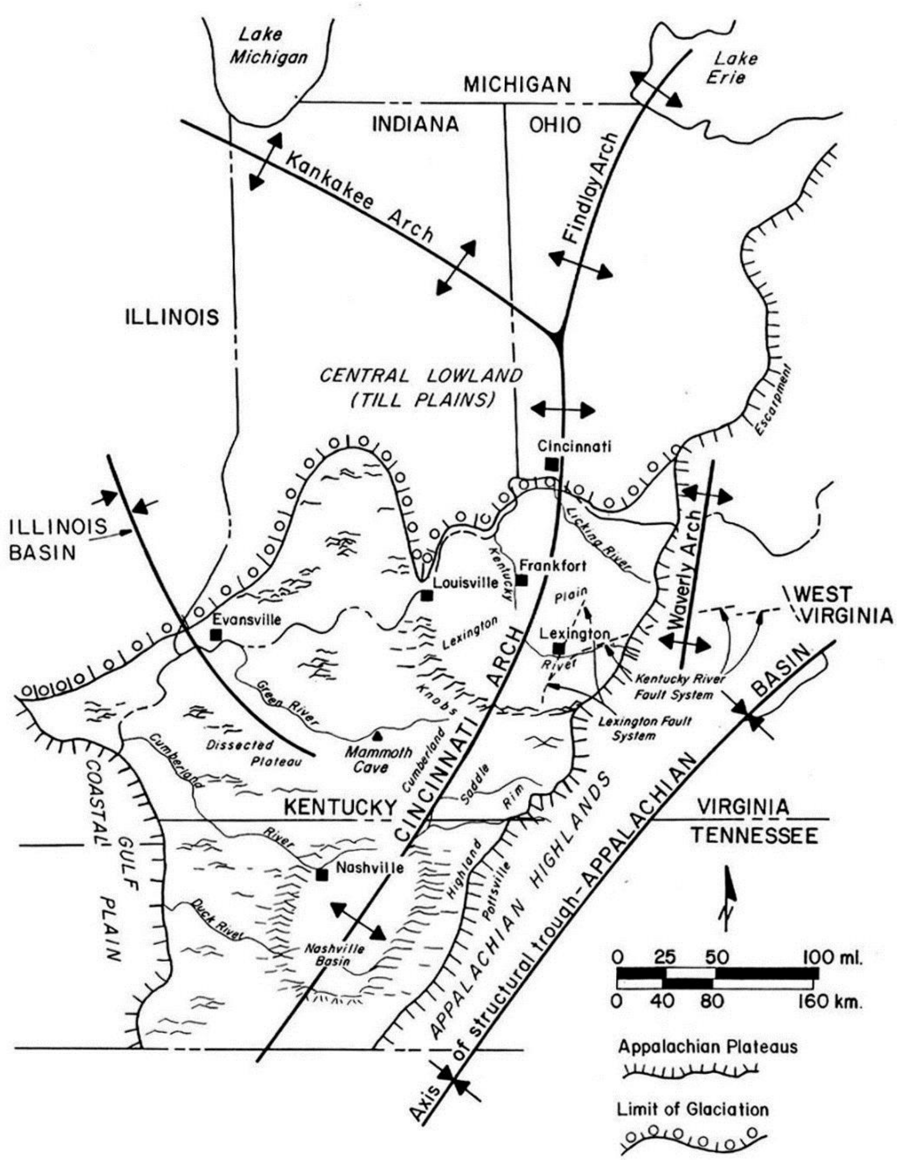

Figure 3. Regional structure map of the Cincinnati Arch showing relationship with adjacent structural and physiographic features (modified from Hunt, 1967).

The older Middle Ordovician strata, predominately carbonate units and subordinate shale, outcrop in circular to slightly elliptical structural domes, including the Nashville Dome and the Jessamine Dome of central Kentucky. The broader intervening region between the Nashville Dome and the Jessamine Dome, known as the Cumberland Saddle, consists predominately of younger bedrock, chiefly middle and upper Mississippian carbonates. The entire region is part of the Interior Low Plateaus Physiographic Province. Land use in Middle Tennessee and south central Kentucky is predominately agricultural, supported by towns and cities with a well-developed road, rail, and river transportation network.

The Nashville Dome and strata are prominently exposed at its central core due to the profound subaerial erosion in the form of the Central (Nashville) Basin, which includes the city of Nashville and surrounding suburbs. Nashville's elevation ranges from a low of 385 ft (117 m) along the Cumberland River, where the stream has locally downcut into the nearly horizontal, carbonate dominated Stones River Group (Middle Ordovician) to a high of 1,163 ft (354 m) in the Sequatchie Formation (Upper Ordovician) at Radnor Lake State Park located about 7 mi (11 km) south of downtown. The range of hills surrounding the Central Basin is known as the Highland Rim, an erosional escarpment consisting of resistant middle and upper Mississippian carbonates, which dip away from the Central Basin in the form of a cuesta. The Highland Rim escarpment is more prominent east of Nashville due to differential erosion and the slightly greater structural dip in that direction.

The Highland Rim and its middle and upper Mississippian strata are continuous with and known as the "Pennyroyal" or Mississippian Plateau region of south central and western Kentucky. The Mississippian Plateau is known for its rolling hills, caves, and karst topography (Figure 4). In the western part of the Mississippian Plateau, there is a prominent, arcuate line of hills formed by isolated but resistant Chesterian (Upper Mississippian) sandstones capping more soluble Mississippian carbonates assigned to the Girkin Limestone and the underlying Ste. Genevieve Limestone. The hills collectively form a cuesta which gently dips to the northwest towards the Eastern Interior (Illinois) Basin and into the subsurface beneath the Pennsylvanian strata of the Western Kentucky Coalfield. The eastern and southern margin of the hills forms a relatively continuous escarpment of up to 200 ft (61 m) of local relief which is known as the Dipping Springs Escarpment. A stratigraphic column for south central Kentucky illustrates the various rock types and the type of land surface they are associated with (Figure 5).

Figure 4. Oblique aerial photograph of a typical landscape of the “Pennyroyal” or Mississippian Plateau sinkhole plain, south central Kentucky (photo by C. Groves).

