THE IMPORTANCE OF CAVE EXPLORATION TO SCIENTIFIC RESEARCH

Patricia Kambesis
1906 College Heights Blvd, Hoffman Environmental Research Institute, Western Kentucky University, Bowling Green, Kentucky 42101, Pat.Kambesis@wku.edu

Abstract: Of the many objects of scientific interest, caves present a unique challenge because, except for entrance areas, caves are largely hidden from view. As a consequence, caves have not generally attracted the attention of mainstream scientists. With the exception of cave entrances noted on some topographic maps, most caves are not apparent from topographic maps, satellite and LANDSAT imagery, or aerial photographs. Caves and their features exist in an environment with no natural light and contain a myriad of physical and psychological obstacles. It is the cave explorer who ventures past these obstacles, motivated by curiosity and the desire to find and document places previously unknown. Systematic cave exploration is a two-fold process that involves the physical pursuit and discovery of caves and cave systems, and field documentation that provides baseline data in the form of cave survey data and notes, cave entrance and cave/karst feature locations and inventories, written observations, and photo-documentation. These data are synthesized into cave maps, topographic overlays, narrative descriptions, and reports that serve as exploration tools for finding more passages and caves. Systematic documentation and its derivative products also bring the hidden nature of caves and their features to the attention of scientists and provide a basis not only for cave-related research but for a wide range of related scientific endeavors.

Introduction

Caves present a unique challenge to scientific study because, except for entrance areas, caves are largely hidden from view. As a consequence, caves have not generally attracted the attention of mainstream scientists. With the exception of cave entrances noted on some topographic maps, most caves are not apparent from topographic maps, satellite and LANDSAT imagery, or aerial photographs which are the tools that many earth scientists use to visualize the shape, form, and orientation of landforms (Kambesis, 2003). Caves and their features exist in an environment with no natural light and contain a myriad of physical and psychological obstacles. It is the cave explorer who ventures past these obstacles, motivated by curiosity, and the desire to find and document places previously unknown.

In scientific research, there are a variety of questions that provide direction to the pursuit of knowledge. In cave exploration, the initial question is very simple: Does it go? This is the question that hooks the cave explorer and drives her/his curiosity toward an answer. But that answer only brings more questions such as how far, how long, how deep? During the exploration process, as a cave system or cave area reveals its complexity, the questions also change. For example, what is the cave's relationship to the surface, and to surrounding caves? What are the features and obstacles that the cave contains? Those involved in serious cave exploration know that the only way to answer these questions is with systematic documentation in the form of cave and surface surveys, detailed notes and observations, cave/karst feature locations and inventories, and photo-documentation. The data are synthesized into cave maps, narrative descriptions, and reports that can serve as a set of exploration tools for finding more passages and caves. The field documentation and its derivative products also serve as the baseline data for all types of cave-related research.

The most important derivative products of systematic cave exploration are maps, which illustrate the extent and layout of the cave, shapes of passages, and if a profile is included, the three dimensional relationship of the passages. A map not only portrays the geography of a cave, but depending on its level of detail, can show the location of features within the cave. Cave/karst feature inventories are becoming more common in the documentation process, especially because of the increased availability and access to GIS technology which allows more detailed cave/karst feature data to be integrated with the survey and cartographic data. Photography is another important aspect of cave documentation; a description of underwater helictites, u-loops, or chandemites pales in comparison to the photographs that record their existence. Systematic documentation and its derivative products such as cave maps, topographic overlays, reports, inventories, and photographs bring the hidden nature of caves and their features to the attention of scientists and provide a basis not only for cave-related research, but for a wide range of scientific endeavors such as archaeology, evolutionary biology, hydrogeology, geology, geomicrobiology, mineralogy, and paleoclimate studies, to name just a few.

In order for exploration documentation to be of value, it must be accessible. Much of the early information generated by cave exploration in the United States was not published in peer-reviewed journals, publications, or popular magazines. With the formation of the National Speleological Society and its many chapters (grottos) came national and regional publications that served as venues for accounts of cave explorations, maps, cave survey/research project reports, and photographs. State cave surveys, usually organized by active cavers within a state or region, served as archives and catalogs of cave data. Many of the state cave surveys published maps, reports, regional overviews, and results of scientific research in caves of their respective areas. Often these are the resources that scientists use to access information about caves, their characteristics, and features.

Systematic cave exploration and documentation provide an essential foundation for cave research. In turn, the results of cave research also serve the cave explorer in her/his efforts in finding more cave. Two case studies are presented to illustrate how cave exploration affects the course of cave science and vice versa. Systematic explorations in the Mammoth Cave area in Kentucky, and in the Guadalupe Mountains of New Mexico, are submitted as examples of how the tangible results of cave exploration (i.e., survey notes, initial observations, and photographs), and their derivative products (i.e., cave maps, topographic overlays, field notes, and summary reports) provided the basis for the cave research that followed.

Case Study 1: Exploration and Scientific Research in the Mammoth Cave Area

Efforts to survey Mammoth Cave began after the War of 1812 (Smith, 1960) with the purpose of establishing the relationship between cave passages and surface properties for commercial development of caves for tourism. Other surveys were made in support of construction projects for tourist entrances, walkways, and lighting systems. Due to commercial competition among show caves in the Mammoth Cave area and the marketability of calcite and sulfate deposits, most of the surveys and maps were kept secret. Access to the caves for scientific study was usually denied (Smith and Watson, 1970).

In 1930, world-renowned geographer and geomorphologist William Morris Davis published a scientific paper arguing that caves were not formed above the water table, as was commonly supposed, but were instead the result of underground water circulating deep below the water table (Davis, 1930). Because of Davis' long and impressive reputation as an earth scientist, the paper was embraced by the U.S. scientific community though it contained little supporting field evidence. Davis used some of the existing maps of Mammoth Cave to help develop his theory (Watson and White, 1985). Unbeknownst to him, most of the early maps were not accurate representations, but were at best, fanciful renditions of the cave which portrayed its morphology as a giant labyrinth (Fig. 1), rather than having a modified dendritic pattern (Watson and White, 1985). In 1942, J Harlen Bretz published a paper on cave development that attempted to provide field evidence in support of Davis' theory (Bretz, 1942). What followed was a fifteen year hiatus in which little of consequence appeared in the scientific literature of North America on cave development (White, 1973). It was not until systematic explorations in the Mammoth Cave area began documenting the nature, extent, and layout of the Mammoth Cave system, was it realized that Davis' theory on cave development might be flawed (White et al., 1970).

Modern Exploration under Flint and Mammoth Cave Ridges

Modern exploration in the Mammoth Cave area began on Flint Ridge in 1947 by Dr. E. R. Pohl, Jim Dyer, and Bill Austin. Their focus included not only extending the physical limits of the caves under Flint Ridge, but also conducting scientific investigations. In 1954 the National Speleological Society sponsored a week-long expedition in Crystal Cave, which in the past had been operated as a show cave. Though no major discoveries were made during that expedition, it proved to be a learning experience in cave project management and in systematic exploration and survey techniques, and ultimately resulted in the establishment of the Cave Research Foundation (CRF) in 1957. The goal of CRF was to explore and map caves for the purposes of furthering scientific research and understanding of caves (Watson, 1981).

CRF adopted a method of systematic exploration that involved mapping cave passages, correlating the surveyed cave passages and their elevations with topographic maps, aerial photographs, and elevation controls such as geographic surface benchmarks (Brucker et al., 1966). Detailed trip reports containing passage and feature descriptions were also important to the systematic documentation process. With these tools, the extent of the Flint Ridge and Mammoth Ridge caves began to be realized along with the establishment of a geographic context for scientific work on cave origin and development.

CRF's work began on Flint Ridge where five major caves and a number of smaller caves were located. The impetus for these efforts was the potential for connections between the major caves of the Mammoth Cave area. This potential was first expressed by E. A. Martel after he visited Mammoth Cave in 1912 (Martel, 1912). He predicted that Flint Ridge and Mammoth Cave systems would some day be physically linked to make a system 241 km in length (Brucker and Watson 1976). Accomplishing such a challenge was a great motivator to the cave explorers and drove them to diligently push and map all varieties of cave passages large and small, dry and wet, magnificent and miserable.

