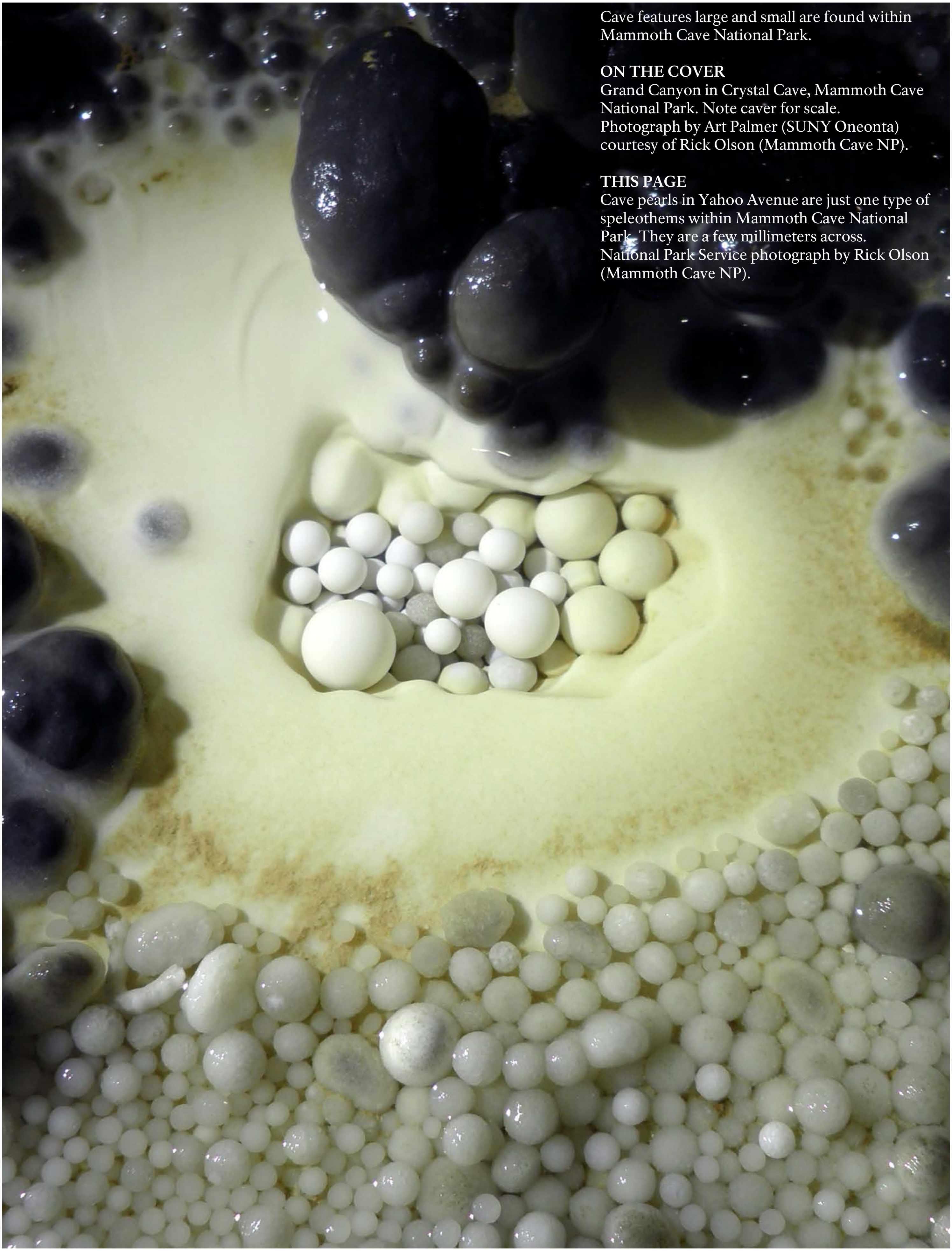
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Mammoth Cave National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/448



Cave features large and small are found within Mammoth Cave National Park.

ON THE COVER
Grand Canyon in Crystal Cave, Mammoth Cave National Park. Note caver for scale. Photograph by Art Palmer (SUNY Oneonta) courtesy of Rick Olson (Mammoth Cave NP).

THIS PAGE
Cave pearls in Yahoo Avenue are just one type of speleothems within Mammoth Cave National Park. They are a few millimeters across. National Park Service photograph by Rick Olson (Mammoth Cave NP).

Mammoth Cave National Park

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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Executive Summary

This report accompanies the digital geologic map data for Mammoth Cave National Park in Kentucky, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

As a World Heritage Site and International Biosphere Reserve, Mammoth Cave National Park preserves part of a complex and spectacular karst ecosystem in south-central Kentucky. The park lies at the edge of the Chester Upland, where resistant sandstones and other rocks support steep ridges separated by limestone-floored valleys. The ridges overlook the Pennyroyal Plateau, a karst sinkhole plain. The site was used by humans for thousands of years as a place of refuge and source of natural resources, has been visited by tourists since 1816, and became a national park in 1941.

Mammoth Cave National Park protects and preserves some of the finest examples of karst landforms in the world. Mammoth Cave System (consisting of the interconnected Mammoth Cave, Flint Ridge, and Roppel Cave systems) is the longest cave in the world; more than 628 km (390 mi) have been explored to date, and the recorded length of the cave increases with each year of exploration. Myriad geologic factors combined to create the setting for the formation of this extensive cave. Over 10 million years ago, groundwater percolating through the soil and cracks within the resistant rocks above reached the relatively pure underlying limestone, dissolving increasingly wider conduits to form cave passages, vertical shafts, and multiple overlapping layers of caves. Other karst features within the park include sinking streams, springs, karst windows, and sinkholes. Given the predominance of karst features and processes at Mammoth Cave National Park, many resource management concerns pertain to karst issues. As discussed at a 2006 scoping meeting, the following issues, features and processes are of primary geological importance and have the highest level of management significance to the park:

- Cave and karst issues. The most serious management concern at the park pertains to the potential contamination of the underlying karst aquifer. Such systems are characterized by rapid infiltration with little or no filtering mechanism. Resource managers would benefit from gaining a quantitative understanding of groundwater movement through the system. Dye tracing and other studies are currently being used to delineate the groundwater basins, much of which extend beyond park boundaries. The cave ecosystem hosts a variety of specialized microbes and fauna that have adapted to the relatively stable microclimate and dark conditions. This environment is fragile and vulnerable to degradation from anthropogenic impacts, including artificial lighting, contamination, and overuse. Karst features are inherently associated with hazards such as cavern collapse and slippery trails. Detailed geologic and cave mapping will facilitate continued research and enhance our understanding of the Mammoth Cave System.
- Fluvial issues. The Green River is the base level for all water at Mammoth Cave National Park. The erosional and depositional history of this river is intimately tied to cave excavation and evolution. Issues associated with the river include flooding, sedimentation, and the negative impacts of Lock and Dam #6. This decrepit structure impounds the Green and Nolin rivers along much of their courses through the park. Lock and Dam #6 has compromised endangered species habitats and degraded the lower portions of the cave through frequent inundation. Because surface water is rare in this karst landscape, that which does appear in the form of sinkhole ponds, upland wetlands, springs, bogs, and farm ponds provides vital habitat for many species. Detailed inventory and monitoring of these surficial water features will enhance their protection and management.
- Mass wasting. Mass wasting refers to the dislodging and downslope movement of soil and rock material, such as during a rockfall, slump, or landslide. The sandstone-capped ridges throughout the park overlie steep cliffs and bluffs above the riverways. Isolated sinkholes within the park are steep-sided and their bases are filled with blocky debris. Blocks of rock and talus that have accumulated at slope bases throughout the area represent a potential mass-wasting hazard. Although uncommon in this part of Kentucky, seismicity and ground-disturbing activities such as blasting could trigger mass wasting within the cave and on the surrounding slopes. Quarrying near the park could also precipitate breakdown in the cave. The identification of areas vulnerable to such processes would help protect visitor safety and park resources.
- Interpretive and educational issues. As a classic example of a karst landscape, Mammoth Cave provides numerous opportunities for education and scientific research. Cave sediments and formations (speleothems) contain information about the evolution of the cave system and past life within the cave. Paleontological resources within the cave include amphibian, peccary, raccoon, bat, bird, fisher, short-faced bear, mastodon, saber-toothed cat, and horse remains. The bedrock in which the cave formed also contains fossils dating to the Mississippian period (approximately 359 to 318 million years ago), primarily

in the form of marine invertebrates. Pennsylvanian (approximately 318 to 299 million years ago) plant fossils occur within the park, but are not present in the cave. Interpretive programs could focus on connecting the geology of the park with the biology and history of the area.

The geologic units at Mammoth Cave National Park have inherent properties that control their surface expression, pose potential hazards, affect the location of infrastructure, influence habitat types, and host natural resources. These units record the Paleozoic (approximately 530 to 280 million years ago) history of the Illinois basin, located on the northwestern flank of the Cincinnati arch. This arch may date to the Ordovician (488 to 444 million years ago). Depositional environments preserved in the bedrock of the park include: deep-water, open-ocean basins; nearshore, shallow marine settings; carbonate platforms and lagoons; and deltaic and fluvial systems. These geologic units have remained relatively undeformed and undisturbed since their deposition. Their gently dipping beds were a major controlling factor in the development of the extensive cave system. The exposure of the bedrock at Mammoth Cave National Park to millions of years of post-Paleozoic weathering and erosion has created the landforms present today. Much younger, unconsolidated units within the park, including alluvium, terrace gravels, and landslide deposits, attest to active Earth surface processes and the evolution of the greater Ohio River valley since the Pleistocene (about 2.6 million to 10,000 years ago).

A Map Unit Properties Table, glossary, and geologic timescale are included in this report. The Map Unit Properties Table describes characteristics such as erosional resistance, suitability for infrastructure development, potential for geologic hazards, geologic significance, and associated paleontological and mineral resources for each mapped geologic unit. The glossary contains explanations of many technical terms used in this report, and the geologic timescale (fig. 25) provides a general reference to major geologic activity in the past 4.6 billion years.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Rickard Toomey (Mammoth Cave International Center for Science and Learning) and Rick Olson (Mammoth Cave National Park) for their thorough, thoughtful review and discussion of cave geology and resource management at Mammoth Cave National Park. The report was greatly improved through their efforts. Colleen O'Connor Olson (Mammoth Cave National Park) also provided comments and feedback on the final draft of the report. Art Palmer (State University of New York, Oneonta) and Joe Meiman (NPS Cumberland Piedmont Inventory and Monitoring Network) also provided information during the assembly of this report.

Credits

Author

Trista Thornberry-Ehrlich (Colorado State University)

Review

Rickard Toomey (Mammoth Cave International Center for Science and Learning)
Rick Olson (Mammoth Cave National Park)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Jennifer Piehl (Write Science Right)

Digital Geologic Data Production

Heather Stanton (Colorado State University)
Jason Isherwood (Colorado State University)
Andrea Croskrey (NPS Geologic Resources Division)
Tim Cleland (Colorado State University intern)
Christopher Kizer (Colorado State University intern)

Digital Geologic Data Overview Layout Design

Derek Witt (Colorado State University intern)
Philip Reiker (NPS Geologic Resources Division)
Georgia Hybels (NPS Geologic Resources Division)

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Mammoth Cave National Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Park Setting

Regional Information

Mammoth Cave National Park is approximately 140 km (90 mi) south of Louisville, Kentucky and 30 km (20 mi) northeast of Bowling Green, Kentucky. Covering 21,380 ha (52,830 ac) of south-central Kentucky, the park contains over 50 km (31 mi) of the scenic Green and Nolin river valleys, which cut down through gently tilting bedrock in Edmonson and Hart counties (fig. 1). This region is one of the world's most famous cave-rich karst landscapes (Livesay 1953) and home to the Mammoth Cave System—the longest in the world with at least 628 km (390 mi) of mapped passages.

The park is located within the Interior Low Plateau on the southeastern edge of the Illinois Sedimentary Basin (Meiman 2006). The regional landscape consists of forested rolling hills, steep-sided plateaus dissected by winding rivers, and karst sinkhole plains.

Regional history and establishment of Mammoth Cave National Park

Approximately 11,000 years ago, American Indians from nearby settlements discovered the entrance of Mammoth Cave. They used the cave intermittently for thousands of years, with use concentrated between 4,000 and 2,000 years ago. American Indian groups stopped using the cave approximately 2,000 years ago, possibly due to increasing reliance on settled agricultural communities or changing social practices. Settlers of European descent found the cave in the late 1700s. During the War of 1812, Mammoth Cave sediments were an important source of saltpeter for gunpowder production. Public visitation of the cave began in 1816, prompting a series of private ownerships characterized by contentious land disputes.

A. K. Lobeck (1928) and J. W. Weller (1927) provided some of the earliest descriptions of the geology of the Mammoth Cave area. In 1926, Congress authorized the formation of a national park to preserve the cave, natural landscape, and cultural resources of the area. Established on July 1, 1941, Mammoth Cave National Park preserves part of the largest cave system in the world; more than 628 km (390 mi) of passages have been explored. The cave currently contains over 16 km (10 mi) of developed trails. On October 27, 1981, the park became a World Heritage Site. The park is also part of a larger UNESCO Man and the Biosphere Program International Biosphere Reserve, designated on September 26, 1990. According to the park's General Management Plan, "The mission of Mammoth Cave National Park is to protect and preserve for the future the extensive limestone caverns and associated karst topography, scenic riverways, original forests, and other biological resources, evidence of past and contemporary lifeways; to provide for public education and enrichment through scientific study, and to provide for development and sustainable use of recreational resources and opportunities."

Additional information may be found on the park's web site at: http://www.nps.gov/maca.

Geologic Setting

Mammoth Cave National Park lies at the edge of the Chester Upland (also called the Mammoth Cave Plateau), where erosion-resistant, rock-capped ridges (e.g., Flint, Joppa, and Mammoth Cave ridges) overlook the Pennyroyal Plateau, a karst sinkhole plain some 45 to 60 m (150 to 200 ft) below (fig. 2). Locally, the ridges are separated by deeply incised karst valleys, including Houchins, Doyel, and Woolsey valleys, and the Green and Nolin rivers. The region is often referred to as the Central Kentucky Karst, and is part of a karstic limestone belt that extends from southern Indiana through Kentucky into Tennessee (White et al. 1970). The underlying geologic framework is comprised of nearly horizontal bedrock.

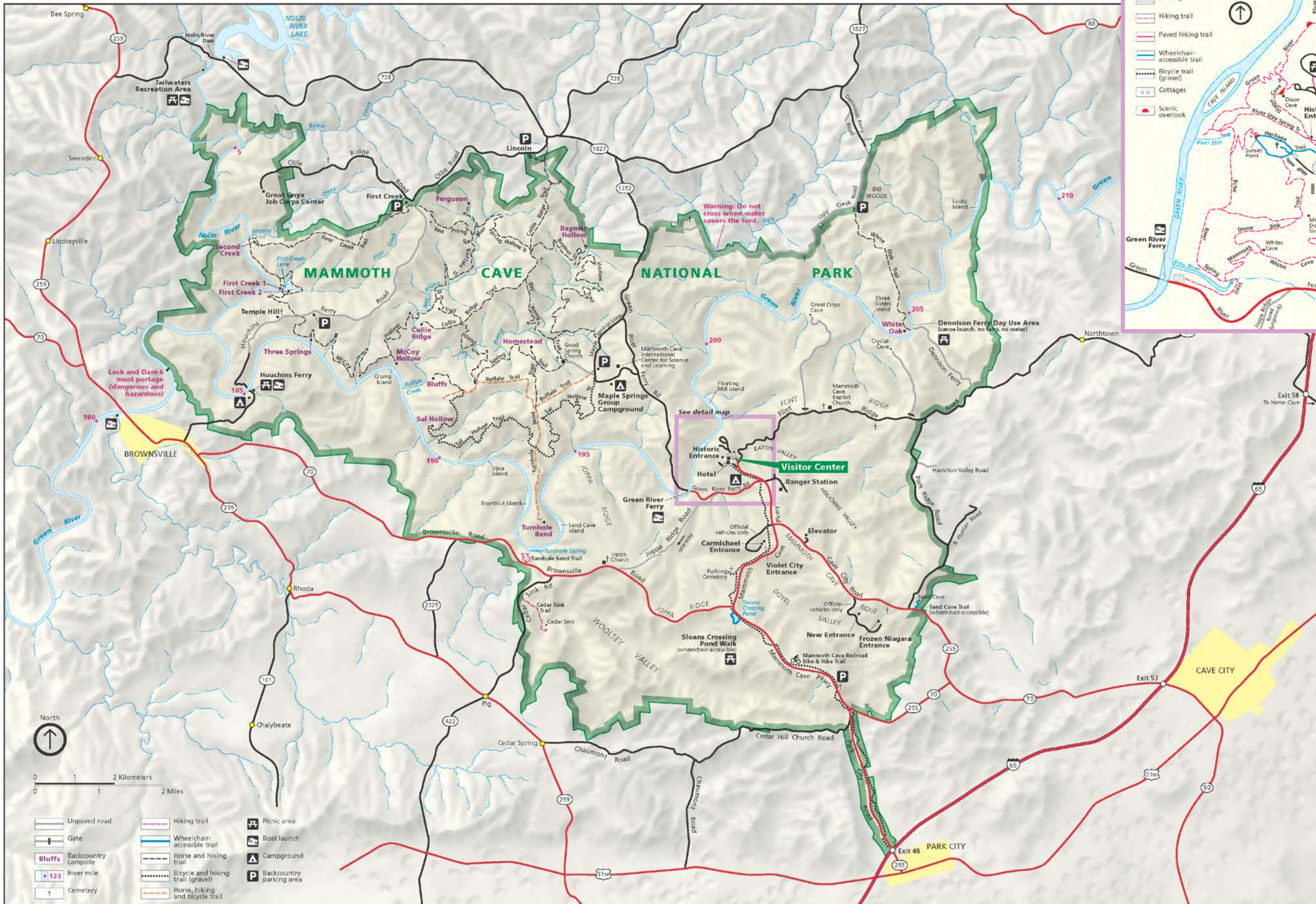
The sedimentary bedrock units at Mammoth Cave National Park are Mississippian to Pennsylvanian in age. During the Mississippian Period (approximately 325 million years ago), North America was located near the equator and was partially covered by a shallow sea. The Mammoth Cave area was on the southeastern edge of the Illinois depositional basin (a major structural depression in the eastern midcontinent) between the Cincinnati Arch (a prominent regional uplift) to the north and east (fig. 3) and the Nashville Dome to the south. The bedrock in this area tilts gently to the northwest, toward the center of the Illinois Basin. The nearly horizontal, very pure Mississippian limestones have strongly influenced the landscape in the area of Mammoth Cave (Kuehn et al. 1994). Regional mapping has documented the presence of a large pull-apart depression, the Rough Creek graben (fig. 4). The eastern end of this graben is delineated by the Cub Run fault, which crosses the northwestern corner of the park. In the deepest portion of the depression, the distance from the surface to the Precambrian (before 542 million years ago) basement rocks is approximately 7,000 m (23,000 ft; Olson and Toomey 2009a).

Carbonate-rich sediments accumulated on the floor of the shallow sea and eventually formed limestone and dolomite, a magnesium-rich carbonate rock. These chemical precipitates were interbedded with smaller amounts of clastic sand, silt, and clay that were transported into the basin from the north. Clastic sediments began to dominate basin deposition near the end of the Mississippian and into the Pennsylvanian (approximately 318 to 299 million years ago) periods.

The largest caves in the Mammoth Cave National Park area formed by dissolution from percolating groundwater and flowing underground streams within the Mississippian-aged, limestone-rich St. Louis, Ste. Genevieve, and Girkin formations (geologic map units Msl, Msg, and Mg, respectively; Palmer 1981). The Haney and Glen Dean limestones (geologic map units Mgh and Mgd, respectively), which lie above the primary Mississippian limestones, contain perched karst systems with upland springs and sporadic caves several hundred feet in length (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). A resistant cap of relatively insoluble, sandstone- and shale-rich rocks allowed the extensive development and preservation of the largest caves in the region. These rocks are contained within the Big Clifty, Hardinsburg, Leitchfield, and Caseyville formations (geologic map units Mgb, Mh, Ml, and PNca, respectively; White et al. 1970; Palmer 1981). Where erosion has removed these resistant rocks, such as on the nearby Pennyroyal Plateau and in karst valleys, limestone dissolution has dramatically lowered the land surface and formed an undulating landscape pitted with sinkhole depressions (Livesay 1953; Palmer 1981).

The Mammoth Cave System (consisting of the interconnected Mammoth Cave, Flint Ridge, and Roppel Cave systems) is the primary focus of the park; however, in addition to the Mammoth Cave, there are more than 300 smaller caves throughout the park (Thornberry-Ehrlich 2006). Mammoth Cave is complexly patterned, containing several levels of cave passages that appear superimposed upon one another in plan view. Cave development rates and patterns have been controlled in part by temporary cessations or reductions in the downcutting activity of the Green River (the major regional drainage; Palmer 1981). Changes in river erosion rates are, in turn, intimately connected with climatic shifts. Stable climates have slowed river erosion, increased active groundwater circulation, and caused extensive cave-passageway excavation, whereas sudden climatic shifts (e.g., during ice-age events) have caused the river to cut downward, shifting active cave development to lower stratigraphic levels (Livesay 1953; Palmer 1981).

The extensive regional underground drainage system is represented by many karst valleys, sinking streams, and springs. The abundant annual precipitation (132 cm [52 in.]) passes rapidly underground through sinkholes and joints to join the base-level flow of the Green River (Livesay 1953). Small-scale ponds have developed in upland areas due to the presence of relatively impermeable layers (e.g., shales; Livesay 1953).



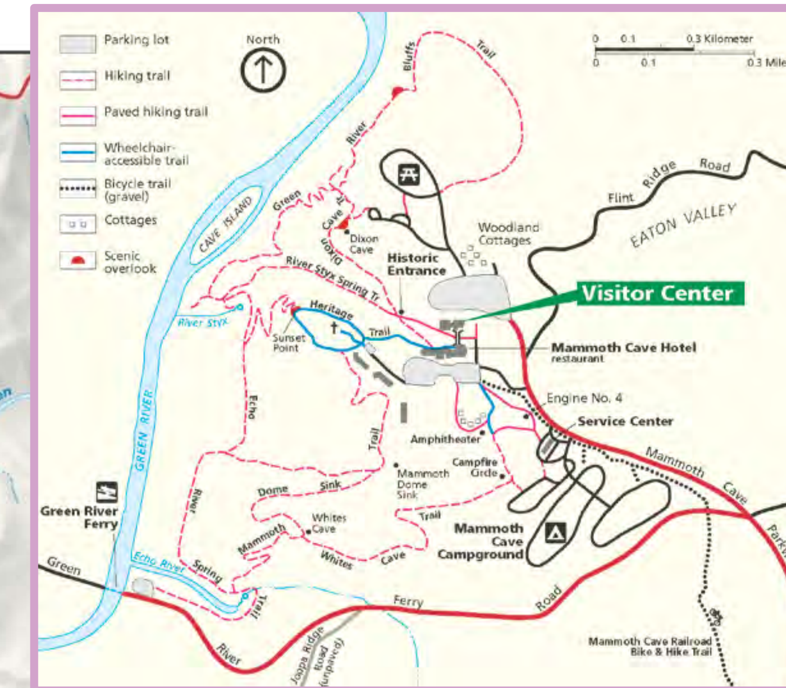


Figure 1. Maps of Mammoth Cave National Park. The large map to the left shows the park area and surrounding towns. Notice the dissected topography typical of karst landscapes. The larger-scale map above (see purple box on large map) details the visitor center and historic entrance area. National Park Service maps.

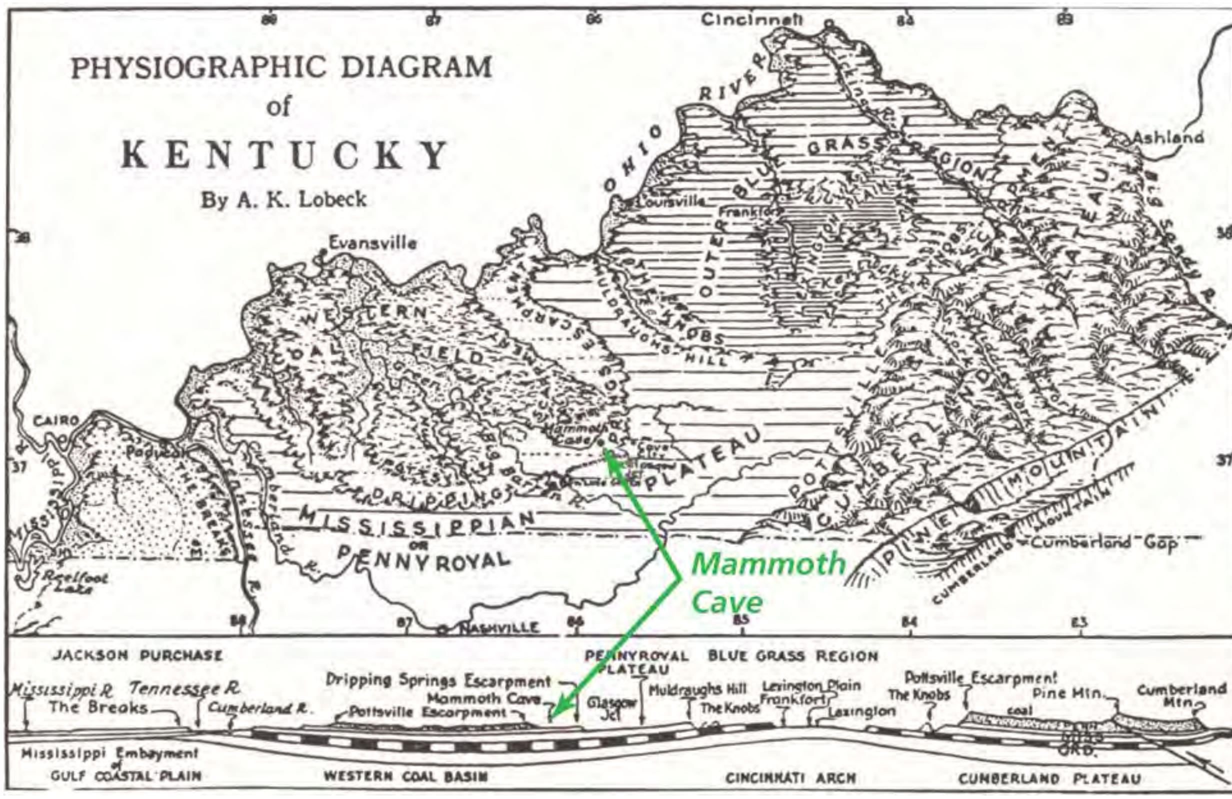


Figure 2. Historic physiographic diagram of Kentucky with geologic cross section. This diagram is still being referenced by geologists due to its accuracy, detail, and aesthetic value. Green arrows point to Mammoth Cave on the map and cross section. Graphic from Lobeck (1928: fig. 1) as part of his comprehensive publication *The Geology and Physiography of the Mammoth Cave National Park*.

