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The Mammoth Cave system, Kentucky, USA

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ABSTRACT

Mammoth Cave is the main attraction of Mammoth Cave National Park. For several decades it has been the longest known cave in the world and currently contains 652 km in 2016 of surveyed passages. It is located in the heart of an extensive karst plateau, in which the stratal dip averages only one degree. The cave is part of a drainage basin of more than 200 km^2. The cave has been known to local inhabitants for several millennia and contains a rich trove of archaeological and historical artifacts. It contains many speleo biota including several rare and endangered species and has been designated a World Heritage Site and an International Biosphere Reserve (UNESCO). Its many passage levels and sediments contain a record of the fluvial history of most of south-eastern North America.

Key words: cave, International Biosphere Reserve, Mammoth Cave National Park, World Heritage Site, Kentucky

El sistema de la Mammoth Cave, Kentucky, EE.UU.

RESUMEN

La Mammoth Cave es la principal atracción del Mammoth Cave National Park. Durante varias décadas ha sido la cueva más larga conocida en el mundo y actualmente tiene 652 km de pasajes topografiados. Está localizada en el corazón de una amplia meseta kárstica, en la cual el promedio del buzamiento de los estratos es de sólo un grado. La cueva es parte de una cuenca de drenaje de más de 200 km^2. La cueva ha sido conocida por los habitantes locales desde hace varios milenios y contiene un rico tesoro de artefactos arqueológicos e históricos. Asimismo contiene una rica biota cavernícola incluyendo varias especies raras y en peligro de extinción y ha sido declarada Patrimonio de la Humanidad y Reserva Internacional de la Biosfera (UNESCO). Sus múltiples niveles de pasajes y sedimentos contienen un registro de la historia fluvial de la mayor parte del sureste de América del Norte.

Palabras clave: cueva, Reserva Internacional de la Biosfera, Parque Nacional de Mammoth Cave, Patrimonio Mundial, Kentucky.

VERSIÓN ABREVIADA EN CASTELLANO

Marco geológico

La cueva ocupa una secuencia de 150 m de espesor de calizas del Mississippiense (Carbonífero inferior) sobre la que se dispone una capa relativamente resistente de estratos mayormente insolubles. Estas rocas forman una meseta irregular baja (Chester Upland) que sobresale aproximadamente a 60 metros por encima de una llanura caliza de bajo relieve (Pennyroyal Plateau), de los cuales la roca barrera más reciente ha sido removida por la erosión. El Pennyroyal es una amplia superficie kárstica en la que se han desarrollado muchas dolinas y corrientes que desaparecen hundiéndose, muchas de las cuales son la alimentación de los niveles más bajos de Mammoth Cave. Una recarga considerable también penetra en la cueva a lo largo de los bordes erosionados de la roca barrera y los valles kársticos locales en la meseta. Todo el drenaje a través de la cueva emerge al norte en manantiales a lo largo del muy encajado Green River. El río ha servido como el nivel de base para la espeleogénesis a lo largo de la historia de la cueva.

Historia geológica

La mayoría de los pasajes de Mammoth Cave son cañones vadosos sinuosos orientados con el buzamiento y conductos tubulares que se formaron en el límite o justo por debajo del nivel freático. La correlación entre la cueva y el paisaje circundante, combinado con el análisis de los radionucleos cosmogénicos en sedimentos de cuarzo en la cueva, ha proporcionado una historia detallada de los cambios del nivel de base y la evolución de los de ríos que abarca más de 4 millones de años. Las primeras etapas del origen de la cueva, que involucraron un lento encajamiento de unas pocas pero grandes corrientes que se hundían, produjeron largas y espaciosas galerías de hasta 30 m de ancho y 25 m de altura. Su desarrollo fue interrumpido por subidas periódicas en el nivel del Green River que causó que estos se rellenasen a diferentes cotas con depósitos estratificados procedentes del arroyo, que casi alcanzó los techos de muchos de los primeros conductos. La mayoría de los sedimentos fueron depositados por corrientes de agua en la cueva. La datación del sedimento muestra que los eventos de relleno más importantes ocurrieron hace unos 2.6 millones de años. En aquel momento el Pennyroyal era una llanura casi plana con pocas características kársticas y drenaje principalmente en superficie. Desde entonces, las bajadas periódicas del nivel de base del río han formado varios niveles de conductos a intervalos verticales de unos 15 m, con escaso relleno de sedimentos. Debido al rápido encajamiento, la Pennyroyal Plateau resulto diseccionada y la mayor parte de su drenaje paso a ser subterráneo. Más tarde, en el Pleistoceno el valle del Green River adquirió unos 15 m de relleno , lo que inundó los conductos inferiores de la cueva. La historia de los cambios de nivel de base parece correlacionarse con cambios en el patrón de drenaje en el sudeste de América del Norte. Como el drenaje del Río Ohio fue desviado progresivamente hacia el oeste y hacia el sur por el avance de los glaciares continentales, el nivel de base del Green River (un afluente del Ohio) sufrió varias caídas abruptas. Estas bajadas del nivel se registraron en la cueva por el abandono de pasajes freáticos tubulares, en los cuales el agua fue desviada a pasajes vadosos con un alto gradiente. Las dataciones cuantitativas de los niveles de sedimento en la cueva ofrecen una rara oportunidad para determinar la historia del desarrollo de los eventos y rasgos geomorfológicos en la superficie del terreno circundante.

Historia humana

La cueva fue primero conocida por nativos hace más de 4000 años. Estos utilizaron las entradas principales de la cueva y exploraron muchos kilómetros de pasajes con sólo la luz de las antorchas. También extrajeron yeso y otros minerales evaporíticos de la cueva y dejaron miles de artefactos tales como huellas, restos de antorcha, herramientas, ropa y varias momias. La cueva fue muy conocida por los pioneros locales a finales de 1700, y durante la guerra de 1812 suministró gran parte del nitrato que se necesitaba para fabricar pólvora. Muy pronto el turismo se convirtió en la principal fuente de ingresos. Varios guías, principalmente esclavos negros, proporcionaron extensas giras que atrajeron a visitantes de todo el mundo. Los propietarios privados continuaron ofreciendo recorridos hasta que la cueva y sus alrededores fueron declarados Parque Nacional. La inauguración oficial del Parque Nacional de Mammoth Cave fue en 1941. La exploración por parte de los guías continuó hasta ese momento. Aunque se habían realizado varios mapas, ninguno mostraba la totalidad de los pasajes conocidos. En la década de 1950, la exploración y cartografía de las cuevas en el vecino Flint Ridge comenzó por la Cave Research Fundation. En 1969 fueron invitados a realizar un mapa de la Mammoth Cave, y en 1972 las dos cuevas estaban vinculadas por un pasaje que se extiende bajo el valle kárstico que separa las dos cuevas. Desde entonces se han efectuado conexiones con otras cuevas cercanas.