Systematic explorations in Flint and Mammoth ridges not only racked up significant survey footage, but also

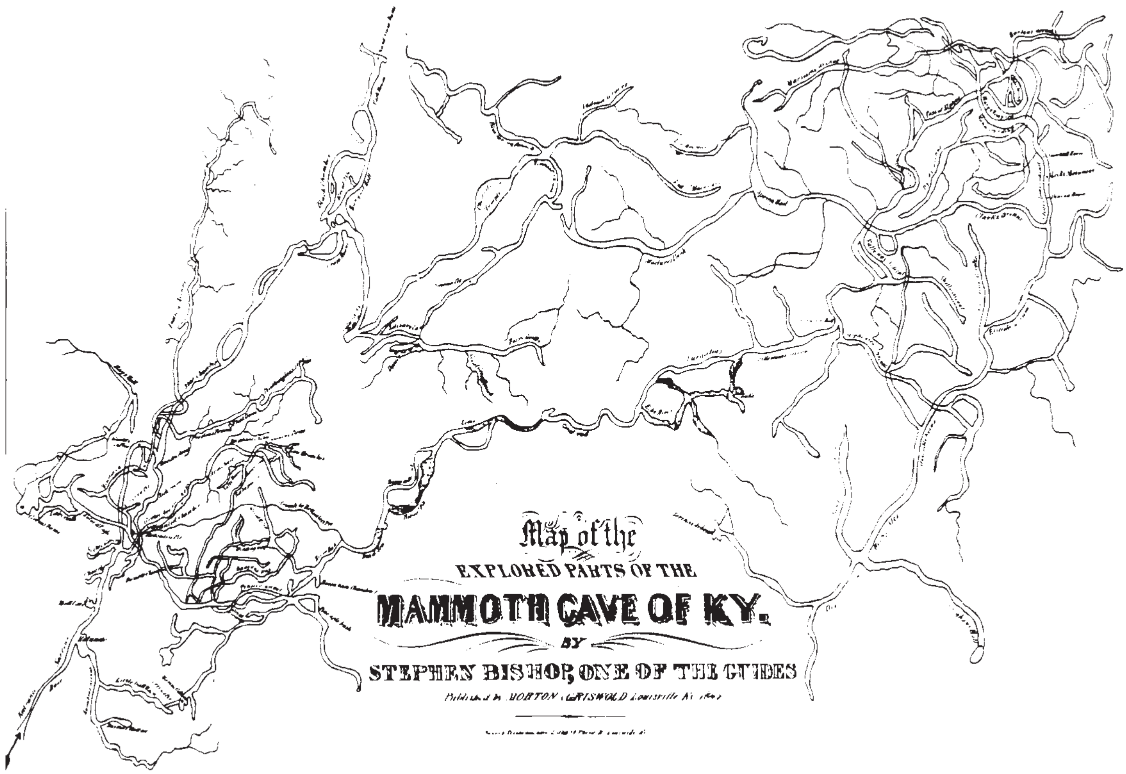

Figure 1. Stephen Bishop's map of Mammoth Cave, 1842 (CRF, 1976)

provided important observations that would impact future explorations and science. Map overlays showed that cave passages could extend out from the major ridges and under the valleys in the Mammoth Cave area (Smith, 1960). Many of the large cave passages were determined to be segmented pieces of longer passages that had been dissected by valley development (Brucker, 1966). Vertical shafts that were very common in the Mammoth Cave area could penetrate through tiers of horizontal passages giving access to previously unexplored cave (Brucker et al., 1972).

By 1961, the major caves of Flint Ridge, including Crystal, Unknown, Colossal, and Salts Cave were connected (Fig. 2). In addition to the speleological accomplishment of connection, systematic exploration also began to confirm and answer geological questions and to cast doubt on Davis' theories on the origins of limestone caves (Smith, 1960). Survey notes, working draft maps, written observations, and detailed reports revealed not only the geographic extent of the caves, but noted the cross-sectional shapes of passages and the features within the passages. These were the types of details necessary to successfully explore a cave system, and also to begin understanding how cave systems formed. Topographic overlays gave geographic context to the morphology and extent of cave passages. In effect, exploring and describing the Flint Ridge System made it possible to begin a rational description of both the cavern-forming process in general, and the history of the Flint Ridge cave complex in particular (Smith, 1964).

One of the first geologic questions that was addressed by the systematic exploration/survey method was the origin of vertical shafts in the caves of Flint Ridge. Though a number of theories were proposed to explain them, a geographic context was missing. Pohl (1955) set forth the hypothesis that the vertical shafts were related to the solutional enlargement of vertical cross joints and that their development was related to the process of headward and areal advance of surface valleys. Cave surveys which located vertical shafts, when added to the topographic overlays, confirmed that the vast majority of these features were indeed located at the edges of the sandstone-capped ridges (Fig. 3). Observations made during survey trips indicated that there was no relationship between the vertical shafts and lateral passages and that shaft drainages use lateral passages only when these passages occur at base level and beneath actively forming shafts (Smith, 1957). Systematic exploration confirmed that vertical shafts were not speleogenetically related to the vast passages and rooms that they intersected (Brucker et al., 1972).

The occurrence and significance of breakdown was another question whose answer was augmented by the observations of cave explorers. According to observations by Davies (1951), limestone and sandstone breakdown can occur where passages are close to the surface, especially where horizontal cave passages are intersected by hillsides. The intersection of large passages could also result in breakdown. However, there were areas in the Flint Ridge caves where none of those conditions existed, but

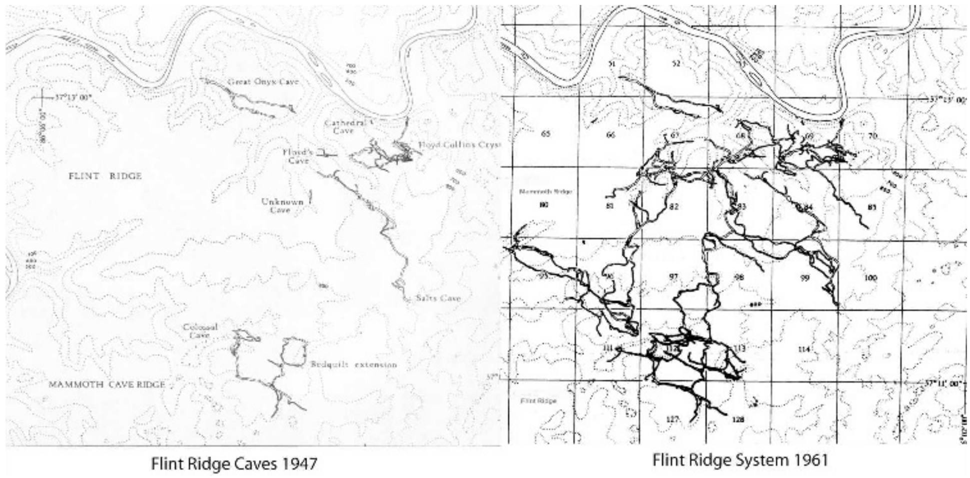

Figure 2. Flint Ridge System 1962 (CRF, 1966).

breakdown still occurred. Cave explorers reported white crystalline coatings and crusts associated with breakdown, and the samples brought back by explorers were identified as gypsum and other sulfates. With that information, it was determined that *in situ* mineral growth of gypsum and other sulfates along bedding planes and joints put pressure on these zones of weakness and caused the rock to peel off the ceiling and walls, thus forming breakdown (Smith, 1957).

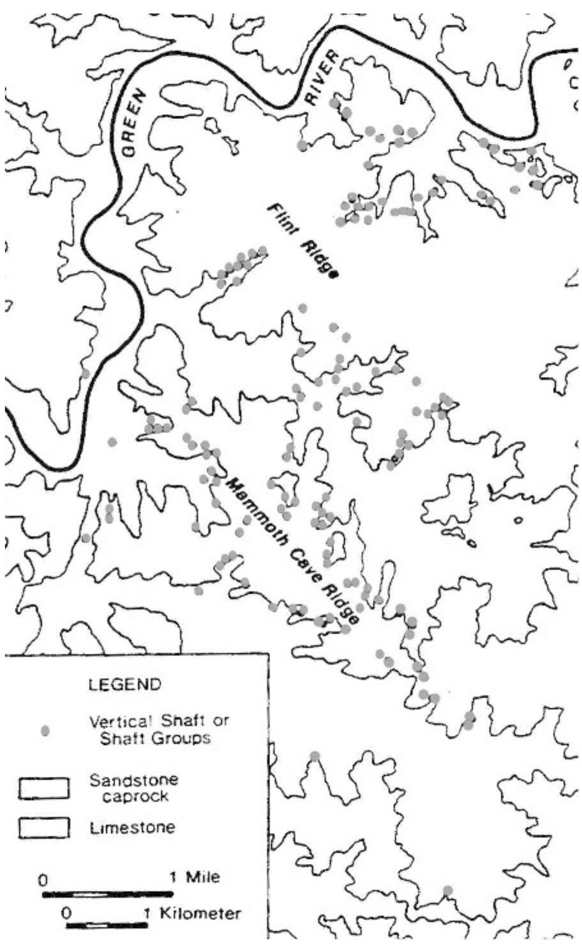

Figure 3. Vertical shafts in the Mammoth Cave area (from White, 1988).