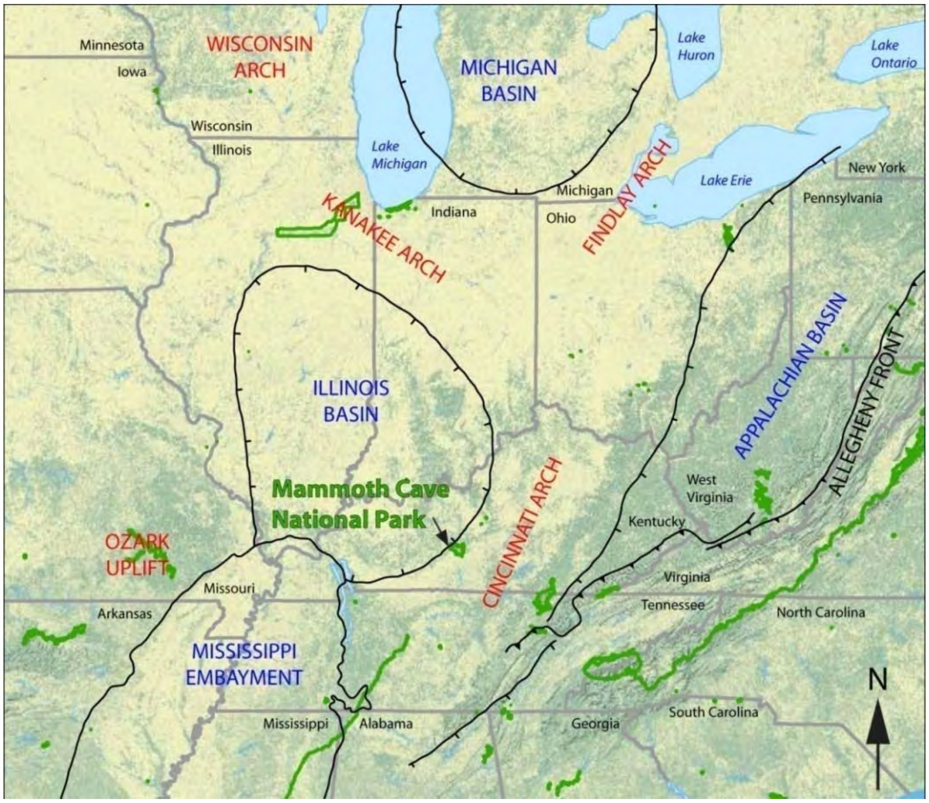


Figure 3. Structural setting of Kentucky and surrounding midcontinental areas, with relief indicated by shading. Basins are downwarped geologic structures typically characterized by thick sedimentary deposition, whereas arches are broad, convex-upward regional folds, often located between basins. Arch erosion exposes rocks at the surface that are older than those in adjacent basins. Tick marks point toward basin centers. Sawteeth indicate the upthrown block along a thrust fault. Mammoth Cave National Park and other National Park Service units are outlined in green. Gray lines indicate state boundaries. Adapted from McDowell (2001; fig. 15) by Trista L. Thornberry-Ehrlich (Colorado State University) and Jason Kenworthy (NPS Geologic Resources Division).

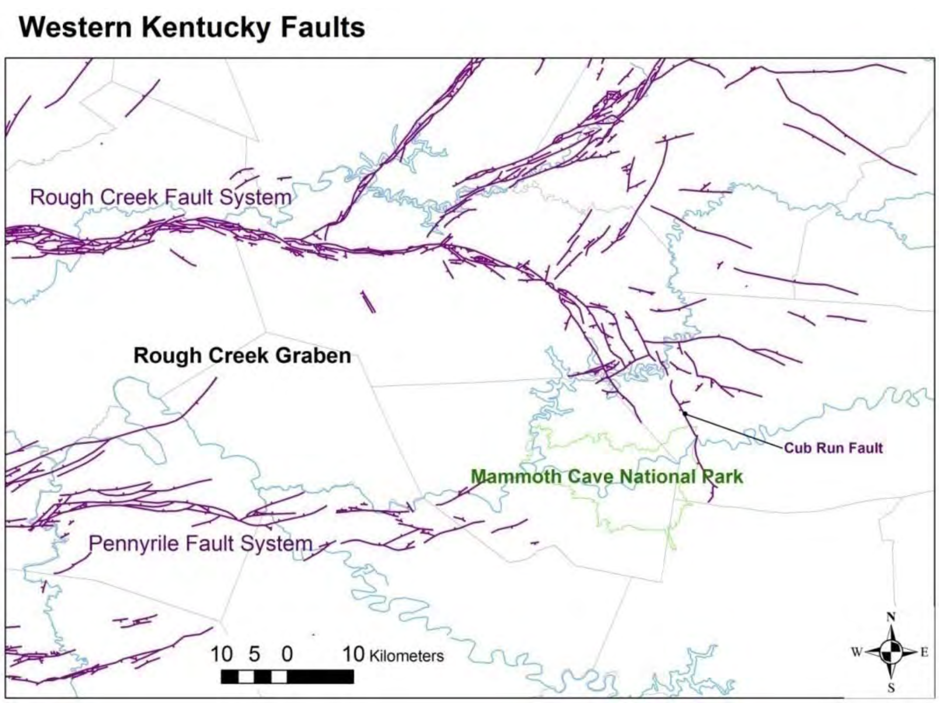


Figure 4. Map of the regional geologic setting of western Kentucky, showing the Rough Creek Graben. The Rough Creek fault system bounds the structure to the north. Several unnamed faults and the Pennyrile fault system form the southern boundary. The Cub Run fault forms the eastern end of the graben. Gray lines are county boundaries. Graphic modified from Olson and Toomey (2009b), courtesy Rickard Toomey (MCICSL) and Rick Olson (Mammoth Cave NP).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Mammoth Cave National Park on June 15 and 16, 2006, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Cave and Karst Issues

Because the Mammoth Cave System is the primary focus at Mammoth Cave National Park, the main geologic issues facing park resource managers pertain to the understanding of this vast system. The hydrogeologic system is intimately tied to cave development at the park, which is described further in the "Features and Processes" section. The understanding of water flow through the system is critical to the successful maintenance of water quality and the ecosystem dependent on it. The porous nature of the karst system is associated with a high potential for groundwater contamination. The mapping of recharge areas and groundwater basins is necessary to determine areas at risk for contamination and in need of protection. A large quantity of spatial and geographic information system (GIS) data is available for the Mammoth Cave area and can serve as a useful tool for resource managers. The karst landscape at the park, including breakdown areas and slippery trails, also presents potential hazards to visitor safety.

Hydrogeology and Cave Development Modeling

Mammoth Cave was formed by the movement of water along cracks and the dissolution of limestone to create cavities. Thus, the management of natural resources at Mammoth Cave National Park requires an understanding of how and where groundwater flows from the surface through aquifers and cave conduits toward the base level, which is controlled by the Green River. Park management has expressed interest in further research into the hydrogeologic history of regional karst development and the creation of hydrologic models to help predict ecosystem response to contaminants and other anthropogenic impacts (Thornberry-Ehrlich 2006). The Mammoth Cave National Park Water Resource Management Plan (Meiman 2006) contains a comprehensive summary of water-related resource-management concerns. The reader should consult Meiman's document for more detailed information about the park's water resources.

The hydrologic system at Mammoth Cave National Park is vast and diverse, covering hundreds of square kilometers. Any hydrologic model developed for this system must take into account the detailed stratigraphic characteristics of the cave-bearing geologic units (fig. 5). Such a model must relate geologic controls, such as composition, fracturing and jointing, layering, and orientation, to karst development (Thornberry-Ehrlich 2006). The bedrock dips away from the Green River on the north, against the overall hydraulic gradient toward the river, and caves are not as well-developed on this side. In contrast, the units dip toward the base level on the south and bedding channels groundwater toward the river, resulting in more extensive cave formation (Meiman 2006). Although the geologic units at Mammoth Cave National Park appear flat and undeformed, local structural flexures have influenced the direction of groundwater flow in some areas of Mammoth Cave (Palmer and Palmer 1993; May et al. 2005; Olson and Toomey 2009a). Minute differences in bedrock composition can affect dissolution rates and the evolution of groundwater conduits. Petrographic analyses of apparently homogenous limestone may reveal many different compositions, bedding structures, grain sizes, origins, and diagenesis (Feiznia and Carozzi 1987). Detailed study of the bedrock exposed within Mammoth and other park caves may reveal complex relationships between the geologic framework and the evolution of the cave network and hydrologic system at the park (fig. 6; Olson 2002).

The management of groundwater resources requires geochemical compositional analysis and monitoring, oxygen isotope studies of flowing and dripping water, water-quality monitoring, and further natural and introduced flow tracer studies (Thornberry-Ehrlich 2006). The hydrogeologic system model of Mammoth Cave would be enhanced by further delineation of the extent and nature of aquifers and flow systems, the examination of interactions between groundwater and surface water, the definition of recharge mechanisms and pathways, and the analysis of changes in recharge rates and the effects groundwater pumping (Thornberry-Ehrlich 2006). The park's Water Resource Management Plan (Meiman 2006) identified the refinement of karst watershed maps as a strategy to improve the hydrologic integrity of park waters and support natural aquifer-system processes and native life.

Aquifer Delineation and Flow Path Mapping

The Mammoth Cave karst aquifer is among the best-understood conduit flow networks in the world. Although nearly 1,000 dye traces have been performed, much more work is needed to provide the level of understanding necessary to manage this resource more effectively (Meiman et al. 2001). The identification of flow paths and recharge points is particularly important. A groundwater-basin boundary may have little relationship to apparent surface-drainage boundaries (Currens 2002). In 1999, the NPS initiated a long-term dye-tracing program in the Mammoth Cave System, with the goal of accurately locating karstic groundwater-basin divides (complex three-dimensional underground surfaces that function similarly to above-ground basin divides). Because the cave passages extend over several major groundwater basins, this program will provide critical knowledge and facilitate the protection of cave ecosystems (Meiman and Groves 1999; Meiman et al. 2001). Early results of this work have shown that groundwater crosses previously established drainage boundaries, indicating the need for further refinement and more accurate mapping (Meiman and Groves 1999). Meiman et al. (2001) has detailed the results of in-cave dye tracing and additional research at several locations, including Turnhole Spring, Denial River, Turnhole-Roaring/Echo Overflow, Crystal Cave, Outward Bound, Three Springs, Service Station (no longer active), and Floating Mill Hollow. Meiman (2006) provides a regional overview of our current understanding of the extent of karst groundwatersheds in the park and throughout south-central Kentucky.

Recharge Areas

Research conducted from the mid 1970s through the early 1980s found that approximately 60% of the recharge area of the Mammoth Cave karst aquifer (approximately 300 km^2 [115 mi^2]) extends beyond the park boundary onto private lands (Quinlan and Ray 1989; Meiman et al. 2001). The Kentucky Geological Survey and other agencies, such as the Kentucky Natural Resources and Environmental Protection Cabinet, have produced groundwater-basin quadrangle maps that include the area of Mammoth Cave National Park (see http://www.uky.edu/KGS/water/research/kaatlas.htm). These maps can be used to quickly identify the groundwater basins and springs to which a particular surface may drain, compare the relative sizes of catchment basins, and evaluate potential water supplies. Although data from groundwater tracer studies are the main sources of information used to construct these types of maps, flow paths remain imprecisely defined and have been inferred or interpreted using water-level, geologic structure, or surficial morphological data (Ray and Currens 1998).

Glennon (2001) analyzed the morphometric relationships among active-flow networks (quantitative drainage-network analysis) within the karst flow system of Mammoth Cave at Turnhole Bend. The karst aquifer displays drainage characteristics that are similar in many ways to surface networks. The ordering of cave streams and their catchments generally follow relationships observed for surface-stream networks (after Horton 1945). However, some groundwater can leak from one basin to another in karst systems, diverging streams can share the same surface catchment, branched distributaries can discharge water to multiple springs, and basin boundaries are three-dimensional and highly complex (Glennon and Groves 1997; Glennon 2001; Meiman et al. 2001; Currens 2002). Mapped active base-flow, stream-drainage density within the Turnhole Bend groundwater basin ranged from 0.24 to 1.13 km/km^2 (0.39 to 1.82 mi/mi^2). These values are lower than those for a nearby, climatologically similar, nonkarstic surface-drainage system (1.36 km/km^2 [2.19 mi/mi^2]; Glennon 2001; Glennon and Groves 2002). This type of analysis yields only minimum values because the mapped cave streams represent only a fraction of all underground streams within any study area. Other calculations have been made with the assumption that each sinkhole drains at least one first-order stream, yielding much higher drainage densities (6.25 to 7.22 km/km^2 [10.05 to 11.63 mi/mi^2]) for Turnhole Bend. Such discrepancies underscore the constant need for additional cave mapping and quantitative analyses. Abundant spatial data that can be manipulated using GIS technology are available for the Mammoth Cave watershed (Glennon 2001).

Cave Development Processes

Cave development processes can theoretically be described mathematically (Groves and Meiman 2003). However, such a mathematical model could never realistically describe the evolution of such a vast and complex system. The application and development of various models can provide a framework within which important processes can be understood and gaps in required information can be identified (Groves and Meiman 2003). Groves and Meiman (2005) used high-resolution flow and chemical data to quantify carbonate dissolution rates (conduit development) and the contribution of solute removal to landscape denudation (the process by which the removal of material through erosion and weathering reduces elevation and landform relief) at Cave City Basin. They found that the rate of landscape denudation through carbonate dissolution could be described using a linear function of the amount of water moving through the system, but that the dissolution of conduit walls depended on the amount of water available and the distribution of above-ground precipitation (Groves and Meiman 2005). Groundwater infiltration was, in turn, influenced by the karst landscape and by interconnectivity with subterranean conduits. A long-term cross-sectional study of the evolution of two active passages created in Mammoth Cave by the Hawkins and Logsdon rivers was completed (Groves and Meiman 2003). As part of the National Park Service Inventory and Monitoring Program, water-quality data (available for many types of research) are being obtained in wells and experiments are underway to determine seasonal and storm-related changes in limestone dissolution rates (Groves and Meiman 2003). These types of targeted monitoring studies will help quantify the evolution of the cave network, the development of the overall landscape, and the extent and behavior of karst aquifer basins of Mammoth Cave National Park.

Contamination Potential

Because the conduits of a karst aquifer are like roofed creek beds, almost no filtration of percolating groundwater occurs (Currens 2002). Groundwater issues originating kilometers away can thus impact streams and rivers within the park. In addition, some species dwelling within the cave depend on the influx of water to carry nutrients (described in the "Biology and Ecosystem Health" section). Thus, the protection of the quality of water percolating through the bedrock and flowing in underground streams is crucial (Culver et al. 1999). Shallow carbonate aquifers in karst areas are extremely vulnerable to contamination from human and animal waste, urban and agricultural land use, industrial practices, and leaking underground storage tanks (Kuehn et al. 1994). The underground streams of the south-central Kentucky karst have been especially affected by human and animal waste contamination (May et al. 2005). Such contaminated water results from three sources: 1) the flow of runoff following heavy rains on farm lands into subsurface streams at swallets (the holes into which sinking streams flow); 2) from the flushing by heavy precipitation of septic-tank effluent from the soil down into underlying conduits; and 3) from the residential use of older homes lacking connections to city sewers (May et al. 2005). In 1997, an oil spill occurred in the Arthur Community along the southwestern edge of Mammoth Cave National Park. An emergency effort prevented the spilled oil from sinking into the karst aquifer, but the incident highlighted the vulnerability of the park's karst system to contamination and confirmed the need for quantitative hydrogeologic models (Hawkins et al. 2001). Because runoff has little or no filtration through the soil, any contaminants present in storm water sink directly into caves and may be carried for miles through the aquifer within a few hours (Kuehn et al. 1994). The natural subsurface conduit system can then carry contaminated water to springs located at major surface streams, such as the Barren River (May et al. 2005).

The karst groundwater basins of the Mammoth Cave System extend well beyond park boundaries, and are crossed by 19 km (12 mi) of Interstate Highway 65. This road is extremely busy, and is therefore a significant source of contamination from routine runoff and also from spills linked to vehicle accidents. Retention and filtration basins with a capacity of 10,000 gallons are being built at every sinkpoint along the highway as it is widened to six lanes (fig. 7). The CSX railroad roughly parallels the highway, but no plan has been devised that would prevent the volumes of liquid in ruptured tank cars from flowing down sinkholes. Fortunately, train derailments and accidents are much less common (Olson and Schaefer 2001; R. Olson, Mammoth Cave NP ecologist, written communication, September 2011).

Geographic Information Systems Data Analysis Potential

Scoping-meeting participants identified the geographic area surrounding the Mammoth Cave System that would be of interest to include in a park-wide GIS (Thornberry-Ehrlich 2006). As cave exploration, mapping, and description continue, existing data and interpretations are constantly augmented and modified. According to Olson (2001), the development of a GIS-based model with multiple data layers is the only practical approach to the three-dimensional presentation of the numerous relationships among component ecosystems within karst landscapes. In addition to increasing our knowledge of regional drainage and cave resources, GIS analyses could help identify critical points of natural (and cultural) resource vulnerability that require targeted management efforts (Olson 2001). New GIS modeling tools are applicable to the management of groundwater resources (Pfaff and Glennon 2004) and may allow the development of a useable working model for Mammoth Cave National Park. Sinking streams, groundwater flow paths, drainage basins, slope aspects, land-use patterns, and transportation corridors can be linked into a groundwater protection model using currently available GIS software. This software allows the user to clip, buffer, and intersect different layers to establish spatial relationships among various factors (Pfaff and Glennon 2004). Because Mammoth Cave National Park has a wealth of geospatial information, such model building could be a valuable resource-management strategy. Much of the existing spatial information about the cave is raster data in Adobe Illustrator, AutoCad, illustrations/maps drawn on mylar, and Walls formats. Although many datasets have been converted to GIS databases to date, some data formats are not adequately supported by GIS software and will require conversion into an appropriate format.

In 2006, scoping-meeting participants developed the following list of questions about data collection, analysis, and future mapping within Mammoth Cave National Park.

- Who is responsible for maintaining the data?
- How do significant cave areas relate to existing park infrastructure?
- When new data are added, what system is in place to ensure integrity between datasets?
- How can cave raster data be vectorized?
- How can different resolutions, interpretations, and scales be captured in one Geodatabase?
- Would the establishment of underground geologic mapping stations, tied to cave maps, help to facilitate connections with the NPS-GRI digital geologic map?
- How can geology and cave layers best be superimposed spatially to determine relationships within a GIS?

These types of questions can help guide park resource managers when scoping, proposing, and funding new cave research within the park. Existing data must also be updated or converted to a format compatible with geospatial analysis. The GRI mapping team is available to help resource managers with GIS data conversion, management, and analysis.

Biology and Ecosystem Health

The caves within Mammoth Cave National Park contain specialized, fragile, and vulnerable ecosystems that are intricately linked to cave hydrology and geology. A biological inventory (unpublished as of 2011) at the park has provided a foundation for monitoring protocols that are now in place. These and future monitoring targets will facilitate the understanding of cave ecosystems and the identification of particular areas of concern. The accumulation of more information about cave biology and the karst ecosystem at Mammoth Cave National Park will help predict the sensitivity of the system to geologic, hydrologic, and anthropogenic changes or disturbances in the ecosystem of the park's caves (Thornberry-Ehrlich 2006).

Cave management would benefit from data collected through further biological resource studies, such as macrobiological, microbiological, biofilm and endangered-threatened-sensitive species surveys. The relationship between ecosystem health and water quality and the assessment of ecological risk require an understanding of the interactions among biological, chemical, and geological factors within cave ecosystems (biogeochemical cycling).

Park management has expressed particular interest in the modeling of cave and karst ecological systems. According to Barr (1967), biological communities in caves such as Mammoth Cave provide opportunities for the investigation of ecological dynamics, due to the relatively small number of species involved, the isolated or discontinuous (island) habitat, the absence of light, and the relatively closed system (silence, constant temperature, high relative humidity). The investigation of patterns of variation and degrees of differentiation within and among species populations provide valuable contributions to the understanding of species evolution (Caccone 1985). Many cave-dwelling species at Mammoth Cave National Park are considered vulnerable to, or imperiled by, local environmental degradation (Culver et al. 1999).

Invasive algae, cyanobacteria, moss, diatom, and fern species (collectively termed "lampen flora") are present in lighted cave areas and are a critical concern for park management (Toomey et al. 2009). Light promotes lampen flora growth, requires the use of chemicals (e.g., bleach) for eradication, consumes electricity, and adds heat to the cave system (Toomey et al. 2009). The presence of lampen flora in Mammoth Cave is currently managed with the use of extinguishable light stations along tour routes to avoid continuous light exposure. An ongoing study is testing the ability of lights with a combination of selected wavelengths (those that are not efficiently used by lampen flora containing chlorophyll) to reduce the growth of such microbes. Lights of different colors are also being tested to determine whether a specific color might reduce the effects of invasive microorganisms in the cave. To date, these lights appear to have slowed lampen flora growth and achieved a shift in taxa (Toomey et al. 2009; R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

To understand speciation within the discontinuous cave habitat, a familiarity with the inputs of nutrients (from geological and biological processes) to the cave ecosystem is critical (Barr 1967; Barr and Holsinger 1985). Nutrients are generally transported down gradients, with some back-flooding from rivers into cave streams (Olson 2003). Sinking streams wash logs, twigs, leaves, bacteria, and epigean (living on or near the ground surface) animals into caves; leaves and debris blow into entrances; and trogloxenes (species that use the cave for refuge, such as cave crickets, bats, and wood rats) deposit eggs and feces in caves and often die there, passively contributing to the ecosystem (Barr 1967; Olson 2003). Diverse cave species, such as mites and springtails, depend on the importation of nutrients into the food/energy-limited Mammoth Cave System by the cave cricket (*Hadenoecus subterraneus*; Poulson et al. 1995). These crickets are, in turn, affected strongly by climate fluctuations; they flourish during temperate summers, warmer winters, and relatively moist conditions (Poulson et al. 1995)

Some elements of the park's cave environment compromise the stability of microbial and faunal populations. Seasonal variations in the physical environment and food supply can have strong negative impacts. Evaporative rates increase in some areas during the winter, and seasonal flooding of underground rivers, such as the Echo and Styx rivers, can change water levels as much as 20 m (60 ft; fig. 8; Barr 1967). Water levels and quantities fluctuate constantly. Cave aquatic habitats can be classified by water quantity, ranging from ephemeral pools, shaft drains, and shallow stream tributaries to base-level streams (Olson 2003).

Extensive research has investigated the influence of cave geology on the biodiversity of the ecosystems developed within them. According to Call (1897), "the conditions under which collections are made in Mammoth Cave are not of the simplest character. The cavern itself is very great, and the forms of life neither large, as a rule, nor abundant…it is only after much search and repeated failures that [the researcher] begins to realize that the distribution of life within the cave obeys certain laws." Vast expanses of thick, flat-lying, relatively pure and soluble limestones in the park area form sinuous passages with a dendritic plan, in which successive levels are commonly superposed (Barr 1967). The cave system is not a single continuous, connected passageway, but rather a complex, stacked system of more or less isolated segments with limited access to the surface. This pattern limits the overall population density of insect species, such as beetles, but results in greater species diversity. Generally, the "twilight zone" (near entrances) hosts the greatest species diversity; the middle zone contains common species that may commute to the surface; and obligate fauna (those whose habitat is limited to the cave) evolve within the unique aspects of the deep interior of the cave environment, which are controlled by geologic factors (Poulson and White 1969). The complex relationship between the geologic attributes of Mammoth Cave and the biodiversity of its ecosystem is currently under study and a full description is beyond the scope of this report.

Cave microbes and fauna can also affect cave geology. Organisms likely play a marked, yet undefined, role in the development of speleothems and other karst features. The geochemical attributes of active streambeds inside the Mammoth Cave System cannot account fully for the observed rates of limestone dissolution; microbial effects, such as the production of acids and acid-forming gases by cave bacteria, must also be implicated (Fowler et al. 2001). Some varieties of carbonate minerals that form the soft, cottage-cheese-like masses of "moonmilk" are also associated with particular species of bacteria (Poulson and White 1969). Cave management would benefit from further investigation of the role of organisms in calcite deposition and dissolution (Thornberry-Ehrlich 2006).

Maintaining Cave Microclimates

In comparison with surface climatic conditions in south-central Kentucky, the microclimate within Mammoth Cave is very stable and moderate. The mean annual temperature is closely correlated with that of the soil at depths of 50 to 100 m (164 to 328 ft; Van Landingham 1965). In the deep, completely dark interior of the cave, away from water inputs, annual temperatures range from 13 to 14°C (55 to 57°F) and humidity is high due to the closed nature of the cave system.

The maintenance of the relatively constant environment in much of Mammoth Cave is vital for the protection of many classes of cave resources and processes, but human activities (e.g., overcrowding, excessive lighting, improper airflow management at entrances) can easily alter this system (Toomey et al. 2009). Changes in the cave's microclimate affect the biota, organic archeological resources, mineralogy, speleothems, airflow dynamics, air quality, dust dispersion, and the condensation, corrosion, and redeposition of speleothems (Thornberry-Ehrlich 2006). Alterations made to the historic entrance of Mammoth Cave, such as the removal of rockfall debris at Houchins Narrows, have disrupted atmospheric conditions in the historic section of the cave (Jernigan and Swift 2001; Olson 1996).