Prospecciones futuras

Aunque la Mammoth Cave presenta una longitud explorada de 645 kilómetros, que es más del doble que cualquier otra cueva conocida, algunas extensas cuevas submarinas de Quintana Roo, México, si se conectasen podrían superar pronto dicho tamaño. No obstante parecen probables las conexiones entre Mammoth Cave y otras cuevas cercanas. El sistema de Fisher Ridge (201 km) se encuentra a sólo unos cientos de metros más allá el pasaje más oriental del sistema de Mammoth Cave. Una conexión transversal que una ambas cuevas, aunque todavía no se ha encontrado, es probablemente inevitable. Al suroeste de Mammoth está la cueva de Whigpistle (56 km), pero es menos factible una conexión en esa dirección. En ninguno de estos sistemas de cuevas principales cercanos parece haberse llegado a su máximo potencial real.

Introduction

Mammoth Cave is the longest known cave in the world, with 652 km of mapped passages. It is located in west-central Kentucky, USA, in Lower Carboniferous limestones and dolomites that were deposited about 350-320 million years ago. Although the cavernous strata are only about 150 m thick, the Mammoth Cave drainage basin includes thousands of square kilometers and is part of the most extensive karst region of North America (Fig.1).

The Mammoth Cave System is a composite of several caves that were explored independently and later integrated by the discovery of connecting passages (Fig. 2). Water in the cave drains to springs along the entrenched Green River, and the cave and river share a close geomorphic relationship. Most of the system is located in Mammoth Cave National Park, and tours are offered year-round in parts of the cave. Visitors are introduced to the basics of cave origin, karst groundwater flow, exploration, and the cave's lengthy archeological and cultural history. The cave is an ideal place to study patterns of karst groundwater flow, and in recent years it has been shown to hold the key to the geomorphic evolution of the entire east-central region of North America. It is also a significant biological preserve, home to several rare and endangered species.

The karst region

Mammoth Cave consists of a complex tangle of interconnected galleries on many different levels, most of which underlie sandstone-capped ridges separated by narrow karst valleys. The largest passages

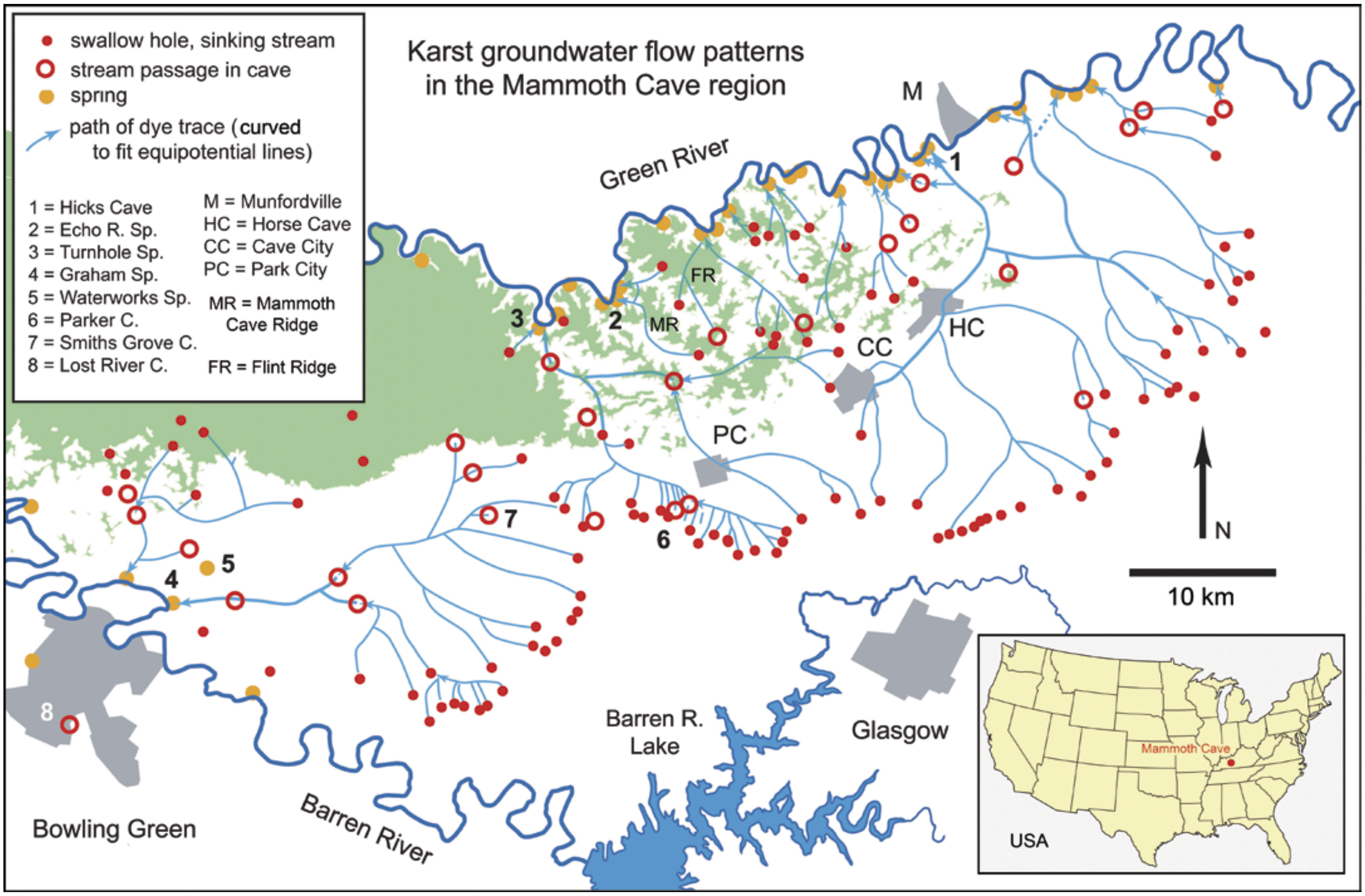

Figure 1: Map of the karst drainage basin of the Mammoth Cave System, simplified from Quinlan and Ray (1981). Sandstone-capped ridges of limestone are shown in green. The broad white area is the Pennyroyal Plateau, in which limestone is exposed directly at the surface.
Figura 1. *Mapa de la cuenca de drenaje kárstico del Sistema Mammoth Cave, simplificado de Quinlan and Ray (1981). Las areniscas que coronan las calizas se muestran en verde. La amplia zona blanca es la Pennyroyal Plateau, en el que las calizas se exponen directamente a la superficie.*