Exploration of new passages in Flint Ridge revealed unusual, previously undescribed speleothems. Photographs were made of the new features and samples were later collected by the exploration team. Laboratory analysis showed that gypsum could combine with other soluble sulfates to produce metastable sulfate minerals like mirabilite. The results of this study were published in an issue of Science (Bennington, 1959) and revealed that thermodynamically unstable mineral phases developing at relatively low temperatures might indicate the occurrence of complex heterogeneous reactions worthy of further kinetic studies (Smith, 1960).

Black coatings observed on the ceilings of passages in Mammoth and Salts Caves were initially thought to be manganese. However, analysis revealed that the coatings were organic; specifically soot (Smith, 1960). Exploration teams reported that soot coatings were always found in association with archaeological material (unpublished Cave Research Foundation reports 1957–1965). As systematic exploration progressed into previously unknown territories, more archaeological artifacts and traces of activities were discovered. In 1962, Watson began a systematic inventory of archaeological features. Not only did she determine that ancient people had used the cave for mining purposes (Watson, 1969), her research ultimately revealed that the prehistoric people in Kentucky and the Eastern Woodlands were among the few indigenous populations in the world to independently develop an agricultural economy, well before domesticated plants were introduced from Mexico (Watson, 1992). Watson was inducted into the National Academy of Sciences in part because of this work.

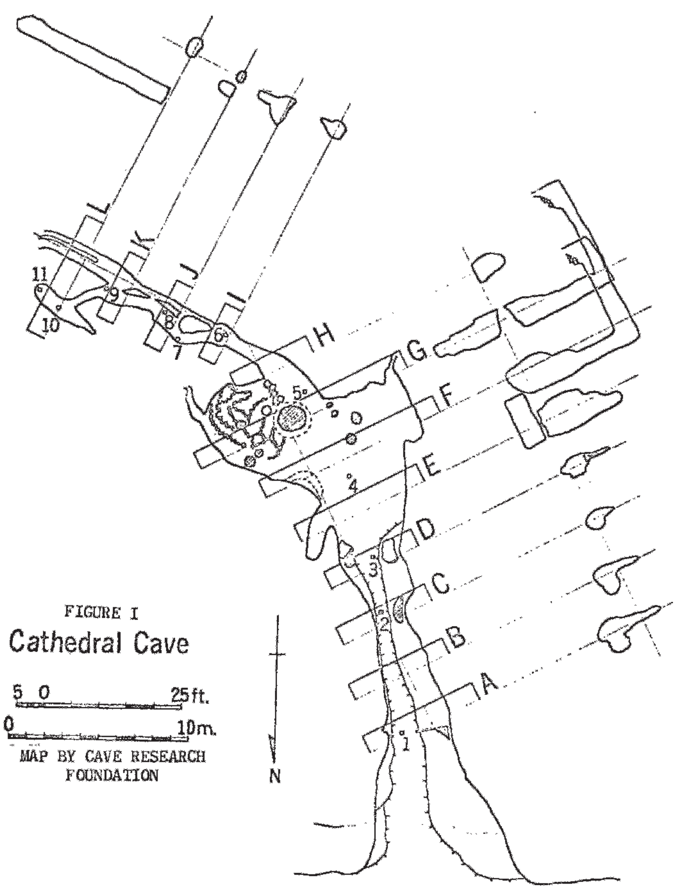

Figure 4. Cathedral Cave, Mammoth Cave National Park (CRF, 1961)

CRF helped support biologic research on cave animals by producing cave maps for baseline ecologic studies. The map of Cathedral Cave (Fig. 4) in Mammoth Cave National Park, with base line transects noted, was provided to researchers who were conducting studies on population dynamics of cave fauna (CRF, 1961). This was the beginning of many biologic studies in the Mammoth Cave area. The observations by survey teams about the composition of sediments and other material on cave passage floors (substrates) provided important information for research on cave ecology. Kane and Poulson (1976) studied the foraging habits of cave beetles in heterogeneous mixes of substrates and homogeneous substrate (uncompacted sand) in Little Beauty Cave and in Great Onyx Cave, respectively. Studies on the long-term effect of weather on cricket populations within White Cave and Little Beauty Cave demonstrated the importance of weather patterns on cricket populations (Poulson, et al., 1995). Poulson (1991) established that aquatic subterranean faunal populations were important indicators of groundwater quality.

The systematic exploration conducted by CRF provided the field evidence necessary for scientists to begin to formulate a regional overview of the geologic processes and cave development of the Mammoth Cave area. As a result of this extensive field work and the interpretation of the data by White et al. (1970), a paper titled "The Central Kentucky Karst" was published in *The Geographical Review*. The paper discussed the geology, mineralogy, and hydrogeology, and their relationship to underground karst features. The work outlined the physiographic evolution of the Mammoth Cave area and classified karst as a dynamic system. This new perspective on cave development replaced the Davisian model of deep phreatic-cave development for the Mammoth Cave region.

After the 1961 connections at Flint Ridge, CRF extended their efforts to Mammoth and Joppa ridges. In 1969 the Flint Ridge System became the longest in the world at 108 km in surveyed length. Concurrent systematic explorations at Mammoth Cave brought its surveyed length to 73 km making it the third longest behind Hoelloch (Switzerland). These impressive accomplishments in speleology were just interim goals for those who were dedicated to systematic exploration. With their eyes on the next prize, CRF explorers aimed at connecting the first and third longest caves in the world. Long and difficult cave trips guided by working maps and the observations and reports of many survey teams pushed the limits of the Flint Ridge System under Houchins Valley and into Mammoth Ridge. In 1972, a small team of CRF cavers, representing the cumulative efforts of all of those before them, connected the Flint Ridge System to the Mammoth Cave System making it the longest cave in the world with a length of 232 km (Brucker and Watson, 1976).

In 1978, cave explorers discovered a subterranean river under Joppa Ridge and it was ultimately connected to the Flint-Mammoth Cave System. Systematic exploration pushed the upstream extent of the Logsdon River east under a valley toward Toohey Ridge, the home of Roppel Cave, whose exploration and survey was a project of the Central Kentucky Karst Coalition (CKKC). In 1983, CRF and CKKC connected Roppel Cave to the Flint-Mammoth Cave System (Borden and Brucker, 2000). The new connection brought the surveyed length of the Flint-Mammoth-Roppel System to 493 km.

While active exploration efforts extended the physical limits of the Flint-Mammoth Cave System into triple digits, scientific research that utilized the baseline data and derivative products generated from cave surveys flourished. In the early seventies, researchers began a leveling and geologic survey in Floyd Collins Crystal Cave with the goals of determining the stratigraphic section in which the Flint-Mammoth Cave system is developed, to clarify the presence of passage levels and their geomorphic significance, and to make a detailed map of the cave (Palmer, 1987). They used copies of the original survey notes that spanned twenty-five years of exploration effort to construct a base map. In 1974, the stratigraphic column from Crystal Cave was extrapolated to most of the major cave passages in the Flint-Mammoth Cave System. Passage levels were

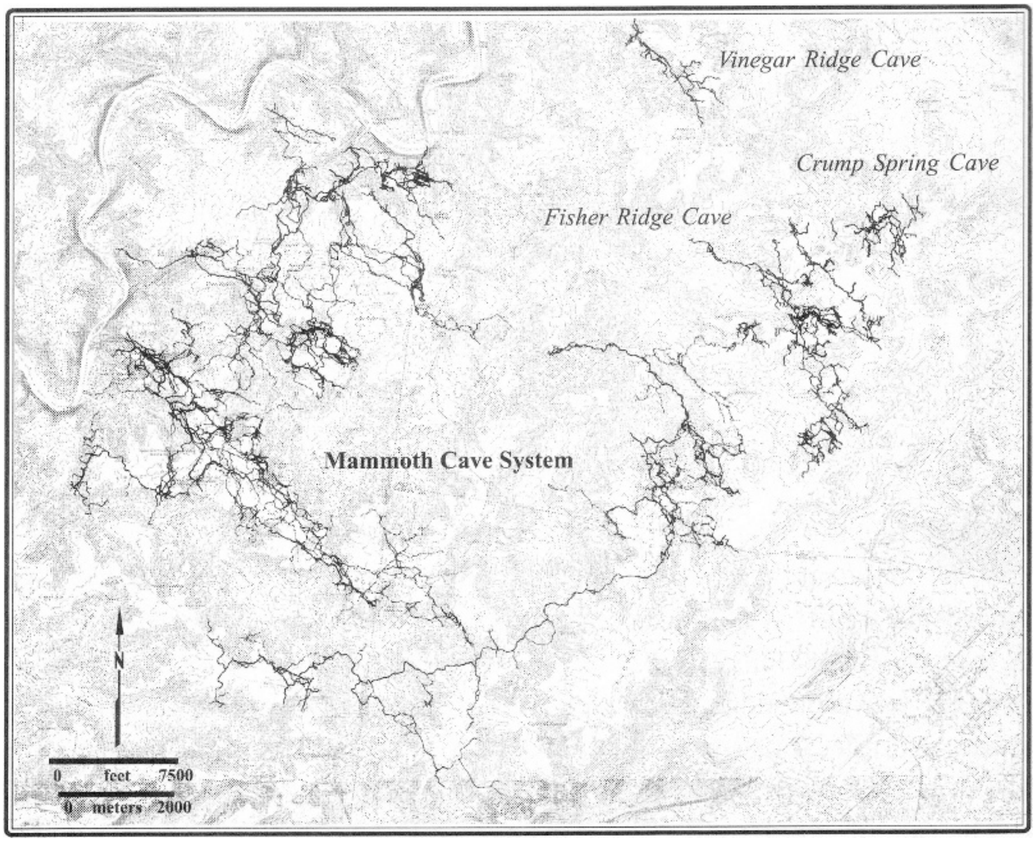

Figure 5. Caves of the Mammoth Cave region (Borden and Brucker, 2000).