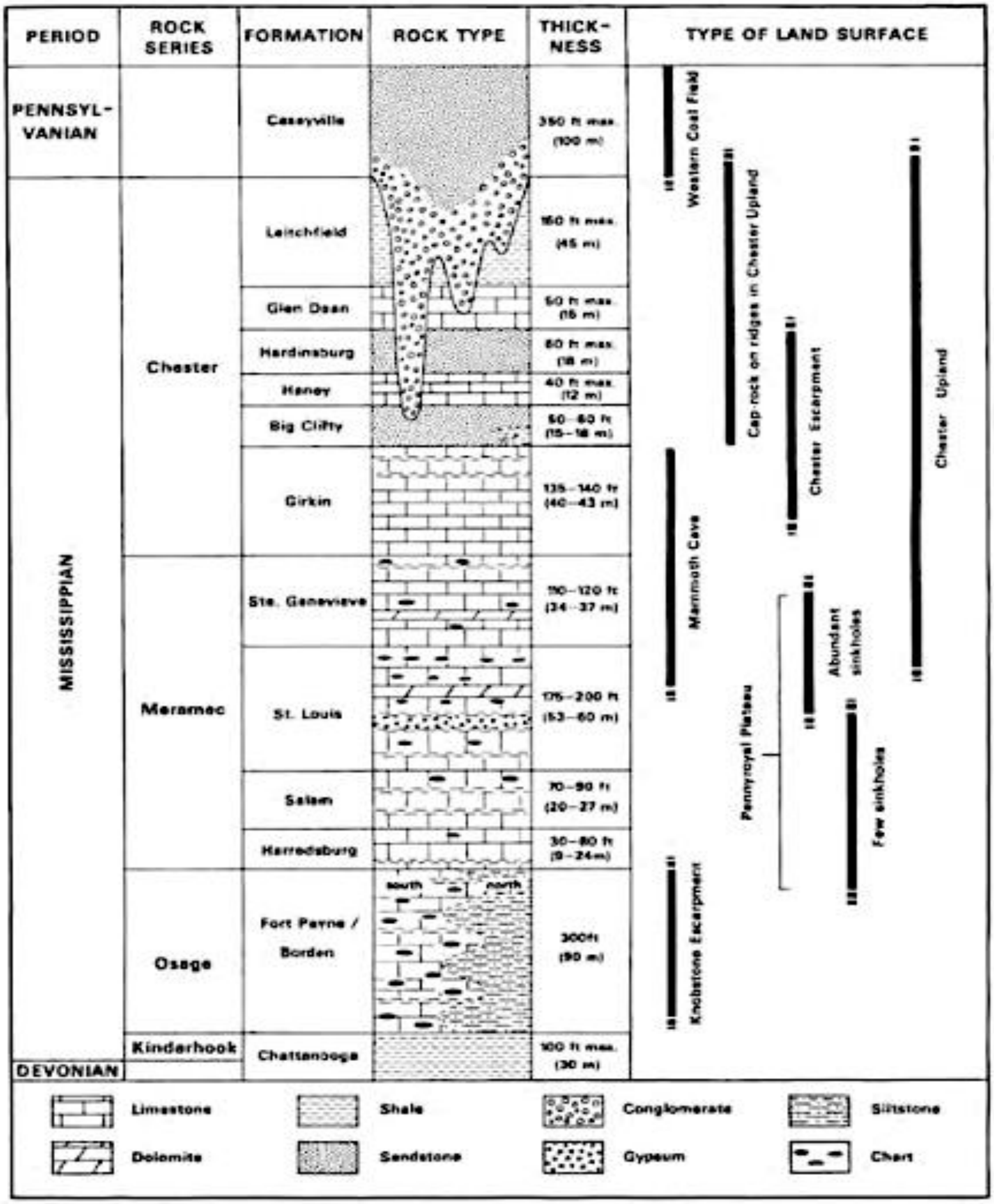

Figure 5. Stratigraphic column of south central Kentucky, showing the various rock units and their associated physiographic areas of outcrop (From Palmer, 1981).

Worthy of discussion is the ore mineralization and presence of other minerals in the region. The Cumberland Saddle hosts a variety of ores and minerals sourced from either deep seated hydrothermal activity, breccia replacement or from deposition of shallow marine strata and organic-rich sediments. The ore minerals are classified as Mississippi Valley Type (MVT) deposits, and include sphalerite (zinc), galena (lead), barite, and fluorite which are present in stratabound and vein deposits of the upper Knox Group (Lower Ordovician) of Middle Tennessee and the High Bridge Group (Middle Ordovician) of central Kentucky. Although ore production has been ongoing since the 1830's, the production has been sporadic, and limited to Tennessee since the 1960's. Oil and gas production has been achieved since the early 1860's from local pools tapping predominately lower and middle Mississippian sandstones and limestones, and also from Devonian shale, Silurian dolomites, and Ordovician dolomites. Since the 1990's, numerous successful but small producing oil wells have been drilled within two miles or less from the western boundary of Mammoth Cave National Park near Rhoda, KY, and close to the eastern boundary of the National Park south of Cub Run, KY. Aggregate production of high-calcium limestone, agricultural limestone, and skid-resistant cherty limestone, predominately from open pit operations in thick Mississippian formations has been historically significant and continues to increase, and a regional export market is well established.

The Field Trip Route

The primary field trip route from the AIPG conference hotel in Nashville, Tennessee to Mammoth Cave National Park Headquarters near Park City, Kentucky is Interstate Highway 65, and the Mapquest© calculated road distance between these locations is 96 mi (156 km). The Interstate 65 segment of the field trip route essentially parallels US Highway 31W, a two-lane primary highway which follows a trail originally created by Native Americans, and which was known as the Louisville & Nashville Turnpike from the mid-19th Century until the early 20th Century. Interstate 65 traverses the northern part of the Highland Rim, and entails a stratigraphic ascent from upper Ordovician, Silurian, and Devonian formations to middle Mississippian formations. The ascent, encompassing approximately 500 ft (152 m) of topographic relief in a five-mile distance, can be viewed in discontinuous roadcuts along I-65 between mile marker (MM) 99 (north of Millersville, TN) to MM 104 (TN 76-Bethel Road interchange, Exit 104). The engineered road grade is relatively steep between MM 102.6 and MM 103.6, and here the southbound lanes bifurcate from the northbound lanes in a greater turn radius because of the safety required for descending vehicles and the effects of occasional wind updrafts from the Central Basin. The top of the Highland Rim at the Bethel Road interchange is composed of Warsaw Limestone and the overlying St. Louis Limestone.

Interstate 65 is built upon the St. Louis Limestone from the Bethel Road interchange to approximately 8 mi (13 km) north of Franklin, KY, a distance of approximately 30 mi (48 km). The St. Louis Limestone varies from 120 to 200 ft (37 to 61 m) thick in the field trip area, and is characterized by medium to dark gray or dark bluish-gray, fine to medium grained, crystalline, thin to thick bedded limestone, with local chert lenses or beds. The road grade and bedrock is mostly level along this section of the route, traversing low, broad hills dissected by small streams and the Red River, west of and parallel to the northeast-southwest striking structural axis of the Cincinnati Arch. Deciduous forests and ground cover vegetation line the divided highway throughout much of north central Tennessee to the border of Kentucky, and geologic exposures are limited to dark reddish-brown, weathered soil and bedrock float derived from the St. Louis Limestone.

From the Tennessee-Kentucky state line northward to the Bowling Green, KY area, the land traversed by Interstate 65 has mostly been clear cut for row crop production and the landscape can be viewed in better detail. A well-developed karst terrain is developed in the St. Louis Limestone from the Kentucky state line (MM 0) to several miles north of Franklin, KY (MM 14). Topographic maps (contour interval = 10 ft) indicate up to 40 ft (12 m) of surface relief on area sinkholes. Many of the sinkholes are relatively small (less than 0.5 acres) and circular in shape. Deeper sinkholes are vegetated and support stands of deciduous trees, but few are submerged. Along this section of the Interstate, the highway trends north-northeast and farther west of the axis of the Cincinnati Arch. Approximately 0.6 mi (1 km) north of the Franklin-Warren County line near MM 14, the St. Louis Limestone dips into the subsurface beneath the overlying Ste. Genevieve Limestone. The Ste. Genevieve Limestone varies from 150 to 200 ft (45 to 61 m) thick in the field trip area, and is generally light to medium gray, fine to coarse grained, very fossiliferous or oolitic, but with argillaceous laminae or shaly beds. The karst of the Ste. Genevieve Limestone is not as prominently developed as in the St. Louis Limestone, primarily because of the inherent clay content, and sinkholes have more gentle slopes. Although the surface depressions in the Ste. Genevieve Limestone are generally much larger in size than those of the St. Louis Limestone, those of the former are much more irregular in shape and less than 20 ft (6 m) deep.

Interstate 65 passes through the extreme southern and eastern city limits of Bowling Green, the regional commercial and industrial hub of western Kentucky, and the third most populous city in Kentucky (after Louisville and Lexington). Bowling Green was chartered in 1798 from a pioneer settlement along the navigable Barren River, and was the provisional capital of Confederate Kentucky during the Civil War (https://en.wikipedia.org/wiki/Bowling_Green,_Kentucky). The city is mostly underlain by the Ste. Genevieve Limestone, and two large surface quarries on the northern and eastern city limits currently produce a high-calcium, oolitic limestone from the Fredonia

Member. In 1906, Western Kentucky University (WKU) was established upon a sizeable circular hill of Girkin Limestone that has a commanding view of the Barren River Valley. The WKU athletic teams are known as the "The Hilltoppers" for this fact.

Interstate 65 briefly follows the sinuous Ste. Genevieve Limestone-St. Louis Limestone contact from approximately 0.4 mi (0.6 km) north of the US 231-Scottsville Road (Exit 22) interchange to approximately 0.1 mi (0.2 km) north of the KY 234-Cemetery Road interchange (Exit 26). I-65 crosses the west flowing Barren River near MM 27, the principal meandering stream that drains much of the Mississippian Plateau in south central Kentucky. The Barren River empties into the Green River approximately 20 mi (32 km, map distance) northwest of the I-65 crossing near Woodbury, KY, and the Green River continues northwestward until its confluence with the Ohio River near Henderson, KY.