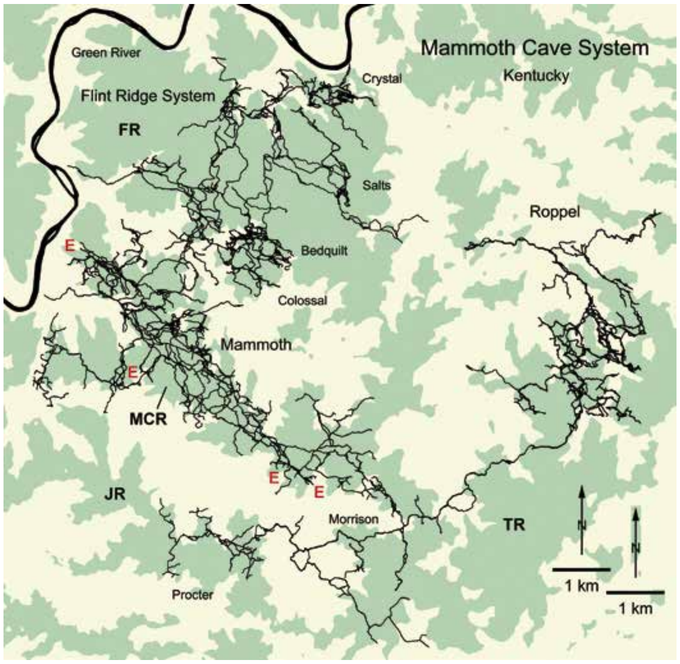

Figure 2: Generalized map of the Mammoth Cave System (major passages shown in black). Green = sandstone-capped ridges of limestone; yellow = exposed limestone. E = entrances to tour routes in the main part of Mammoth Cave. MCR = Mammoth Cave Ridge; FR = Flint Ridge; TR = Toohey Ridge; JR = Joppa Ridge. Based on surveys by the Cave Research Foundation and Central Kentucky Karst Coalition (for Roppel Cave).

Figura 2: *Mapa general del Sistema de la Mammoth Cave (grandes pasajes que aparecen en negro). Verde = areniscas que coronan las calizas; amarillo = afloramientos de caliza. E = entradas para recorrer rutas en la parte principal de la Mammoth Cave. MCR = Mammoth Cave Ridge; FR = Flint Ridge; TR = Toohey Ridge; JR = Joppa Ridge. Sobre la base de investigaciones realizadas por la Cave Research Foundation and Central Kentucky Karst Coalition (para Roppel Cave).*

Figure 3: Collins Avenue, in Crystal Cave, was the first passage to form in the known parts of the Mammoth Cave System. It is located in the Girkin Formation, the highest of the three major limestones exposed in the cave. Photos by A.N. Palmer, except where noted otherwise.

Figura 3: *Collins Avenue, en Crystal Cave, fue el primer pasaje en formarse en las partes más conocidas del Sistema de la Mammoth Cave. Se encuentra en la Formación Girkin, la más alta de las tres calizas principales expuestas en la cueva. Fotos por A.N. Palmer, excepto donde se indique lo contrario.*

have cross sections up to several hundred square meters, which provide easy travel (Fig. 3). Many caves throughout the world contain larger passages and rooms, but few can match the complexity of Mammoth Cave's pattern and developmental history.

The cave extends through three carbonate formations (Pohl, 1970). From bottom to top these are the St. Louis, Ste. Genevieve, and Girkin Formations (Fig. 4). The carbonate rocks are interbedded with thin shales, and chert is common in the lower part of the section. Overlying these strata are quartz sandstones that alternate with thin limestones and shales. The sandstones form a resistant cap overlying the cavernous rocks. The insoluble rocks thicken to the northwest, and karst features diminish abruptly in that direction. For a more complete description of the strata in Mammoth Cave, see Palmer (1981, 1989a, 2007).

The landscape consists of low plateaus only about 200–250 m above sea level, with a vertical relief of 150 m. The great expanse of karst is made possible by a low stratal dip of 1–2 degrees toward the northwest. The sandstone-capped plateau is named the Chester Upland. To the southeast, in the up-dip direction, the sandstone has been removed by erosion. The limestones are exposed about 100 m lower in a vast karst plain, the Pennyroyal Plateau, which contains thousands of dolines (sinkholes) and sinking streams (Figs. 4, 5). Throughout the development of

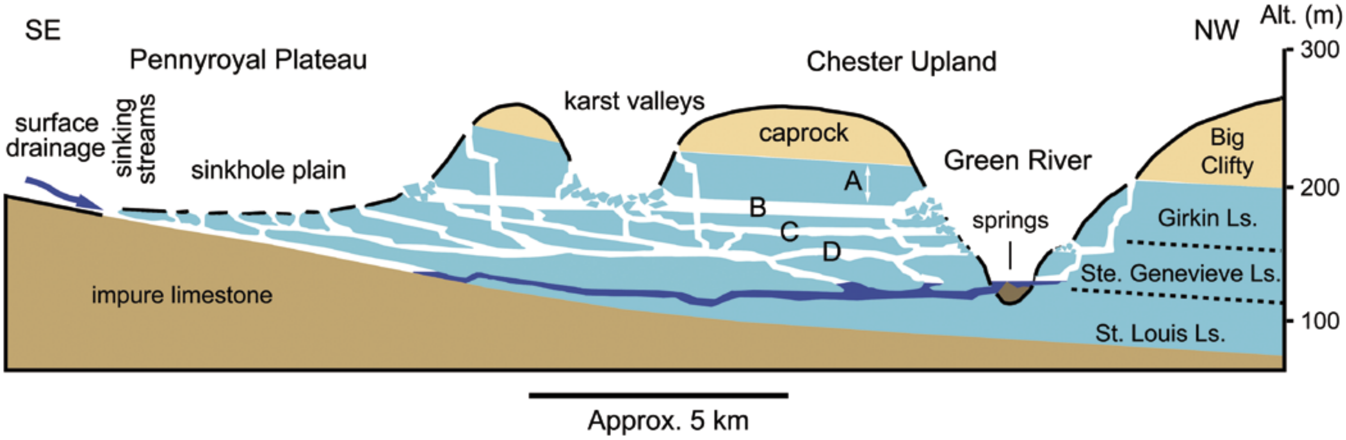

Figure 4: Geologic cross section through Mammoth Cave. The caprock is composed mainly of sandstone and shale. A–D = distinct cave levels: a; B = large upper-level canyons and tubes (late Miocene, Pliocene); C, D = tubular passage levels (Pleistocene). The lowest passages have been flooded by a late Pleistocene rise in base level. The profile shows continuity between drainage in the Pennyroyal Plateau and Chester Upland, but no explored connection has yet been made.