described and correlated with the geomorphic history of the surrounding landscape (Miotke and Palmer 1972). The relevance of the passage level data from the geologic and leveling study was augmented with cosmogenic dating of gravels from Mammoth Cave. The results of this collaboration illustrated the far-reaching effects of Pleistocene glaciation on the evolution of the Ohio River valley, on the Green River, and ultimately on the Flint-Mammoth Cave System (Granger et al., 2001).

Hydrogeology is an important research frontier in the Mammoth Cave area. With a current extent of over 608 km, the Flint-Mammoth Cave System consists of a huge collection of active, semi-active, and inactive conduits that are parts of a vast karst aquifer.

Early work on hydrogeology in the Mammoth Cave area was conducted by White et al., (1970), White (1976), Hess and White (1973, 1974), and Miotke (1975). Extensive dye tracing and geochemical analysis by Jim Quinlan, who worked as the geologist for Mammoth Cave National Park, augmented the ongoing hydrogeologic studies. Quinlan maintained that systematic cave exploration/survey was the key to discovering and understanding the hydrology of the flow system of a principle karst aquifer (Quinlan et al., 1983). CRF provided support for Quinlan's hydrogeologic studies in the form of cave maps that he considered critical for his research inside Mammoth Cave National Park (Zopf, 1982). Quinlan also utilized teams of cave explorers who worked outside of the National Park to provide the data and insight necessary to study the vast aquifer of the Mammoth Cave region (Quinlan et al., 1983). His teams discovered and documented an underground distributary system on the Green River, the Hidden River Complex that was hydrogeologically related to Hidden River Cave in Horse Cave, Kentucky (Coons, 1978). They also discovered and conducted systematic exploration in Whigpistle Cave which Quinlan proved via dye traces to be hydrogeologically connected to the Flint-Mammoth Cave System (Coons, 1978). Exploration-related data augmented Quinlan's study of the movement of groundwater in the Mammoth Cave region. His research ultimately revealed that agricultural and industrial contaminants were entering the Flint-Mammoth Cave System from places outside of the national park (Quinlan, 1989).

A specific example of the practical application of Quinlan's findings involved his identification of a sewage treatment plant in Horse Cave, Kentucky as a source of groundwater pollution. The seriousness of the pollution was reflected in Hidden River Cave, located in the middle of town. The stench of sewage rose from the cave entrance and permeated the downtown area. The treatment plant was discharging heavy metals into the groundwater and

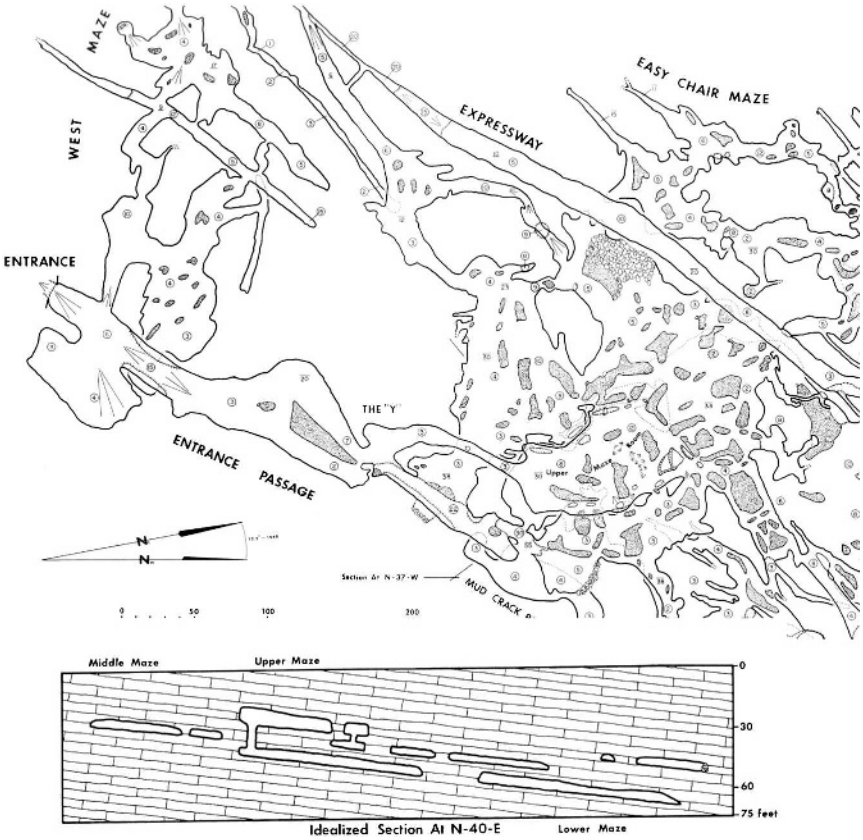

Figure 6. A section of Endless Cave, New Mexico (from Kunath, 1978).

was not effectively treating sewage (Quinlan, 1989). Once the physical functioning of the sewage treatment plant was upgraded, there were significant improvements in the water and air quality of Hidden River Cave.

The 1978 discovery of the Logsdon River made it possible for scientists to study the behavior and characteristics of a karst aquifer from the inside. Based on cave survey and cave radio-locations, Quinlan instigated the drilling of an entrance shaft and a series of wells directly into the Logsdon River to facilitate ongoing hydrogeology-related research. The new entrance shaft allowed the installation of data-logging equipment that monitored changes in stream flow and groundwater chemistry over a variety of timescales. Groves and Meiman (2001) were able to quantify that large storm events play a significant role on karst aquifer development. Groves et al. (2001) also observed that interstitial cave-stream fluids showed evidence of bacterial functions that may influence aquifer evolution.

A regional map of the Mammoth Cave area (Fig. 5) shows the results of fifty years of systematic cave exploration in the region. Over 833 km of passages have been explored and mapped not only within the Flint-Mammoth Cave System, but in other caves located outside of the national park. Quinlan et al., (1983) suggested that the potential for over 1,600 km of human-sized passages exists in the Mammoth Cave area. This potential continues to motivate cave explorers to extend the limits of the world's longest cave system, and for cave scientists to expand the frontiers of knowledge about such topics as karst aquifers, ancient human use of caves, water-rock interactions and their effects on cave development, and the role of microbiology in speleogenesis.

Case Study 2: Cave Exploration and Science in the Guadalupe Mountains, New Mexico

The caves of the Guadalupe Mountains have long held the fascination of cave explorers and cave scientists alike. In the early days of cave exploration and research, the caves proved to be enigmatic to both groups because of the morphology and layout of the caves, by the seeming lack of relationship between cave and surface features, and by the occurrence of massive gypsum deposits and other unusual mineralogy. The first two factors made caves difficult to find, explore, and map. All three proved puzzling within the scientific context of what was known about cave development.

Earliest explorations of caves in the Guadalupe Mountains began in the latter part of the 19th century (Kunath, 1978). Jim White first entered Carlsbad Cavern in 1898 (Selcer, 2006) and extensively explored it for thirty years (White, 1932). In the early part of the twentieth century, Nymeyer (1978) photographed many of the caves in the Guadalupe Mountains and published photographs along with accounts of his explorations in a book titled *Carlsbad, Caves and a Camera*. However, systematic exploration and mapping of Guadalupe Mountain caves did not begin until the 1960s (Kunath, 1978) with work by the Texas Speleological Survey, the Guadalupe Cave Survey (which later became part of Cave Research Foundation) and, some of the local grottos in Texas and New Mexico. The cave maps produced from those efforts illustrated the complex three-dimensional morphology of the caves (Fig. 6). Some sections of cave maps were intentionally omitted due to the difficulty of graphically rendering multi-level mazes in two dimensions (Lindsley and Lindsley, 1978). Detailed descriptive summaries written by cave explorers provided information about cave features (Kunath, 1978) and reported on unusual mineralogy (Davis, 1973).