Interstate 65 passes directly by and south of the National Corvette Museum immediately before the KY 446 (Exit 28) interchange. The Corvette Museum can be recognized by the landmark Skydome, a bright yellow, inverted cone shaped roof that is topped by a tall red spire, which houses a circular Corvette salon. Field trip participants will visit the Corvette Museum on the return route of the field trip. The Corvette Museum exhibits and details of an onsite sinkhole collapse are discussed in this guidebook under Stop 4.

Approximately 4 mi (6.5 km) northeast of the Corvette Museum and 1.6 mi (2.6 km) north of the recently completed Interstate 65 interchange with KY 3145 (Exit 30) is the Kentucky Trimodal Transpark. This 1,200-acre site, located at the junction of US 31W (Louisville Road) and US 68 (Glasgow Road), has been under development since 2003. The Trimodal Transpark moniker connotes the intermodal transportation by truck, rail, and air, with onsite storage facilities as well as a business and manufacturing park. The Transpark has been heralded by local civic leaders and financial investors to be the 21st Century industrial and economic engine for Bowling Green, Warren County, and the western Kentucky region. The Transpark development plans received public scrutiny and local media attention because of the formal and legal opposition from organized environmental groups to industrial development, specifically addressing the potential environmental impacts to the karst hydrogeology and groundwater quality. The Transpark is sited on the Ste. Genevieve Limestone, and some irregularly shaped contour depressions on the Bristow 7.5' Quadrangle (Gildersleeve, 1963) indicate a local relief of 20 feet (6 m). Geologists and geotechnical engineers were previously aware that the residual clay-rich soils are relatively impermeable and insufficient to filter surface runoff, and that dye tracing experiments and mapping indicated that the subsurface karst groundwater network at the Transpark site was connected to and would impact Graham Springs near Bowling Green on the Barren River to the west

(Figure 6). Furthermore, much of the groundwater flow would affect the city of Bowling Green to the west. A Phase 1 Environmental Impact Statement was commissioned and completed in 2005, and the results indicated the need for permit requirements to address storm water collection and surface treatment of total suspended solids (TSS) prior to subsurface discharge into the “Lost River Cave system.” An example of a commercial application to filter and reduce TSS from storm water at the Transpark site is shown in Figures 7 and 8. As of 2012, four businesses associated with the automotive sector and three educational facilities had established operations at the Transpark, however, several parcels totaling more than 600 acres had not been sold or developed (Elliott, 2012, http://www.civicmanagementservices.com/uploads/1/1/8/4/11845728/kentucky_transpark_development_case_study.pdf)

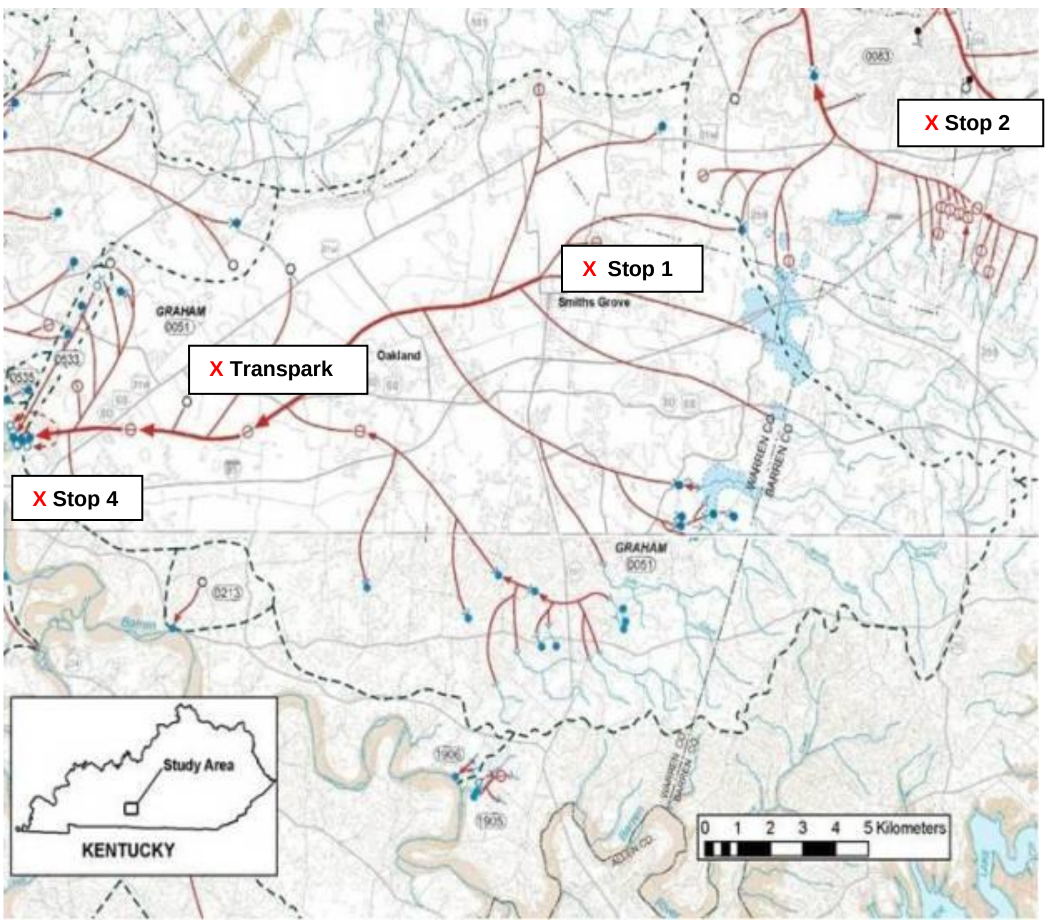

Figure 6. Map of the Graham Springs karst basin, delineated by the dashed black line, which includes the Kentucky Transpark and Crumps Cave (Stop 1) sites. The map shows tracer inferred subsurface flow (red paths), sinking streams (light blue), and water drained by the basin is discharge from multiple karst springs (open and closed blue dots; from Ray and Currens, 1998, 2000).

Figure 7. Photograph of installation of storm water treatment bunkers at Kentucky Transpark, Bowling Green, KY (Photo courtesy of Contech Engineered Solutions, (http://www.conteches.com/DesktopModules/Bring2mind/DMX/Download.aspx?EntryId=750)

Figure 8. Another view of installation of storm water treatment bunkers and supply pipeline at Kentucky Transpark, Bowling Green, KY (Photo courtesy of Contech Engineered Solutions, (http://www.conteches.com/DesktopModules/Bring2mind/DMX/Download.aspx?EntryId=750)

East of Bowling Green, Interstate 65 bends from a north-northeast direction to a more easterly direction in order to conform to the prevailing local topography, namely the Dipping Springs Escarpment. US 31W (Louisville Road), the two-lane predecessor to I-65, is sited within 0.5 mi (0.9 km) or less from the base of the west-east trending escarpment from Bowling Green to Horse Cave, KY. The Louisville and Nashville (L&N) Railroad, completed between its namesake cities in 1859 (now operated by CSX RR) was constructed south of US 31W. The part of I-65 between Bowling Green and Elizabethtown, KY, completed during the early 1960's, was built farther south of the railroad because of ease of right of way acquisition.

As the field trip route progresses eastward on Interstate 65 near the US 68/KY 80 interchange (Exit 36) at Oakland, KY, field trip participants may have a distant view of the Dripping Springs Escarpment. The escarpment is located approximately 4 mi (6.5 km) to the north (left) of the interstate highway and can be identified by the dark colored tree line which tops the hills. Participants will observe the Dipping Springs Escarpment first-hand from a topographic promontory at Stop 2 near Park City, KY. The first stop, however, will be to observe a working example of an academic research and monitoring facility within a natural cave developed in the Mississippian or "Pennyroyal" Plateau near Smiths Grove, KY, located north of the interchange with KY 101 (Exit 38) of I-65.