Figura 4: *Sección geológica a través de la Mammoth Cave. La roca caja está compuesta principalmente de piedra arenisca y pizarra. A-D = niveles diferenciados de la cueva. A, B = grandes cañones del nivel superior y tubos (finales del Mioceno, Plioceno); C, D = niveles de pasadizos tubulares (Pleistoceno). Los pasajes más bajos se han inundado por un aumento en el nivel de base durante el Pleistoceno tardío. El perfil muestra una continuidad entre el drenaje en la meseta Pennyroyal y Chester Upland, pero todavía sin conexión conocida.*

Mammoth Cave, the Pennyroyal has supplied a large portion of its water.

The cave is located along the southeastern edge of the Chester Upland, which is dissected by small stream valleys. The valleys intersect the main carbonate rocks and are floored with dolines, and drainage into them contributes to the cave development. The valley floors are about 50 m higher than the Green River, and caves can pass beneath them without interruption. The well-publicized 1972 connection between the caves of Flint Ridge and Mammoth Cave Ridge was achieved through wet crawlways beneath the intervening valley.

History

Mammoth Cave was known to paleo-Indians as much as 4000 years ago (Watson, 1974). They used the larger entrances for shelter and ventured far underground to mine gypsum and chert. With light from reed torches, and wearing only sandals, or sometimes even bare feet, they explored up to several kilometers from the nearest entrances in the Mammoth and Salts sections of the cave. Artifacts include baskets, footwear, torches, mining scars, ladders, and desiccated feces. Most intriguing are several mummies of people who died in the cave, mostly of natural causes, but include one who was flattened by a large block that fell while he was digging for minerals. These parts of the cave are fairly dry, with a nearly constant temperature of ~12 °C.

The latest phase of exploration began about 200 years ago (Brucker and Watson, 1976; Borden and Brucker, 2000). White settlers first noticed the cave in the late 18th century, and soon it was exploited for "saltpeter" (nitrates) – which helped to supply the young United States with gunpowder during the War of 1812 (Fig. 6). But within a few years the

Figure 5: Aerial view of the Pennyroyal Plateau. Beyond lies the wooded Chester Upland, in which Mammoth Cave is located. Photo by Gary Berdeaux.

Figura 5: *Vista aérea del Pennyroyal Plateau. Al fondo se observa la zona boscosa del Chester Upland, en la que se encuentra la Mammoth Cave. Foto por Gary Berdeaux.*

main attraction switched to tourism. Several African-American slaves were recruited to guide tourists through the cave. The concept of slavery, unthinkable today, is softened a little by the fact that these explorers were allowed unlimited access to the cave and were acclaimed by visitors as the true authorities on the subject. Of the guides, Stephen Bishop was the most famous for his entertaining tours and his daring as an explorer (Brucker, 2009). An early owner of the cave was a medical doctor who ran a short and unsuccessful experiment in spelotherapy for tuberculosis patients (Bullitt, 1845). The huts in which the patients lived are still standing.

In nearby Flint Ridge, Salts Cave had long been known, but near the turn of the 20th century several new and large caves were discovered nearby and opened for tours. New entrances to Mammoth Cave were also dug by neighboring landowners to provide access to remote parts of the cave. The fierce conflict to attract tourists became known as the "Kentucky cave wars."

In 1907, Max Kämper, a young German engineer on an American tour, stopped at Mammoth Cave and was so enchanted that he offered to provide an accurate survey. With the guidance of Ed Bishop (grand-nephew of Stephen), he produced an astonishingly detailed and accurate map that included about 70 km of passages. Max returned home the next year but died in World War I. His descendants, who were unaware of his achievement, were recently contacted by the Mammoth Cave staff and invited to make several cordial visits to the cave.

Figure 6: Remnants of saltpeter vats in Mammoth Cave, used in the early 19th century for leaching soluble nitrates from cave sediments for the manufacture of gunpowder.

Figura 6: *Los restos de cubas de salitre en la Mammoth Cave, utilizadas en el siglo XIX para la lixiviación de nitratos solubles de los sedimentos de la cueva, para la fabricación de la pólvora.*

The pioneering French speleologist E.A. Martel visited Mammoth Cave in 1912 and became convinced that the caves of Flint Ridge would one day connect to it. He predicted a length of at least 250 km. Enthusiasm grew for establishing a Mammoth Cave National Park. This became reality in 1941. Since then it has been designated a World Heritage Site (1981) and an International Biosphere Reserve (1990). The Park now includes 213 km^2, and most of the known cave. Adjacent parts of the Pennyroyal were well populated and could not be included, but a recently installed regional wastewater treatment system minimizes groundwater contamination.

The modern phase of exploration began at Crystal Cave, discovered and developed for tours by local lad Floyd Collins in 1917. In 1925, while digging in a nearby cave for a more accessible entrance, he was trapped and died before rescuers could free him. National coverage made "Floyd Collins' Crystal Cave" famous. In 1954, when the cave was still under private management, the National Speleological Society ran a week-long camp to explore and map it. Although little was accomplished by the expedition, later that year some of the most avid explorers made a huge breakthrough into the heart of Flint Ridge. In 1957 they established the Cave Research Foundation (CRF), to promote the exploration, mapping, and scientific study of caves in that region. When the Park acquired Crystal Cave, CRF obtained permission to explore and map beneath Flint Ridge, and eventually throughout the entire Park.

CRF cavers finally linked most of the known caves of Flint Ridge, and in 1972 they connected with Mammoth Cave to produce a single system with 252.5 km of mapped passages – almost exactly what Martel had predicted 60 years before. Further extensions and connections with other caves have more than doubled that length.

Character of Mammoth Cave

The simple geologic structure at Mammoth Cave has allowed its passages to be equally simple in form. Many are vadose canyons of various widths up to tens of meters wide, but mostly much narrower (Fig. 7). These tend to be interrupted by vertical shafts up to 60 m deep with round or elliptical cross sections (Fig. 8). Others are tubular passages with elliptical or lens-shaped cross sections enlarged along the strata (Fig. 9). Straight fissure-shaped passages are rare because major joints and faults are uncommon. The basic pattern of passages is dendritic, with sinuous curving passages that join each other like tributaries in surface rivers.

Figure 7: An active vadose canyon in the Ste. Genevieve Limestone.
Figura 7: *Un cañón vadoso activo en la caliza Ste. Genevieve.*

Figure 8: Edna's Dome is a typical vertical shaft in Mammoth Cave. It is located along the eroded edge of Mammoth Cave Ridge in the lower part of the Ste. Genevieve Limestone. Many feminine names were shown on the 1907-1908 Kämper map to honor his family and local friends.
Figura 8: *La cúpula Edna es un pozo vertical típico de la Mammoth Cave. Se encuentra a lo largo del borde erosionado del Mammoth Cave Ridge en la parte inferior de la caliza Ste. Genevieve. Muchos nombres femeninos se muestran en el mapa de Kämper , 1907-1908 para honrar a sus familiares y amigos locales.*

Most vadose passages (shafts, canyons, and small perched tubes) are fed by small surface streams that drain off the sandstone cap and sink underground where they encounter limestone. As canyons deepen, they encounter a variety of bedding-plane partings with slightly different dip patterns, so new passages at lower levels tend to deviate from the original paths. In this way, many canyons split in the downstream direction, and each may lead to different parts of the cave. In a similar way, shafts evolve by water dissolving downward through the beds from one level to another. As each new bedding plane is encountered, it can serve as a separate drain for the water. What may seem at first like a simple passage pattern can become very complex.