Light is a limiting factor for most surface organisms but not for cave life, which lives in largely isolated ecosystems adapted to total darkness. The introduction of artificial illumination into this environment at Mammoth Cave has produced changes that are difficult to assess (Van Landingham 1965). According to Toomey et al. (2009), lampen flora distort cave minerals and biological communities, and the biocides used to kill the microbes damage the cave ecosystem. This effect may be cascading. Lampen flora displace natural microbes, including bacteria, fungi, and algae, that are vital, nutrient-providing components of the cave ecosystem (Aley and Aley 1992; Toomey et al. 2009). Bacterial metabolism may facilitate mineral deposition on calcite formations (Northrup et al. 1997). Ongoing studies at Mammoth Cave, Carlsbad Caverns, Great Basin, and Wind Cave national parks are investigating the impacts of artificial light on cave ecosystems, with the goal of determining the most prudent approach to artificial lighting.

The microclimate in park caves is related to airflow and airflow in controlling condensation also influences rockfall potential. Condensing fluids may cause cave-wall corrosion and precipitate minerals into cracks which may act as wedges. Understanding fluctuations in humidity, airflow, and temperature within the cave may help predict rockfall in areas identified as prone to collapse and allow management to prevent potential condensation problems. Airflow is incredibly important to many cave processes; variations in airflow are related to the formation of speleothems, including rims and popcorn. Cave geometry, which is controlled by anthropogenic alteration and geologic processes and features such as joints, fractures, conduits, and dissolution, strongly affects airflow. Cave resource management and visitor comfort depend on an understanding of the ways in which geology controls airflow and the "chimney effect" in Mammoth Cave, which is driven by air density and temperature (Thornberry-Ehrlich 2006; R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). Additional airflow mapping is needed for resource management at Mammoth Cave National Park.

Air temperatures at various sites within the cave system can be predicted using a mathematical model developed by Jernigan and Swift (2001). This model used data from eight stations in the historic section of Mammoth Cave to describe the specific cave geometry and natural forces driving airflow within the cave. Such models can help resource managers predict and understand cave responses to anthropogenic changes.

Windblown (aeolian) deposits are present within several caves at Mammoth Cave National Park and represent discrete events. For example, the aeolian deposits at Turner Avenue (part of Flint Ridge Cave) likely resulted from a sudden gust of strong wind at an unknown time. Aeolian deposits are relatively rare in Mammoth Cave. The creation of such deposits depends on prevailing wind orientation (aligned with a cave opening) and the presence of readily available (entrainable) loose sediments. The identification and mapping of localized aeolian deposits within the cave system could enhance understanding of past climate and cave-development conditions.

Karst Hazards

Several hazards are unique to cave and karst environments, including the confined nature of caves (fig. 9), underground and sinkhole flooding, sinkhole collapse, rockfall and cave instability ("breakdown"), gas circulation and concentrations (e.g., radon, carbon dioxide, toxic vapors), and the presence of bat guano, which causes histoplasmosis, a fungal infection know as "valley fever." In addition to the Mammoth Cave System, more than 300 smaller caves throughout the park must be accurately mapped and protected (Thornberry-Ehrlich 2006). Sinkhole flooding (in solutional and collapse sinks) is a natural hydrologic process that occurs during intense rainfall events when the quantity of storm water flowing into the sinkhole exceeds its capacity to drain into underlying conduits, conduit transmissivity has already been exceeded, or the water table is already high. Increased urban development has aggravated sinkhole flooding by creating extensive impervious surfaces that increase local runoff. Developers have also filled in many sinkholes (May et al. 2005).

Gently sloped, dolines are much more common than collapse sinks at Mammoth Cave National Park. These features represent a minimal hazard because they form slowly by solution and subsidence and are easily identified and avoided. Sinkholes may rarely form through the collapse of underground caverns, depositing large amounts of debris within the sinkhole (Purdue 1907). Collapse sinks are rapid and could potentially swallow roads and other infrastructure within the park. Sinkhole collapse has not impacted any major structure within the park to date; most park structures have been built on resistant sandstone cap rock and would only be impacted by a very large collapse (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

The term "cave breakdown" refers to the collapse of a cave ceiling or wall, or to the debris accumulated through such collapse. Many processes likely contribute to breakdowns at all scales, including cold weather, changes in airflow patterns, seismicity, groundwater fluctuations, and anthropogenic activities. Mammoth Cave contains several massive breakdown areas, such as the Corkscrew, Vanderbilt Hall, and Ina's Hall. In the past, some breakdown areas in the historic section were cleared; this activity changed the airflow dynamics of the cave (described above in the "Cave Microclimate" section). An earthquake in 1987 triggered a rockfall (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). In 1994, a misguided effort initiated in 1989 to restore airflow for hibernating bats during the winter, caused a 40-ton rockfall from the roof of the Rotunda near the historic entrance to Mammoth Cave (fig. 10). Geologist Richard L. Powell concluded that thermal contraction was the ultimate cause of the rockfall. Previous alteration of iron sulphide minerals and subsequent capillary water movement along fractures in the silty streaks of the Beaver Bend Limestone was likely a contributing factor (Powell 1994). Such a collapse demonstrates the delicate balance inherent in the cave environment (Olson 1996). Some breakdowns may have resulted from the creation of large solutional spaces between bedding layers by groundwater injection. The ancestral Echo River welled up into such spaces about 700,000 years ago, due to hydraulic damming caused by sedimentation within the Green River. The breakdown cone in Ina's Hall could continue to propagate upward, forming another "Corkscrew" in the Main Cave between Booth's Amphitheater and Standing Rocks. Similarly, the Vanderbilt Hall breakdown could continue to form and connect into Broadway, opposite the Kentucky Cliffs (Olson 2002). Olson (2002) lists other areas within Mammoth Cave that may contain similar features.

Many other segments of dry passages in the Mammoth Cave System contain unusual breakdown debris lying over stream sediments. These areas are associated with sulfate minerals, suggesting that crystal wedging (sulfate minerals are less dense than calcite and exert pressure that spalls off bits of rock) and the replacement of limestone by gypsum are important processes to consider when studying cavern collapse (White and White 2003). The following characteristics of mineral-activated breakdown can be used to map potential and/or past breakdown zones: (1) irregular patterns of wall and ceiling fractures with visible gypsum veins following the fractures; (2) breakdown debris containing thin, irregular splinters and shards of bedrock; (3) curved plates of bedrock hanging from the ceiling at steep angles; and (4) vertical size gradation of collapse debris, with irregular blocks at the base and symmetrical mounds of rock flour at the top (White and White 2003). Breakdowns can result from collapse alonog bedding-planes, triggered by extreme temperature changes (Thornberry-Ehrlich 2006). These conditions and sites of potential breakdown underscore the need for more detailed mapping and monitoring studies within the cave system.

Regional human activities, such as mining, blasting, quarrying, drilling, and visitor use, can initiate geologic hazards in cave and karst environments. Groundshaking increases the likelihood of collapse or blockfall within caves. The overuse of surface trails may cause severe erosion and degrade adjacent vegetation. In the cave, lighting along visitor trails causes the growth of lampen flora that may cause slipping hazards. To adequately protect visitors and staff, park resource managers must understand the potential hazards associated with cave and karst environments.

The Kentucky Geological Survey produces county-scale, generalized geologic maps for land-use planning. For instance, the Edmonson County map details geologic features and lists potential geologic hazards, such as sinkhole collapse, seismicity, mass wasting, shrink-and-swell soils, potential for radon hazards, and groundwater issues. Each map includes a table that lists the rock types found within the county and provides planning guidance with respect to factors such as foundation stability, wastewater treatment, access roads, and recreation potential (Beck et al. 2003). Crawford et al. (2008) produced a poster in collaboration with the NPS that presents the geology of Mammoth Cave National Park. Such products provide powerful visual representations of the park's geologic framework and can help park resource managers identify and address related concerns.

Radon is a colorless, odorless, radioactive gas that accumulates naturally in the Mammoth Cave System through the decay of uranium-238 and thorium-232, which occur naturally in the region's bedrock (Smith et al. 1997). Mammoth Cave National Park managers have long been concerned about the potential for radon (isotope radon-222) concentration within the caves; research has been conducted and radiation levels and employee exposure are monitored (Yarborough 1980, 1981). The airflow in Mammoth Cave is a function of interior cave and exterior ambient temperatures (seasonally variable) and of the cave's geophysical configuration. Cave airflow mobilizes radon gas. Temperature gradients produce density differences between the cave interior and exterior, causing air to move under the action of gravity (Yarborough 1980). Radioactive decay of the gases into their ionized progeny, which are particulates, allows the distribution of alpha radiation throughout an entire cave system. Because the half-life of radon-222 is 3.8 days, it can travel far from its origin. The inherent confinement of the cave environment results in higher radiation levels than found in surface atmospheres (Yarborough 1981). Anthropogenic alterations in Mammoth Cave, such as the installation of elevator shafts, gateways, and access portals, have caused radiation levels to increase during the winter (Yarborough 1980). The cave environment cannot support forced ventilation, which would negatively impact many cave resources (Eheman et al. 1991).

Management of the radon threat at Mammoth Cave National Park includes the rotation of personnel shifts to limit exposure, the limitation of tour rotations and durations, and the monitoring of radon concentrations (Carson 1981; Eheman et al. 1991; Smith et al. 1997). Eheman et al. (1981) reviewed the exposure records for employees of Mammoth Cave National Park between 1976 and 1986. Cumulative employee exposure doubled between 1981 and 1986. The findings of this study suggest that radon and radioactive progeny are highly unlikely to pose a hazard to occasional visitors, but that the exposure of long-term employees to radon and radioactive-progeny concentrations may be higher than those permitted in active underground mines (Eheman et al. 1991). The NPS uses an exposure standard of 3 working level months (WLM) per year, wherein WLM is defined as a unit of radon exposure equivalent to an exposure to one working level of radon decay products for 1 working month (170 hours; Smith et al. 1997). As of the late 1990s, the exposure of employees working in Mammoth Cave did not exceed this standard; the highest individual annual exposure was 1.9 WLM (recorded in 1995; Smith et al. 1997). Park managers continue to seek ways to reduce radon exposure while providing ample visitor access and minimizing the disturbance to the cave environment.

Resource Management Suggestions for Cave and Karst Issues

- Conduct geological monitoring of cave and karst resources following the suggestions and vital signs provided by Toomey (2009).
- Continue to refine the definition of karst and hydrologic systems at Mammoth Cave National Park using tracer and isotopic studies to delineate aquifers and flow systems, including recharge dynamics in the cave network.
- Perform comprehensive fault mapping of the park's land surface, sinkholes, and caves to enhance the understanding of regional geologic structures and fault-related controls on cave formation, and to identify areas at potential risk for hazards.
- Investigate the possibility of integrating the NPS-GRI geodatabase with the cave/karst geodatabase being developed by Aaron Addison (GIS specialist, Cave Research Foundation).
- Inventory, map, and describe the more than 300 small caves within park boundaries. Obtain baseline biological, geological, hydrological, and hazard information for each cave and implement routine monitoring.
- Research fluvial geomorphology in cave streams to understand the role of the streamflow in cave development over time. These data may also be compared with geomorphological data for surficial streams.
- Perform additional dye-trace testing and groundwater-flow mapping, especially in the Cub Run area and other regions in the biosphere located north of the park boundary.
- Explore the utilization of karst vulnerability maps for areas especially prone to karst hazards and ecological impacts.
- Continue cave mapping and incorporate mapping data into a GIS geodatabase.
- Perform inventories to establish baseline conditions for future monitoring of the health of the cave system's watersheds, flow regimes, and water chemistry.
- Research the effects of local geologic conditions, bedrock, and particular cave deposits on faunal biodiversity and habitat.
- Perform a mineralogical inventory of the caves, focusing on bedrock mineralogy and secondary minerals.
- Improve existing biological inventory to establish baseline conditions for monitoring. Focus on ecosystem level and interrelationships between biological resources and geology/hydrology of the cave and karst system. Use results to create an ecological risk assessment and working ecosystem model.
- Study the response of the Mammoth Cave microclimate to heating associated with cave lighting.
- Use cave spatial information and digital geologic map to predict locations of undocumented caves based on known relationships (e.g., small caves along certain geologic contacts).

Fluvial Issues

As the master stream of south-central Kentucky, the Green River forms the base level for cave development and the ultimate drain for all surface and groundwater at Mammoth Cave National Park (fig. 11; Meiman 2006). The Green River is a tributary of the Ohio River that flows through a 100-m- (330-ft-) deep canyon. Its major tributaries include Russell Creek and the Little Barren, Nolin, Barren, and Rough rivers (Meiman 2006). Flooding along the Green and Nolin rivers poses threats to park infrastructure and inundates low-lying caves with water and sediments (Thornberry-Ehrlich 2006). Floodplain deposits and perched terraces along the park's riverways record the history of stream-channel morphology and levels. This record contains information relevant to cave formation and the Cenozoic (about 65 million years ago to present) history of the greater Ohio River drainage (Thornberry-Ehrlich 2006). The Water Resource Management Plan for Mammoth Cave National Park (Meiman 2006) has noted that current river-channel morphology (including bedrock substrates and fluvial deposits) within the park should be inventoried and monitored to improve or maintain the hydrologic integrity of park waters. As described in the "Biology and Ecosystem Health" section, cave ecosystems depend on regular water influxes into caves, which supply food and nutrients to cave life. If this water is contaminated, it can have disastrous effects on the cave biota.

Surface water is generally rare in the karst landscape at Mammoth Cave National Park. Streams tend to flow over resistant rocks, such as sandstone, shale, and conglomerate, and through the soluble limestones in a stair-step manner (Meiman 2006). Most precipitation filters quickly through the soils into underground conduits and then into the cave system, where it ultimately drains to the base level of the Green River. Given the relative scarcity of water, all surface-water expressions in the park, such as springs, ponds (natural, farm, and sinkhole), bogs, disappearing streams, dolines, and karst windows, provide vital wildlife habitat (figs. 12 and 13; Meiman 2006; Thornberry-Ehrlich 2006). Small, abandoned farm ponds, many of which formed in natural depressions, dot the ridge-tops south of the Green River. First Creek Lake, a shallow (<2 m [6 ft]) lake augmented by a beaver dam at its outfall run to the Nolin River, is located at the mouth of First Creek (Meiman 2006). Most wetlands in the park are very small and relatively unstudied (Meiman 2006). Some surface-water features have implications for cave development; upland stagnant ponds or bogs amass, store, and produce abundant amounts of humic material and organic acids, which promote mineral dissolution through acidification (Timmons et al. 1999).

Because percolating water from the surface rapidly enters the cave system, activities such as agriculture, surface construction, septic systems and sewage disposal, and, locally, sinkhole dumping can negatively impact cave ecosystems and water quality at Mammoth Cave National Park (Thornberry-Ehrlich 2006). Eroding soils and loose sediments (fig. 14) are quickly carried into open conduits below the surface and deposited in cave passageways. Species such as cave shrimp are negatively impacted by this deposition, particularly when the runoff contains organic matter such as lawn, animal, and human waste. Excessive organic matter lowers the oxygen content of the groundwater (Currens 2002). Runoff from parking lots and other human-use facilities carries pollutants directly into the water system at the park. In 2001, the park installed runoff filters near the visitor center, hotel, post office, maintenance yard, and Sloan's Pond parking lot. Ongoing research is evaluating the effectiveness of these filters. Runoff from the Mammoth Cave Hotel parking lot drains into an aqueduct near the historic entrance and is eroding a nearby large gully (Thornberry-Ehrlich 2006). Any change in road drainage that diverts runoff into a sinkhole can have drastic effects on sinkhole morphology and the underlying cave structure and ecosystem (Thornberry-Ehrlich 2006).

Given the extensive nature of the cave network and its groundwater-source (hydrogeologic) area, oil and gasoline spills associated with traffic on Highway 65, railroads, and in towns have significant potential to adversely impact the caves and water quality at the park (Olson 2003; Thornberry-Ehrlich 2006). Nearby coal power plants release airborne pollutants that can acidify soils (Thornberry-Ehrlich 2006).

In association with the development of a massive transportation hub (Kentucky Trimodal TransPark) west of Bowling Green, an industrial park will be located on the karst plain less than 13 km (8 mi) from Mammoth Cave National Park. This hub would bring together railroad, highway, airline, and manufacturing centers (May et al. 2005). According to May et al. (2005), key geologic issues were not addressed during the selection of the TransPark site. In environmental assessments performed before the TransPark development proposal was submitted, fundamental misconceptions about the nature of karst terrain included the underestimation of potential karst hazards in the underlying Ste. Genevieve Formation and the misinterpretation of arrows indicating the direction of groundwater flow on a topographic map as caves or conduits. Park resource managers are concerned that this development may threaten water quality, viewshed, and air quality, and create noise and light pollution at the park (Thornberry-Ehrlich 2006).

Lock and Dam #6

A decrepit concrete lock and dam (Lock and Dam #6) is located on the Green River just downstream from Mammoth Cave National Park. This feature affects the Green and Nolin rivers, as well as cave streams throughout the park. Built in 1904–1905 to allow the navigation of barges carrying natural asphalt from mines near Nolin River, this structure was last used in the 1950s. The U.S. Army Corps of Engineers (USACE) is responsible for its management (Olson 2006; Thornberry-Ehrlich 2006). In a 1995 disposition study that included Lock and Dam #6, the USACE noted that the removal of the dam would enhance recreational opportunities and restore the cave aquatic and Green River ecosystems by returning free-flowing conditions (Olson 2006). The flow regimes of the Green River can be divided into impounded, transitional, and free-flowing (erosional) zones based on the degree of influence of Lock and Dam #6 (Meiman 2006).

Park managers are interested in restoring the river system to a condition similar to that preceding the construction of the lock and dam. This manmade structure affects as much as half of the Green River's length within the park (Thornberry-Ehrlich 2006). Free-flowing conditions create riffle, run, and pool habitats that are extremely important for the conservation of fishes and mussels (Olson 2006). The structure ponds water up into Mammoth Cave, causes increased sedimentation in the cave, and degrades habitat for the endangered Kentucky cave shrimp (Olson and Leibfreid 1999; Olson 2003, 2006). The integrity of the structure is weak and a large seasonal flood may undermine it.

Research, Inventory, and Monitoring Suggestions for Fluvial Issues

- Perform mapping of Quaternary floodplain and river-terrace deposits to better understand and date the formation of various levels within the Mammoth Cave System. The Kentucky Geological Survey is currently mapping Quaternary geology in the western Kentucky–Ohio River area.
- Study the relationships between geology and water quality as they pertain to the hydrogeologic system and the flow of contaminants. Monitor pH, aluminum, and mercury levels in springs. Attempt to characterize the mobilization, transportation, and aerial distribution of contaminants from surrounding industrial features, including nearby coal power plants.
- Investigate the effects of the release of the Green River's impoundment at Lock and Dam #6 on cave hydrology.
- Refer to Lord et al. (2009) for suggested vital signs and information regarding the monitoring of fluvial geomorphology and stream system.

Mass Wasting

Mass wasting is a general term used to describe the dislodgement and downslope transport of soil and rock material influenced by gravity. Mass wasting includes creep and solifluction, rockfalls, rockslides, and debris flows. Certain geologic settings are conducive to mass-wasting processes. At Mammoth Cave National Park, steep slopes and carbonate dissolution have resulted in extensive mass wasting.

The Interior Low Plateau region of Kentucky is characterized by sandstone-capped uplands and steep river valleys. Granger et al. (2001) demonstrated that the uplands are eroding very slowly (perhaps < 2 m [6 ft]/million years). Upland erosion has been much slower than river entrenchment since at least the middle Pliocene (about 3.6 to 2.7 million years ago), despite accelerated river incision rates associated with major climate changes and drainage reorganizations (described in the "Geologic History" section). The absence of integrated surface drainage in the Mammoth Cave area due to extensive underground dissolution contributes to this disequilibrium (Granger et al. 2001). Steep slopes throughout the Chester Upland area, including river and stream valleys, are prone to rockfall, slumping, and topple (figs. 15 and 16). Seasonal precipitation events and freeze-thaw cycles can locally exacerbate mass wasting. Block falls occur at cliff bases and near cave entrances in the park (Thornberry-Ehrlich 2006).

Given the degree of limestone bedrock dissolution beneath the surface at the park, sinkhole development is possible. In general, the development of sinkholes in a karst landscape is a mass-wasting process. Sinkholes rarely form by dramatic and sudden cave collapse; instead, the bedrock underlying a sinkhole is typically dissolved and transported underground, causing the soil to gently slump or erode into the depression and slowly creating a sinkhole (Currens 2002). When the underlying conduits become sufficiently large, larger soil and rock particles and blocks may also be removed (Currens 2002). Cover material, such as organics and artificial fill, can fall into larger conduits. A 27-m- (90-ft-) deep pit collapsed on the park road to the Carmichael entrance in the early 2000s. Extreme erosion can soften sinkhole edges into gentle depressions, such as those present on the Pennyroyal Plateau. Near Mammoth Cave, the insoluble bedrock capping most of the upland areas prevents the gentle slumping that forms shallow depressions. Instead, many sinkhole rims, such as those at Cedar Sink and near Turnhole Bend, are steep-sided (Thornberry-Ehrlich 2006). Most sinks and karst valleys in the park resemble the dolines of the Pennyroyal Plateau.

Although earthquakes can trigger mass wasting within and outside the park's caves, seismic activity is locally rare. The Cub Run fault, which runs along the northeastern edge of Mammoth Cave National Park, is the only large fault mapped in the park. Recent research has identified a larger fault in Ganter Cave with a 11.5-m (38-ft) offset (Olson and Toomey 2009a). Although Mammoth Cave contains no known active fault, the park is near the Rough Creek and Pennyrile fault systems (bounding the Rough Creek graben, as described in the "Geologic Setting" section), and is only some 320 km (200 mi) from the New Madrid Fault (Palmer 1981). The massive 1811–1812 earthquakes on the New Madrid Fault caused some local rockfall and disrupted saltpeter-mining operations in Mammoth Cave. In 1987, a minor earthquake caused a large rock (about 1.5 m, or 5 ft, across) to fall on Audubon Avenue (Thornberry-Ehrlich 2006). The identification of areas prone to potential mass wasting would be valuable for resource management. Refer to Wieczorek and Snyder (2009) for suggested vital signs and information regarding the monitoring of slope movements and mass wasting.

Disturbed Lands

The Mammoth Cave National Park region has a long history of human occupation, extending from use by prehistoric American Indians to historic cave tourism (see the “Cultural Features Associated with Park Geology” section). This long history of human use within and surrounding the cave system has compromised some features, which require restoration and remediation. Disturbed areas at Mammoth Cave include abandoned roads, logged areas, abandoned rock quarries, and overgrazed areas. Many abandoned roads have been closed and some are susceptible to heavy erosion. Numerous cisterns and wells belonging to historic home sites need to be capped or covered; this work is in progress (figs. 17 and 18; R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). Many of these features were excavated by hand before the establishment of the park and are up to 2 m (5 ft) in diameter and 20 m (60 ft) deep. A funded project at Mammoth Cave National Park seeks to make these areas safe while preserving any significant historic architecture. Old water tanks in the park are being demolished (Thornberry-Ehrlich 2006). A Job Corps Center in the northwestern corner of the park should also be addressed.

The Geologic Resources Division Abandoned Mineral Lands database lists 16 disturbed features at Mammoth Cave National Park. Nine of these features are oil and gas well sites, such as Dry Prong, White Oak, Big Woods (dry well), Doyle Valley, Cedar Springs Ridge, and Hickory Cabin. The remaining disturbed lands are surface mines at Bee Springs, Mill Branch, Adwell Cemetery, Elevator (Doyle Valley), White Oak, and Katy Pace Valley. Mines were excavated to extract limestone, saltpeter, sand and gravel, and other mineral materials. These areas are small in extent, typically covering less than 4 ha (10 ac).

Saltpeter mine operations within Mammoth Cave sought to extract nitrates leached from bat guano that had accumulated in cave sediments. After the demand for saltpeter plummeted following the War of 1812, miners abandoned the leaching structures and pipelines within the caves. The dry conditions within Mammoth Cave preserved the relatively large-scale production system, which includes large, box-type leaching vats, hoppers, and water pipes (Duncan 1997). These disturbed, historic relics appear on the National Historic Register and are considered to be the park’s most significant historic structures (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

Mineral exploration and development continue outside the boundaries of Mammoth Cave National Park. Nearby asphalt mines are currently dormant, but may be reactivated in a favorable economic environment. Lock and Dam # 6 was constructed in part to support asphalt-mining activities. These mines may further impact the Nolin River. Thin coal seams in the Tar Springs Sandstone and Chester Formation northwest of the park (but within the International Biosphere) continue to support small-scale extraction coal-mining operations (Thornberry-Ehrlich 2006).

Oil and gas exploration occurs along a roughly northeast–southwest band in the cave area. In the 1920s, exploration and production sparked an oil boom in Barren County. Predating the park’s establishment, Arthur Oil Field is located in Edmonson County, just outside the southwestern corner of the park. The discovery of a series of faults through geophysical surveys sparked drilling along the southwestern edge of the park in the early 1990s (Meiman 2006). Most of the oil and gas wells are shallow (<500 m [1,640 ft]), with 3-m (10-ft) pump jacks. The oil- or gas-producing unit lies below the St. Louis Formation, and may be the New Albany Formation or the Chattanooga Shale. Groundwater dye tracing and basin mapping have indicated that groundwater flows from this area into the park and ultimately to the Green River. As described in the “Contamination Potential” section, past spills have compromised water quality at the park and required immediate resource-management response. In 2006, park managers doubted that all former wells within park boundaries had been plugged (Thornberry-Ehrlich 2006).

Suggestions for Geological Work at Mammoth Cave National Park

During the scoping meeting, a number of potential geologic projects were discussed. They are listed here.

- Continue to inventory paleontological resources (see “Paleontological Resources” section) in the park’s caves and extend the inventory to surface areas. Excavations, if deemed appropriate by expert consultation, and inventories should include the dating and identification of all fossil remains, the distinction of extinct and extirpated species, and the calculation of number of individuals present to allow comparison with current population lists and ranges. Pollen and radiocarbon (C-14) samples should also be collected from fossil remains of Pleistocene or Holocene organisms that lived in the cave after it formed. The marine invertebrate fossils in the cave bedrock are hundreds of millions of years older. Charcoal deposits should be collected with care and according to established protocol. Samples should be stored and catalogued in park collections.
- Continue to research speleogenesis, paleoclimatology, and cave sediments for interpretation and management purposes.
- Use charcoal horizons within the valley fill and thick floodplain deposits to investigate the fire history of the region.
- Use oxygen and stable-carbon isotopic analyses to gain information about the types of overlying vegetation at the park through time and improve the understanding of the area’s paleoclimate. Relate isotopic data to the hydrologic system at the park.
- Acquire geologic maps of areas beneath reservoirs in the biosphere, such as Nolin and Barren River lakes.