Stop 1: Crumps Cave, Smiths Grove, KY

Crumps Cave is located approximately 1.0 mi (1.6 km) northeast of Smiths Grove, Warren County, KY, and 10.0 mi (16 km) southwest of the Historic Entrance to Mammoth Cave, Edmonson County, KY (37°.062163 N Lat., 86°.197508 W Long.) The cave entrance, about 8 ft (2.4 m) tall and 60 ft (18 m) wide, is located in a small (2.5 acre/1 ha) wooded area within a topographic depression-collapse feature surrounded by extensive fields of privately managed row crops (Groves et al., 2013; Figure 9). The surface elevation above the cave is 635 ft MSL (194 m) and the elevation at the cave floor is approximately 580 ft MSL (175 m). The surface bedrock is mapped as St. Louis Limestone on the Smiths Grove 7.5' Geologic Quadrangle Map (Richards, 1964). About 9 ft (3 m) of Baxter silt-loam soils overlie the bedrock on the flat surface surrounding the sink, with an additional 59 ft (18 m) of cave ceiling. The Lost River Chert, an interbedded, silicified limestone within the upper part of the St. Louis Limestone, is present between the surface and cave ceiling. The local structural dip is approximately 2° west (Groves et al., 2013).

The only known entrance to Crumps Cave was purchased by WKU in 2008 through a land grant from the Kentucky Heritage Land Conservation Fund. The cave is managed as a focal point of a research and education preserve to study a wide range of

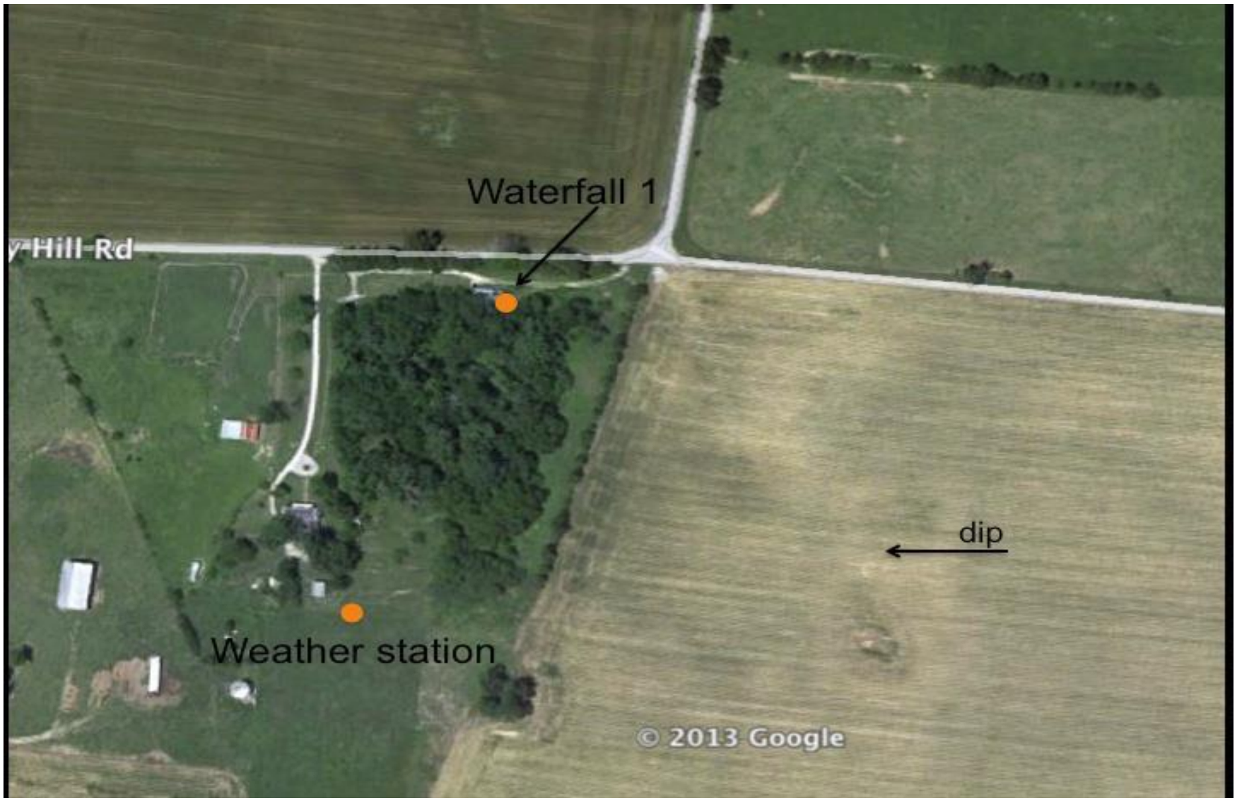

Figure 9. Aerial view of Crumps Cave Preserve (located in the wooded area enveloping a sinkhole) near Smiths Grove, KY (image from Google Earth).

environmental conditions and dynamics, and their interactions, using high-resolution electronic monitoring along with geochemical sampling, analysis and modeling (Groves et al., 2013). Access to the private cave is controlled by academic researchers from WKU. A padlocked gate and chain link fence is present near the cave entrance to control the potential theft and vandalism of monitoring equipment and the cave formations.

Crews from WKU visit the cave weekly for sampling, data downloading, and equipment maintenance, with an emphasis on high quality data collection and management. Guest scientists and students from around the country and world visit the cave on a regular basis to observe or participate in educational activities. Since acquisition, numerous inventories have been conducted at the preserve to identify and document the floral, faunal, archaeological, and biospeleological resources located in and around the cave. A world-class research facility has been established at the cave, which allows for examining epikarstic processes and the impacts of local agricultural activities on the quality of karst groundwater. An extensive monitoring network has been established both in and outside of the cave to measure atmospheric/weather conditions, cave microclimate, surface discharge, water chemistry parameters, and bat activity (Figure

10, Groves et al., 2013). Field trip participants will have the opportunity to observe, discuss and photograph the cave laboratory and surroundings.

Figure 10. Photograph of barrel-shaped weir at Waterfall 1 in Crumps Cave used for discharge measurements. The water level is measured with a pressure transducer in the barrel and the temperature, pH, and specific conductance probes are in the bucket below (photo by Jason Polk).

The route from Stop 1 to Stop 2 returns to Interstate 65 at the KY 101 interchange (Exit 38), and then proceeds north along I-65 upon the well-developed karst terrain developed in the upper part of the St. Louis Limestone. The topographic map (contour interval = 10 ft) indicates a sinkhole surface relief of up to 40 ft (12 m). The surface drainage pattern is a classic deranged pattern.

Approximately 2 mi (3 km) east of the Smiths Grove interchange between MM 39.2 and MM 39.8, and on the south (right) side of Interstate 65, a prominent bedrock outlier known as Pilot Knob (Elev. 956 ft MSL) towers above the St. Louis Limestone-Pennyroyal Plateau sinkhole plain. Although densely wooded and poorly exposed, the entire 200 ft (61 m) section of Ste. Genevieve Limestone is mapped, and is in turn is overlain by 60 ft (18 m) of Girkin Limestone at the uppermost part the knob. The bedrock outlier is located 4 mi (6.5 km) from its associated strata types at the Dipping Springs Escarpment.

Stop 2. Park Mammoth Resort Overlook, Park City, KY

The Park Mammoth Resort overlook is located 1.2 mi (1.9 km) west of the Interstate 65-Kentucky 255 interchange (Exit 48), Park City, and 6.4 mi (10.3 km) south of the Historic Entrance to Mammoth Cave, Edmonson County, KY (37.095487° N Lat., 86.076045° W Long.). The Resort property includes a 93-room commercial hotel, restaurant, and nearby golf course and winery. More importantly, the property provides a south and west facing promontory from Bald Knob (Elev. 825 ft MSL), one the many sandstone capped hills comprising the Dripping Springs Escarpment, affording a view of the extensive karst terrain of the Mississippian or “Pennyroyal” Plateau. The schematic cross section below exhibits the primary lithologic, structural, topographic, and physiographic elements that can be observed from the overlook (Figure 11).