The first geologist to study Guadalupe Mountain caves was Willis T. Lee. He participated in two expeditions to Carlsbad Cavern sponsored by the National Geographic Society. Lee's contributions were mostly descriptive in nature and he made a preliminary survey of the cavern which was published in National Geographic Magazine along with photographs by Ray Davis (Lee, 1924, 1925). J Harlen Bretz conducted scientific field work in Guadalupe Mountain caves in 1948 (without the benefit of cave maps), proposing that the caves were phreatic in origin. Bretz (1949) identified the gypsum deposits he observed as a type of gypsum flowstone. Other geologists hypothesized that massive gypsum was the result of a late-stage backup of water from the Castile Formation of the Delaware basin (Jagnow et al., 2000).

As cave scientists began to develop models for speleogenesis in the Guadalupe Mountains, they realized that the models needed to take into account the morphology and layout of the caves had to explain the lack of relationship between cave and surface features, and needed to account for the occurrence of massive gypsum deposits and other unusual mineralogy (Smith, 1978).

Queen (1973) and Palmer et al., (1977) suggested that the gypsum deposits might be related to a process of speleogenesis rather than being the result of vadose secondary mineralization. According to their speculations, the origin of the gypsum deposits could result from replacement of carbonate rocks by gypsum as a result of fresh meteoric water mixing with gypsum-saturated brine already in the rock. Palmer prefaced the hypothesis by expressing caution in accepting it without substantial field evidence (Smith, 1978).

Stephen Egemeier suggested that Carlsbad Cavern may have been dissolved by sulfuric acid (Egemeier, 1971). Other geologists began to see evidence from their field work and observations, of the possibility of a sulfuric acid origin of caves in the Guadalupe Mountains (Davis, 1973; Jagnow, 1978; Hill 1981).

In 1986, an important cave exploration breakthrough in Lechuguilla Cave provided a unique opportunity to test and expand the ideas of a sulfuric acid speleogenesis model and ultimately shifted the focus of research from Carlsbad Cavern to Lechuguilla Cave (Jagnow et al., 2000).

Exploration of Lechuguilla Cave: a Bigger Piece of the Puzzle

For decades, cave explorers had been intrigued by a small guano cave located above Walnut Canyon in Carlsbad Caverns National Park. The cave had a vertical entrance, was not very extensive, and did not contain any speleothems of interest. It was mined for guano for a short time, but then abandoned (Frank, 1988). However, a gale of air issued from a breakdown pile at the base of the entrance shaft. On some days, it sounded like an underground freight train and wisps of dusty sediment were blown up the 27 m long entrance shaft. The source of that wind enticed cave explorers to attempt digging the sediment encrusted breakdown pile at the base of the entrance shaft. Several digging projects were conducted by different caving groups beginning in the 1950's. A group of Colorado cavers re-energized the digging effort in 1984 and in May of 1986 they lucked out when a section of breakdown collapsed into going cave passage (Bridges, 1988). The breakthrough in Lechuguilla Cave would become one of the most significant discoveries of the twentieth century both in terms of cave exploration and cave science (Turin and Plummer, 2000).

The gale-force winds issuing from the breakdown pile in the entrance of Lechuguilla Cave practically guaranteed the existence of a vast cave system. And cave explorers knew that the geology of the area provided the potential for significant depth. The Lechuguilla Cave Project (later replaced by Lechuguilla Exploration and Research Network formed in 1991) was formed in 1987 to provide structure to the systematic exploration effort. Survey standards were established that were similar to those utilized by CRF. However, a much stronger emphasis was placed on vertical control and all surveys were required to include running vertical profiles (Kambesis and Bridges, 1988).

Cave explorers from all over the US and the world participated in the exploration and survey of Lechuguilla Cave. Exploration and mapping moved at breakneck speed with the discovery of 33 km of new passages within the first year (Reames et al., 1999). In order to keep up with the large volume of survey data generated by the exploration effort, computer programs were specifically written to process and plot the survey data (Petrie, 1988). Project members took turns inputting survey data to the ever-expanding database that grew by leaps and bounds after each trip. This mode of exploration and survey assured that the next team who continued the exploration would have a plot of passages that had already been mapped and a view of the relationship between areas of ongoing exploration.

Figure 7. Massive gypsum in Lechuguilla Cave.

This tag-team style of exploration ensured that survey data was continuously being produced for the entire duration of each expedition (Bridges, 1988). Exploration teams consulted the survey notes, line plots, and trip reports, and used the information to plan their next push.

Photography was a regular part of the documentation effort. As exploration progressed, so did photo-documentation of incredible new areas, spectacular speleothems, and highly unusual sediments and mineralogy. Each survey team was required to write a detailed account of their findings, including routes to the survey area, descriptions of unusual cave features, observations about air movement, location of water, and a summary list of unexplored leads. At the end of each expedition, a detailed summary report, with survey statistics, line plots, and trip reports was submitted to the cave specialist at Carlsbad Caverns National Park. Photographs were provided as they became available.

With each expedition, the depth of the cave survey plummeted until it was stopped in the lower part of a water-filled fissure where the cave attained a vertical extent of 489 m (Davis, 1990). Explorers speculated that this was the water table, which was an unprecedented find in any cave of the Guadalupe Mountains (Kambesis, 1991). Exploration reports described the existence of superlative speleothems, some never before documented (Davis, 1990). Fluffy piles of sediment, initially identified as corrosion residues, were observed to occur in hues of tan, red, yellow, black, and brown. Massive gypsum glaciers (Fig. 7) and mounds of sulfur covered the floors of some passages. Though the cave was situated under the Chihuahuan Desert, each expedition revealed the existence of more pools and lakes throughout the vertical extent of the cave. Flowing water was even observed in the Far East section of the cave (Kambesis, 1991). By 1990, the explorers of Lechuguilla Cave had discovered and mapped over 83 km of passages. In 1998 the cave length had reached 166 km with a vertical extent of 489 m.

ON THE HEELS OF EXPLORATION

The availability of line plots and preliminary maps, elevation data, detailed reports, and spectacular photographs from the exploration effort instigated field work for cave research to follow on the heels of exploration.

When the profile map of Lechuguilla Cave was correlated to the stratigraphic section of the Guadalupe Mountains, it revealed that the cave spanned most of the Permian-aged reef complex from the back reef Yates formation, through the massive Capitan Formation and down to the Goats Seep (Jagnow, 1989). The profile illustrated that the cave cut through the heart of the fossil reef (Jagnow, 1989; DuChene, 2000). From the study of cave maps came insights into the characteristic morphologies and patterns of caves formed by sulfuric acid (Palmer, 1991).

Researchers conducted a geologic survey of Lechuguilla Cave and other caves in the Guadalupe Mountains in order to relate geomorphic features of the caves to past hydrologic- and geochemical-dissolution regimes (Palmer and Palmer, 2000). The discovery of alunite, natroalunite, and dickite in Lechuguilla Cave (Palmer and Palmer, 1992), and the subsequent finding of the same minerals plus a suite of uranium-vanadium minerals and hydrobasaluminte in other Guadalupe Mountain caves (Polyak and Mosch, 1995; Polyak and Provencio, 1998) established that these minerals, along with sulfur and gypsum, and the occurrence of gypsum deposits, were characteristic of the sulfuric acid mode of cave dissolution. In addition, the sulfuric acid model of speleogenesis seemed to account for the cave patterns and morphologies, and explained the lack of relationship between surface and cave features in

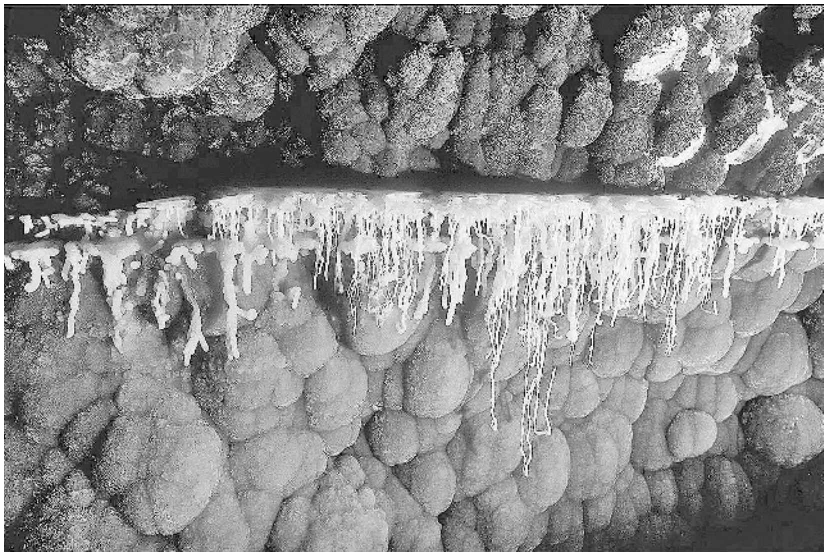

Figure 8. Underwater helictites, Lechuguilla Cave.