- Consult publications and topographic maps by J. A. Ray (Kentucky Division of Water) for information about geomorphic features, surficial mapping, karst landscape development, and river and paleoriver channels and terraces.
- Study the effects of groundwater pumping on the hydrologic system at the park.

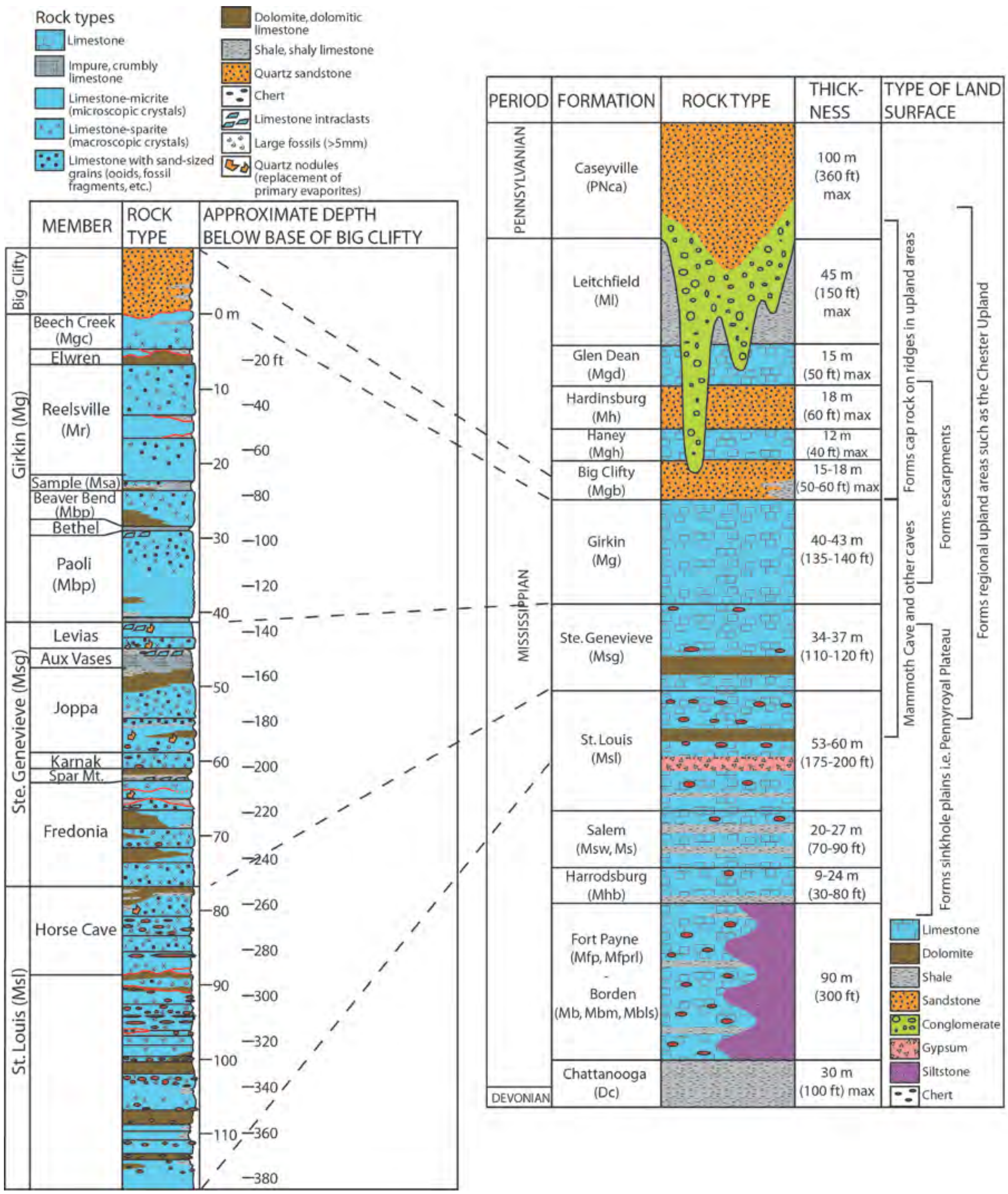


Figure 5. Generalized stratigraphic column for Mammoth Cave National Park, including rock units of the Central Kentucky Karst (right column) and a detail of the major cave-forming units (left column) mapped inside caves (unit names are from Sandburg and Bowles [1965]). Note the deep erosional surface between the Pennsylvanian and Mississippian units. Geologic map unit symbols (from the GRI digital geologic map) are included in parentheses where available. Graphic adapted from Palmer (1981, 2007) by Trista L. Thornberry-Ehrlich (Colorado State University).

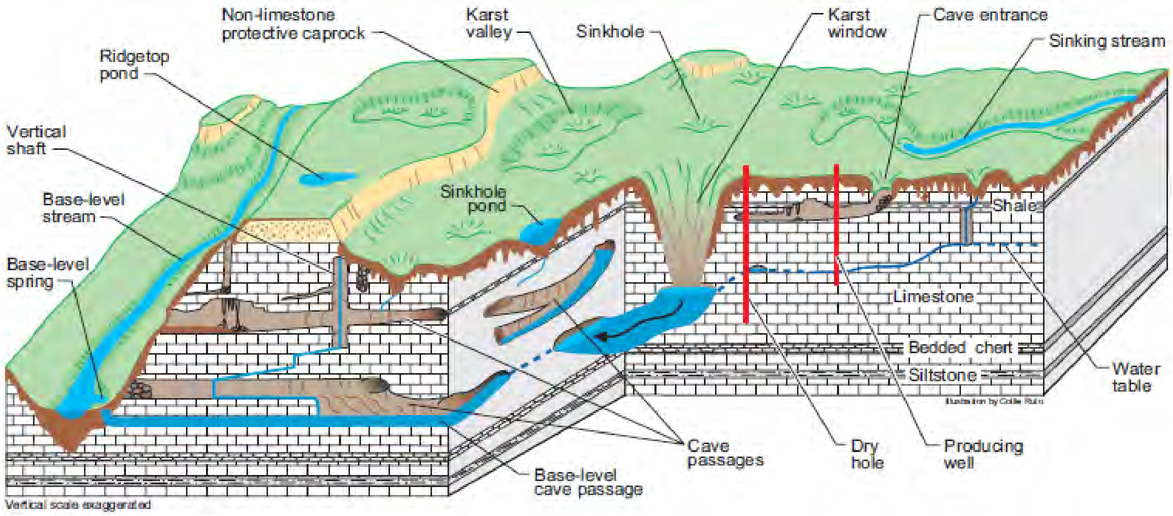


Figure 6. Generalized block diagram of karst features on the western Pennyroyal Plateau. At Mammoth Cave National Park, the Green River is the base-level stream; a base-level cave passage is visible at River Styx Spring; a cave entrance is obvious at the historic entrance; sinkholes and karst windows occur at Cedar Sink and Double Cellars Sinkhole; the Bottomless Pit is an example of a vertical shaft; and numerous sinking streams cross the upland areas. Graphic by Currens (1995).

Figure 7. Retention and filtration basin. Basins, with a capacity of 37,900 liters (10,000 gallons)are being constructed at every sinkpoint along Interstate 65 as the highway is being widened. The basins are designed to minimize contamination from runoff and spills. Note heavy truck traffic. National Park Service photograph by Rick Olson (Mammoth Cave NP) taken in February 2011.

Figure 8. Styx Spring below the historic entrance to Mammoth Cave. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 9. Confined passageway. A caver's feet in a tube at Rock Dismal Cave demonstrate the confined nature of many passageways. Photograph by Norman Warnell, courtesy of Rick Olson (pictured, Mammoth Cave NP).

Figure 10. Breakdown debris. The debris on the floor of the Rotunda in Mammoth Cave resulted from material falling from the roof of the cave in January of 1994. Breakdown is a natural cave process, although in this instance, the process was accelerated by an excessive influx of cold winter air. National Park Service photograph by Tim Connors (NPS Geologic Resources Division).

Figure 11. The Green River just north of the historic entrance to Mammoth Cave, as seen from the Green River Bluffs Trail at Mammoth Cave National Park. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 12. Karst window or doline in the Cub Run area. Karst windows are open access points to underground conduits formed by dissolution in carbonate rocks. Note the presence of blocky rubble at the base of the depression (orange arrow). Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 13. Short segment of a surficial stream in the upland area above Mammoth Cave. Such surficial water features are rare on the karst landscape. Flow is from the top to the bottom of the image. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 14. Soils exposed to erosion during construction activities along a park road at Mammoth Cave National Park. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 15. Steep cliffs expose bedrock at Mammoth Cave National Park above the historic entrance to Mammoth Cave. National Park Service photograph by Tim Connors (NPS Geologic Resources Division).

Figure 16. Mixed limestone and siliciclastic cliffs within the upper Girkin Formation to lower Big Clifty Formation exposed at Mammoth Cave National Park. Note the presence of blockfall and talus at the base of the slope (orange arrow). Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 17. Abandoned rock-wall-lined access road constructed by the Civilian Conservation Corps (CCC) at Mammoth Cave National Park. Note the presence of pervasive vegetation obscuring the structure (orange arrow). National Park Service photograph by Tim Connors (NPS Geologic Resources Division).

Figure 18. Abandoned CCC-era cistern (orange arrow) within Mammoth Cave National Park. The cistern is the approximate size of a large vehicle. Because the cistern is roofed, it is not considered to be a significant hazard, but rather forms part of the park's cultural landscape. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Mammoth Cave National Park.

Karst Features and Processes

The south-central Kentucky karst, situated between the Green and Barren rivers, is among the most well-developed karst landscapes in the world (fig. 6; May et al. 2005). The term "karst" is derived from a Slavic word that means "barren, stony ground." The karst landscape of central Kentucky consists of the characteristic sinkhole plains of the Pennyroyal Plateau, and the Mammoth Cave Plateau (also called the Chester Upland), which rises some 45 to 60 m (150 to 200 ft) above the sinkhole plain. The Dripping Springs Escarpment separates these two plateaus (Lobeck 1928; May et al. 2005).

In addition to Mammoth Cave, the park contains other classic examples of karst features, such as sinkholes and karst windows, sinking streams, karst springs, and karst valleys. Cedar Sink and Double Cellars Sinkhole feature the typical steep-sided walls and rubble-laden bases of karst windows and collapsed sinkholes. The River Styx, Echo River, Pike, Big, Buffalo, and Turnhole springs are outlets for groundwater-drainage basins. Woolsey, Doyel, and Houchins valleys are separated by Joppa and Mammoth Cave ridges, respectively.

White et al. (1970), Palmer (1981), and Currens (2002) provide comprehensive geologic surveys of the Central Kentucky Karst and Mammoth Cave, a full description of which is beyond the scope of this report; a brief summary of the most distinctive features and processes in the park is presented here. The reader is encouraged to consult these resources for a full description of the geologic features and history of exploration in the area.

Mammoth Cave Formation

In addition to the known 628 km (390 mi) of surveyed passages in the Mammoth Cave System, geologists and cave explorers surmise there may be hundreds of miles of unexplored passages awaiting further discovery. The cave-passage network is incredibly complex. Mammoth Cave formed as a product of the regional geologic setting and the climatic conditions of central Kentucky.

The extensive Mammoth Cave System formed in the Central Kentucky Karst due to the presence of conditions necessary for cave development, including suitable rocks, a solvent, hydraulic gradients, and time. First among these conditions is the existence of a suitable body of rock, in this case pure limestone in nearly horizontal beds. Limestone is ideal for the development of karst features because it is highly soluble in carbonic acid. At Mammoth Cave, extensive passageways formed in the St. Louis, Ste. Genevieve, and Girkin limestones (geologic map units Msl, Msg, and Mg, respectively), which contain only minor amounts of dolomite, clay, and other insoluble clastic impurities (Kuehn et al. 1994). Because these units are nearly horizontal and have vast surface exposures, hundreds of miles of cave passageways developed within a thickness of only about 90 m (300 ft; Kuehn et al. 1994).

The second condition required for extensive cave development is the presence of a suitable solvent. Limestones readily dissolve in acidic solutions, such as carbonic acid. The natural formation of carbonic acid requires carbon dioxide, which is present in the atmosphere but is produced more efficiently in the soil through the microbial degradation of organic material. This process increases the pressure of carbon dioxide and, therefore, its solubility in pure water (White 1988; Kuehn et al. 1994). The increased saturation of water with carbon dioxide augments the ability of groundwater to dissolve limestone (White 1988; Anthony et al. 2003). Located in a temperate climate, central Kentucky receives an average of nearly 130 cm (50 in) of precipitation per year and has relatively thick soils that contain abundant carbonic acid, resulting in extensive limestone dissolution (Kuehn et al. 1994).

The third basic element upon which the excavation of the Mammoth Cave System depends is the hydrogeologic framework, which provides a sufficient hydraulic gradient. When carbonic acid contacts limestone, the solution quickly becomes saturated and ceases limestone dissolution. For this reason, a high hydraulic gradient (inherent in steep slopes), such as that above the Green River Valley at Mammoth Cave, must be present to provide sufficient energy to rapidly move the solvent through the rock (Kuehn et al. 1994). South of the Green River, the bedding dips gently toward the river, contributing to the overall gradient; north of the river, the beds dip away and cave development is less extensive (Meiman 2006).

Time is the final major condition necessary for the formation of extensive cave-passage networks. Karst landscapes form through decay and erosion (White 1988). At Mammoth Cave, groundwater first came into contact with the Girkin Limestone (geologic map unit Mg) about 10 million years ago; eventually, all of the rock will be dissolved away (Palmer 1981; Kuehn et al. 1994). During this time, the Green River has incised the valley at variable rates. During periods of relative base-level stability, a large amount of dissolution occurred at associated water-table elevations, resulting in well-developed cave levels (Palmer 1981; Kuehn et al. 1994). When the base level dropped suddenly and the river downcut quickly, lower water-table dissolution zones resulted in rapid vertical excavation and the eventual reestablishment of lower cave levels. See the “Geologic History” section for more information.

The geometry of the cave system depends on the individual growth rates of sequential and overlapping sets of cave-passage cross-sections (Groves and Meiman 2003). The growth rate of each cross-section is determined by major processes, such as limestone dissolution coupled with precipitation, which in turn depend on water and rock chemistry, flow characteristics, wetted-passage perimeters, and ambient temperature. The linked processes of sediment entrainment, deposition, and abrasion, which also affect passage growth rates, depend on flow-velocity distributions and sediment-supply properties. The mechanical erosion of cave passages by subterranean rivers also played a role in the development of the large canyon passageways in Mammoth Cave National Park. Breakdown processes depend on the fracture characteristics of wall rocks (Groves and Meiman 2003).

The ability to trace individual stratigraphic layers for kilometers throughout Mammoth Cave facilitates cave mapping and allows the identification of particular cave levels. The correlative stratigraphy, cave sediments (which contain dateable cosmogenic isotopes of aluminum [aluminum-26] and beryllium [beryllium-10]), and cave network provide information about the area’s drainage history since the Miocene (about 23 million years ago; Granger et al. 2001). This history is connected to the evolution of the Ohio River Valley drainage, before and after Pleistocene glacial events. Prior to the global ice ages of the Pleistocene (2.6 million to 10,000 years ago), the Ohio River was a small tributary to the Mississippi River drainage. Drainage of the greater north-central Appalachian area was focused further north. The ancient Teays River flowed north–northwest through central Ohio. Glaciers flowing south from Canada dammed this drainage and the impounded water carved the present Ohio River Valley around 1.5 million years ago (Granger et al. 2001; R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

As described in detail in the “Geologic History” section, periods of intermittent cave stability were followed by the capture of the ancient Teays River, the relatively rapid incision of the present course of the Ohio River Valley, and the major downcutting of its tributaries, including the Green River. Many smaller streams were diverted underground because their incision rates were slower than those of the larger waterways (Thornberry-Ehrlich 2006). The development of cave levels and the Mammoth Cave network correspond to the drainage, downcutting, depositional, and ice-age history of the region. These relationships are complex and a full understanding requires further mapping and research.

Cave Passages and Speleogens

Caves are the prominent features in Mammoth Cave National Park. Their passages contain evidence of present and past flow regimes, such as canyons, vertical shafts, passages, and domes (figs. 19 and 20). The larger passages are classic examples of karst tubular passages. Tubular passages originate by solution along partings or jointed beds at or below the water table. They tend to be relatively gently sloped and are often partially filled with cave sediment. Canyons originate along partings or highly jointed beds above the water table and their floors are dissolved downward by flowing water (fig. 20). Canyon ceilings appear flat and do not dissolve upward, whereas their floors are more steeply sloped (Palmer 1981). Most canyons and tubes within Mammoth Cave are highly concordant with the overall bedding of the bedrock. The main passage, leading from the historic entrance, follows the same beds of the lower Girkin and upper Ste. Genevieve limestones (geologic map units Mg and Msg, respectively) for several kilometers (Palmer 1981). X Pit in Crystal Cave is an intersection of two canyons. A vertical shaft forms wherever a large amount of water in the aerated zone (above the water table) flows straight downward through the limestone. This flow can range from a trickle to a flood depending on the weather (fig. 19; Palmer 1981).

The Logsdon River, draining nearly 23 km (14 mi) from the sinkhole plain between Park City and Cave City, Kentucky, to its discharge at Turnhole Bend, flows through nearly 10 km (6 mi) of open cave passages and is one of the world’s longest continuously traversable underground rivers (Anthony et al. 2003).

Speleogens are cave surfaces that formed by solution and abrasion. Speleogen features, such as small pits, domes, and scallops, record conditions during primary cave development. Features such as scallops on cave passage walls indicate the direction and relative velocity of water flow (Curl 1974). Water in the phreatic zone (below the water table) occasionally flows uphill in response to changes in hydraulic head (a specific measurement of water pressure above a geodetic datum, usually measured as a water surface elevation). The limestone surfaces of most tubes and canyons are covered by a nearly continuous dimpling of variously sized scallops (figs. 20, 31, and front cover). The steep side of a scallop is on the upstream end and faces downstream. The size and length of the scallop is inversely proportional to flow velocity, in other words, the smaller the scallops, the faster the water flowed (Palmer 1981). Rose’s Pass in Mammoth Cave contains good examples of scalloping and flow reversal over time.

Other solutional features include flutes, anastomoses, solution pockets, and scours. Flutes are parallel grooves formed when water drips vertically or down a steep slope. They are aligned with the direction of flow (Palmer 1981). Anastomoses form as networks of small, winding tubes that interconnect like a maze. They can include remnants of solution channels formed during early cave development, or result from the periodic flooding of passages located at or slightly above the water table, which forces water into the spaces under pressure (Palmer 1981). Solution pockets form dead-end holes in passage walls and ceilings and are typically oriented along joints (Palmer 1981). Scour marks indicate rapid and turbulent flow, often including entrained abrasive sediments.

Speleothems

Brilliant cave formations (speleothems), including calcite flowstone and gypsum flowers, decorate the reaches of Mammoth Cave and other park caves (figs. 21 and 22). The term speleothem refers to any secondary mineral deposit that is formed in a cave. Understanding of cave processes at Mammoth Cave National Park would be increased by further study of the many speleothems.

The most common cave minerals are gypsum and other sulfates, calcite and other carbonates, nitrates, and manganese-oxide coatings. The deposition of cave minerals in the cave environment is a complex process that depends on numerous chemical reactions and cave conditions. The study of in situ speleothem deposition in the park's caves would provide valuable information about the geochemical parameters of these processes. Speleothem mineralogy is complex due to the interaction of carbonate minerals with organic materials or vein minerals in the wall rock (Poulson and White 1969). Research has revealed that cave microclimates, water quantity, and trace-element chemistry also play important roles in the formation of speleothems (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

Calcite speleothem precipitation is the converse of limestone dissolution. Calcite-depositing waters evolve in several stages (fig. 23), including the equilibration of groundwater in the soil zone and carbonate dissolution in narrow cave fissures (capillaries). The solution is then transported more rapidly without carbon-dioxide loss through larger subterranean joints to the cave passage, and finally re-equilibrated to the carbon-dioxide pressure of the cave atmosphere (usually lower than that of the rest of the aerated zone). The loss of carbon dioxide (degassing), rather than evaporation, typically causes calcite deposition (Holland et al. 1964; Poulson and White 1969).

Sulfate minerals are deposited primarily through the evaporation of imperceptibly small seeping solutions. The source material for sulfate solutions at Mammoth Cave may be pyrite from the Big Clifty Sandstone formation (Pohl and White 1965; Poulson and White 1969). As described above in the "Karst Hazards" section, gypsum precipitation and replacement of limestone can wedge rocks apart (White and White 2003). Gypsum, which occurs only in dry passages where evaporative rates are high, forms some of the most delicate speleothems in Mammoth Cave, including crusts, crystals, and gypsum flowers. Many forms of gypsum deposits can be seen on the half-day tour (now called the Grand Avenue tour) of Mammoth Cave (Palmer 1981).

Calcite speleothems at Mammoth Cave include flowstone, stalactites, stalagmites, columns, helictites, cave popcorn, and rimstone. Many of these forms can be seen on the Frozen Niagara cave tour (Palmer 1981). The type of carbonate speleothems that form in an area are determined by, the amount of water, type of flow, carbon dioxide levels in both the water and air, relative humidity, airflow, evaporation rates, type of bedrock, and the presence of various kinds of microbes. Flowstone, such as the Frozen Niagara formation, forms sheets on cave walls that resemble draperies in areas with relatively abundant groundwater flow. The dripping of water creates icicle-shaped stalactites that grow from the cave ceiling and stalagmites that rise from the cave floor. Columns form where stalactites and stalagmites grow together. Helictites form where a thin film of water seeps into the cave along a wall surface. In Crystal Cave, helictites appear as erratic, noodle-like formations. Cave popcorn forms knobby clusters on areas kept moist by seepage or waterfall splattering. The junction of Boone and Cleaveland avenues in Mammoth Cave contains fine examples of cave popcorn. Rimstone and crusts form around the edges of pools containing calcium-carbonate-saturated water (Palmer 1981).

Resource managers at Mammoth Cave National Park strive to maintain a proper balance between the use of speleothems for scientific research (which may include destructive sampling) and the preservation of existing cave features. Carbon and oxygen isotopic analyses and paleofloral studies can use previously collected samples. All samples taken from Mammoth Cave should be curated at the park (Thornberry-Ehrlich 2006).

Paleontological Resources

The Mississippian- (about 359 to 318 million years ago) and Pennsylvanian- (about 318 to 299 million years ago) aged rocks at Mammoth Cave National Park contain abundant fossil resources. Fossils are exposed in these units at the surface and on cave walls. Exposures in caves include remarkable shark-cartilage remains, teeth, and fin spines, as well as numerous marine invertebrate fossils, including corals, brachiopods, and crinoids within the Upper Mississippian (328 to 318 million years ago) St. Louis Limestone and Ste. Genevieve and Girkin formations (Thornberry-Ehrlich 2006; Hunt-Foster et al. 2009). A preliminary fossil inventory has been conducted along the first 3–5 km (2–3 mi) of Mammoth Cave. A paleontological resource summary of Mammoth Cave National Park (Hunt-Foster et al. 2009) reported that the St. Louis Limestone (geologic map unit Msl) contains fossil marine invertebrates (corals, bryozoans, bivalves, brachiopods, gastropods, and crinoids) as well as shark and plant remains. The Ste. Genevieve Formation (Msg) contains crinoids, corals, bryozoans, brachiopods, echinoderms, conodonts, and shark teeth, fin spires, and calcified cartilage. The Girkin Formation (Mg) contains bryozoans, gastropods, colonial corals, crinoid calyxes and columnals, echinoids, and spiriferid and productid brachiopods.

Mississippian shales of the Illinois Basin contain numerous, well-preserved, diverse faunal species, including crinoids, foraminifera, and ostracods

(McGuire 1966; Gutschick 1968; Pohl et al. 1968). Other Mississippian units within Mammoth Cave National Park (but not in caves), such as the Big Clifty (Mgb), contain *Lepidodendron* tree trunks, crinoids, horn corals, foraminifera, bryozoans, and echinoderms. The Glen Dean Limestone (Mgd) includes abundant fossil fragments and casts of horn corals, bryozoans, brachiopods, crinoids, and blastoids (Horowitz and Perry 1961; Hunt-Foster et al. 2009). Many units exposed within the park have been documented as fossiliferous in other locations and likely bear fossils within park boundaries.

Recent inventory efforts in Mammoth Cave target younger paleontological remains, rather than the marine invertebrates within the Mississippian limestones (Santucci et al. 2001, Colburn 2005, 2006). The caves at Mammoth Cave National Park contain a variety of significant paleontological resources in different contexts. Most of the fossil deposits that have been located in park caves are probably Pleistocene (2.8 million to 10,000 years ago) or Holocene (less than 10,000 years ago) in age, but some deposits probably date from the late Pliocene (3.6 million to 2.8 million years ago). A cooperative research project initiated in 1997 with the participation of Mammoth Cave National Park, the Illinois State Museum, and the Cave Research Foundation found fossil remains in four primary contexts in Mammoth Cave: 1) older (Pliocene or Pleistocene) deposits associated with water-lain sediments representing cave streams that flowed in now abandoned levels, 2) surficial and shallowly buried deposits associated with past cave use as well as materials from cave streams eroded out of such deposits, 3) relictual deposits on the cave surface prior to human utilization, and 4) recent surficial remains (often less than 4,000 years old) (Toomey et al. 2000; Colburn 2005, 2006; Hunt-Foster et al. 2009). This study found extensive bat remains from diverse species, raccoon scat, isolated bones of woodrats (*Neotoma* sp.), mice (*Peromyscus* sp.), raccoon (*Procyon lotor)*, deer (*Odocoileus virginianus*), pig (*Sus scrofa*), reptiles (turtles, snakes, and lizards), birds, mammals, and various amphibians (Toomey et al. 1998; Colburn et al. 2000; Santucci et al. 2001; Colburn 2005, 2006).