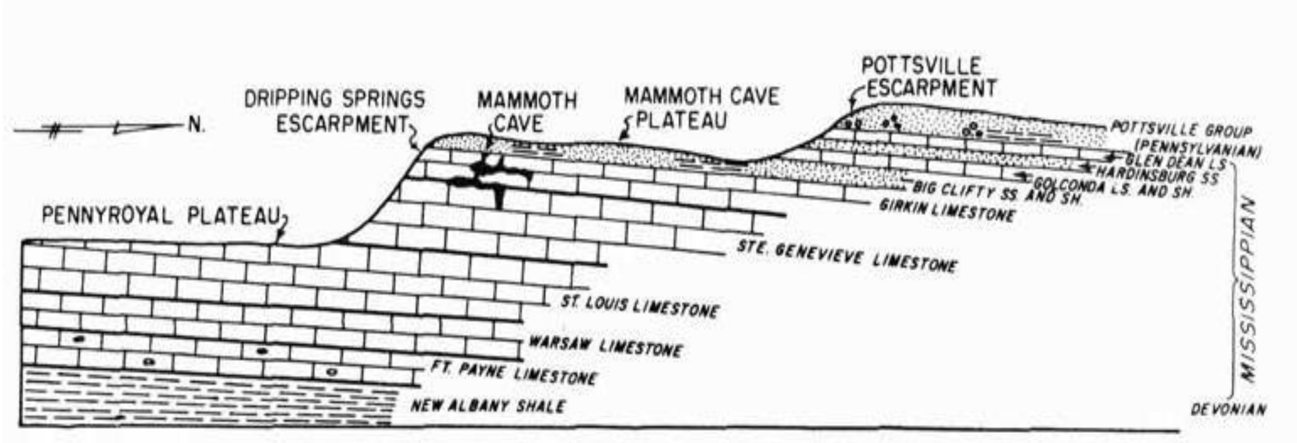

Figure 11. Schematic north-south cross section of the stratigraphic formations in the vicinity of Mammoth Cave, which exhibits the primary lithologies, structural dip, topographic profile, and regional physiographic features. The relative horizontal distance is 20 mi (32 km) and the relative stratigraphic section portrayed is 1,000 ft (305 m; from McGrain, 1962).

The geologic bedrock of the overlook and vicinity is mapped on the Park City 7.5' Geologic Quadrangle Map (Haynes, 1962). The geologic map indicates that the Bald Knob hilltop area is correlated with the Big Clifty Sandstone Member of the Golconda Formation (map symbol "Mgb"). The Big Clifty Sandstone (Chesterian-Upper Mississippian) is locally composed of up to 25 ft (40 m) of light to dark-brown, well-cemented, fine to medium grained, thick to massive and cross bedded sandstone. Upon casual inspection of the ground or land surface at the overlook site, located near the wood frame gazebo and south of the large parking lot, field trip participants might disregard or not be impressed with the poorly exposed, weathered sandstone bedrock and talus. However, the Big Clifty Sandstone is a very significant lithologic element, in that it forms the regional protective caprock for the thick underlying carbonate and karstic formations comprising Mammoth Cave. The Big Clifty Sandstone is well exposed and can be observed in better detail at Stop 3 near the opening and approach footpath of the Historic Entrance to Mammoth Cave. At the Park Mammoth Resort overlook, the Big Clifty is underlain by 120 ft (37 m) of buff to light gray, coarsely crystalline limestone, with some white to dark gray, fine grained, oolitic limestone, and subordinate gray shale of the Girkin Limestone (map symbol "Mg"). These strata are also poorly exposed on the south-facing hillslope, but can be observed at the Historic Entrance where the limestone forms the walls and roof of the upper most level of the cave void. The lower one-half of the hillslope and most of the northern part of the valley bottom is mapped as the Ste. Genevieve Limestone (map symbol "Msg"). The limestone is typically white to light gray, fine to medium grained, and thin bedded.

Much of the Pennyroyal Plateau in the vicinity of Park City and a part of the Mammoth Cave Plateau including the southern part of Mammoth Cave National Park is mapped in the Mammoth Cave Watershed area (Figure 12). This area is east of and adjacent to the previously described Graham Springs Basin (Figure 6). The map detail indicates a west and northwest groundwater flow direction, and that there are at least four discharge points in the form of springs that flow directly into the west flowing Green River.

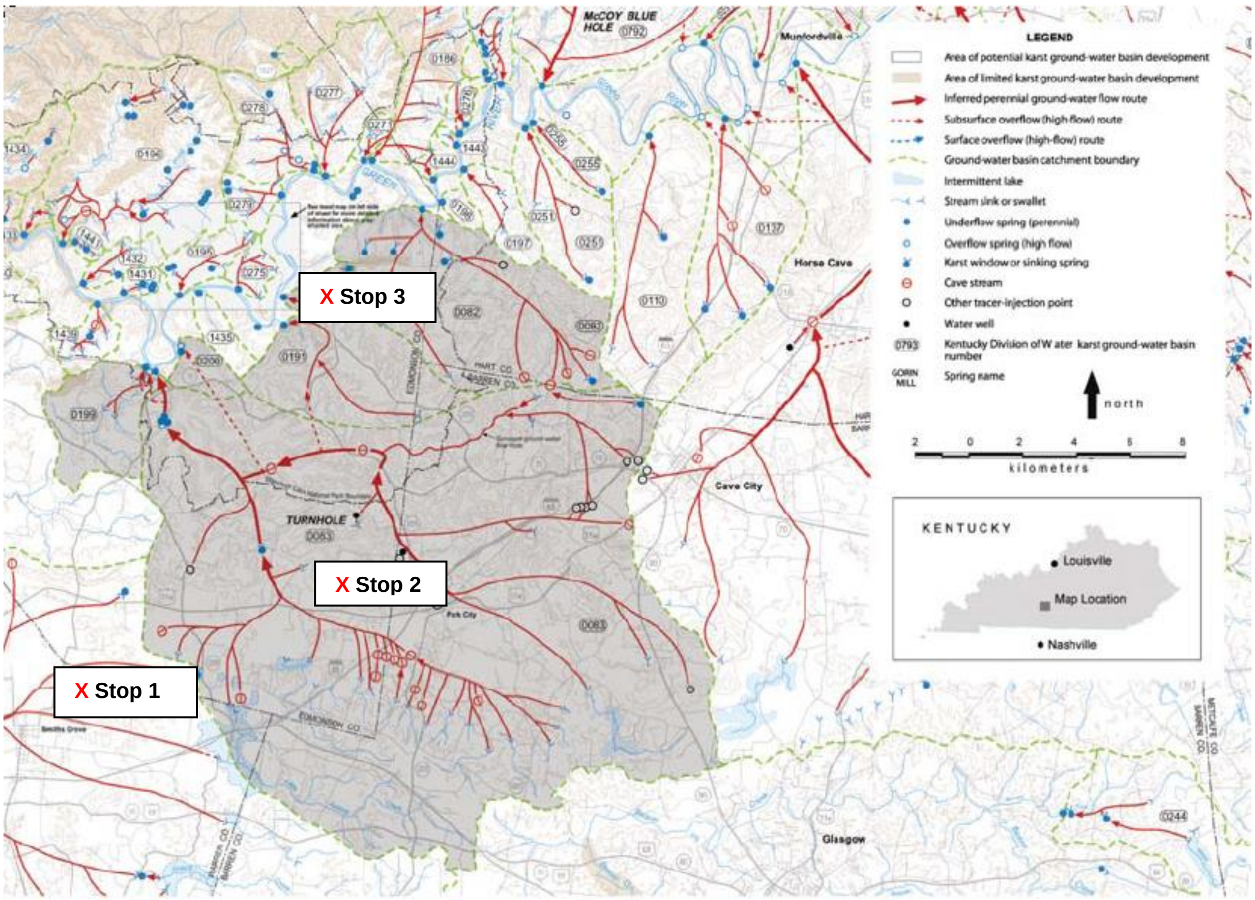

Figure 12. Map of karst drainage basin for Mammoth Cave Watershed (gray shaded area) showing principal groundwater flow paths (red paths), sinking streams (light blue), and water drained by the basin is discharge from multiple karst springs (open and closed blue dots; from Glennon and Groves, 2002).

The route from Park Mammoth Resort to the Mammoth Cave National Park Visitor Center follows US 31W to Park City and subsequently KY 255 and KY 70, ascending the Mammoth Cave Plateau. The terrain is extensively forested, and exposures of the Ste. Genevieve Limestone and Girkin Limestone along the highway are uncommon. The Big Clifty Sandstone caps the higher ridge tops along the route (Figure 13).