Most tubular passages are formed where descending water reaches the water table. They have very low gradients and maintain uniform cross sections over long distances (Fig. 9). They have sinuous profiles that wander up and down along geologic structures. Most have very subtle vertical sinuosity, detectable

Figure 9: Cleaveland Avenue is a broad tubular passage formed at the water table in the middle of the Ste. Genevieve Limestone. The prominent bedding plane that guides the passage varies less than half a meter in elevation along the 1.5 km passage length.
Figura 9: *Cleaveland Avenue es un amplio pasaje tubular formado en el nivel freático en el medio de la caliza Ste. Genevieve. El plano de estratificación prominente que guía el paso varía de menos de medio metro de altura a lo largo de los 1.5 kilómetros de longitud del pasaje.*

only by careful surveys, although some tubes descend as much as 25 m below the original water table along favorable fractures or partings. Most tubes are intersected by canyons or shafts, which give access to other passages at different levels. Small tubes can form above the water table, but as they enlarge they eventually deepen into canyons.

Many large passages in the cave can be traveled easily by walking. However, most are interrupted in places by towering piles of collapse blocks, which can provide connections between two or more levels. Nearly all large passages eventually terminate in breakdown, especially where they encounter the edge of a ridge. Inputs of vadose water tend to concentrate at these locations, and they typically produce shafts (Fig. 8). For cavers, such terminations serve the same function as stairwells in a building, making it possible to change to higher or lower levels. Although much climbing is involved, artificial aids are rarely needed because such places contain many small intersecting passages that allow scrambling up or down. Shaly beds provide recesses in the cave walls that can be used as footholds. Active and abandoned shaft drains wander in many directions and connect with other passages. Their small size makes them resistant to collapse, and they can easily sneak beneath valleys. All of the characteristics described here for Mammoth Cave are typical of most caves in the sandstone-capped plateaus of Carboniferous limestones in east-central and southeastern USA.

Much exploration in Mammoth Cave involves crawling. Many kilometers of low passages require travel on one's hands and knees or stomach, and kneepads are standard equipment on nearly every trip. But overall, exploration in Mammoth Cave is fairly comfortable and poses few serious challenges such as those in alpine caves.

Speleothems are not common in Mammoth Cave. They include calcite travertine, which is concentrated around the eroded flanks of ridges, and also evaporative minerals such as gypsum ($CaSO_4{\cdot}2H_2O$), epsomite ($MgSO_4{\cdot}6H_2O$), and mirabilite ($Na_2SO_4{\cdot}10H_2O$), which are common in dry passages beneath the sandstone cap (Fig. 10). Their various forms include gypsum "flowers," cotton-like tufts, and even "chandeliers" resembling the famous larger ones in Lechuguilla Cave, New Mexico. Gypsum has two different sources, as shown by isotope studies: oxidation of pyrite, and recrystallization of native gypsum incorporated in the bedrock. The most soluble minerals such as mirabilite tend to grow only when the humidity of the cave air is low, for example where cold winter air warms as it descends into cave entrances. Grass-like patches of these minerals can appear and disappear within a few months or even weeks.

Above the main limestones, sandwiched between two sandstone formations within the cap-rock, is the

Figure 10: A gypsum "flower" in a dry passage in Crystal Cave, formed by oxidation of local pyrite in the Ste. Genevieve Limestone.
***Figura 10**: Flor de yeso en un pasaje seco en la Crystal Cave, formado por oxidación de la pirita local en la caliza Ste. Genevieve.*

Haney Limestone, only about 9 m thick. It contains many small stream caves, perched on the underlying shaly sandstone, which feed hillside springs. By diverting underground water to the sides of the ridges, the Haney diminishes the amount of seepage into the underlying passages of Mammoth Cave so that only evaporative minerals such as gypsum can form beneath the sandstone cap. Most of the water from the Haney springs runs downhill across the eroded edge of the Big Clifty Formation and into dolines in the major limestones below, where it forms steeply descending passages along the fringes of Mammoth Cave. So the same water has the rare chance to form caves in two entirely separate limestone bodies.

Structural control of passages

At first glance, the map of Mammoth Cave looks like a bowl of spaghetti. Some areas contain up to 10 independent passage levels. Even frequent visitors can lose their way. But the cave pattern is not at all random: it is closely related to the structural setting and hydrology, with well-defined passage shapes that clearly reveal their developmental history.

The carbonate rocks at Mammoth Cave are rather thin-bedded, typically less than a meter thick. More than 100 bedding-plane partings have served as initial flow paths for cave development. Their dips vary considerably in both inclination and direction, and they provide a great variety of passage patterns. Vadose canyons and tubes almost invariably follow the local dip direction. In contrast, phreatic tubes have a tendency to follow the local strike of the beds, because the shallowest bedding-plane partings are widest. Thus the phreatic passages have no inherent tendency to extend down the dip, unless that is by chance the most efficient path (i.e., shortest and widest). Phreatic passages that extend below the water table in Mammoth Cave tend to wander in various directions independent of the dip.

Even in passages that are now dry, the original positions of the water table can be detected from the transition from vadose to phreatic passage types (Fig. 11). The best example is a change in shape from a canyon to a tube. At that point the passage also tends to change course form directly down the dip of the beds to a different path, most commonly along the strike of the beds. A passage can also show its former vadose-phreatic transition point where the gradient decreases significantly. Most phreatic passages loop up and down along their length, but the irregularities may be imperceptible without detailed surveying. This general pattern is repeated in many different passages, and at many different elevations, with control by many different angles and directions of dip. The result is the confusing pattern seen on the cave maps.

Traditional cave-mapping methods are not precise enough to detect the small-scale structural variations that guide passage trends and gradients. Structures in large passages are mapped with a tripod-mounted automatic level, and in smaller ones with hand-level surveys (Palmer, 1989a, 2007). About 50% of the large passages in Mammoth Cave Ridge and Flint Ridge (and nearly every passage in Crystal Cave) have been mapped in this way – enough to clarify the effect of geologic structure on the passage trends.