Fossils are poorly represented in the water-lain sediments associated with the primary cave streams that formed the large passages in Mammoth Cave. However, significant fossils associated sediments from Pliocene-Pleistocene flooding deposits in Backsliders' Alley off Main Cave in Mammoth Cave are some of the oldest non-bedrock fossils that have been found in the caves of the park (Colburn 2005, 2006). These deposits contain the remains of two hellbenders (*Cryptobranchus* sp.), as well as, other possible fish and amphibian remains. The upper portions of these deposits also yielded parts of an extinct vampire bat (*Desmodus stocki*).

Sedimentary deposits associated with former entrances that have since closed may contain fossils of animals that utilized or lived near these entrances. In the Proctor section of the Mammoth Cave System, various remains, including mastodon (*Mammut americanum*) are associated with a sinkhole fill that almost certainly represents a former entrance. In a modern cave stream deposit that is eroding sediments associated with these deposits, additional bones have been found. Some of these represent Pleistocene animals, such as giant short-faced bear (*Arctodus simus*), flat-headed peccary (*Platygonus* sp.), and saber-toothed cat (*Smilodon* sp.). However, modern bone from a cow (*Bos taurus*) was also found in the same stream. In addition, a number of bones of animals that could have been Pleistocene or modern also were found (Wilson 1985; Colburn 2005, 2006). Another important fauna associated with sediments from a former opening is found near the modern, constructed Frozen Niagara entrance. In this area, bone-bearing sediments are sealed with a carbonate crust which yielded a uranium-series date of 125,000 to 126,000 years B.P. (Colburn et al. 2000; Santucci et al. 2001). This inter-glacial fauna from the deposits included extinct species of horse (*Equus)*, *Platygonus*, and beautiful armadillo (*Dasypus bellus)*, and Leonard's water rat (*Neofiber leonardi*) (Colburn, 2006), In addition, extant species such as pocket gopher (*Geomys* sp.) were also abundant (Colburn et al. 2000; Santucci et al. 2001; Colburn 2006; Hunt-Foster et al. 2009).

Guano and bones associated with former bat roosts are also an important type of fossils found in the caves in the park. In the large upper passages of the Historic Section of Mammoth Cave ancient guano deposits and bones from colonies of free-tailed bats (*Tadarida* sp.) can be found under large rocks and as bands within sediments (Jegla and Hall 1962; Santucci et al. 2001; Colburn 2005, 2006). Dating in the late 1950s found the deposits to be beyond the range of radiocarbon dating (Jegla and Hall 1962). The stratigraphic position of these deposits within the sediments and under substantial rockfall suggests the deposits are probably several hundred years old.

Bones associated with a fossil roost utilized by gray bats (*Myotis grisescens*) in the Proctor section of Mammoth Cave are probably associated with an ancient entrance, since they are far from modern entrances through very small, convoluted passages. Other bones in that area may also be associated with that previous entrance including those of a marten (*Martes americana*) and a smoky shrew (*Sorex fumeus*). Martens are not known from the modern Kentucky fauna and the specimen may represent a Pleistocene or early Holocene fossil.

In addition to fossils and guano representing older bat roosts in the caves of the park, there are also bat bones and guano that are from prehistoric to historic bat roosts. These now-abandoned roosts provide important information on the changes that have occurred in the caves since human exploitation of the cave's resources began (Olson 1996, Toomey et al. 2002). The roosts primarily represent various species of the genus *Myotis* (including endangered Indiana bats, *M. sodalis*, little brown bats, *M. lucifugus* and gray bats, *M. grisescens*). However, tricolored bats (*Perimyotis subflavus*) and big brown bats (*Eptesicus fuscus*) remains are also commonly found (Colburn 2005).

Some remains from Mammoth Cave, such as those of *Gallus gallus* (domestic chicken), are very young and obviously represent anthropogenic input (Santucci et al. 2001). Given the vast area of uninventoried and unexplored cave passages, paleontological study of the cave system could yield striking new discoveries.

Several factors can result in the deposition of animal remains in deep cave interiors. They can be washed in during flood events, or animals may wander far from cave entrances before dying. Vertical shafts within caves act as traps. Woodrats, carnivores, raptors, and humans transport animals or their remains into caves (Wilson 1985). Beyond the caves at Mammoth Cave National Park, floodplain deposits along the Green and Nolin rivers may also contain significant fossil remains (Thornberry-Ehrlich 2006). Sinkholes throughout the area can act as steep-sided traps for animal and plant remains. Fossil studies can provide important indicators of paleoclimatic conditions and help constrain the timing of cave development in some cases.

Santucci and others (2009) have outlined potential threats to in situ paleontological resources and suggested the monitoring of "vital signs" to qualitatively and quantitatively assess the potential impacts of these threats.

Connections between Park Biology and Geology

The relatively stable environment and closed ecosystem of Mammoth Cave, characterized by stable temperatures and humidity, has allowed the evolution of many microbial, invertebrate, and vertebrate) species. The Mammoth Cave biota is among the most diverse assemblages of cave fauna in the world (Culver et al. 1999). Packard (1871, 1875), Call (1897), and Bailey (1933) conducted extensive early surveys of cave life in Kentucky, focusing in great detail on Mammoth Cave.

Approximately 130 species of troglobites (cave-adapted, cannot survive in surface habitats), troglophiles (can live in cave and surface habitats), and trogloxenes (use caves for refuge or hunting) live within the Mammoth Cave System, one of the highest subterranean biodiversities in the world (Olson 2003; Culver and Sket 2000; Barr 1967). These species range from microorganisms to mammals such as bats. In 1965, scientists identified 16 diatom taxa in samples from Mammoth Cave, several of which had not been found elsewhere (Van Landingham 1965). Cave-wall scrapings, cave-floor clay, small pond sediments, and stalactites and stalagmites have yielded myriad species (27 taxa) of living algae within Mammoth Cave (Jones 1965). The metabolism of cave-dwelling bacteria associated with calcite formations may facilitate mineral deposition (Northrup et al. 1997).

Cave biology in the Mammoth Cave area is very diverse and well-studied. Scientific biological study of the Mammoth Cave system began in the middle 1800s; notable studies were published by Bailey (1933) and Barr (1962) and research continues today. Taxonomic studies of specific organisms, ecological studies of terrestrial and aquatic systems, and evolutionary studies of the adaptation of cave animals have been performed. Many cave-specific species have evolved special adaptations to the cave habitat (Thornberry-Ehrlich 2006). Cave adaptation progressively causes eyes to become reduced, lose pigment, and eventually disappear altogether (Poulson 1963). Poulson (1992) maintains that Mammoth Cave is the best-studied and -understood cave ecosystem in the world. Notable species include the endangered, endemic Mammoth Cave shrimp (*Palaemonias ganteri*), two species of troglobitic fish, and five co-occurring cave trechine beetle species. Park caves also host two endangered bat species: Indiana bats (*Myotis sodalis*) and gray bats (*Myotis grisescens*). The caves of Mammoth Cave National Park are the type locality (place of first species description and primary example) of over 25 cave-adapted species.

At the surface, geologic factors control the expression of several distinctive ecosystems, including upland swamps, hemlock groves, and sinkhole microclimates. Although not well studied, the park's lacustrine features include upland swamps and acidic fern bogs. Wetland deposits may contain pollen or other organic remains that record paleoclimatic conditions. These upland wetland habitats are usually associated with local aquifers perched atop relatively resistant noncarbonate rocks. Such perennial surface-water sources, in contrast to the typically ephemeral sinkhole ponds, are rare in karst landscapes and provide vital water to plants and animals in the area. The rapid drainage or collapse of sinkholes may cause local slurry flows within caves; an example is visible in the Labyrinth of Mammoth Cave (Thornberry-Ehrlich 2006).

For a given climate, bedrock geology largely determines soil type and thus strongly impacts the distribution of vegetation communities. For example, chestnut oak trees (*Quercus prinus*) tend to grow over sandstone bedrock, whereas Chinkapin oak trees (*Quercus muehlenbergii*) prefer to grow in limestone soils (Thornberry-Ehrlich 2006). In karst landscapes underlain by calcareous bedrock, subsurface drainage causes the regolith to be more xeric (dry) than an equivalent soil underlain by other rock types (Olson and Noble 2005). Soils are a major factor in habitat development. Areal habitats, mapped based on geology, slope, and aspect, include calcareous and acid xeric, sub-xeric, mesic, and supra-mesic types and alluvium (Olson and Noble 2005). Acid types indicate the presence of noncarbonate bedrock (acid soils), and calcareous types indicate carbonate bedrock (less-acidic soils). Of interest to fire management, one-fourth of the park acreage consists of habitat types (calcareous mesic and supra-mesic, acid supra-mesic, and alluvium) that do not support fire-dependant or fire-tolerant plant communities. These habitats can be excluded from prescribed burns (Olson and Noble 2005).

Most of the vegetation at Mammoth Cave National Park is second-growth forest; however, several special plant communities, including wetlands, prairies, and hemlock groves, are also present within park boundaries. Sinkhole microclimates support rare and potentially endangered plant species. These plant communities support deer, raccoons, opossums, gray squirrels, rabbits, woodchucks, muskrats, beavers, red foxes, coyotes, hawks, owls, and wild turkey. The sand, gravel, and mud of the Green River and its flanking riparian areas support more than 80 species of fish and more than 70 species of freshwater mussels. This biodiversity makes the Green River one of the most biologically varied riverine habitats in the National Park system.

Cultural Features Associated with Park Geology

Humans have been using cave entrances and shelters in the Mammoth Cave National Park area since about 11,000 years ago (projectile points date back to 9,500 B.C.E.; Tankersley 1996). Signatures of their presence in Mammoth Cave include petroglyphs and rock art. In Mammoth Cave, evidence of human occupation includes 2,200- to 2,400-year-old mummified remains, torch material, food, clothing material, and mineral-extraction tools and baskets (Livesay 1953). American Indians entered the cave to mine sulfate minerals, such as gypsum, epsomite, and mirabilite (Palmer 1981; Kuehn et al. 1994). American Indians also used rock shelters as habitation sites.

In the early part of the 19th century, sediments in limestone caves of Kentucky produced the majority of saltpeter extracted from the southeastern United States (Duncan 1997; Mickelson 2008; De Paepe 1985). During the War of 1812, saltpeter mining of Mammoth Cave sediments yielded some 4,000 pounds of nitrates for the manufacture of gunpowder. Each bushel of cave earth yielded 1.4 to 2.3 kg (3 to 5 lb) of nitrate (Duncan 1997), likely originating primarily from guano and other fecal matter left by former populations of bats, woodrats, and raccoons in the cave (Olson and Krapac 2001). Cave dirt was leached to obtain calcium nitrate, which was then mixed with wood ashes to form potassium nitrate (Kuehn et al. 1994). Remnants of the historic mining activities are visible in the Rotunda near the historic entrance to Mammoth Cave. They were damaged in January 1994 when a large slab (21 by 6 m [70 by 20 ft]) of limestone fell onto the tourist trail, due to extremely cold temperatures and elevated air flow rate (fig. 10) (Livesay 1953; Kuehn et al. 1994; Powell 1994).

Other portions of Mammoth Cave, such as Booth's Amphitheatre and Ole Bull's Concert Hall, have provided natural stages for dramatic performances and concerts. The Bridal Altar located in Gothic Avenue has been the site of several marriage ceremonies (Livesay 1953). In 1842–1843, huts were constructed along Broadway to house patients suffering from tuberculosis. The constant cool temperature and humidity in the cave were believed to benefit these patients (Livesay 1953). Crump (1890) suggested that the cool dry air of caves such as Grand Avenue Cave could be collected and used for sanitary (e.g., surgical) purposes and for temperature regulation in buildings.

Historic remains include graffiti in Mammoth Cave (fig. 24). Many miles of Mammoth Cave were explored in the middle 1800s by the famous guide (and slave) Steven Bishop (Kuehn et al. 1994). In 1908, Max Kämper mapped approximately 56 km (35 mi) of the cave using a pace-and-compass method (Palmer 1981). Other local caves, including Salts, Colossal, Unknown, Great Onyx, and Great Crystal caves, were also discovered, explored, and utilized for tourism around the turn of the 20th century (Palmer 1981). Cave exploration has flourished in the Mammoth Cave System since the park's establishment in 1941, when the caves on Flint Ridge were systematically explored. On September 8, 1972, after a long, wet crawl beneath Houchen's Valley, cave explorers reached a low passage into Echo River that connected Flint Ridge and Mammoth caves; this discovery was climactic after nearly 200 years of exploration (Palmer 1981; Kuehn et al. 1994). Other ridges in the area support vast cave networks that may also be connected to the Mammoth Cave System. The known length of Mammoth Cave in 1980 exceeded 344 km (215 mi; Palmer 1981), and subsequent mapping and exploration have documented an additional 541 km (335 mi) of passages in the system.

The following website contains a brief history of Mammoth Cave National Park: http://www.nps.gov/maca/historyculture/abriefhistoryofmammothcave.htm (accessed 29 June 2011). Notable connections between geology and history of the region beyond the cave include the nature of human settlement being influenced by the limestone geology of the region, and hydrocarbon resources (coal, oil and gas, asphalt) extraction (as described above under "Disturbed Lands"). Lack of abundant surface water, high drainage, and poor soils left much of the upland areas unsuitable for agriculture. Only the river bottoms were appropriate for farms and cattle grazing. Logging and cave tourism operations abounded instead. Roads, trails, and the Mammoth Cave Railroad railways were constructed to lead visitors to the caves in the area.

Figure 19. The Maelstrom. This feature is a vertical shaft with flowing water in Mammoth Cave National Park. National Park Service photograph by Rick Olson (Mammoth Cave NP).

Figure 20. Marion Avenue in the Mammoth Cave system. National Park Service photograph by Rick Olson (Mammoth Cave NP) in 2003.

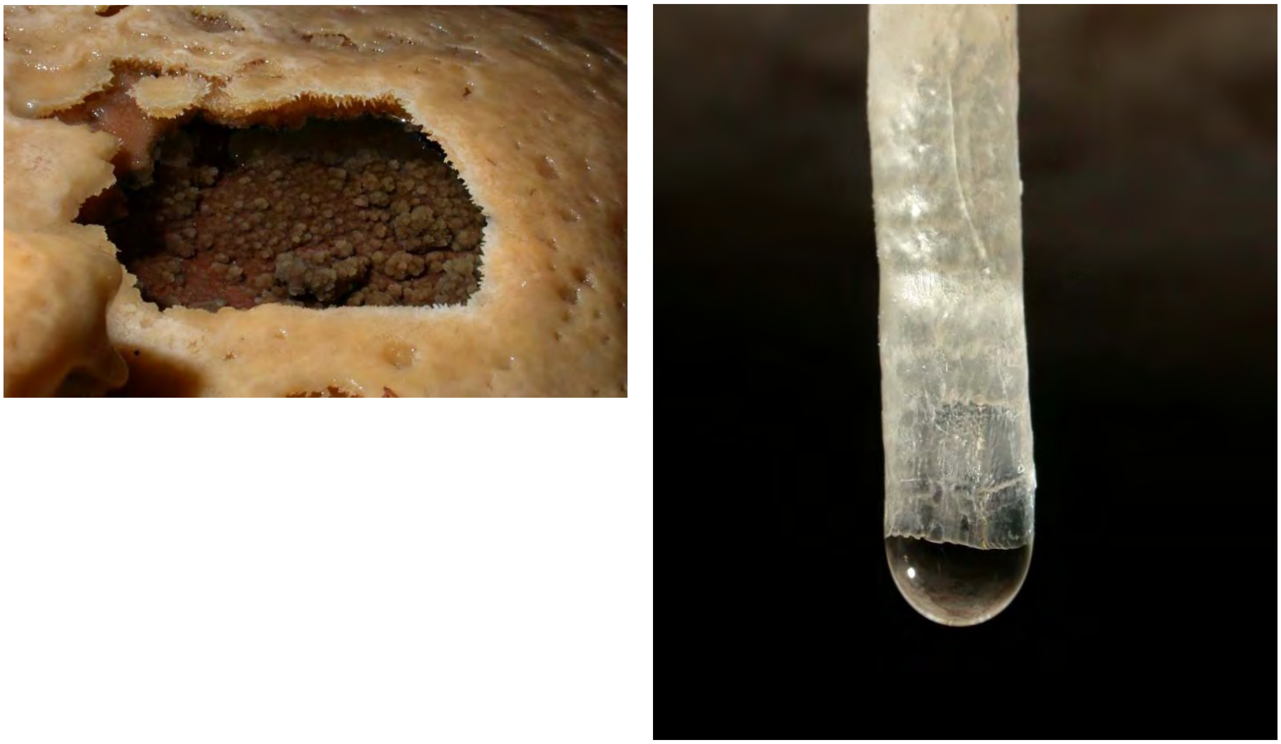


Figure 21. Calcite speleothems. Flowstone (left) and a soda straw (right) are just two examples of calcite speleothems within the Mammoth Cave System. National Park Service photographs courtesy Rick Olson (Mammoth Cave NP).

Figure 22. Gypsum flower speleothems. These features are located in Yahoo Avenue. The features on the right may be helictites. National Park Service photographs by Rick Olson (Mammoth Cave NP).

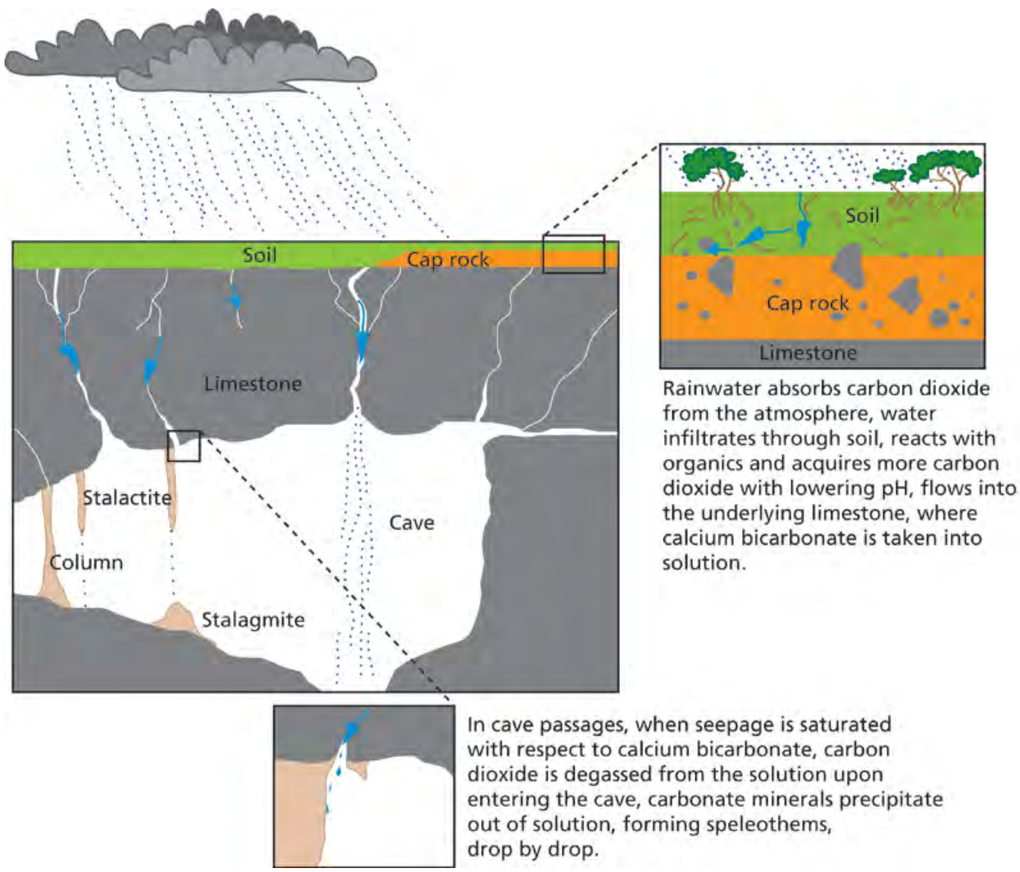


Figure 23. Generalized diagram of the chemical evolution of seepage from rainfall to the cave environment and the formation of speleothems. "Cap rock" may include sandstone and/or shale. For more information on cave development and speleothem formation, refer to Palmer (2007). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

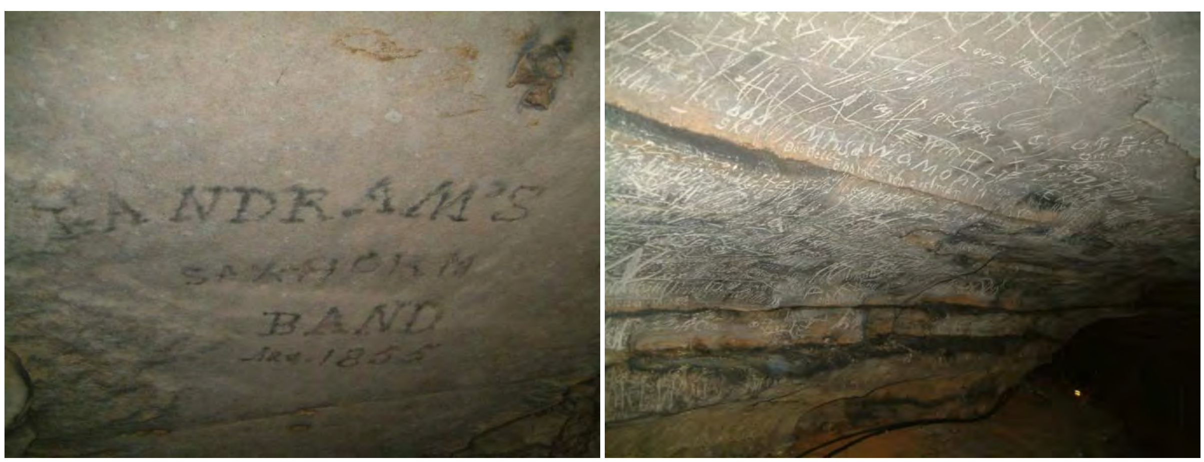


Figure 24. Graffiti. Historic graffiti (left) are cultural features and are considered to add to the historic significance of Mammoth Cave by recording the presence of early explorers. Modern graffiti (right) is considered vandalism that degrades cave surfaces, obscures geologic features, and masks historically significant graffiti. National Park Service photographs by Tim Connors (NPS Geologic Resources Division).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Mammoth Cave National Park, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic framework of Mammoth Cave National Park contains a record of millions of years of deposition and landscape development. Mammoth Cave began forming some 10 million years ago, as groundwater excavated conduits and passageways through Mississippian limestones (more than 300 million years old) capped by resistant Pennsylvanian sandstones. The geologic record at the park is a valuable resource for park managers and visitors.

Precambrian (before 542 million years ago)

No Precambrian basement rock is exposed in Kentucky (figs. 5 and 25). Knowledge about the history of this time has been derived from deep-well data, gravity surveys, seismic refraction, and magnetic surveys. Several rift zones indicate that Earth's crust was being pulled apart following the Grenville Orogeny (ancient Appalachian Mountain-building event) in the late Proterozoic (about 1 billion years ago). Another rifting event may have occurred in the Middle Cambrian (about 500 million years ago). Large-scale strike-slip and normal faults likely formed during the Grenville Orogeny and subsequent rifting (McDowell 2001). These faults were buried beneath a thick stack of sedimentary rocks in central Kentucky, although many reactivated during the Paleozoic, Mesozoic, and Cenozoic (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

Early Paleozoic Era (542 to 416 million years ago)

Bedrock strata in the Mammoth Cave area document the presence of the Illinois depositional basin, an embayment open to the present-day south (fig. 26; Langhorne and Read 2001). The basin is separated from the Appalachian Basin to the east by the Cincinnati arch, a prominent regional uplift that extends from the Nashville dome in central Tennessee north to northwestern Ohio. The arch and adjacent depositional basins were present throughout most of the Paleozoic. Stratigraphic data show that individual units thicken toward the centers of the depositional basins, suggesting that the arch was present as early as the Ordovician (about 487 to 444 million years ago; McDowell 2001). The base of the Ordovician rocks, located primarily on the crest and flanks of the Cincinnati arch, is not exposed within Kentucky (Cressman and Peterson 2001). Ordovician rocks do not appear on the map of Mammoth Cave National Park and are likely buried beneath younger rocks. However, these rocks consist primarily of limestone, dolomite, and shale, reflecting deposition within a shallow marine environment (Cressman and Peterson 2001).

Geologists generally use fossil assemblages to determine the ages of limestone units because these units typically lack sufficient uranium or other radioactive minerals for dating (Olson et al. 2006). The oldest rocks in the region are exposed in the deepest eroded valleys on the Nashville arch, approximately 30 km (18 mi) south of the Mammoth Cave area. From oldest to youngest, these rocks are the Laurel Dolomite, Waldron Shale, and Louisville Limestone (geologic map unit Slwl) from the Middle Silurian (about 430 million years ago; Moore 1961; Peterson 2001). The Laurel Dolomite includes interbedded dolomite and shale, and is divisible into six subunits in the area. The Waldron Shale is at least 95% shale, with some dolomite in discontinuous beds. The Louisville Limestone is mostly thin-bedded gray dolomitic limestone. These three units represent entirely marine deposition within a longstanding, stable basin. Associated fossil assemblages contain the remains of animals that thrived in warm, shallow, mildly agitated seas (Peterson 2001). Silurian rocks rest above Ordovician rocks in central Kentucky, although the boundary does not represent continuous deposition (Cressman and Peterson 2001). The sequence contains an unconformity between the Middle Silurian and Devonian rocks that records a period of erosion, possibly reflecting the uplift of the Cincinnati arch (Cressman and Peterson 2001; Kepferle 2001).