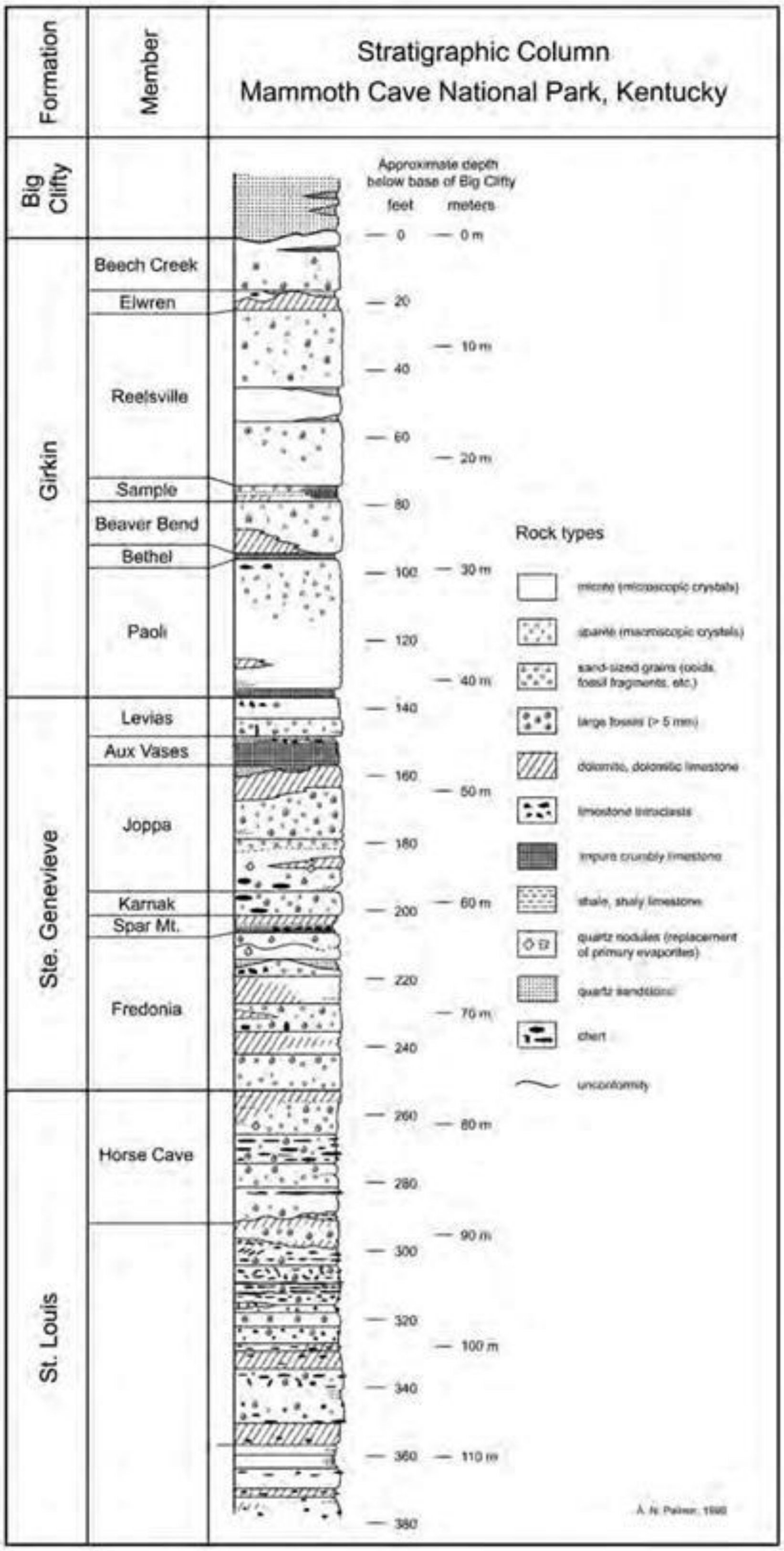

Figure 13. Stratigraphic column of Mammoth Cave and vicinity (from Palmer, 1989).

Stop 3: Mammoth Cave National Park

Mammoth Cave is the longest cave system known in the world, and as of 2017, has 405 miles (652 km) of surveyed passageways. Up to five local subterranean levels are known, and the deepest extends to a depth of approximately 500 ft (150 m) below the highest surface ridgetop. Mammoth Cave currently has 30 entrances, and about one-fourth of these are natural entrances, whereas the majority are modified natural entrances or engineered openings.

Mammoth Cave was established as a National Park on July 1, 1941. It was recognized as a World Heritage Site on October 27, 1981 and an International Biosphere Reserve on September 26, 1990. Mammoth Cave's 52,830 acres (21,380 ha or 82.55 mi^2) are located primarily in Edmonson County, with small areas extending eastward into Hart County and Barren County. It is bisected by the Green River, a meandering, west flowing tributary of the Ohio River.

The human history, culture, exploration, and uses surrounding Mammoth Cave are well documented. Native Americans began exploring the cave approximately 4,000 years ago until about 2,000 years ago, apparently for gypsum, selenite, and other related minerals. The discovery of the cave (the "Historic Entrance") by settlers of European decent is attributed to Robert Houchins, who shot and pursed a wounded bear in 1798. Potassium nitrate ("saltpeter") was commercially produced during the War of 1812, but quickly declined thereafter. Commercial tours began in 1816, and during the early 1840's the cave was used as a medical experiment for the cure of tuberculosis (https://www.nps.gov/maca/learn/historyculture/abriefhistoryofmammothcave.htm). The Civil War effectively shut down visitation to Mammoth Cave and other nearby smaller commercial caves, including Diamond Caverns (discovered 1859). The number of visitors began to steadily increase with the completion of the Mammoth Cave Railroad in 1886, which connected with the Louisville and Nashville Railroad mainline at Glasgow Junction (now Park City). In 1904 an Indianapolis judge drove the first automobile to Mammoth Cave, which heralded the eventual doom of the short line railroad in 1931 (https://en.wikipedia.org/wiki/Mammoth_Cave_Railroad). Political efforts to convert the cave by condemnation of private ownership and poorly maintained conditions to an organized, government managed conservation area began in the very early 1900's. Congress authorized the formation of a national park in 1926, and the National Park was officially established in 1941 (https://www.nps.gov/maca/learn/historyculture/abriefhistoryofmammothcave.htm) Great Onyx Cave (discovered 1915), a small but separate commercial enclave within the borders of Mammoth Cave National Park, was ultimately sold from private owners to the federal government in 1961, however, Diamond Caverns remains the only private commercial enclave within the National Park boundaries. Great Onyx Cave is unusual in that it has not yet been mapped as connected to Mammoth Cave (https://en.wikipedia.org/wiki/Great_Onyx_Cave), even though passages in the cave cross directly over Mammoth Cave. Mammoth Cave National Park currently receives approximately 600,000 to 650,000 annual visitors. The reader is referred to the National Park Service website, specifically the link for "History & Culture" for additional information (https://www.nps.gov/maca/learn/historyculture/abriefhistoryofmammothcave.htm).

The geologic evolution of the cave system began with down cutting of the Green River during the Late Pliocene Epoch (Granger et al., 2001), lowering the water table, and producing erosive voids in the soluble bedrock, particularly along the bedding planes. Continued downcutting during the Pleistocene Epoch produced new underground drains, abandoning the higher conduits as caves. Thus, the oldest cave passages are closer to the surface, and the youngest horizontal passages are deepest underground. A generalized cross section of the five levels of cave voids and their host stratigraphic formations is shown below (Figure 14).