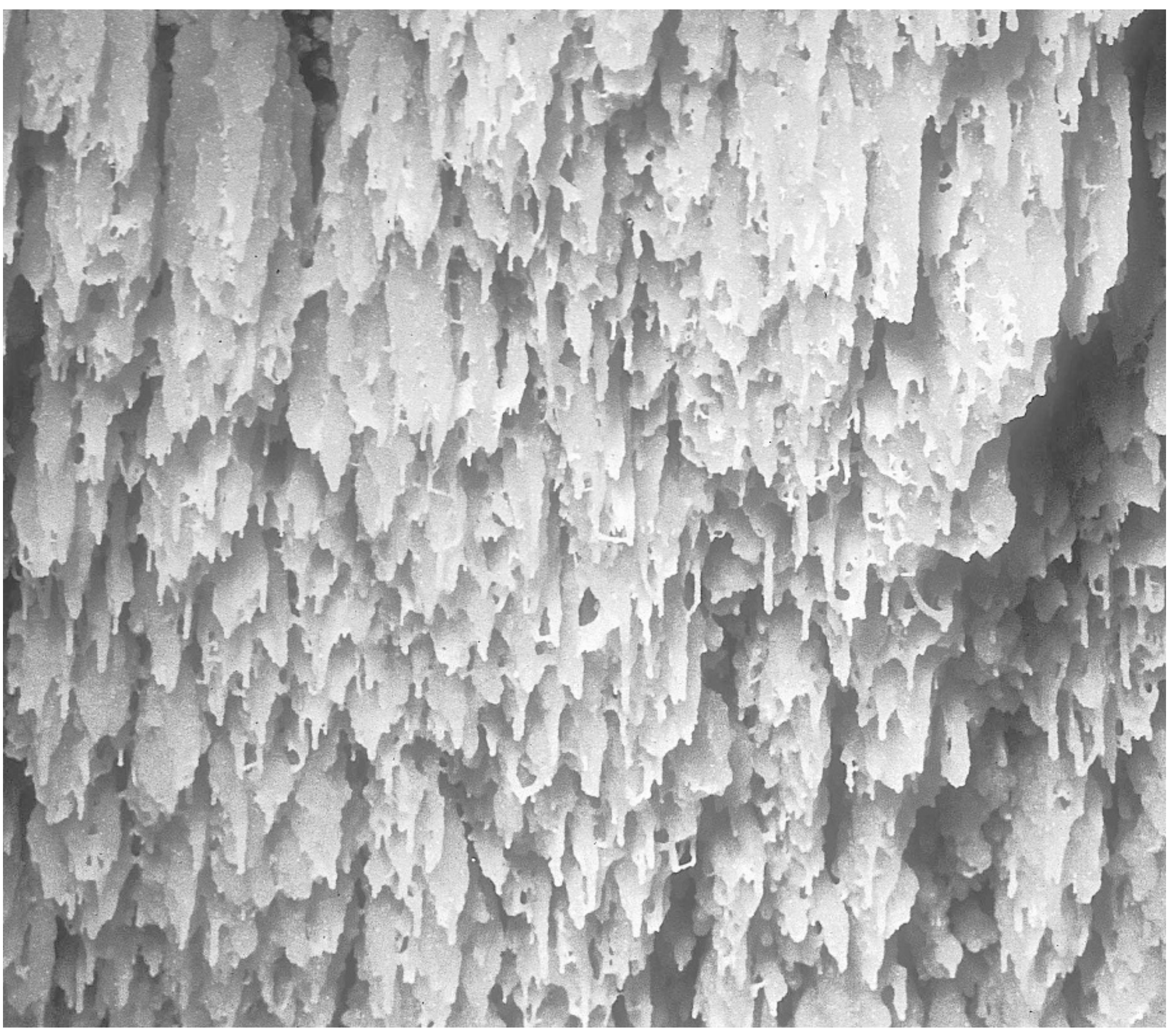

Figure 9. Webulites in Lechuguilla Cave.

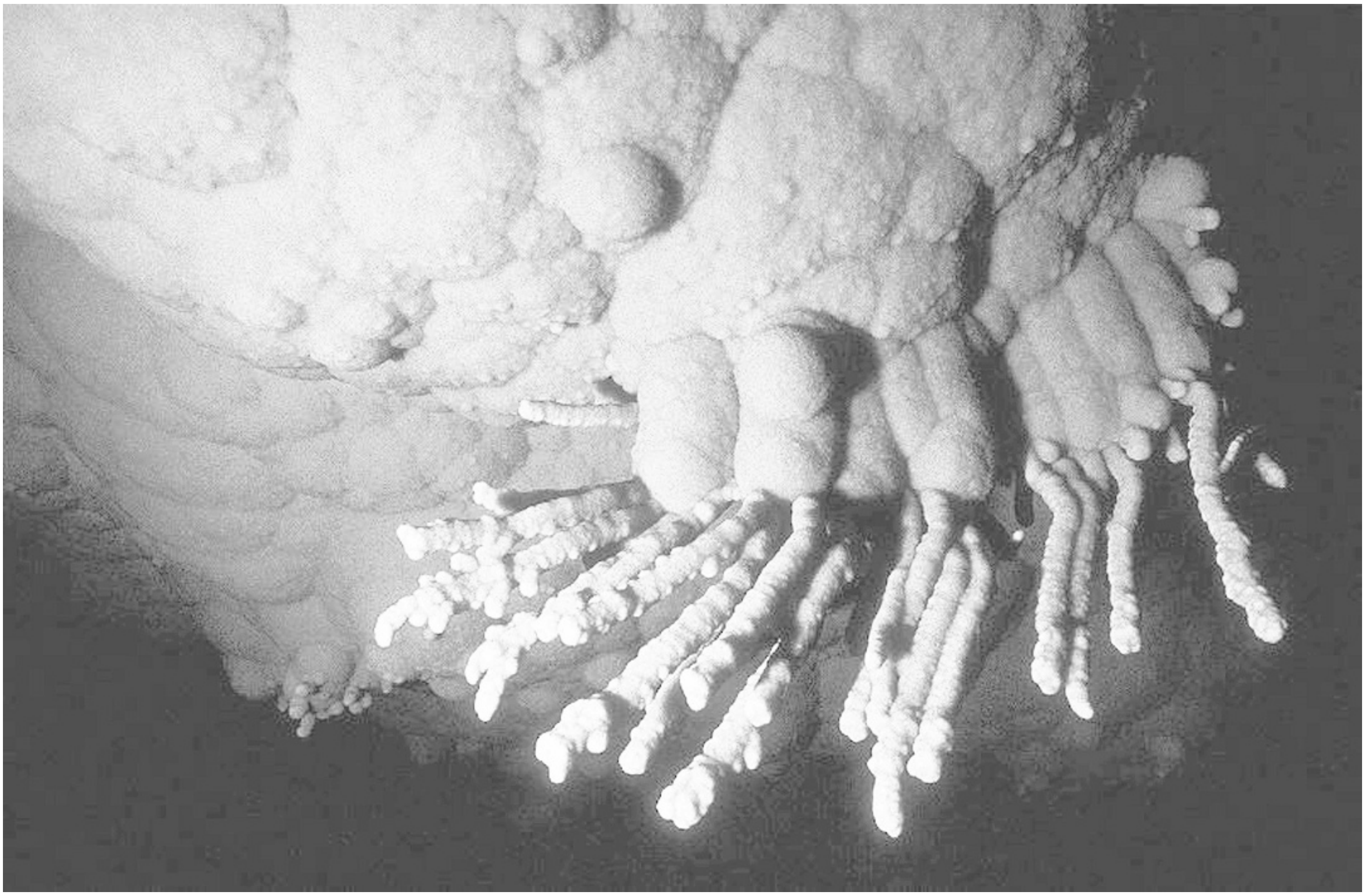

Figure 10. Pool fingers in Lechuguilla Cave.

Guadalupe Mountain caves. The model also established a characteristic set of minerals that were considered definitive indicators of sulfuric acid dissolution. And finally, from $^{40}Ar/^{39}Ar$ dates on alunite, absolute dates were determined for four elevation levels that were correlated across a series of Guadalupe Mountain caves (Polyak and Provencio, 1998).