Late Paleozoic Era (416 to 251 million years ago)

Throughout the Devonian (about 416 to 359 million years ago), carbonate precipitates and organic matter that eventually became the Jeffersonville and Sellersburg limestones (geologic map unit Dsj) were deposited in a shallow marine basin. Although an erosional unconformity marked by phosphatic pebbles, quartz sand, pyrite, and glauconite separates them, the Jeffersonville and Sellersburg limestones are commonly grouped together and contain fossiliferous, sometimes dolomitic limestone (Kepferle 2001). The basal layers of the Jeffersonville Limestone contain corals that indicate a shallow-water depositional environment; the upper layers of this limestone indicate that this water grew deeper (Kepferle 2001). The Chattanooga Shale (geologic map unit Dc) was deposited atop these limestones during the Middle to Upper Devonian. The Chattanooga Shale records a resurgence of clastic sediments shed into the basin by rivers and streams from nearby land sources (Livesay 1953; Moore 1961). This organic-rich black shale contains silt-rich layers (Kepferle 2001); rapid burial and subsequent diagenesis of the organic-rich layers developed the shale into a regional oil/gas-producing unit. The younger rocks above serve as reservoir rocks. Intermittent sandstone beds, or "bone beds," within the Devonian sequence likely reflect widespread erosional periods during the Devonian (Conkin and Conkin 1969; Kepferle 2001). Devonian rocks in Kentucky thicken away from the crest of the Cincinnati arch (Kepferle 2001).

Mississippian Period (359 to 318 million years ago)

The Mississippian is divided into Lower (early, between 359 and 345 million years ago), Middle (between 345 and 328 million years ago, and Upper (late, between 328 and 318 million years ago). Mississippian-aged strata dominate the geologic units exposed within Mammoth Cave National Park. These Mississippian rocks record the long-term presence of an open basin (Illinois Basin) that formed the depositional setting throughout this period. The basin was located between 5 and 15 degrees south of the equator (Langhorne and Read 2001). Most deposition occurred in shallow marine environments during this period, although a range of fluvial and marine environments was present (Pohl et al. 1968; Grabowski 2001). Lower Mississippian units include, from oldest to youngest, the Borden (geologic map units Mb, Mbm, and Mbls) and Fort Payne formations (geologic map units Mfp and Mfprl). These units mark a transition from the widespread, distal deep-basin deposition of the Devonian shales to the deposition of coarser clastics (shallow shelf to deltaic deposits) along the Illinois basin margin (Grabowski 2001). The depositional environment shifted again from basinal and deltaic (Borden Formation) to shallow-marine carbonate (Fort Payne Formation) near the end of the Early Mississippian (Grabowski 2001).

Upper Mississippian strata include the Harrodsburg Limestone (geologic map unit Mhb); Salem and Warsaw limestones (Ms and Msw); St. Louis Limestone (Msl); Lost River Chert (Mlr); Ste. Genevieve Limestone (Msg); Beaver Bend, Mooretown Formation, and Paoli Limestone (Mbp); Sample Sandstone and Reelsville Limestone (Mr); Girkin Limestone (Mg; although sometimes mapped separately, recent mapping by Palmer [2007] considers the Beaver Bend , Mooretown, Paoli, and Reelsville Limestone [Mbp] to be members of the Girkin limestone [fig. 5]); Golconda Formation (Beech Creek Limestone [Mgc], Big Clifty Sandstone [Mgb], and Haney Limestone [Mgh] members; recent mapping by Palmer [2007] separates these members into their own formations and places the Beech Creek as a member of the Girkin); Hardinsburg Sandstone (Mg); Glen Dean Limestone (Mgd); Tar Springs Sandstone (Mts); Vienna Limestone (Mv); Waltersburg Sandstone (Mwl); Menard Limestone (Mme); Palestine Sandstone (Mpt); Clore Limestone (Mcl); and Leitchfield Formation (Ml; includes Waltersburg, Menard, Palestine, Clore, Vienna Limestone and Tar Springs Sandstone locally, particularly west of the park). The park's geology has been mapped by many geologists, whose interpretations differ among quadrangles. Unit correlation differs from the center to the northwestern corner of the digital geologic map provided by the GRI, due to differing geological interpretations among mapping organizations. For instance, the Vienna Limestone and Tar Springs Sandstone (geologic map units Mv and Mts, respectively) are mapped locally within the Leitchfield Formation (geologic map unit Ml) in the northwestern part of the park, whereas they are separated elsewhere. Detailed stratigraphic descriptions of these units are beyond the scope of this report; however, the reader may consult the stratigraphic column (fig. 5), the "Map Unit Properties Table," and source map reports for more information. Map units exposed within the park are highlighted on the table.

The Harrodsburg, Salem, and Warsaw limestones (geologic map units Mhb, Ms, and Msw) reflect the shallowing that followed the deposition of the basin-filling Fort Payne and Borden formations (geologic map units Mfp, Mfprl, Mb, Mbm, and Mbls; Grabowski 2001). The St. Louis, Ste. Genevieve, and Girkin limestones (geologic map units Msl, Msg, and Mg) host the Mammoth Cave System and reflect shallow marine deposition with scant chert and silty layers. In general, the Upper Mississippian strata contain sequences of alternating sandstones and limestones or shales that reflect shifts among open-marine, shallow-marine shelf, and river-delta depositional settings (Grabwoski 2001). The younger rocks of the Upper Mississippian are more terrestrial in nature, indicating the advance of deltaic and coastal sediments across the carbonate shelf from the north (Grabowski 2001). These terrestrial rocks frequently form resistant caps on ridges throughout the region. Plant fossils in the basal Big Clifty sandstone (geologic map unit Mgh) also record terrestrial conditions. Regional coal beds within the upper Mississippian to lower Pennsylvanian units are evidence of widespread peat-marsh and swamp environments. They contain naturally occurring asphalt, the mining of which precipitated the construction of Lock and Dam #6 (Thornberry-Ehrlich 2006).

Even units with seemingly monotonous successions of limestone have complex histories, as revealed by detailed mapping, chemical analyses, and microscopic investigations. For example, the Glen Dean Formation (geologic map unit Mgd) in the Illinois Basin has at least 16 distinct carbonate microfacies within the greater shallow, open-marine subtidal carbonate platform. These include including lower slope, upper slope, outer bank (with three sub-bank environments), interbank, inner bank (with three sub-bank environments), and lagoon microfacies (Feiznia and Carozzi 1987). Clastic sedimentary rocks, such as siltstone, quartz arenite (with and without argillaceous matrix), quartz wacke, and shale interlayered with the limestones reflect the advancement of a deltaic system over the eastern shelf of the Illinois Basin (Feiznia and Carozzi 1987). The rock series between the Ste. Genevieve and Glen Dean limestones (Msg and Mgd) reflect the transition from shallow-marine carbonate deposition to mixed carbonate-siliciclastic sedimentation. They contain evidence of differential subsidence between the Cincinnati arch and Illinois Basin that provides clues about the regional depositional environment and geologic structural controls on deposition, as well as glacial events during the late Paleozoic. This unit contains sequences of widespread unconformities, deep incised valleys, and paleosols (fossil soils). The frequency of the sequences correlates with Milankovitch eccentricities that are known to trigger cooler climates. Glacial events are connected with major sea-level fluctuations (Smith and Read 2000, 2001).

Pennsylvanian Period (318 to 299 million years ago)

At the beginning of the Pennsylvanian, seas largely withdrew from the region and a channelized erosional surface (major unconformity) formed atop the uppermost Mississippian rocks (fig. 5; Livesay 1953). Erosion locally removed more than 250 m (820 ft) of Mississippian strata before deposition resumed during the Pennsylvanian (Rice 2001). At this time, Kentucky was near sea level and was alternately covered by lakes, extensive swamps, estuaries, and shallow bays (Rice 2001). Rivers deposited sand and gravel atop the Mississippian units (fig. 27; Livesay 1953). The Lower Pennsylvanian Caseyville Formation (geologic map unit PNca) contains channelized conglomerate, sandstone, siltstone, coal, and shale (Haynes 1964b). This unit also contains plant fossils indicative of terrestrial depositional environments. The Middle Pennsylvanian Tradewater Formation (geologic map unit PNt) includes sandstone, siltstone, and shale in roughly equal amounts, as well as limestone with economically valuable coal beds (Haynes 1964b; Rice 2001). Thin limestone beds record periodic marine transgression across the Cincinnati arch (Rice 2001). The coal beds are evidence of lush forests growing under humid conditions. Although some regional mapping has grouped the Pennsylvanian units together, they are differentiated on the GRI digital geologic map (Sandberg and Bowles 1965). Within the park, the Mississippian Big Clifty Sandstone (geologic map unit Mgb) and some of the Pennsylvanian Caseyville Formation (geologic map unit PNca) are the primary cap rocks; however, the Pennsylvanian units cap ridges throughout eastern Kentucky and southern Illinois, protecting the underlying, soluble limestones from being completely eroded away.

Mesozoic and Cenozoic Eras (251 million years ago to present)

Since the end of the Paleozoic, the geologic history of the Mammoth Cave National Park area has been characterized primarily by erosion and weathering that have removed Pennsylvanian and older strata from structurally higher areas, such as the Cincinnati arch (Livesay 1953; Rice 2001). The geologic units within the park weather and erode to form distinctive landforms. The upper part of the Mississippian St. Louis Limestone (geologic map unit Msl) characteristically weathers to form numerous small sinkholes, whereas the lower St. Louis beds do not tend to form sinkholes, but erode deeply into steep valleys (Weller 1927; Palmer 1981). Sinkhole development in the St. Louis beds is limited primarily by the presence of major, thick-bedded chert layers. Deep sinkholes develop when weathering processes wear through these chert layers. These sinkholes may then coalesce into larger valleys (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). The Ste. Genevieve Limestone (geologic map unit Msg), typically found on hillsides, tends to weather readily and develop large sinkholes. The overlying limestone (Girkin Formation [Mg]) tends to weather in much the same way as the Ste. Genevieve Limestone, forming steep hillsides (such as those on the Dripping Spring Escarpment), valley sinks, and sinkholes (Weller 1927; Palmer 1981). The geologic units capping ridges in the park area, including the Big Clifty Sandstone, Haney Limestone, Hardinsburg Sandstone, and Glen Dean Limestone (geologic map units Mgb, Mgh, Mh, and Mgd), tend to form gently rolling, nearly level country traversed by steep, incised gullies and cliffs (fig. 28; Weller 1927; Palmer 1981). This cap rock series, especially the Big Clifty Sandstone, moves water to the edges of ridges and protects the major cave-bearing limestones from intensive weathering.

Development of the Mammoth Cave System

Geologists estimate that the cave has been forming for approximately 15 million years. However determining the actual age is very difficult. Age data from cave sediments suggest that the upper-most (oldest) levels of the cave were abandoned approximately 3 million years ago. Those cave passages must have been fully formed by that time. Correlation with the Green River terraces indicates that Mammoth Cave began forming at least 10 million years ago; it now spans a vertical range of approximately 150 m (500 ft). The development of the cave has been controlled by the erosional and depositional history of the Green River. Perched terraces record periods of river deposition followed by relatively rapid incision, which has left terrace deposits above the present active channel. Data indicating the ages of the terraces has helped to constrain the timing of cave formation. The evidence recorded in the cave network and sediments can help geologists to understand the evolution of Mammoth Cave and its relationship with the Green River and greater Ohio River drainage history. The causes of river entrenchment are debatable; two leading theories ascribe it to broad regional uplift (Potter 1955) or climate change (i.e., global-scale glacial events; Teller and Goldthswait 1991; Granger et al. 2001).

Multiple approaches are necessary to determine the age of Mammoth Cave. Because the cave is a void, it is inherently difficult to date directly (Schmidt 1982). Sediments washed into the cave contain radioactive elements that indicate the sandstone-capped uplands have eroded 2 to 7 m (6 to 23 ft) per million years for the past 3.5 million years (Granger et al. 2001). During the extreme climate changes of the Pleistocene, this rate accelerated intermittently to approximately 30 m (100 ft) per million years (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). Beneath this cap rock, the cave network formed in intermittent episodes of dissolution, erosion, and deposition as Green River erosion outpaced hillslope erosion for more than the past 2 million years (Granger et al. 2001).

Carbon dating of prehistoric artifacts in Mammoth Cave, the oldest of which are about 4,100 years old, constrains the timing of human presence in the cave. Analyses of isotopes derived from radioactive uranium within speleothems have yielded ages of more than 350,000 years. Cave sediments contain isotopes that form only by exposure to cosmic rays. Such cosmogenic isotopes indicate the timing of sedimentation; more specifically, they record the bombardment of exposed quartz by cosmic rays before sediments were washed from the surface into the cave. As detailed below, the oldest dated cave sediments washed into the cave more than 2 million years ago, indicating that the cave passages must have begun to form much earlier (Olson et al. 2006).

Upon deposition, some clastic-sediment deposits retained a magnetic signature, with some grains aligned to the north–south polarity of Earth's magnetic field at the time. The direction of polarity is not constant and the poles occasionally reverse (e.g., the magnetic north pole is replaced by a south pole). The record of polarity reversals has been well dated. The pattern of magnetic polarity reversals in oriented cave-sediment samples collected at measured levels throughout the cave indicates that they were deposited during at least the past 1 to 2 million years (Schmidt 1982). According to Granger et al. (2001), radioactive decay of cosmogenic aluminum (26Al) and beryllium (10Be) in sediments washed into the cave at various levels record 3.5 million years of water-table positions. This history was governed by the erosion and deposition of the Green River, which in turn correspond to major climate changes and a reorganization of the local drainage pattern.

Research suggests the five widespread and distinctive cave levels of Mammoth Cave formed over at least the past 3.2 million years (fig. 29; Granger et al. 2001; R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). The uppermost level is 200 m (656 ft) above sea level and was being actively excavated over 3.2 million years ago. The upper levels of the cave network, including Grand Canyon and Crystal Cave, formed during a period of slow river incision; deposition subsequently filled these levels with sediments around 2.3 to 2.4 million years ago. Below this level, many regional underground streams and the largest passages in the park attest to millions of years of excavation at 170 to 180 m (558 to 591 ft) below the surface. Large horizontal passages were formed as tributaries of the Green River during times of relative stability (figs. 30 and 31). Approximately 2 million years ago, this longstanding level was abandoned as the Green River began rapid downcutting coincident with Pleistocene ice-age glacial advances and meltwater pulses. Another period of excavation began, resulting in the formation of a cave level at 167 m (548 ft) elevation that was active for 500,000 years, until it was abandoned 1.5 million years ago. This level includes Cleveland, Turner, and Black Snake avenues. At this time, the ancient Teays River system (the Pleistocene equivalent of the Ohio River, which drained much of the Midwest and Midatlantic regions) was captured by the Ohio River drainage. The Ohio River was a tributary of the Teays until the lower Teays River drainage was blocked by glacial ice and diverted through the highlands between Cincinnati and Louisville. This blockage caused the upper Teays River flow to be redirected suddenly into the much smaller Ohio River drainage, resulting in rapid incision and lowering the regional base level. The same process occurred in the Green River, now a tributary of the Ohio River. The excavation of Mammoth Cave moved rapidly to a lower level, at 150 m (492 ft) elevation. This level includes Colossal Trunk, Great Relief Hall, Floyd's Lost Passage, and the ancestral Echo River passage. This level was abandoned approximately 1.24 million years ago, with intermittent periods of aggradation and downcutting episodes around 0.7 and 0.8 million years ago. The modern level of cave excavation is at 125 m (410 ft) elevation.

Modern Wind-blown and River Deposits (approximately 1 million years ago to present)

Unconsolidated Quaternary deposits occur locally as a relatively thin, surficial veneer throughout most of Kentucky (McDowell and Newell 2001). Windblown loess deposits, incorporated into upland soils, probably formed during Pleistocene glaciations when the Mammoth Cave area was characterized by a cooler, periglacial (describing areas near glacial ice masses) climate (Thornberry-Ehrlich 2006). In the Mammoth Cave National Park area, Quaternary deposits include terrace gravels (geologic map units Qtg and Qtt), broken-up rock (breccia) and slumped sandstone (geologic map unit QTb), landslide deposits (geologic map unit Ql), and alluvium (geologic map unit Qal; Haynes 1964b; Cattermole 1966; Shaw 1966; Moore 1973). These units reflect active Earth surface processes. Terrace deposits record higher river levels along the Green and Nolin rivers, reflecting the complex history of deposition and incision described above. These deposits are typically of local provenance and contain quartz gravel and sand, silt, and clay (Shawe 1966; Moore 1973; McDowell and Newell 2001). Brecciated and slumped sandstone and landslide deposits contain sandstone and shale blocks in a matrix of sand, gravel, and clay. These deposits are the result of mass wasting along steep slopes throughout the Mammoth Cave area (Cattermole 1966; Shawe 1966). Approximately 10 m (30 ft) of sediment aggradation occurred in the late Pleistocene (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011). Alluvium (silt, clay, sand, and gravel) is being actively deposited along park streams and river channels, in floodplain areas, low-lying cave passages, and alluvial fans (Haynes 1964b). Human activities, such as dam construction and land clearing, are impacting the alluvial deposition within the park. The balance among sediment aggradation, erosion, and stability is disrupted. Upstream and downstream dams on the Green River have reduced the amount of sediment deposition; it is unknown whether the system is actively aggrading, eroding, or relatively stable at present (R. Toomey, MCICSL director, and R. Olson, Mammoth Cave NP ecologist, written communication, March 2011).

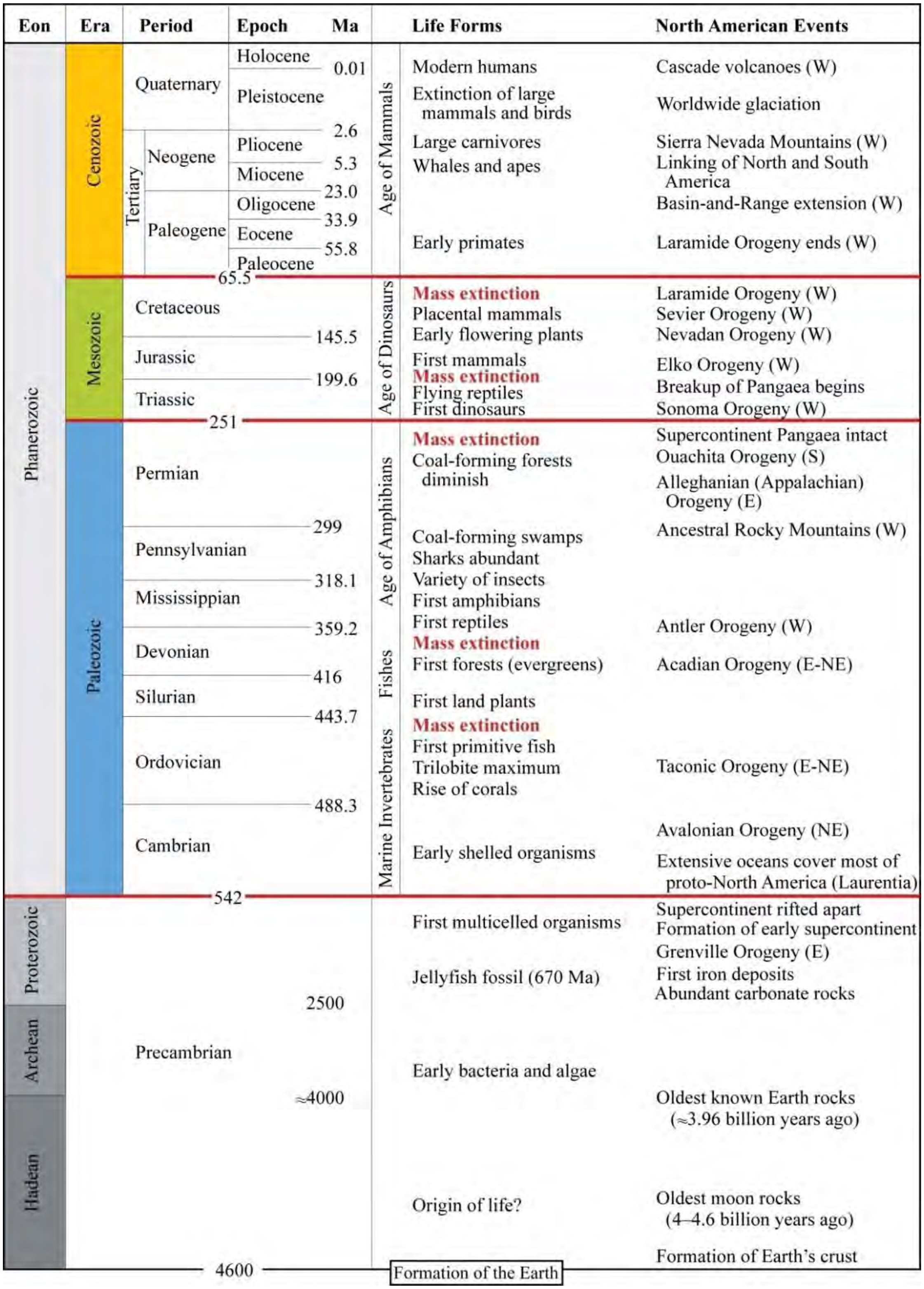


Figure 25. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Drafted by Trista Thornberry-Ehrlich (Colorado State University) with information from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25).

Figure 26. Paleogeographic map showing the regional setting of the Illinois Basin during the Mississippian. Green star indicates position of Mammoth Cave National Park in a shallow marine environment. Note that North America was positioned about the equator (red line). Base paleogeographic map by Ron Blakey, Colorado Geosystems, Inc., available online (http://cpgeosystems.com/paleomaps.html). Annotation by Jason Kenworthy (NPS Geologic Resources Division) after Langhorne and Read (2001; fig. 1A).

Figure 27. Crossbeds (tilted layers) deposited in a fluvial environment during the Pennsylvanian at Mammoth Cave National Park. This unit now forms part of the cap rock over the soluble limestones that host the Mammoth Cave System. National Park Service photograph by Tim Connors (NPS Geologic Resources Division).

Figure 28. Active gullies forming at Mammoth Cave National Park. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

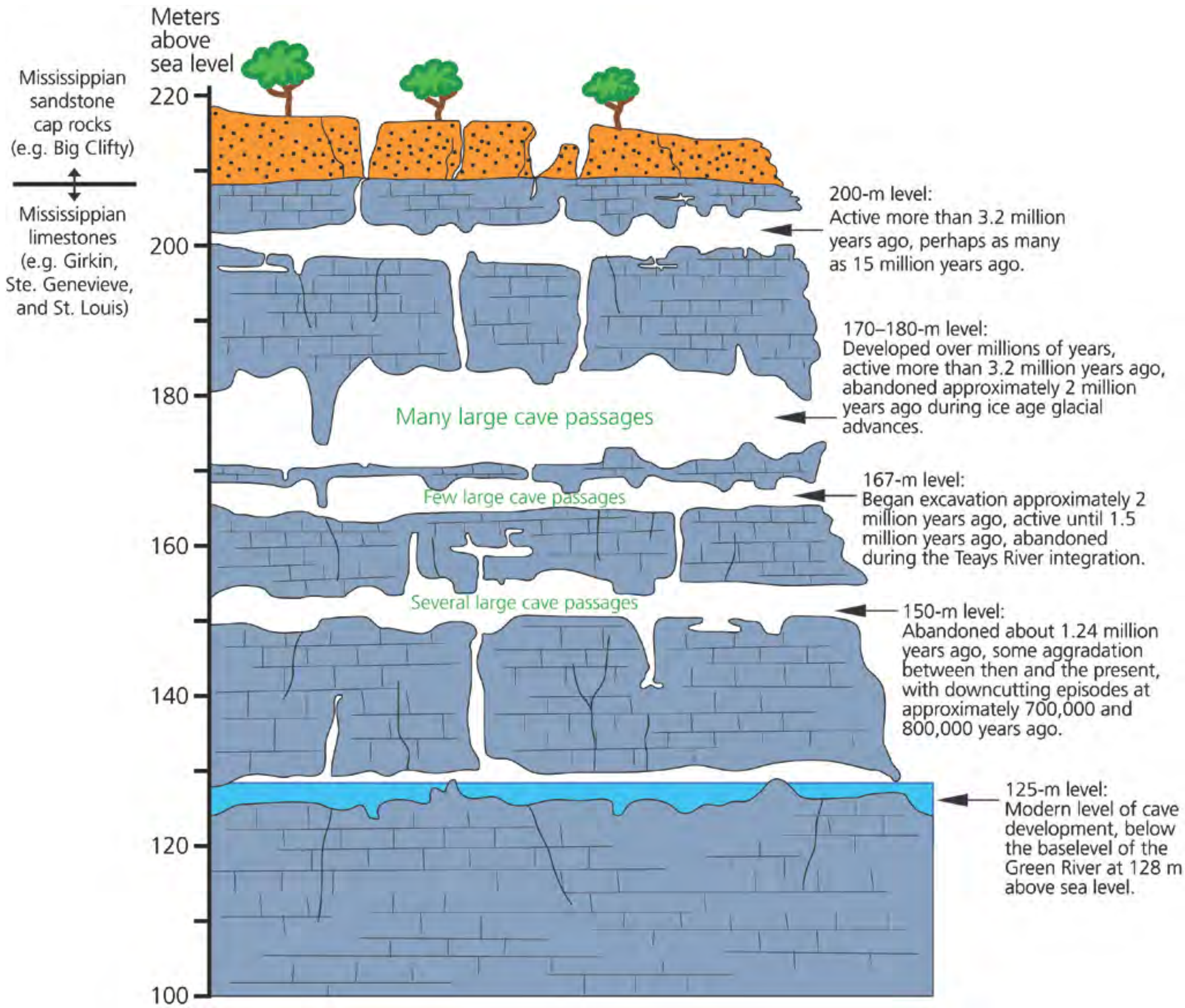


Figure 29. Five levels of major cave formation at Mammoth Cave National Park. Intermittent periods of stability of the Green River baselevel resulted in periods of widespread cave development at a particular level. When the river's baselevel lowered—such as in response to climate changes or diversions of the Ohio River system—downcutting occurred until a new stable baselevel was reached at a lower elevation. Vertical shafts commonly form during periods of downcutting. Larger passages generally indicate longer periods of cave formation at a particular level, which would occur during long periods of river system stability. Relative amounts of large cave passages within Mammoth Cave National Park are listed in green. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 30. Flowing Roaring River within the Mammoth Cave system, an example of a tubular passage that forms at or near the water table. Some portions of the passage are dry under base-flow conditions, while others continue active formation. National Park Service photograph by Rick Olson (Mammoth Cave NP) in 2010.