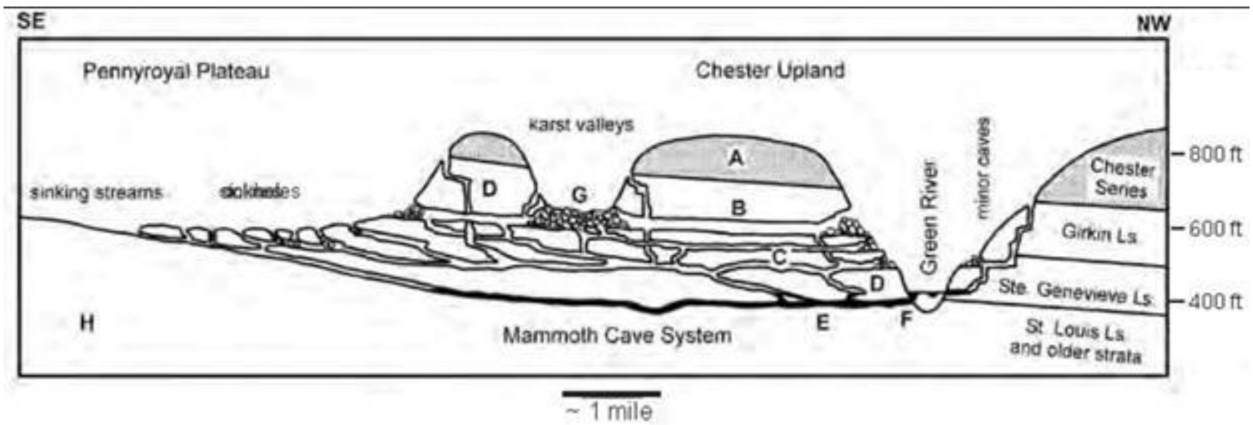

Figure 14. Generalized southeast-northwest cross section of Mammoth Cave showing the levels of cave voids developed within the local landscapes and relation to stratigraphic formations (from USGS, Scientific Investigations Report 2008-5023; https://pubs.usgs.gov/sir/2008/5023/44toomey.htm)

Field trip participants will enter the cave at the Historic Entrance, and observe numerous cave features on the Historic Tour route. The route and named features are indicated on the simplified map below (Figure 15). The official tour duration listed by the National Park Service is 2 hours and the route distance is 2 miles (3.2 km). There are 440 stair steps, including 155 at Mammoth Dome. Please be advised that flash photography and rock collecting is prohibited. Non-flash camera use is permitted.

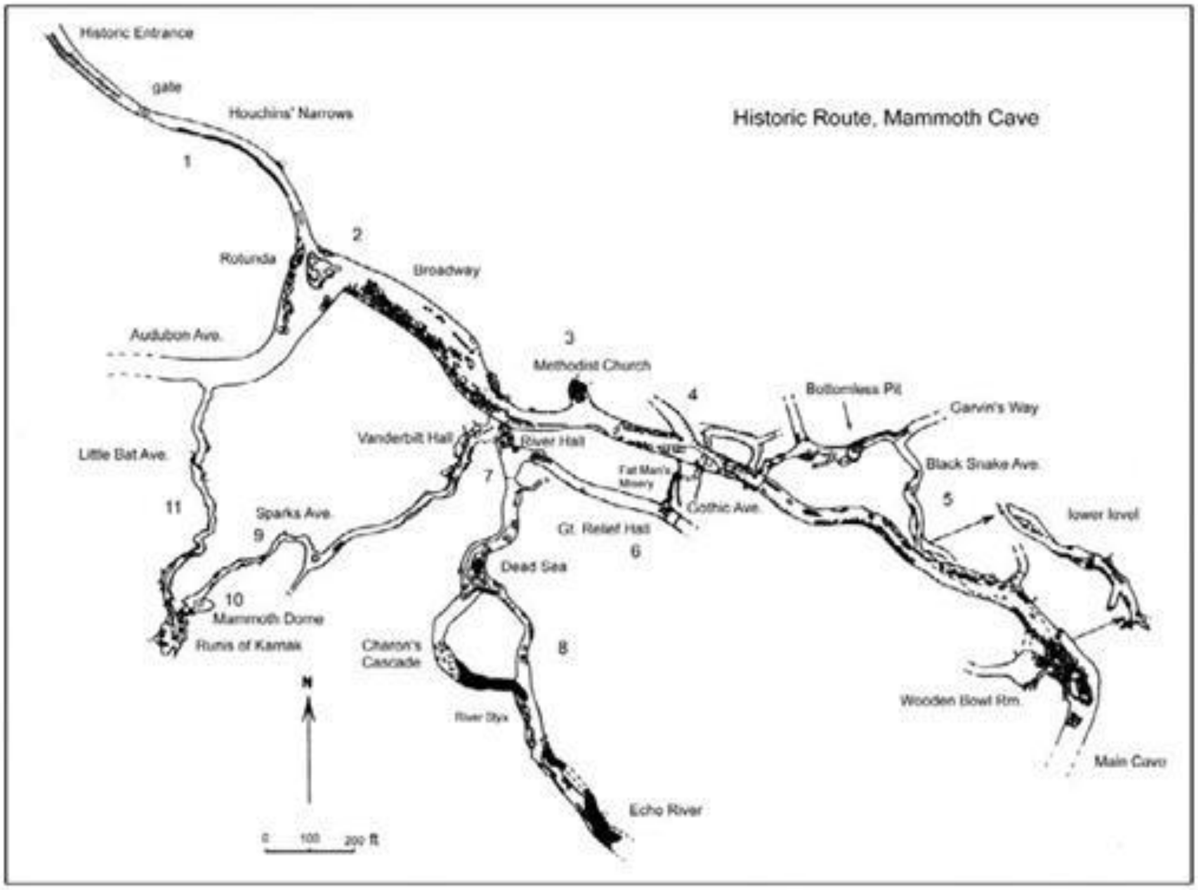

Figure 15. Simplified map of Historic Tour Route of Mammoth Cave (modified from Palmer, 1981).

Some of the main named features of the Historic Tour route include:

- *The Rotunda*, a huge chamber 139 ft (42 m) wide and 40 ft (12 m) high, developed by collapse of large amounts of thinly bedded limestone, and saltpeter vats, used in the leaching of nitrates from the cave floor sediment;
- *Audubon Avenue*, one of the large flat-ceiling passage ways, developed in the Girkin Limestone and the Ste. Genevieve Limestone;
- *Broadway*, a long, high-level corridor on average 40 ft (12 m) high and 60 ft (18 m) wide;
- *Giant's Coffin*, a huge block of fallen limestone which measures 50 ft (15 m) long, 20 ft (6 m) wide, and 16 ft (5 m) high with the edges rounded by solution. The block has been estimated to weigh 2,000 tons;
- *Fat Man's Misery*, a narrow winding passage, formed by a cave stream downcutting along a vertical joint; and
- *Bottomless Pit*, a circular well 105 ft (32 m) deep, leading to a deeper level of the cave (McGrain, 1962).

It is difficult to describe every form of the thousands of deposits in Mammoth Cave, but most of them are variations of three or four types. The major number of forms are essentially *dripstones*, including stalactites and stalagmites. When a stalactite and its corresponding stalagmite continue to grow for a long time, the two may join together to form a *pillar* or *column*. A *drapery* is often formed by a row of stalactites joining together as they grow downward from a ceiling joint. A *flowstone* results from water flowing over instead of dripping from a rock surface (McGrain, 1962).

The route from the Mammoth Cave National Park Visitor Center to the National Corvette Museum retraces the roads and highways taken earlier.

Stop 4: National Corvette Museum, Bowling Green, KY

The National Corvette Museum is located north of Interstate 65 near the KY 446 interchange (Exit 28) at 350 Corvette Drive, Bowling Green, Warren County, KY 42101 (Figure 16). The land for constructing the museum buildings and parking area, located within view of the General Motors (GM) Corvette Assembly Plant was selected by virtue of an outright donation of a 23.9 acre (9.67 ha) tract from the city of Bowling Green to the non-profit National Corvette Restorers Society (NCRS), who in turn funded the $15 million construction from the sale of bonds and bank loans. Ground was broken on June 5, 1992, and the museum opened its doors on September 2, 1994 (https://www.corvettemuseum.org/learn/about-the-museum/). The 115,000 ft^2 building houses more than 80 Corvette models, many of which are portrayed in various exhibits or dioramas with related photographs, videos, advertisements, scale models, and rare memorabilia. The building also includes a library and archives, gift shop (“Corvette Store”), and theme restaurant (“Corvette Café”).

Figure 16. Oblique aerial view of the National Corvette Museum, Bowling Green, KY (Photo courtesy of National Corvette Museum website: https://www.corvettemuseum.org/learn/about-the-museum/).