Water sampling in the numerous pools scattered throughout the vertical extent of Lechuguilla Cave commenced shortly after these features were first reported. Water analyses indicated that the pools represented isolated samples of vadose-zone water infiltrating along separate and independent flow paths (Turin and Plummer, 2000). Pool composition, which is a function of precipitation chemistry, bedrock, and the occurrence of gypsum deposits, could also affect the development of some speleothems such as underwater helictites (Fig. 8). The geochemistry of water from the deep points in the cave confirmed that the water table had indeed been reached (Turin and Plummer, 2000).

Analyses of pieces of some of the more unusual speleothems reported on and collected by cave explorers (with permission of Carlsbad Caverns National Park) revealed a totally unexpected result. Features such as webulites and u-loops (Fig. 9) appeared to be calcified filamentous microorganisms (Cunningham et al., 1995). Pool fingers (Fig. 10) provided evidence of possible bacterial/mineral interaction in their formation (Northup et al., 1997). Iron oxide speleothems (rusticles) showed the presence of organic filaments in their cores (Davis et al., 1990). Corrosion residues, which are common throughout Lechuguilla Cave and also occur in many other caves in the Guadalupe Mountains, are composed of iron oxide and manganese materials containing bacterial and fungal communities (Cunningham, 1991; Cunningham et al., 1995). Northup et al. (1997) proposed that microbes could dissolve cave features via acidic metabolic byproducts.

Recent studies on the ecologic interactions of bacteria that exist in Lechuguilla Cave have shown that the enzymes they produce may be beneficial to the treatment and potential cure for some human diseases (Northup et al., 1997). Researchers from NASA, who have been looking for extreme environments on the earth that may be analogous to life on other planets, have been studying the microorganisms in Lechuguilla Cave (Boston, 2000).

Though exploration and survey have been ongoing in Lechuguilla Cave for the past twenty years, the full extent of the cave system has not yet been realized. Despite great progress in defining the processes that formed the cave, the boundary conditions that resulted in its development are not yet fully understood. As explorers venture into unknown territories in their pursuit of more cave passages, they will uncover more evidence that will result in the continued evolution of theory on Guadalupe Mountain cave development. Cave scientists will continue to pursue the fruits of exploration for analysis and study.

Conclusion

Systematic cave exploration involves not only the physical pursuit and discovery of caves and cave systems, but also includes the systematic documentation of those discoveries. The field documentation that defines systematic cave exploration includes cave and surface surveys, detailed notes and observations, cave and karst feature inventories, and photo-documentation. The data are synthesized into cave maps, narrative descriptions, and reports that can serve as a set of exploration tools for finding more passages and caves and also serve as the baseline for all types of cave-related research. Cave exploration is a fundamental element of cave research and cave-related science.

Acknowledgements

The author would like to thank Dave Bunnell for the photographs that appear in Figures 7 through 10.

References

Bennington, F., 1959, Preliminary identification of crystalline phases in a transparent stalactite: Science, v. 120, p. 1227.

Borden, J.D., and Brucker, R.W., 2000, Beyond Mammoth Cave, Southern Illinois University Press, Carbondale and Edwardsville, Illinois.

Boston, P., 2000, Life Below and Life 'Out There': Geotimes. http://www.agiweb.org/geotimes/aug00/lechuguilla.html

Bretz, J H., 1942, Vadose and phreatic features of limestone caverns: Journal of Geology, v. 50, p. 675–811.

Bretz, J H., 1949, Carlsbad Caverns and other caves of the Guadalupe Block, New Mexico: Journal of Geology, v. 57, p. 447–463.

Bridges, R.A., 1988, Exploration and survey of Lechguilla Cave, New Mexico: National Speleological Society News, v. 46, p. 372–76.

Brucker, R.W., 1966, Truncated Cave Passages and Terminal Breakdown in the Central Kentucky Karst: Bulletin of the National Speleological Society, v. 28, p. 171–178.

Brucker, R.W., Smith, P.M., Lawrence, J.D., and Jones, D.B., 1966, Some new approaches to speleology, *in* Cave Research Foundation, Origins and the first twelve years, Watson, R.W., ed., p. 49–60.

Brucker, R.W., Hess, J.W., and White, W.B., 1972, Role of vertical shafts in movement of groundwater in carbonate aquifers: Ground Water, v. 10, p. 5–13.

Brucker, R.W., and Watson, R.A., 1976, The Longest Cave, Cave Research Foundation, Knopf, New York.

Cave Research Foundation, 1957–1965, unpublished reports.

Cave Research Foundation, 1961, Biology and Ecology of Cathedral Cave, *in* CRF Third Annual Report to the Park Service, Brucker, R., ed., p. 10.

Cave Research Foundation, 1966, Map of Flint Ridge System, *in* CRF 1966 Annual Report, Brucker, B., ed., Yellow Springs, Ohio, p. 21.

Cave Research Foundation, 1976, Stephen Bishop map of the Mammoth Cave System 1842, *in* CRF 1976 Annual Report, Cave Research Foundation, Yellow Springs, Ohio, p. 15.

Coons, D.E., 1978, Cartography and Exploration: Uplands Research Laboratory: Cave Research Foundation Annual Report, Cave Research Foundation, Yellow Springs, Ohio, p. 11.

Cunningham, K.I., 1991, Preliminary report on the organic and inorganic composition of colored corrosion residues, Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico: NSS News, v. 49, no. 8, p. 252–254.

Cunningham, K.I., and LaRock, E.J., 1991, Recognition of microclimate zones through radon mapping, Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico: Health Physics, v. 61, p. 493–500.

Cunningham, K.I., Northup, D.E., Pollastro, R.M., Wright, W.G., and LaRock, E.J., 1995, Bacteria, fungi and biokarst in Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico: Environmental Geology, v. 25, p. 2–8.

Davis, D.G., 1973, Sulfur in Cottonwood Cave, Eddy County, New Mexico: Bulletin of the National Speleological Society, v. 35, p. 89–95.

Davis, D.G., 1990, Lechuguilla: A view of the eighties: Rocky Mountain Caving, v. 7, p. 32.

Davis, D.G., Palmer, A.N., and Palmer, M.V., 1990, Extraordinary subaqueous speleothems in Lechuguilla Cave, New Mexico: Bulletin of the National Speleological Society, v. 52, no. 2, p. 70–86.

Davies, W.E., 1951, Mechanics of cavern breakdown: Bulletin of the National Speleological Society, v. 13, p. 36–43.

Davis, W.M., 1930, Origin of limestone caverns: Geological Society of American Bulletin, v. 43, p. 475–528.

DuChene, H., 2000, Bedrock Features of Lechuguilla Cave, Guadalupe Mountains, New Mexico: Journal of Cave and Karst Studies, v. 62, p. 109–119.

Egemeier, S.J., 1971, A comparison of two types of solution caves: Unpublished report to Carlsbad Caverns National Park, April 12: 7 p.

Frank, E.F., 1988, Cave History: NSS News, v. 46, p. 378–79.

Groves, C., and Meiman, J., 2001, Inorganic carbon flux and aquifer evolution in the South Central Kentucky Karst, *in* U.S. Geological Survey Karst Interest Group Proceedings: Water-Resources Investigations Report 01-4011, p. 99–105.

Groves, C., Vaughan, K., and Meiman, J., 2001, Karst aquifer conduit sediment interstitial fluids and aquifer evolution, Geological Society of America Abstracts with Program, November 2001.

Granger, D.E., Fabel, D., and Palmer, A.N., 2001, Pliocene-Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave sediments: Geological Society of America Bulletin, v. 113, p. 825–836.

Hess, J.W., and White, W.B., 1973, Hydrology of the Central Kentucky Karst: Cave Research Foundation Report 1973, Yellow Springs, Ohio, p. 21–24.

Hess, J.W., and White, W.B., 1974, Evolutionary Trends in Groundwater geochemistry in the Central Kentucky Karst, Cave Research Foundation Report 1974: Cave Research Foundation, Yellow Springs, Ohio, p. 22–26.

Hill, C.A., 1981, Speleogenesis of Carlsbad Caverns and other Caves in the Guadalupe Mountains, *in* Beck, B.F., ed., Proceedings of the International Congress of Speleology, Bowling Green, Kentucky, p. 143–44.

Jagnow, D.H., 1978, Geology and speleogenesis of Ogle Cave, New Mexico: Bulletin of the National Speleological Society, v. 40, p. 7–18.

Jagnow, D.H., 1989, The geology of Lechuguilla Cave, New Mexico, *in* Harris, P.M., and Grover, G.A., eds., Subsurface and outcrop examination of the Capitan shelf margin, northern Delaware Basin: Society of Economic Paleontologists and Mineralogists Core Workshop No. 13, p. 459–466.