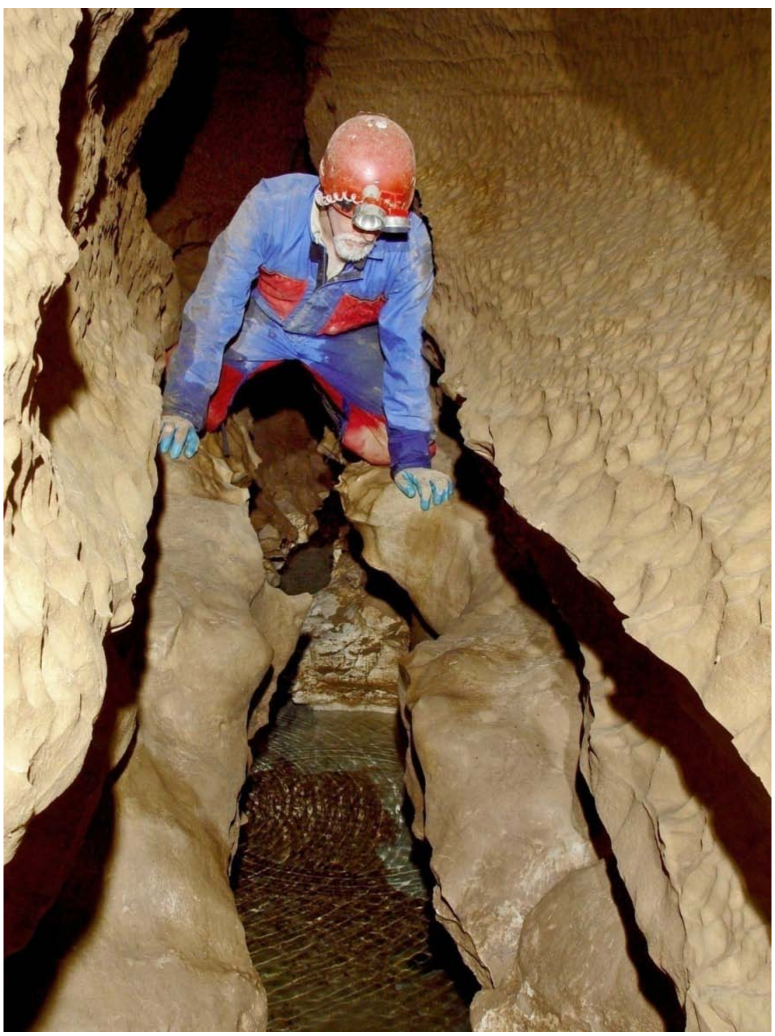


Figure 31. Flowing Bretz River within the Mammoth Cave system. The canyon passage is braided and the stream crosses beneath the upper part of the canyon. Note the scallops on the canyon walls. Photograph by Art Palmer (SUNY-Oneonta).

Geologic Map Data

This section summarizes the geologic map data available for Mammoth Cave National Park. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Mammoth Cave National Park. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

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Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Mammoth Cave National Park using data model version 1.4.

GRI digital geologic data for Mammoth Cave National Park are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) Portal (https://irma.nps.gov/App/Reference/Search). Enter "GRI" as the search text and select Mammoth Cave National Park from the unit list. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.hlp) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data

Table 2. Geology data layers in the Mammoth Cave National Park GIS data.

Data Layer	Code	On Geologic Map Overview?
Cross Section Lines	sec	No
Geologic Attitude and Observation Points	atd	No
Mine Point Features	min	No
Geologic Observation Point Localities	gol	No
Geologic Point Features	gpf	No
Fault and Fold Map Symbology	sym	No
Folds	fld	No
Faults	flt	Yes
Structure Contours	cn[*x*]	No
Mine Feature Lines	mfl	No
Linear Geologic Units	gln	No
Mine Area Feature Boundaries	mafa	No
Mine Area Features	maf	No
Hazard Area Features	hza	No
Surficial Contacts	sura	Yes
Geologic Contacts	glga	Yes
Surficial Units	sur	Yes
Geologic Units	glg	Yes

Note: All data layers may not be visible on the geologic map overview graphic. [x] = structure contour layer number.

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic data draped over a shaded relief image of Mammoth Cave National Park and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the “Geologic History” section. Please refer to the geologic timescale (fig. 25) for the geologic period and age associated with each unit.

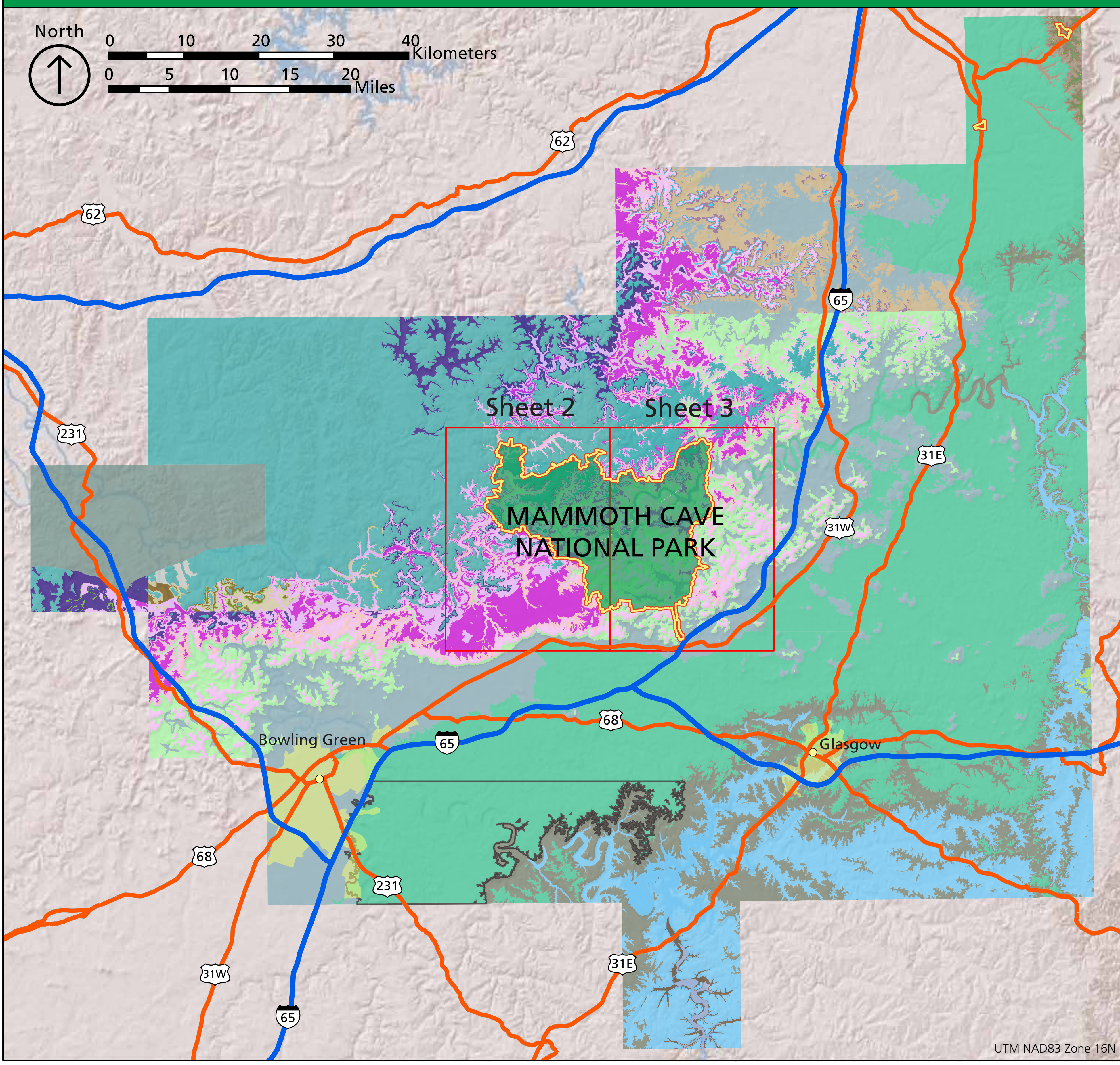
Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

Please contact GRI with any questions.

Overview of Digital Geologic Data for Mammoth Cave National Park

Sheet 1: Full Extent



NPS Boundary

Faults

- normal fault, approximate, D is downthrown side
- normal fault, concealed D is downthrown side

Surficial Contacts

- approximate
- concealed

Geologic Contacts

- approximate
- concealed
- inferred
- quadrangle boundary
- subaqueous (inferred)

Surficial Units

- Qaf - Artificial fill
- Qal - Alluvium
- QTg - Terrace gravels

Geologic Units

- PNtc - Tradewater and Caseyville Formations
- PNca - Caseyville Formation
- Ml - Leitchfield Formation
- Mv - Vienna Limestone
- Mts - Tar Springs Sandstone
- Mgd - Glen Dean Limestone
- Mh - Hardinsburg Sandstone
- Mgh - Haney Limestone Member, Golconda Formation
- Mgb - Big Clifty Sandstone Member, Golconda Formation
- Mg - Girkin Limestone
- Msg - Ste. Genevieve Limestone
- Msl - St. Louis Limestone

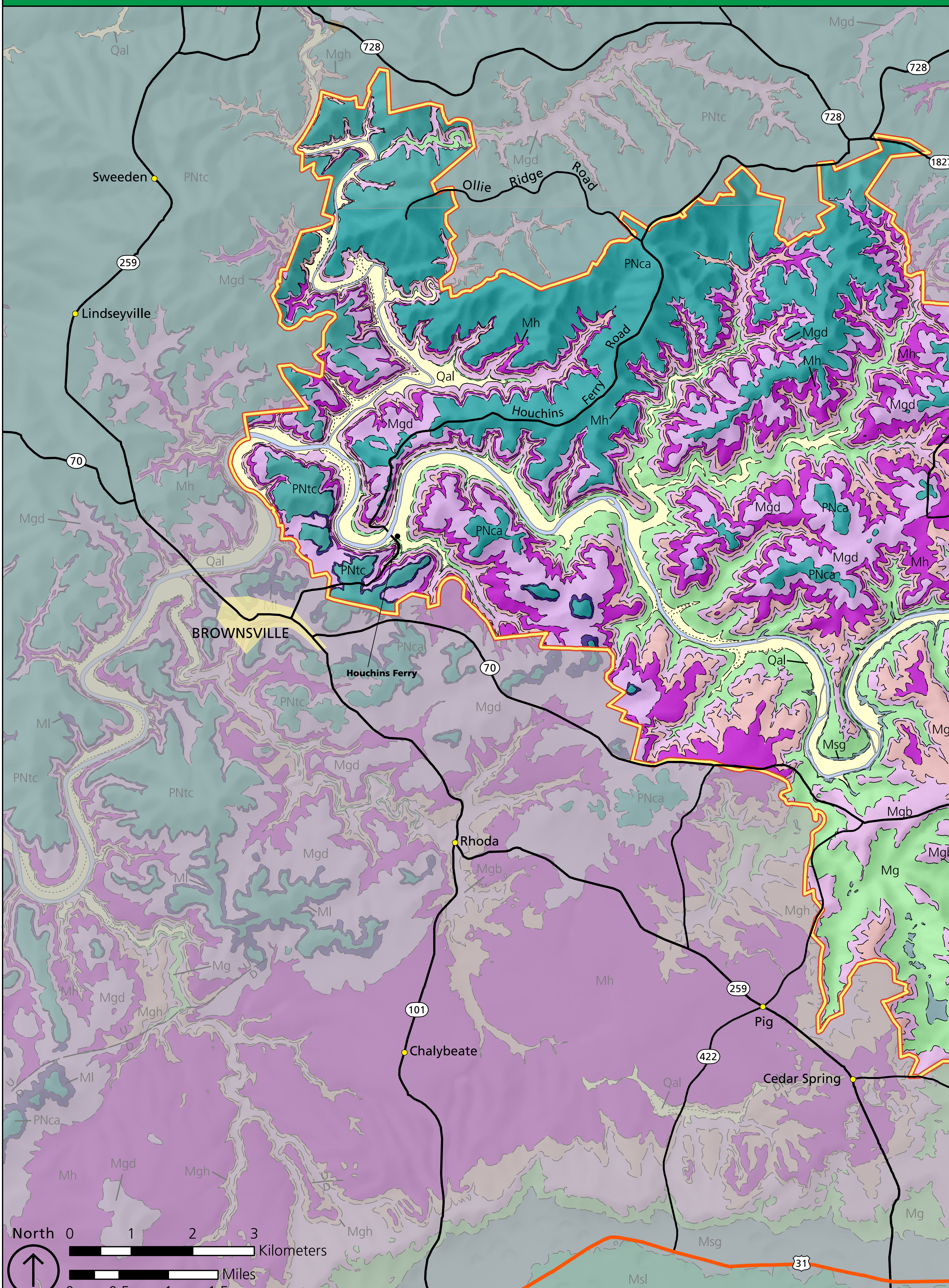
This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. It is an overview of compiled digital geologic data, and not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scales (1:24,000 and 1:100,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (24k), 50 meters / 166 feet (100k) (horizontally) of their true location.

The source maps used in creation of the digital geologic data product include digital Kentucky Geological Survey publications (including some unpublished sources) and paper U.S. Geological Survey Publications (see literature cited section for specific sources).

Overview of Digital Geologic Data for Mammoth Cave National Park

Sheet 2

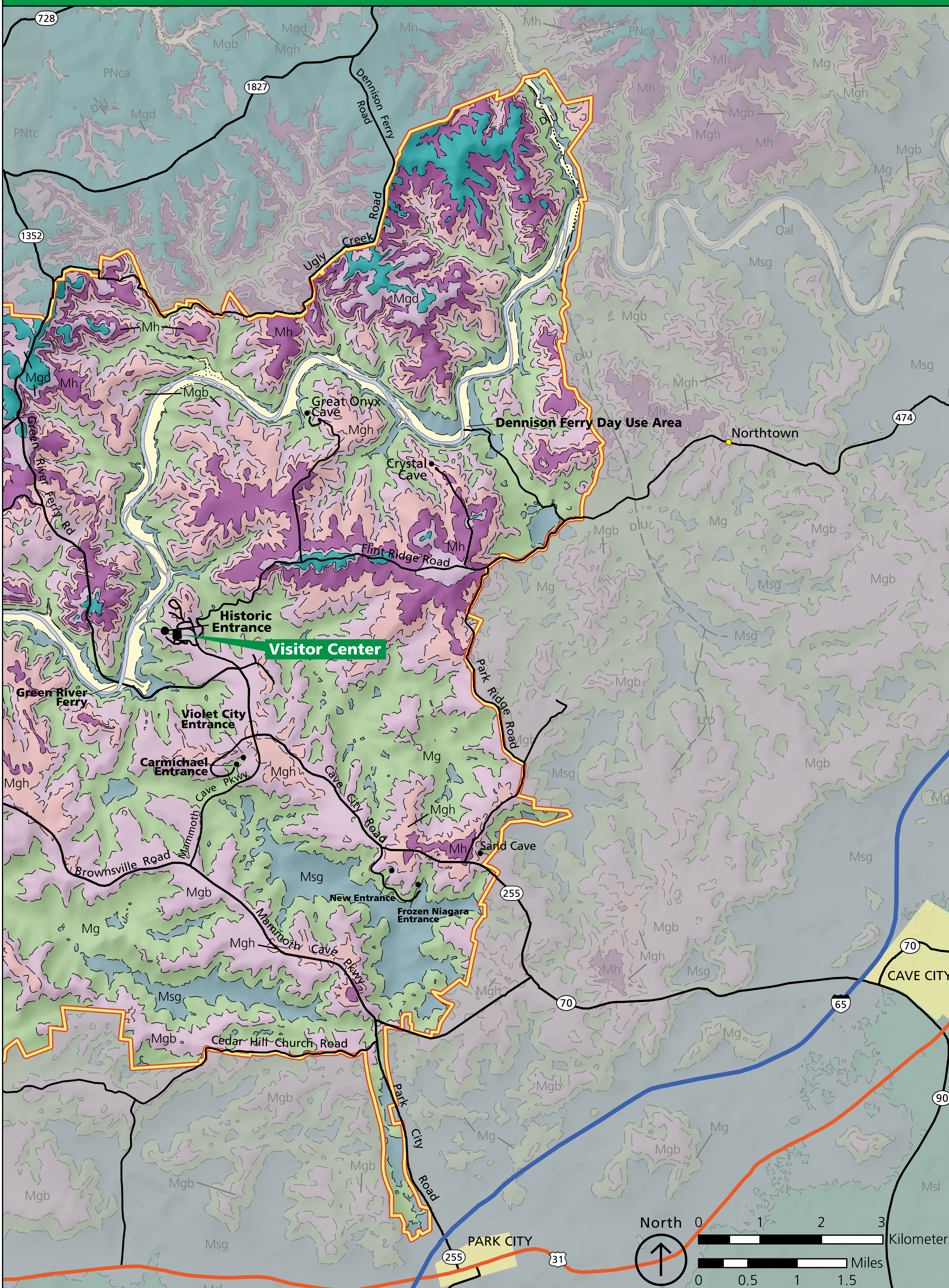


Produced by the Geologic Resources Inventory

September 2011

Overview of Digital Geologic Data for Mammoth Cave National Park

Sheet 3



Produced by the Geologic Resources Inventory

September 2011

Map Unit Properties Table: Mammoth Cave National Park

Gray-shaded rows indicate geologic units that are not mapped within Mammoth Cave National Park, but are included in the digital geologic data for the park. Colors based on U.S. Geological Survey standard colors.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Paleontological Resources	Karst	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
QUATERNARY	Artificial fill (*Qaf*) Alluvium (*Qal*) Landslide deposits (*Ql*)	***Qaf*** is a mixture of imported material used for the construction of dams and other structures. ***Qal*** contains silt, clay, sand, and gravel inclusive of floodplain, channel, and alluvial-fan deposits along rivers and streams, as well as some colluvium on steep slopes and, locally, lacustrine clay and silt. ***Ql*** contains sandstone blocks in crushed shale and sandstone matrix, which collapsed due to instability within shale beds. ***Qal*** is mapped within the park.	Low	Units are associated with riparian areas and steep slopes, active floodplains, and impoundment features. These considerations should be taken into account when planning development. Wells dug in floodplain deposits can yield up to 1,900 liters (500 gallons) per day.	***Qal*** may be prone to flooding, and slumping and erosion when exposed on a slope. ***Ql*** is formed during landslides and is prone to further mass movement.	Chert pebbles and cobbles may have provided tool material.	May contain modern remains.	***Ql*** may be present in sinkholes.	Sand, gravel, silt, clay, ironstone pebbles, white quartzite pebbles, coal pebbles.	Riparian habitat flanking rivers and streams.	Units record modern land use, riparian evolution, and slope processes that constantly change the landscape at Mammoth Cave National Park.
QUATERNARY-TERTIARY	Terrace gravels (*QTg*) Terrace deposits (*QTt*) Brecciated and slumped sandstone (*QTb*)	***QTg*** contains mostly gravel with a median grain size of 10 mm in a matrix of finer quartz sand and silt with minor amounts of clay. Unit is poorly to moderately sorted, unconsolidated, with some crossbedding. Some hydrous iron oxide-cemented lenses are present in lower layers. ***QTt*** contains gravel, sand, silt, and clay, and locally ranges from 5 to 17 m (16 to 56 ft) thick, approximately 15 to 35 m (49 to 115 ft) above the present floodplain level in some reaches. ***QTb*** contains slumped sandstone, conglomerate, and shale blocks in a matrix of sand, gravel, and clay.	Moderately high for gravel-rich layers	Deposits are present atop hills and slumped rock and on older erosional surfaces. Heterogeneous nature of unit may render it unstable if undercut on steep slopes. ***QTb*** is associated with active karst processes and should be avoided for infrastructure.	***QTg*** forms resistant caps atop hills and may be prone to blockfall. ***QTb*** is prone to slumping and sliding into sinkholes.	None documented	Marine invertebrate fossils in bedrock pebbles, including corals, brachiopods, bryozoans, and crinoid columnals.	***QTb*** is associated with active sinkhole development and slumps into solution cavities of underlying units.	Quartz pebbles, sand, silt, clay, ferruginous quartz conglomerate, hydrous iron oxide, jasper-like quartz, geodes.	Units support upland forests with well-drained soils.	Terrace gravels cap hills and are derived from Pennsylvanian rocks. Units are remnants of an ancient stream channel cut on Mississippian and Pennsylvanian rocks. ***QTb*** records the development of the karst landscape throughout the area, especially during the extensive Tertiary dissolution of the Mississippian limestone units along and below the unconformable contact at the base of ***PNtc***.
MIDDLE-LOWER PENNSYLVANIAN	Tradewater and Caseyville formations (*PNtc*)	Lumped unit consists of interlayered conglomerate, sandstone, siltstone, coal, and shale. Most cobbles in the conglomerate are about 7.5 cm (3.0 in) in diameter and can be conspicuous white quartzite. Massive, crossbedded layers form cliffs regionally. Some asphalt-bearing zones occur locally. Colors range from light-reddish-brown, brown, and very-light-gray (conglomerate) to yellowish-brown and bluish-gray (sandstone and shale). ***PNtc*** is mapped within the park.	High	Unit is often undercut and exposed as cliffs. Avoid development on sloped or heavily fractured areas.	Unit is frequently covered with talus and colluvium resulting from active slope processes. Unit is prone to undercutting, cliff formation, and blockfall.	Unit may be part of large rock shelters, which may have contained American Indian habitation sites.	Root casts, stems	Unit forms cap rock over units of active karst formation.	Conglomerate, sandstone, iron-oxide nodules, coal.	Formation caps highest hills throughout the area and supports upland forests.	Unit forms the cap rock above soluble carbonate formations regionally. Unit contains the “Main Nolin” coal at prospects and mines locally.
MIDDLE PENNSYLVANIAN	Tradewater Formation (*PNt*)	Unit contains fine- to medium-grained, silty, friable, mica-rich, thick-bedded, crossbedded sandstone layered with sandy, silty, carbonaceous shale and limestone. Many coal beds are locally persistent throughout this unit (linear units: ***PNls***, ***PNc1***, ***PNcu***, ***PNmc***, ***PNmca***, ***PNmmcl***, ***PNd***, ***PNa***, ***PNf***, and ***PNam***). Many coal beds are underlain by several cm of gray underclay.	Moderately high	Unit is often undercut and exposed as cliffs. Avoid development on sloped or heavily fractured areas.	Unit is frequently covered with talus and colluvium resulting from active slope processes. Unit is prone to undercutting, cliff formation, and blockfall.	Prominent coal beds were mined from the late 1800s through most of the 1900s.	Unit contains fossiliferous limestone.	Limestone layers within this unit are prone to dissolution.	Coal, sandstone, limestone, iron-clay concretions.	Formation caps highest hills throughout the area and supports upland forests.	Unit contains Mining City, Mannington, Lewisport, Dunbar, Aberdeen, Foster, and Amos coal beds.

Gray-shaded rows indicate geologic units that are not mapped within Mammoth Cave National Park, but are included in the digital geologic data for the park. Colors based on U.S. Geological Survey standard colors.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Paleontological Resources	Karst	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
LOWER PENNSYLVANIAN	Caseyville Formation (*PNca*)	Unit contains conglomerate, sandstone, siltstone, coal, and shale. Conglomerate has well-rounded quartz pebbles as large as 30 mm (1 in.) in diameter in a quartz-rich matrix. Sandstone is fine- to coarse-grained, thin- to thick-bedded, with local iron-oxide staining. Siltstone and shale are yellowish-brown with lenses of sandstone. Asphaltic conglomerate occurs in a 2- to 3–m- (6- to 9–ft-) thick basal zone locally. ***PNca*** is mapped within the park.	High	Wells into the sandstone in lower beds of this unit can produce up to 230 liters (60 gallons) of water per minute. Groundwater is rich in sodium bicarbonate. Unit is often undercut and exposed as cliffs. Avoid development on sloped or heavily fractured areas.	Unit is frequently covered with talus and colluvium resulting from active slope processes. Unit is prone to undercutting, cliff formation, and blockfall.	Prominent coal beds were mined from the late 1800s through most of the 1900s. Unit forms rock shelters that may have been inhabited. A steam boiler was used to extract asphalt from the unit to make "paint."	Plant stem impressions, some plant remains	Unit forms cap rock over units of active karst formation.	Quartz pebbles, sandstone, shale, iron-oxide nodules, vein quartz, manganiferous cement, rock asphalt.	Formation caps highest hills throughout the area and supports upland forests.	Unit contains the Nolin coal bed. Unit marks a regional unconformity of Pennsylvanian rocks atop Mississippian rocks. Unit fills channels eroded into the upper surface of the Mississippian rocks.
UPPER MISSSSIPPIAN	Leitchfield Formation (*Ml*) Clore Limestone (*Mcl*) Palestine Sandstone (*Mpt*) Menard Limestone (*Mme*) Waltersburg Sandstone (*Mwl*)	***Ml*** contains clayey to silty, soft, thin-bedded shale interlayered with limestone, laminated siltstone, and fine- to medium-grained, massive sandstone. Shale appears green, gray, and red in outcrop and weathers to brown. ***Mcl*** consists of fine- to medium-grained limestone; clayey, calcareous, thinly parted shale; and thin-bedded, rippled sandstone. ***Mcl*** appears medium- to dark-gray in weathered outcrops. ***Mpt*** includes fine-grained, argillaceous sandstone; laminated siltstone; and clay-rich shale. ***Mpt*** appears yellowish-gray in fresh exposures and reddish-brown in weathered outcrops. ***Mme*** contains fine- to medium-grained, thin- to medium-bedded limestone and shale. Mme appears yellowish-gray in fresh exposures and weathers to orangish-gray. ***Mwl*** contains yellowish-gray, carbonaceous, clayey, locally marly, poorly exposed shale; very fine- to fine-grained, argillaceous, laminated sandstone; and thin beds of fine-grained limestone. ***Ml*** is mapped within the park.	Moderate	When water-saturated, clays within ***Ml*** become plastic and could be unstable as a foundation base.	Slabby- to blocky-weathering sandstone in ***Mpt*** may pose a rockfall hazard if undercut. ***Mme*** commonly forms ledges that may be prone to blockfall. ***Mwl*** weathers into rhombic-shaped blocks that may be prone to blockfall when exposed on a slope.	Some bedded and angular chert in ***Ml***, ***Mwl***, and ***Mme*** may have provided tool material.	***Ml*** has fossiliferous limestone with crinoids. ***Mcl*** has fossiliferous layers in upper portions of the limestone beds with numerous brachiopods. ***Mme*** contains oolites, bryozoans, gastropods, and crinoid, brachiopod, and blastoid fragments.	***Ml*** has a conspicuous limestone layer (Vienna Limestone) that could be prone to dissolution. Discontinuous, relatively thin limestones could be prone to local dissolution.	Shale, sandstone, siltstone, limestone.	***Ml*** forms subdued topography and weathers to a clay-rich soil.	***Mme*** contains the ***Mmels*** limestone marker bed. Units form the uppermost (youngest) Mississippian geologic record beneath a regional unconformity.
UPPER MISSSSIPPIAN	Vienna Limestone (*Mv*) Tar Springs Sandstone (*Mts*) Glen Dean Limestone (*Mgd*) Hardinsburg Sandstone (*Mh*)	***Mv*** contains finely crystalline to coarse-grained, dense, locally argillaceous or dolomitic, laminated to thick-bedded limestone. Unit appears dark-brownish-gray in fresh exposures and weathers to a lighter olive-gray. ***Mts*** contains interbedded silty, calcareous shale; very fine- to fine-grained, crossbedded, iron-stained sandstone; laminated and nodular siltstone; and fine- to medium-grained, argillaceous, thin-bedded, locally coarsely crystalline limestone. ***Mgd*** contains finely to coarsely crystalline, locally argillaceous, thin-bedded to massive limestone; and clayey to silty, calcareous, greenish-gray, laminated shale. ***Mh*** consists of medium-grained, crossbedded, iron-stained sandstone; and silty, fissile shale. ***Mgd*** and ***Mh*** are mapped within the park.	Moderately high, lower for weakly cemented layers in ***Mh***	***Mts*** is characterized by rapid lithological changes that render its physical properties spatially variable. Dissolution of underlying units has made weathered ***Mh*** exposures locally unstable, contorted, and slabby.	***Mv*** commonly forms narrow ledges that may slough off, causing blockfall along streams. Heterogeneous layering in ***Mts*** could render the unit unstable on steep slopes. Upper beds of ***Mgd*** commonly weather to rubble and may be prone to slope processes.	Abundant chert in ***Mv*** and ***Mgd*** may have provided tool material. Limestone was locally quarried from ***Mgd***.	Units contain brachiopods, crinoid stems, horn corals, blastoids, and bryozoans, including *Archimedes*. Abundant casts in ***Mgd***.	***Mv*** dissolves into vuggy or highly porous outcrops. Massive limestone beds in ***Mgd*** could be prone to karst processes.	Limestone, chert, sandstone, shale, siltstone, limonite pebbles.	Vugs in ***Mv*** may provide burrow habitat. ***Mh*** may weather to form clayey, sand-rich soils in upland areas.	Chert layers (with angular fragments) in ***Mv*** form distinctive marker beds. ***Mts*** and ***Mv*** interfinger with ***Ml*** and are sometimes considered equivalent to or members of ***Ml***. The base of ***Mh*** has been lowered approximately 6 m (20 ft) due to the dissolution of underlying limestone units.