“The museum welcomed 228,363 visitors in 2016, the museum’s second highest annual attendance in history, the top attendance being achieved in 2014 with the now famous Corvette sinkhole taking most of the credit for the spike.” https://www.corvettemuseum.org/corvette-museum-and-motorsports-park-achieve-increased-attendance-for-2016/

The Chevrolet Corvette was first introduced to the public in January 17, 1953 as a “show car” for the 1953 GM Motorama display at the New York Auto Show. The model generated enough interest to induce GM to make a production version to sell to the public, and the first unit rolled off the assembly line in Flint, MI on June 30, 1953. Only 300 hand assembled cars were built during the first production year https://cars.usnews.com/cars-trucks/chevrolet-corvette-history

Production of the Corvette, known colloquially as the “Vette”, was moved to a new GM assembly plant in St. Louis, MO in 1954 in order to mass produce the vehicle. Significant engineering and chassis redesigning of the first generation “Concept Car” occurred in 1962, heralding a successive and progressive generation of new designs. The first through third generations of Corvettes (C1 thru C3) were produced in St. Louis until mid-1981. In 1981, production was moved to a new factory in Bowling Green, KY, and the C3 through current C7 models have been produced here. The Corvette is the official sports care of the Commonwealth of Kentucky (https://en.wikipedia.org/wiki/Chevrolet_Corvette).

Public plant tours of the Corvette assembly factory, managed by General Motors, are currently unavailable until late 2018, reportedly due to the current and proprietary development of the mid-engine, C-8 generation Corvette (http://www.thedrive.com/news/9802/corvette-factory-closing-to-visitors-until-late-2018).

A sinkhole collapse occurred in the iconic Skydome annex of the Museum during the pre-dawn hours of February 12, 2014, swallowing eight prized corvettes. Security cameras and motion detectors record the 5:44 a.m. collapse and opening of a 36 ft (11 m) wide and 80 ft (25 m) deep sinkhole in the Skydome floor (Figure 17). Engineers soon determined that the building did not sustain any structural damage because the sinkhole was located in the middle of the Skydome. Only one Corvette in the Skydome did not fall into the hole and was undamaged. The eight Corvettes were subsequently recovered from the sinkhole. One of these (2009 Blue Devil ZR1) sustained little or no damage, and two others (1992 white convertible and 1962 tuxedo black) were restored.

The published geologic map of the Bowling Green North 7.5’ Quadrangle (Shawe, 1963) indicates that the Skydome is built upon the St. Louis Limestone, and south of the

Figure 17. Photograph of sinkhole collapse at National Corvette Museum (Photo Courtesy of National Corvette Museum).

contact of the Ste. Genevieve Limestone (Figure 18). The local dip is approximately 1-2° north. Although masked by the satellite image layer of the geologic map, the historic (1959) topographic map (contour interval = 10 ft) indicates a well-developed sinkhole plain in the St. Louis Limestone between the current location of the Skydome and the Barren River to the west. The main museum building was constructed on relatively level ground (approximately 530 ft MSL), but within 400 ft (121 m) west of the Skydome annex there are “subsidence” type sinkholes having up to 50 ft (15 m) of relief. Subsidence sinkholes develop where surface soils slowly spall into cavities below over long periods of time. These features create a gentle depression in the landscape that may have a “throat” in the center, but usually pose little risk to life or property (Polk et al., 2015). Prior to construction of the museum, a few exploratory bore holes were drilled in the Skydome area, and competent bedrock was penetrated (Jason Polk, written communication, September 13, 2017).

Figure 18. Geologic map of National Corvette Museum Skydome and vicinity showing the site mapped as St. Louis Limestone (green colored area), and south of the contact with the Ste. Genevieve Limestone (gray colored area). The yellow colored area in the extreme western part of the map image is mapped as Quaternary Alluvium associated with the floodplain of the Barren River (scale approx. 1:12,000; from Polk et al., 2015).

A geotechnical investigation of the sinkhole began immediately after the collapse and prior to recovery of the Corvettes. A drone fitted with a camera was initially used to determine the presence of any additional voids or passages, but the data were inconclusive. Micropile drilling was performed to temporarily support the Skydome structure and spire, and downhole cameras were deployed into the micropile holes to detect any cavities or passages extending from the main sinkhole collapse. The micropile drill logs were used to construct generalized fence diagrams which showed the depth to competent bedrock and the presence and depth of voids surrounding the main collapse. Subsequently, a microgravity survey using a 10-ft (3 m) grid was conducted in the area surrounding the sinkhole and a buffer area outside of the Skydome. The analysis of these data, prior to direct physical exploration of the sinkhole, indicated the possibility of additional voids extending from the main sinkhole opening to the north and to the south of the debris cone (Polk et al., 2015).

After retrieval of the Corvettes and stabilization of the sinkhole, a team of karst scientists from Western Kentucky University and a local civil engineering firm explored, observed, and surveyed the interior of the sinkhole and cave passages. The debris cone consists primarily of broken and weathered limestone, with some overlying soils. The cave measures 220 ft (67 m) in length, averages 40 ft (12 m) wide, and is up to 80 ft (25 m) deep below the floor of the Skydome. The passages extend beyond the Skydome toward existing sinkholes to the north and south, which may represent collapsed portions of the same relic cave system. The cave walls are composed of thinly bedded St. Louis Limestone (Figure 19), and the contact of the overlying Ste. Genevieve Limestone is identified by the presence of the Corydon ball chert bed (Polk et al., 2015). No water flow or seeps were observed before, during, or after the sinkhole collapse and repair (Jason Polk, written communication, September 13, 2017).

Figure 19. Photograph of light gray, thinly bedded St. Louis Limestone in the walls of the cave passage near the Skydome collapse sinkhole entrance. The contact with the roof, represented by the overlying, reddish-brown colored Ste. Genevieve Limestone is identified from the presence of the Corydon ball chert bed (from Polk et al., 2015).

The geotechnical data, cave observations, and surveying were analyzed to conclude that the sinkhole resulted from the failure of the cave's roof. It was determined that the presence of the Corydon ball chert bed in the present roof created a weakness zone for local instability. Over a span of unknown geologic time, the succession of thin bedded rock failed, and the breakdown dome continued to migrate upward toward the floor of the Skydome, thinning the bedrock support of the surface, and ultimately leading to structural failure and collapse (Polk et al., 2015).

The sinkhole was carefully filled with a combination and succession of earthen and construction materials. The debris cone was graded to a flat profile and upon it a one foot (0.3 m) thick concrete slab was poured. A double layer of metal sheet pilings was placed horizontally upon the concrete slab and also cut to form fit the vertical or steeply sloping sinkhole walls. The sinkhole walls were then covered in specific areas with shotcrete to stabilize them further. The sheet pilings provided a base for filling the remainder of the hole to the floor with 4,000 tons of manufactured sand to support the concrete floor. Holes were cut into the sheet pilings to drill the micropiles down to bedrock. Forty-six micropiles were installed on a 20 x 25 ft (6 to 7.6 m) grid under the Skydome. The 7-in (17 cm) diameter micropiles were placed at an average depth of 141 ft (43 m) below the Skydome floor to penetrate competent bedrock. A 4-ft (1.2 m) manhole was left in the floor to access the southern cave passage for additional scientific monitoring and also to integrate into a museum exhibit (Polk et al., 2015).

Construction repair costs were not reported to the public, but the destroyed vehicles and subsequent repairs represented a loss of over $3 million. The Skydome reopened to the public on September 3, 2015. The sinkhole event has itself become a public attraction and focal point of interest at the museum. “A semi-permanent exhibit to tell the story” opened on February 12, 2016, two years after the collapse. The five destroyed Corvettes, one of the restored Corvettes, and the undamaged Corvette are all back on display, with a “before and after” video on each of the affected vehicles. Security video footage of the collapse, vehicle recovery efforts, shop restoration clips, and time-lapse photography of the material fill-in of the hole are presented in a special media display. Related exhibits include sinkholes and their sensation in pop culture, an actual geologic explanation of karst landscapes and cave formations, and by a virtual simulation exhibit of a cave collapse while in a specially constructed mini-cave.

The field trip route will return to Nashville via Interstate 65. As you return, consider what you have observed today and the impact of the history, culture, and expansion of human development upon a fragile karst system and groundwater resource network. In our economically driven world, we will be faced with more frequent and costly challenges to mitigate and repair the effects of urban flooding, contamination, and disruption to the landscape and water supply. What will be your response?

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