The largest irregularities in dip are caused by broad domes, basins, and folds produced by stresses within the Earth. For example, the overall trend of many cave passages in Mammoth Cave is toward the northwest, into the Illinois Basin. Dip variations of smaller scale are caused mainly by irregularities in the thickness of the beds. These control the trends of individual passages or parts of passages. The

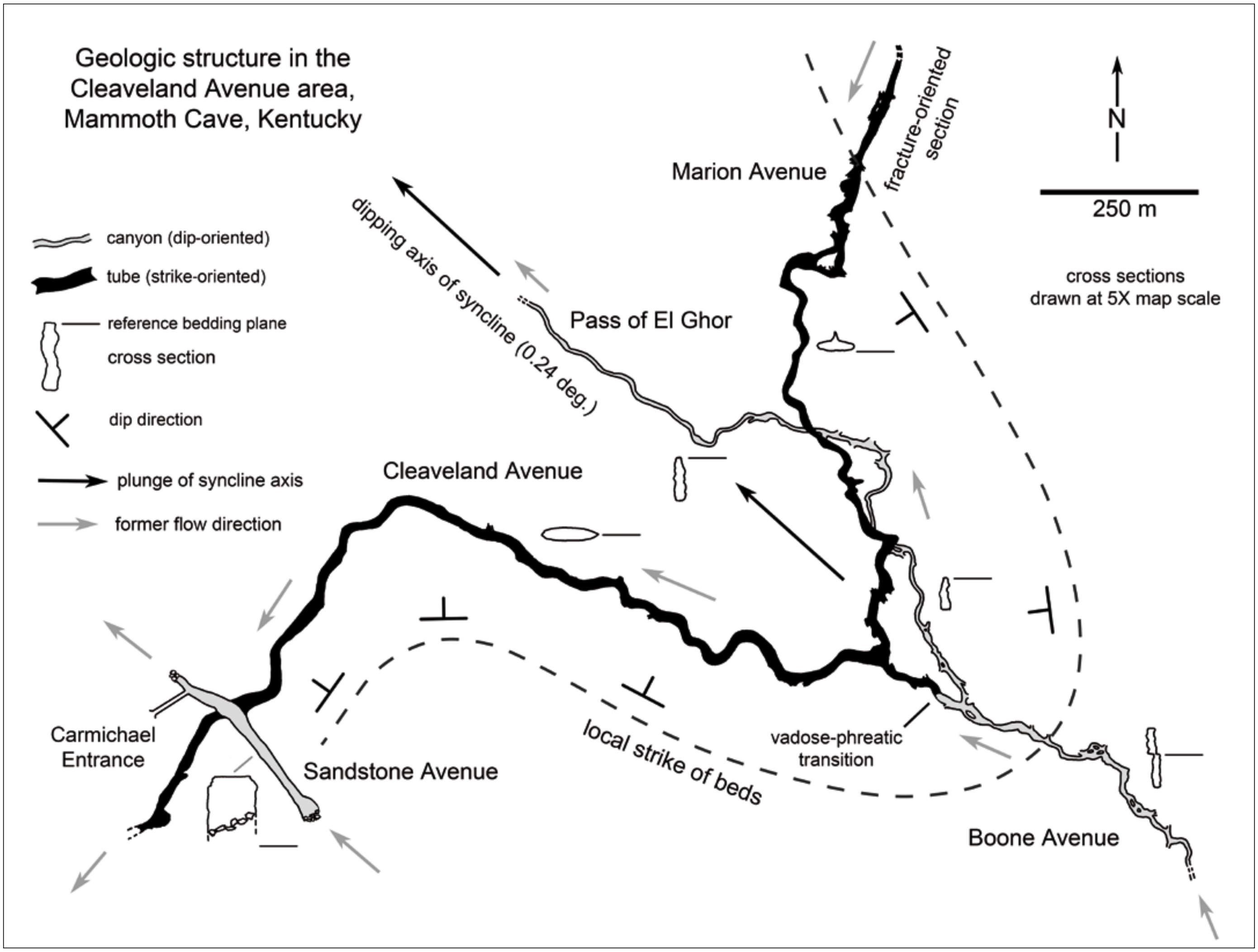

Figure 11: Map of major passages in the Cleaveland Avenue area of Mammoth Cave, showing their relation to geologic structures. Boone Avenue is a dip-oriented canyon located along the trough of a syncline. Cleaveland Avenue (Figure 9) is oriented along the strike of the beds, and its curves follow the contours of the syncline and, farther west, an adjacent anticline. Boone was originally a major tributary of Cleaveland, but when the water table dropped below the Cleaveland level, the Boone Avenue water continued down the dip to form a vadose canyon (Pass of El Ghor) while Cleaveland was left behind as a dry tube.

Figura 11: *Mapa de las principales vías de la zona de la Cleaveland Avenue de la Mammoth Cave, mostrando su relación con las estructuras geológicas. Boone Avenue es un cañón orientado con el buzamiento a lo largo del eje de un sinclinal. Cleaveland Avenue (Figura 9) se orienta según los planos de estratificación, y sus curvas siguen los contornos del sinclinal y, más al oeste, de un anticlinal adyacente. Boone fue originalmente un importante afluente del Cleaveland, pero cuando la capa freática bajó por debajo del nivel de Cleaveland, el agua de Boone Avenue continuó en sentido de la dirección del buzamiento para formar un cañón vadoso (Pass de El Ghor) mientras Cleaveland se quedó atrás como un tubo seco.*

smallest irregularities, reflecting depositional conditions such as currents and wave action, control the small-scale sinuosity seen in narrow vadose canyons. As a passage grows, the small irregularities are gradually overwhelmed and only the large ones dominate the pattern. Figure 11 shows the contrast between narrow sinuous canyons (Boone Avenue, Pass of El Ghor) and the wide tube (Cleaveland Avenue) with its broad, open bends.

Phreatic tubes are less sensitive to variations in dip because of their preference for the widest initial openings instead of the steepest. However, adjacent tubes at different elevations can wander over and under each other with few interconnections and with different trends. Explorers are entirely unaware of nearby passages only a few meters away, but which require many kilometers of devious travel to reach. Mammoth is not a maze cave, in which passages interconnect regularly at many junctions. The dendritic pattern of its individual components is dominant. But with so many different inputs and flow paths at different levels it is far more difficult to navigate than the typical maze cave.

Geologic history

Mammoth Cave drains into the Green River, a tributary of the Ohio River, which has the largest drainage basin in eastern North America. The Ohio discharges into the Mississippi River and from there to the Gulf of Mexico. So Mammoth Cave has a genetic relationship to the drainage history of the entire region. This history was complicated by continental glaciation during the past two million years. Although the southern extent of the ice sheets fell about 100 km short of Mammoth Cave, they had a great effect on the Ohio drainage and therefore on the cave origin.