Jagnow, D.H., Hill, C.A., Davis, D.G., DuChene, H.R., Cunningham, K.I., Northup, D.E., and Queen, J.M., 2000, History of sulfuric acid theory of speleogenesis in the Guadalupe Mountains, New Mexico and west Texas: Journal of Cave and Karst Studies, v. 62, p. 54–59.

Kambesis, P., 1991, 50 mile plus — when will it end? More on Lechuguilla Cave: National Speleological Society News, v. 53, p. 300–305.

Kambesis, P., 2003, Subterranean field studies in Lechuguilla Cave, New Mexico, South-Central Section (37th) and Southeastern Section (52nd): Geological Society of America Joint Annual Meeting, Abstract.

Kambesis, P., and Bridges, R., 1988, Survey Methods and Standards used by the Lechuguilla Cave Project: NSS News, v. 46, p. 400–401.

Kane, T.C., and Poulson, T.L., 1976, Foraging of Cave Beetles: Spatial and Temporal heterogeneity of Prey: Ecology, v. 57, p. 793–800.

Kunath, C.E., 1978, History, *in* The Caves of McKittrick Hill, Eddy County, New Mexico, History and Results of Field Work 1965–1976: Texas Speleological Survey, p. 2–18.

Lee, Willis T., 1924, A visit to Carlsbad Caverns: National Geographic Magazine, v. XLV, p. 1–40.

Lee, Willis T., 1925, New Discoveries in Carlsbad Caverns: National Geographic Magazine, v. XLVII, p. 301–320.

Lindsey, P., and Lindsey, K., 1978, Dry Cave, in The Caves of McKittrick Hill, Eddy County, New Mexico, History and Results of Field Work 1965–1976: Texas Speleological Survey, p. 36–46.

Martel, E.A., 1912, Explorations sur Mammoth Cave: Spelunca, v. 9, 64 p.

Miotke, F.D., and Palmer, A.N., 1972, Genetic relationships between caves and landforms in the Mammoth Cave National Park Area, Verlag, Wurtzburg, Bholer, 69 p.

Miotke, F.D., 1975, Der Karst in zentralen Kentucky bei Mammoth Cave: Geog. Geseel, Hannoer, Jahrf. Fur 1973, 360 p.

Northup, D.E., Lavoie, K., and Mallory, L., 1997, Microbes in Caves: NSS News, v. 5, p. 111.

Nymeyer, R., 1978, Carlsbad, Caves, and a Camera, Zephyrus Press, Inc., Teaneck, New Jersey, 318 p.

Palmer, A.N., 1987, Cave levels and their interpretation: Bulletin of the National Speleological Society, v. 49, p. 50–66.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1–21.

Palmer, A.N., and Palmer, M.V., 1992, Geochemical and petrologic observations in Lechuguilla Cave, New Mexico, *in* Ogden, A.E., ed., Friends of Karst Meeting [abs.]: Proceedings, Tennessee Technological University, Cookeville, Tennessee, p. 25–26.

Palmer, A.N., and Palmer, M.V., 2000, Hydrochemical interpretation of cave patterns in the Guadalupe Mountains, New Mexico: Journal of Cave and Karst Studies, v. 62, p. 91–108.

Palmer, A.N., Palmer, M.V., and Queen, M.J., 1977, Speleogenesis in the Guadalupe Mountains, New Mexico: Gypsum replacement of carbonate by brine mixing, *in* 7th International Speleological Congress Proceedings, p. 333–336.

Petrie, G., 1988, The Dawning of the Age of High Tech Cave Surveying: National Speleological Society News, v. 46, p. 402–404.

Pohl, E.R., 1955, Vertical shafts in limestone caves, Occasional Paper No. 2, National Speleological Society, p. 5–22.

Polyak, V.J., and Mosch, C.J., 1995, Metatyuyamunite from Spider Cave, Carlsbad Caverns National Park, New Mexico: Bulletin of the National Speleological Society, v. 57, p. 85–90.

Polyak, V.J., and Provencio, P., 1998, Hydrobasaluminite and aluminite in caves of the Guadalupe Mountains, New Mexico: Journal of Cave and Karst Studies, v. 60, p. 51–57.

Poulson, T.L., 1991, Assessing groundwater quality in caves using indices of biological integrity, *in* Proceedings of the Third Conference of Hydrology, Ecology, Monitoring and Management of Groundwater Karst Terrains, December 1991, Nashville, Tennessee, p. 495–511.

Poulson, T.L., Lavoie, K.H., and Helf, K., 1995, Long-term effects of Weather on the Cricket (*Hadoneoecus subterraneus*, *Orthoptera, Rhaphidophoridae*), Guano Community in Mammoth Cave National Park: American Midland Naturalist, v. 134, p. 226–234.

Queen, M.J., 1973, Large scale replacement of carbonate by gypsum in some new Mexico caves [abs.]: National Speleological Society Program, 30th Anniversary, p. 12.

Quinlan, J.F., 1989, Groundwater monitoring in karst terrains: recommended protocols and implicit assumptions: Las Vegas, Nev., U. S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, EPA/600X-89/050, 100 p.

Quinlan, J.F., Ewers, R.O., Ray, J.A., Power, R.L., and Krothe, Noel C., 1983, Hydrology and geomorphology of the Mammoth Cave Region, Kentucky, and of the Mitchell Plain, Indiana, *in* Shaver, R.H., and Sunderman, J.A., eds., Field Trips in Midwestern Geology: Bloomington, Indiana, Geological Society of America and Indiana Geological Survey, v. 2, p. 1–85.

Reames, S., Fish, L., Burger, P., and Kambesis, P., 1999, Deep Secrets, The Discovery and Exploration of Lechuguilla Cave, Cave Books, St. Louis, Missouri.

Selcer, R.F., 2006, Carlsbad Caverns, Primedia Publications, http://away.com/primedia/pol_soc/carlsbad_Caverns_1.html

Smith, A.R., 1978, Geology *in* The Caves of McKittrick Hill, Eddy County, New Mexico, History and Results of Field Work 1965–1976: Texas Speleological Survey, p. 56–68.

Smith, P.M., 1957, Discovery in Flint Ridge, 1954–57: Bulletin of the National Speleological Society, v. 19, p. 1–10.

Smith, P.M., 1960, Speleological Research in the Mammoth Cave Region, Kentucky: elements of an Integrated Program: Cave Research Foundation Annual Report 1957–1968, 18 p.

Smith, P.M., 1964, The Flint Ridge Cave System: 1957–1962: Bulletin of the National Speleological Society, v. 26, p. 17–27.

Smith, P.M., and Watson, R.A., 1970, The Development of the Cave Research Foundation: Studies in Speleology, v. 2, Part 2, 81 p.

Turin, H.J., and Plummer, M.A., 2000, Lechuguilla Cave Pool Chemistry, 1986–2000: Journal of Cave and Karst Studies, v. 62, p. 135–143.

Watson, P.J., 1969, The Prehistory of Salts Cave, Kentucky: Illinois State Museum Reports of Investigations, no. 16, 86 p.

Watson, P.J., 1992, The origins of food production in Western Asia and Eastern North America, *in* Shane, L., Shane, O., and Cushing, E., eds., Quaternary Landscapes, University of Minneapolis Press, Minneapolis.

Watson, R., ed., 1981, Cave Research Foundation: Origins and the first 12 years, CRF, Mammoth Cave, KY.

Watson, R., and White, W.B., 1985, The History of American Theories of Cave Origin: Geological Society of America Centennial Special, v. 1, p. 109–123.

White, J., 1932, Jim White's Own Story, The discovery and history of Carlsbad Caverns by James Larkin White, The Cave's Original Discovered and Explorer, as told to Frank Ernest Nicholson, copyright 1932 by Jim White and Charley Lee White.

White, W.B., 1973, Some Hindsights, an overview and perhaps a bit of Foresight: Cave Research Foundation Annual Report 15, p. 2–4.

White, W.B., 1976, Conceptual Models for Carbonate Aquifers, Cave Research Foundation Annual Report 1976: Cave Research Foundation, Yellow Springs, Ohio.

White, W.B., 1988, Geomorphology and Hydrology of Karst Terrains, Oxford University Press, New York, 464 p.

White, W.B., Watson, R.A., Pohl, E.R., and Brucker, R., 1970, The Central Kentucky Karst: The Geographical Review, v. 60, p. 88–114.

Zopf, R.B., 1982, Cartography and exploration in the Mammoth Cave Region, *in* Cave Research Foundation Annual Report 1982, Palmer, M.V., ed., 34 p.

[1] Editor's Note: Quinlan (1989) has never been published although it was released selectively in draft form.