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Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Paleontological Resources	Karst	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
UPPER MISSSSIPPIAN	Golconda Formation: Haney Limestone Member (*Mgh*) Big Clifty Sandstone Member (*Mgb*) Beech Creek Limestone Member (*Mgc*)	***Mgh*** comprises fine- to coarse-grained, crystalline, massive, fossiliferous, and partly oolitic limestone; and calcareous, laminated shale. ***Mgb*** consists of fine- to medium-grained sandstone, scattered lenses of dark-gray siltstone, and fissile shale. ***Mgc*** contains finely crystalline to fossil fragmental, hard, medium- to thick-bedded limestone; and calcareous, thin-bedded shale ***Mgh*** and ***Mgb*** are mapped within the park.	Moderate to moderately high for dense limestone cliff-forming units	***Mgh*** is highly soluble and not suitable for most development. Heavy development on ***Mgb*** should be avoided where it forms steep ledges and cliffs or is highly fractured. ***Mgc*** is highly vertically jointed and is unsuitable for wastewater treatment facilities.	***Mgh*** is associated with active dissolution and karst processes. It can form cliff exposures and contains slumped blocks of ***Mh***; it could be prone to further slope processes. ***Mgb*** is prone to blockfall along cliff exposures. ***Mgb*** readily forms abundant talus slopes.	Dense gray chert in ***Mgh*** may have provided tool material. Local coal lenses within ***Mgb*** were mined for private use. Overhanging cliffs of ***Mgb*** may have provided temporary shelters for American Indians. ***Mgb*** contains asphalt resources.	Crinoid stems, blastoids, bryozoans, carbonized plant fragments, pelecypod casts, horn corals, the fenestrate bryozoans *Archimedes*, gastropods, brachiopod *Inflatia inflata*.	***Mgh*** is very soluble and prone to solution-cavity formation. ***Mgc*** is also prone to karst dissolution, especially along vertical fractures.	Limestone, sparry calcite, ***Mgb*** contains asphaltic sandstone.	Numerous karst springs form at base of ***Mgh***. ***Mgh*** weathers to reddish-brown, clayey soil with abundant residuum. Springs are common atop shale layers within ***Mgb***.	The *Inflatia inflata*-rich layer in ***Mgc*** is an excellent stratigraphic marker in the Mississippian units. Golconda Formation may be included in the upper part of ***Mg***.
	Girkin Limestone (*Mg*) Reelsville Limestone (*Mr*) Sample Sandstone (*Msa*) Beaver Bend, Mooretown Formation, and Paoli Limestone (*Mbp*)	***Mg*** contains fine- to coarse-grained, crystalline, medium- to thick-bedded, locally crossbedded limestone. Some shale and sandstone interbeds are present locally and often separate the limestone into an upper fossiliferous and lower oolitic layers. Limestone ranges in color from medium-light-gray, brownish-gray, to mottled gray and white and weathers to orangish- or yellowish-brown. Shale is typically greenish. ***Mr*** contains finely crystalline to fine-grained fossil fragmental, dense, thin- to medium-bedded, oolitic limestone; and shale. ***Msa*** contains fine-grained, rippled, quartz-rich sandstone interbedded with silty, laminated shale. ***Mbp*** consists of fine- to medium-grained, well-sorted, thick-bedded, weathered sandstone; and very fine- to medium-grained, thin- to thick-bedded, oolitic, locally argillaceous limestone. ***Mg*** is mapped within the park.	Moderately high for resistant, hard limestones, moderately low for poorly cemented, weathered sandstone	Due to highly soluble nature and degree of limestone dissolution within these units, development requires detailed knowledge of subsurface structures. Deeply weathered ***Mbp*** may be unsuitable for structural foundations.	***Mg*** is associated with karst-related hazards, such as sinkhole collapse and cave-ins. Upper portion of ***Mr*** forms prominent ledges where exposed and may pose blockfall hazards. Clay-rich layers in ***Msa*** may become local slip surfaces. ***Mbp*** forms thin ledges on steep slopes and is prone to slumping.	Limestone was quarried from ***Mg*** and ***Mbp*** for local road material. ***Mg*** hosts caves that have been used throughout the region's history, including portions of Mammoth Cave. Chert may have provided tool material. ***Mg*** contains asphalt resources.	Stems of *Platycrinites* crinoid are an index fossil in ***Mg***; brachiopods including *Inflatia inflata*, *Talarocrinus* sp. calyxes, echinoids, coral colonies, blastoid *Pentrimites*.	***Mg*** is considered karstic, forming deep sinks, caves, and vertical shafts. The upper reaches of Mammoth Cave are within ***Mg***.	Limestone, calcite-lined vugs, geodes, quartz rosettes, fluorite, asphalt-bearing stylolites in ***Mg***, colored chert, pyritic inclusions, sandstone.	Caves and other solutional cavities provide habitat for bats and burrowing animals.	***Mg*** hosts numerous caves throughout the area. ***Mg*** has several types of limestone, including calcarenite, calculite, oolitic, and argillaceous. ***Mg*** is sometimes divided into Upper, Middle, and Lower members (***Mgu***, ***Mgm***, and ***Mgl***). ***Mbp*** rests on deeply weathered residuum of ***Msl*** and occupies a well-defined channel cut into rocks overlying ***Msl***.
	Ste. Genevieve Limestone (*Msg*) Lost River Chert (*Mls*)	***Msg*** comprises very fine- to medium-grained, thick-bedded, crossbedded limestone; and very fine-grained, massive, calcareous dolomite. Different compositions of limestone and dolomite are interlayered. ***Msg*** appears gray, tan, and buff in fresh exposures, with more brownish weathering on smooth, rounded surfaces. ***Mlr*** contains very fine-grained, resistant, chert-rich limestone. Chert weathers from yellowish-gray, to angular, reddish-gray. Chert blocks average around 30 cm (12 in) thick. ***Msg*** is mapped within the park.	Moderately high	Soluble, cave-forming nature of ***Msg*** makes it an unsuitable target for most development. ***Mlr*** forms resistant ledges that may fail when undercut by dissolving underlying limestone units.	Units are associated with active karst processes. Presence of slumped sandstone within sinkholes attests to slope processes.	***Msg*** is a primary cave-forming unit. It was quarried locally for road material, aggregate, and agricultural lime. Chert may have provided tool material. Caves have been used throughout the region's history.	Echinoids, crinoids (*Platycrinites*), blastoids, solitary corals, brachiopods, bryozoans, straw-like coral *Lithostrotion (Siphonoden-dron) genevievensis*, coral *Schoenophyllum aggregatum*, fenestrate bryozoans.	***Msg*** is very karstic with numerous caves, including the middle sections of Mammoth Cave, and sinkholes. Unit forms large, complex sinkholes called "uvalas" and sinkhole plains.	Calcite-filled vugs, limestone, dolomite, chert blocks, geodes.	Cave habitats, vugs for burrowing animals. ***Msg*** weathers to produce reddish-brown, clay-rich residuum.	***Msg*** contains the Lost River Chert (of Elrod [1899]) and numerous types of limestone, including oolitic, brecciated, calcarenite, calcilutite. ***Mlr*** occurs at the contact between ***Msg*** and ***Msl*** and appears as a resistant ledge between the two.

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Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Paleontological Resources	Karst	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
UPPER MISSISSIPPIAN	St. Louis Limestone (*Msl*) Salem and Warsaw limestones (*Msw*) Salem Limestone (*Ms*) Harrodsburg Limestone (*Mhb*)	***Msl*** contains interbedded fine- to medium-grained, silty, locally carbonaceous, siliceous, thin- to thick-bedded limestone; argillaceous dolomite; sandstone; siltstone; and greenish-gray shale. ***Msl*** appears mostly gray to dark-gray on fresh and weathered surfaces. Chert in ***Msl*** occurs in beds, stringers, and nodules and weathers to white, cream, and reddish-brown. ***Msw*** consists of fine- to coarse-grained, thin-bedded to massive limestone; argillaceous dolomite; and argillaceous, calcareous, dolomitic siltstone. ***Ms*** contains coarse- and fine-grained limestone. The former is light-olive-gray with local crossbeds and abundant fossils, whereas the latter is yellowish-gray, silty, and clay-rich with interlayered silty, fissile shale. Other components in ***Ms*** include very fine-grained, thick-bedded dolomite and dolomitic siltstone. ***Mhb*** contains coarse- to very coarse-grained, thin- to thick-bedded, crossbedded, styloltic limestone with some silty, dolomitic interbeds present locally. Unit can appear homogenous in outcrop as massive, light- to yellowish-gray beds. ***Msl, Mhb,*** and ***Ms*** are mapped within the park.	Moderately high	Locally, ***Msl*** is exposed primarily in steep-walled sinkholes and should be avoided for infrastructure. Excavations into this unit may encounter large cavities.	***Msl*** forms steep-walled sinkholes and is subject to collapse and slumping.	***Msl*** is mostly exposed in steep-walled sinks, but forms caves. ***Msl*** has been quarried. Chert may have been used for tool material.	***Msl*** contains nodules with diagnostic fossils of corals *Lithostrotion proliferum* and *Lithostrotionella castelnaui*, brachiopod fragments, colonial coral *Arcocyathus*, blastoids, horn coral *Hapsiphyllum* in ***Msw***, brachiopod *Spirifer lateralis*, ***Ms*** contains trilobites, echinoid plates.	Msl is karstic and hosts caves, sinkholes, and forms karst landforms. Lower portions of Mammoth Cave are within this ***Msl***. ***Mhb*** contains sinkholes.	Calcite-filled vugs, limestone, dolomite, sandstone, shale, chert, oolite, geodes, gypsum, glauconite.	Vugs may provide burrow habitat. Much of ***Msl*** is weathered and covered with thick, residual soil. Springs are common at the base of ***Mhb***.	***Msl*** contains several different types of limestone with a gradational lower contact. ***Msw*** has limestone with various secondary components, including silt, sand, and oolites. ***Msw*** interfingers with underlying ***Mfp*** locally. Lower contact of ***Mhb*** is sharp, except where it overlays bioclastic limestone of ***Mbm***.
LOWER MISSISSIPPIAN	Fort Payne Formation (*Mfp*) Reef limestone of Fort Payne Formation (*Mfprl*)	***Mfp*** consists of light-gray or brown interbedded argillaceous, dolomitic, fine-grained, thin- to medium-bedded siltstone; argillaceous, dolomitic, fine- to very coarse-grained limestone; dolomitic fissile shale; claystone; chert; and argillaceous, silty, laminated dolomite. Thickness of formation ranges from 100 to 107 m (328 to 351 ft). ***Mfprl*** contains medium- to very coarse-grained, detrital, siliceous, cherty, glauconitic, fossiliferous, medium- to thick-bedded, crossbedded limestone with shale interbeds. Thickness of this member can reach 90 m (295 ft) locally.	Moderate	Units are suitable for most infrastructure unless highly weathered, dissolved, or fractured. Units may be prone to blockfall if exposed on steep slopes.	Claystone at the base of ***Mfp*** crumbles and disintegrates (“slakes”) on contact with air and can be plastic when water–saturated; it is thus locally unstable.	Chert in ***Mfp*** may have provided tool material. Lower members of ***Mfp*** (reef limestone, unit ***Mfprl***) are known to produce oil.	Brachiopods, blastoids, bryozoans, echinoderms, crinoid stem fragments, trilobites. ***Mfprl*** contains crinoids, brachiopods, bryozoans, and fossil reefs.	Limestone units are prone to karst dissolution.	Disseminated geodes filled with quartz, calcite, barite, and gypsum; pyrite; limestone; sandstone; glauconite; phosphatic nodules.	Units weather to produce red residual soils.	***Mfp*** is a widespread unit recording conditions during the Mississippian. ***Mfprl*** is an oil-producing unit and contains the Cane Valley Member.
	<u>Borden Formation</u>: (*Mb*) Muldraugh Member (*Mbm*) Crinoidal limestone (*Mbls*)	***Mb*** consists of clayey, silty, irregularly bedded shale; thick-bedded, massive, brownish-gray, quartzose siltstone; and silty, thin- to thick-bedded, light-olive-gray dolomitic limestone. ***Mbm*** contains dolomitic, calcareous, yellowish-gray, micaceous siltstone interlayered with very fine-grained, calcareous, silty, and argillaceous dolomite; fine- to very fine-grained, crossbedded sandstone; and dolomitic, siliceous, sandy, silty, thin-bedded limestone. ***Mbls*** contains fine- to coarse-grained, fossiliferous limestone in thin- to thick-bedded, crossbedded lenses interlayered with siltstone. ***Mbm*** is mapped within the park.	Moderate	***Mb*** tends to form steep slopes (Muldraugh Escarpment) and steeply plunging gullies. Given the propensity for landslides, this unit should probably be avoided for most infrastructure.	Shale in ***Mb*** becomes plastic when wet and is very prone to landslides.	Chert nodules and lenses in ***Mbm*** may have provided tool material.	Crinoid columnals, fossiliferous limestone, bryozoans and brachiopod fragments.	Thick-bedded layers of limestone may be susceptible to dissolution.	Limestone, ironstone concretions, phosphatic nodules, quartz-lined geodes, glauconite, pyrite nodules, chert.	Units form steep slopes and gullies.	***Mb*** contains seven members in ascending order: New Providence Shale, Nancy, Cowbell, Halls Gap, Wildie, Nada, and Muldraugh members. ***Mbls*** resembles reef-like deposits in south-central Kentucky.
UPPER-MIDDLE DEVONIAN	Chattanooga Shale (*Dc*)	***Dc*** contains fissile, carbonaceous, silty, thinly laminated, dark, brownish-black, bituminous shale. Quartzose, fine- to coarse-grained, poorly sorted sandstone occurs in lower portions of the unit.	Moderately low	***Dc*** contains uranium in places and may pose a radon hazard for basements.	Shale is fissile to slabby and can be unstable when exposed on slopes. ***Dc*** is the primary source of the radon gas that accumulates in the caves.	Devonian units tapped for “Corniferous” or lowermost Devonian-age oil shows.	Brachiopods, fish scales, worm tracks, fish teeth, conodonts.	No karst dissolution associated with this unit.	Shale, sandstone, marcasite nodules, cubic pyrite, phosphatic concretions, sulfur, iron oxide.	Weathers to a thick reddish-yellow soil.	***Dc*** is a widespread unit recording marine conditions during the Devonian.

Gray-shaded rows indicate geologic units that are not mapped within Mammoth Cave National Park, but are included in the digital geologic data for the park. Colors based on U.S. Geological Survey standard colors.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Paleontological Resources	Karst	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
MIDDLE-LOWER DEVONIAN	Sellersburg and Jeffersonville limestones (***Dsj***)	***Dsj*** consists of fine- to coarse-grained, partially recrystallized, thick-bedded limestone; and silty, argillaceous, medium- to dark-gray dolomite.	Moderate	Unit is locally limited in exposure.	Unit could be prone to karst dissolution.	None documented	Crinoid stems, horn (rugose) corals (*Hapsiphyllum, Eridophyllum)*, colonial corals (*Favosites*).	Karst dissolution is possible in these carbonate-rich units	Limestone, prismatic dolomite crystals, marcasite laminae and nodules.	None documented	***Dsj*** rests unconformably on the Laurel Dolomite (***Slwl***).
MIDDLE SILURIAN	Louisville Limestone, Waldron Shale, and Laurel Dolomite (***Slwl***)	***Slwl*** contains three units in ascending order: Laurel Dolomite, Waldron Shale, and Louisville Limestone. The Laurel Dolomite and Louisville Limestone are lithologically similar, composed of fine- to medium-grained, greenish- to yellowish-gray, thick-bedded, mottled dolomite. Dolomite units are separated by the Waldron Shale, a medium- to thick-bedded, blocky, silty, fissile, dolomitic shale.	Moderate to moderately high for Waldron Shale	Avoid development on heavily fractured and weathered exposures.	Units may be prone to blockfall, especially where shale ledges are exposed over dissolved limestone.	Laurel dolomite has a “blue sand” horizon known to produce oil in local wells.	Crinoids, brachiopod valves (*Pentamerus oblongus*).	Dolomite and limestone prone to dissolution, primarily small-scale.	Dolomite, limestone, calcite crystals, pyrite, nodular aggregates of dolomite crystals.	Waldron Shale forms ledges that could provide nesting and den habitat. Dolomite is vuggy and could provide cache locations or burrows.	Units are gradational and record relatively continuous deposition.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

allochthonous. Describes rocks or materials formed elsewhere and subsequently transported to their present location. Accreted terranes are one example.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."

anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.

anticlinorium. A large, regional feature with an overall shape of an anticline. Composed of many smaller folds.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

authochthonous. Formed or produced in the place where now found. Similar to "authigenic," which refers to constituents rather than whole formations.

axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

bioturbation. The reworking of sediment by organisms.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

concretion. A hard, compact aggregate of mineral matter, subspherical to irregular in shape; formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock. Concretions are generally different in composition from the rocks in which they occur.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

convergent boundary. A plate boundary where two tectonic plates are colliding.

core. The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules. Diatoms live in freshwater or marine environment.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

disconformity. An unconformity where the bedding of the strata above and below are parallel.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or a reduction in pressure when overlying rocks erode away.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fan delta. An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

fanglomerate. A sedimentary rock of heterogeneous materials that were originally deposited in an alluvial fan and have since been cemented into solid rock.

fault. A break in rock along which relative movement has occurred between the two sides.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

groundwater basin. An area of bedrock in a karst spring that collects drainage from all the sinkholes and sinking streams in its drainage area.

hanging wall. The mass of rock above a fault surface (also see "footwall").

helictites. Delicate speleothems that grow in all directions.

hinge line. A line or boundary between a stable region and one undergoing upward or downward movement.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

hydraulic conductivity. Measure of permeability coefficient.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

kkarst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

karst valley. A closed depression formed by the coalescence of several sinkholes.

karst window. A collapse sinkhole opening into a cave.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lag gravel. An accumulation of coarse material remaining on a surface after the finer material has been blown away by winds.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lignite. A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

limb. Either side of a structural fold.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

lithostratigraphy. The element of stratigraphy that deals with the lithology of strata, their organization into units based on lithologic characteristics, and their correlation.

loess. Windblown silt-sized sediment, generally of glacial origin.

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

mantle. The zone of Earth's interior between the crust and core.

marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

monocline. A one-limbed fold in strata that is otherwise flat-lying.

moraine. A mound, ridge, or other distinct accumulation of

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

nonconformity. An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

obduction. The process by which the crust is thickened by thrust faulting at a convergent margin.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.

orogeny. A mountain-building event.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

overbank deposit. Alluvium deposited outside a stream channel during flooding.

overburden. Rock and sediment, not of economic value, and often unconsolidated, that overlies an ore, fuel, or sedimentary deposit.

oxbow. A closely looping stream meander resembling the U-shaped frame embracing an ox's neck; having an extreme curvature such that only a neck of land is left between two parts of the stream.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleosol. A ancient soil layer preserved in the geologic record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parent material. The unconsolidated organic and mineral material in which soil forms.

parent rock. Rock from which soil, sediments, or other rocks are derived.

partings. A plane or surface along which a rock readily separates.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

pendant. A solutional remnant hanging from the ceiling or wall of a cave.

peneplain. A geomorphic term for a broad area of low topographic relief resulting from long-term, extensive erosion.

phreatic zone. The zone of saturation. Phreatic water is groundwater.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

pluvial. Describes geologic processes or features resulting from rain.

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area due to sedimentary deposition.

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

pseudomorph. A mineral whose outward crystal form takes after that of another mineral; described as being "after" the mineral whose outward form it has (e.g., quartz after fluorite).

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

recharge. Infiltration processes that replenish groundwater.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

sapping. The undercutting of a cliff by erosion of softer underlying rock layers.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

sheet flow. An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

sinkhole. A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.

skarn. Calcium-bearing silicates derived from nearly pure limestone and dolomite with the introduction of large amounts of silica, aluminum, iron, and magnesium.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stalactites. Calcite deposits that form as water drips from the roof of a cave.

stalagmites. Mounds of calcite that commonly form beneath stalactites from dripping water in a cave.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream piracy. The process by which active headward stream erosion breaches a drainage divide and intercepts part of an adjacent drainage basin.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

suture. The linear zone where two continental landmasses become joined via obduction.

swallow holes. Points along streams and in sinkholes where surface flow is lost to underground conduits.

syncline. A downward curving (concave-up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

synclinorium. A composite synclinal structure of regional extent composed of lesser folds.

system (stratigraphy). The group of rocks formed during a period of geologic time.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

tongue (stratigraphy). A member of a formation that extends and wedges out away from the main body of a formation.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

travertine. A limestone deposit or crust, often banded, formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves.

trend. The direction or azimuth of elongation of a linear geologic feature.

tufa. A chemical sedimentary rock composed of calcium carbonate, formed by evaporation as an incrustation around the mouth of a spring, along a stream, or exceptionally as a thick, concretionary deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. A hard, dense variety of travertine.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vadose water. Water of the unsaturated zone or zone of aeration.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of September 2011.

Geology of National Park Service Areas

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado.
http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey and Society Websites

Kentucky Geological Survey: http://www.uky.edu/KGS/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”).

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.er.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Mammoth Cave National Park, held on June 15 and 16, 2006. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Name	Affiliation	Position	Phone	E-mail
Addison, Aaron	Cave Research Foundation	Academic GIS	314-369-6562	aadison@wustl.edu
Chappell, Jim	Colorado State University	Geologist GIS	970-491-5147	jrchapp@lamar.colostate.edu
Connors, Tim	NPS – GRD	Geologist	303-969-2093	Tim_Connors@nps.gov
Crawford, Matt	Kentucky Geological Survey	Geologist	859-257-5500 ext. 140	mcrawford@uky.edu
Edwards, Amy	NPS – MACA	Geologist – intern		Amy_Edwards@wicu.edu
Finn, Meg	Grayson County Middle School	Teacher	270-286-9910	Meg_Finn@grayson.kyschools.us
Heise, Bruce	NPS – GRD	Geologist	303-969-2017	Bruce_Heise@nps.gov
Kerbo, Ron	NPS – GRD	Cave Specialist	303-969-2097	Ron_Kerbo@nps.gov
Liebfried, Teresa	NPS – Cumberland Piedmont Networkr	Coordinator	270-758-2135	Teresa_Liebfried@nps.gov
Meiman, Joe	NPS – GULN & CUPD Networks	Hydrologist	270-758-2137	Joe_Meiman@nps.gov
Merideth, Johny	NPS – MACA	Interpreter	270-758-2434	Johny_Merideth@nps.gov
Olson, Rick	NPS – MACA	Ecologist	270-758-2138	Rick_Olson@nps.gov
Osborn, Bob	Cave Research Foundation	Academic Geologist	314-984-8453	osburn@levee.wust1.edu
Palmer, Art	State University of New York – Cave Research Foundation	Academic Hydrologist	607-432-6024	palmeran@oneonta.edu
Palmer, Peggy	State University of New York – Cave Research Foundation	Academic Hydrologist		
Scoggins, Lillian	NPS – MACA	GIS Specialist	270-758-2149	Lillian_Scoggins@nps.gov
Thornberry-Ehrlich, Trista	Colorado State University	Geologist Report Writer	757-416-5928	tthorn@cnr.colostate.edu
Toomey, Rick	NPS – MACA/Western RLC Kentucky University	Director	270-758-2145	Rick_Toomey@contractor.nps.gov

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