The following history was originally inferred from the elevations of major passages in the cave and their relation to surface geomorphology (Palmer, 1989b). It was first necessary to identify the major cave levels. These are best recognized by the transition from vadose canyons to phreatic tubes (Fig. 11). Throughout the cave, but especially near the Green River valley where the control of water-table elevation was most significant, these transitions cluster at elevations of 210 m, 180-190 m, 168 m, and 153 m above present sea level. These are shown diagrammatically on Figure 4 as levels A, B, C, and D. The 180-190 m range includes two closely spaced stages of very large passages. These and the 210 m level experienced much sediment fill to depths as much as 20-30 m. In this low-dip structural setting, it might appear that these levels were stratigraphically controlled; but surveys show that they are entirely independent of strata and their structure (Palmer, 1989b, 2007). Their clarity and consistency show that they must relate to major pauses in the downcutting of the river.

Approximate dates for cave sediment were first inferred from paleomagnetic measurements (Schmidt, 1982). However, it was not until the late 1990s that relatively precise numerical dates became possible with the aid of aluminum-beryllium analysis of quartz sediment in the cave (Granger et al., 2001). This was the first extensive application of the procedure to cave dating. Quartz grains exposed to cosmic radiation at the Earth's surface acquire traces of radioactive ^{26}Al and ^{10}Be in a 7:1 ratio. If the grains then enter a cave the process stops, and the Al and Be decay at different rates. From today's $^{26}Al/^{10}Be$ ratio one can estimate the time since the grains were carried underground.

Most cave sediment is deposited by the same water that forms the passages, so the Al/Be dates should represent the last phase of passage enlargement. These dates are roughly 1.0 Ma (million years ago) for the 153 m level; 1.5 Ma for the 168 m level; and up to 4 Ma for the 180-190 m levels. Oddly, even though the upper-level passages are of widely different ages, the thick sediment that nearly filled them gave a rather uniform spread of about 2.6-3.7 Ma (adjusted for recent re-calibration of ^{10}Be decay; see Anthony and Granger, 2004). This episode of sediment fill apparently represents a rise in the Green River. This period of filling correlates approximately

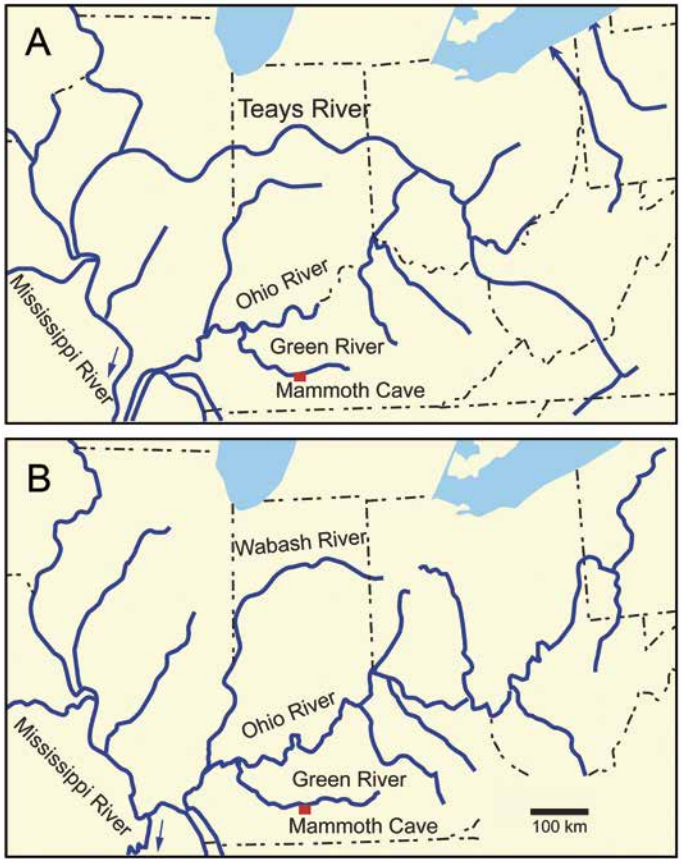

Figure 12: Late Cenozoic evolution of the Ohio River drainage. A = early drainage patterns, showing the original flow to the north, and later capture of much of it through the Teays River valley. B = present river pattern, showing the large drainage area acquired by the Ohio River when continental glaciers diverted the Teays River water southward (Palmer, 1981).

Figura 12: *Evolución del drenaje de la cuenca del río Ohio en el Cenozoico tardío. A = patrones de drenaje tempranos que muestran el flujo original hacia el norte, y la posterior captura de gran parte a través del valle del río Teays. B = patrón actual del río que muestra la gran* área de drenaje *adquirida por el río Ohio cuando los glaciares continentales desviaron el agua del Río Teays hacia el sur (Palmer, 1981).*

with remnants of thick sediment that once covered the Pennyroyal Plateau.

The clearly defined lower levels at 168 and 153 m appear to relate to changes in river pattern in the east-central USA (Fig. 12). Prior to about 2 Ma, much of the drainage apparently went north to the Atlantic through the area now occupied by the St. Lawrence River. Continental glaciers blocked these paths and diverted the water westward into the Mississippi River through the area now occupied by Ohio, Indiana, and Illinois. This river, whose valley is now buried beneath thick glacial deposits, is known to geologists as the Teays River. At that time the Ohio River was fairly short – no longer than the present Green River. Later and more southerly glacial advances blocked the Teays and diverted its water into the Ohio, turning it into the largest river of the eastern USA. Each of these diversions caused erosional deepening of the Mississippi, Ohio, and Green River valleys. Although the details of continental glaciation are still uncertain, these changes in drainage pattern seem to account for the pattern of levels in Mammoth Cave.

Geologic mapping of the cave and Al/Be dating of its deposits suggest the following history of cave development:

1. More than about 10 million years ago, the land around Mammoth Cave was fairly stable and had low relief. The sandstone-capped ridges of the Chester Upland stood only slightly higher than the limestone area that is the Pennyroyal Plateau today. The Pennyroyal at that time was drained by surface rivers. Mammoth Cave, as we know it, had not yet begun to form.
2. The Green River eventually eroded through the sandstone into the underlying limestone. In our region of interest, this first took place in the vicinity of Crystal Cave. The first passage to form was Collins Avenue, at today's elevation of 210 m. This developed into a wide, deep canyon as the Green River continued to deepen its channel below the sandstone (Fig. 3). Some of this "deepening" may have been accounted for by uplift of the continental surface.
3. As the Green River deepened its channel to about 180–190 m above present sea level, very large passages formed in Flint Ridge and Mammoth Cave Ridge, fed mainly by drainage from sinking streams at the northeastern edge of the Pennyroyal. These passages included the giant trunk passage of Salts Cave and the major upper levels of Mammoth Cave. Except near the Green River, most of these passages are high down-dip canyons that formed at least partly above the water table. For this to be valid, the entire Pennyroyal must have eroded downward to almost its present position after the origin of Collins Avenue. This must have taken many millions of years, and thus the crude estimate of 10 Ma as the age of Collins Avenue. The presence of large sinking streams fed by runoff from the Pennyroyal at 180-190 m suggests that deeper karst features had not yet developed below that surface.
4. All of these cave passages were filled almost to the ceiling by stream-borne sediment about 2.6–3.7 Ma. Sediment and residual weathering debris also accumulated on the Pennyroyal, filling any of its early karst features. This event was apparently caused by a temporary sea-level rise.
5. Rapid downcutting of the Green River, with periodic interruptions, formed at least 2 major levels (at 168 m and 153 m). These include most of the large tubular passages in the cave, such as Cleaveland Avenue (Figs. 9, 11). The clarity of these levels indicates very static base levels. The 168 m level was abandoned rather abruptly, and its water drained straight down the dip to the 153 m level without interruption. This rapid drop in base level suggests deepening of the Green River valley by the headward erosion of waterfalls and rapids, rather than uniform erosion over much of the river's length. This process is compatible with the rapid rearrangement of river patterns by glacial damming, as described above.
6. Renewed but slower entrenchment of the Green River drained the passages at 153 m. Many new passages formed at a variety of elevations, but not at consistent levels. There are some large passages in this interval, but most are remnants of phreatic loops that formed below the water table during the 153 m event (Fig. 13). Passages formed at this time include the ones that pass beneath the karst valleys between ridges.
7. Rather recently, perhaps post-glacially (last 14 000 yrs), the Green River valley filled with about 15 m of sediment. The lowest passages in Mammoth Cave were flooded, and many springs now flow upward through the river sediment at "rise pools" along the river banks.

A more complete geomorphic history of the cave is given by Palmer (1989b) and, with more accurate dates, by Granger et al. (2001).

The time trap

Cave biologist Tom Poulson offers the interesting idea that Mammoth Cave acts as a "time trap" – i.e.,

Figure 13: Echo River is genetically part of the 153 m level, but it consists of a downward loop that extended 25 m below the water table while that level was forming. It is located in the St. Louis Limestone at the elevation of the Green River and contains water year-round.
Figura 13*: El Río Echo es genéticamente parte del nivel 153 m, pero consiste en un bucle hacia abajo que se extendía 25 m por debajo del nivel freático, mientras que el nivel estaba formándose. Está situado en la caliza St. Louis en la elevación del Green River y contiene agua durante todo el año.*

like a net through which time has moved, capturing objects and events over millions of years and preserving them all in the same location. Although this concept applies to many caves, it is especially true in the ancient upper levels of Mammoth Cave, which are so dry that organic material does not decay. It is apparently preserved by the low humidity and the internal growth of evaporative, water-trapping minerals such as gypsum ($CaSO_4{\cdot}2H_2O$) and epsomite ($MgSO_4{\cdot}7H_2O$). Sediments, fossils, archeological sites, traces of early visitation (mummies, footprints), biota (cave crickets, bats), newspaper fragments, ancient graffiti, etc., are all preserved in their original position. At the surface they would be easily scattered and destroyed. In the cave they remain intact almost indefinitely, at least by human standards.

Why is Mammoth Cave so long?

The great extent of Mammoth Cave is the result of several favorable conditions. First, it has the perfect geologic setting, in which an unusually large recharge area of dolines and sinking streams, nourished by a humid climate, delivers much water to a distant target – the deeply entrenched Green River. Although the carbonate rocks are relatively thin, their low dip provides a large area of exposure. The finely dissected plateaus of the region are host to hundreds of individual sources of groundwater, and the continuous, highly soluble carbonate beds contain no geologic barriers to flow. An unusually large number of bedding planes provide abundant paths for water to divert from layer to layer and allow flow to take place along irregular sinuous paths.

The Green, Ohio, and Mississippi Rivers have low gradients and are subject only to slow, long-term changes in base level. Therefore, base-level changes have been relatively small and of long duration, allowing many discrete passage levels to form within the limited vertical range of soluble rock. Finally the resistant sandstone cap-rock in the Chester Upland protects many old cave passages from collapse and erosion. The cumulative effect of all of these variables has produced what is now the world's longest known cave.

The future

Mammoth Cave's present mapped length of 652 km is almost twice that of the world's second-longest (Mexico's Sistema Sac Actun, 335 km). The Mexican giant is almost entirely water-filled, so that diving is necessary. It is a complex anastomotic maze with many interconnections both internally and with adjacent caves. A connection is feasible with nearby caves such as Ox Bel Ha, 257 km long and presently #4 on the world list. Third longest is Jewel Cave, in the Black Hills of South Dakota (USA), a vast network maze probably formed by the mixing of two or more water sources with contrasting CO_2 concentrations. Exploration in Jewel is difficult, so even if it is much longer than its present 290 km, progress will be relatively slow.

In recent decades the main emphasis in Mammoth Cave has been resurveying to provide greater accuracy and detail in the map. This goal is being achieved and a period of accelerated exploration is at hand. Pushing the boundaries to make further discoveries yields benefits far more than passage length: it expands our understanding of the regional hydrology and geomorphic history.

There are several puzzles. For example, no passages in Mammoth Cave have been explored upstream into the Pennyroyal Plateau. Dye tracing shows that a large amount of water enters the cave from this source, but sumps, breakdown, and sediment block easy access. Diving has been partially successful but there is still no significant link with the Pennyroyal.

Connections are also likely between Mammoth Cave and other nearby caves. The Fisher Ridge System (201 km) lies only a few hundred meters beyond the easternmost passage in the Roppel section of the Mammoth Cave System. A connection has been elusive, and not wholeheartedly sought (it would remove the world's 9th longest from the list); but it is probably inevitable. To the southwest is Whigpistle Cave (56 km), but a connection in that direction is less feasible and may require diving.

The karst area is limited by several discrete boundaries: the up-dip extent of relatively pure carbonate rocks to the southeast, the Green River valley to the north, and the Barren River valley to the southwest (Fig. 1). Dye tracing has established the limits of the present drainage basin, but it cannot identify dry cave passages, which can easily cross over drainage divides. Mammoth Cave occupies only about 5 to 6 % of the available space within these boundaries. This estimate is not entirely valid, because areas considered to be occupied by caves actually contain much volume in which new discoveries can still be made. Part of the potential area is already occupied by known caves other than Mammoth. On the other hand, some of the area included in the potential karst basin receives little subsurface drainage and is unlikely to contain many cave passages.

It is reasonable to say that the present cave is nowhere close to its true potential, but much exploration, perhaps including diving and excavation of sediment, will be needed to expand it greatly beyond its present boundaries. The fact that caves in other parts of the world are beginning to compete with Mammoth Cave in size is a testament to the great expansion in speleology that has taken place in the past few decades.

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