

# CAVE GEOLOGY AND SPELEOGENESIS OVER THE PAST 65 YEARS: ROLE OF THE NATIONAL SPELEOLOGICAL SOCIETY IN ADVANCING THE SCIENCE

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**Abstract:** The National Speleological Society was founded in 1941, near the end of a remarkable period in the history of speleogenesis. Many well-known geologists had published on the topic during the previous decade. For various reasons the NSS did not benefit from this wave of interest, and its members were faced with reconstructing the subject from a fresh beginning. The topic was developed mainly by individuals who started as cave explorers and extended that interest into science. Some of the advances over the past 65 years include new field and laboratory techniques, models of cave origin, introduction of sulfuric acid speleogenesis, coastal cave studies, recognition of microbial mediation of cave processes, geochronology and paleoclimatology, digital modeling, and growing attention toward lava caves.

## INTRODUCTION

Since its founding in 1941, the National Speleological Society (NSS) has grown from a small regional group into one of the world's largest and most influential organizations in cave science. Over the past 65 years it has helped to foster some of the most notable advances in cave geology and speleogenesis. This paper concerns the history of this field and the role that the NSS has played in its development. There is no need for a rigorous historical record or a detailed description of ideas, as these are provided in recent books edited by Klimchouk et al. (2000), Gunn (2004), and Culver and White (2005). Instead, the aim is to look behind the scenes at the interaction among cave geologists and how their ideas developed.

In summarizing the advances in karst geology for the 25<sup>th</sup> anniversary of the NSS, Davies (1966) noted that early progress in that field had taken place in spurts, with intervening periods of relative inactivity. He predicted a burst of quantitative advances in speleology in the years to come, and the validity of his prediction is illustrated here.

## BEGINNINGS

The NSS was conceived, as Dickens would have said, in both the best of times and the worst of times. During the prior decade there had been a flowering of interest in cave origin, and many of the classic American papers on the subject were produced at that time. The authors include some of history's best-known geologists. William Morris Davis, who wrote a 154-page paper on cave origin (Davis, 1930), is probably the most influential geomorphologist who ever lived. J Harlen Bretz (no period after the J) was one of America's boldest and clear-sighted geologists. Most of his work on caves followed the birth of the NSS (e.g.,

Bretz, 1942), but he had made his reputation long before. Clyde Malott, who was among Indiana's foremost stratigraphers and geomorphologists, devoted much of his attention for several decades to caves and karst (e.g., Malott, 1937). Allyn Swinnerton was a well-known professor of geology at Stanford, Harvard, and Antioch College (Swinnerton, 1932).

There was considerable disparity of opinion among these early authors. Davis and Bretz championed deep-phreatic cave origin. Swinnerton favored cave origin at or just below the water table. Malott described caves in terms of invasion by surface streams. This brief outline does no justice to any of the authors and omits many others, but it is enough to set the stage. For details see Watson and White (1985) and Lowe (2000).

The founding of the NSS near the end of this period placed it in a position to ride the wave of enthusiasm for speleogenesis, but for several reasons the organization gained little benefit from it. First, none of the contributors to the classic papers were involved in founding the Society. The founders were mainly cave explorers, and although they regarded science as important, they had few credentials in the field.

A second problem was that the ideas developed during this classic period of speleogenesis contradicted one another. They were published before cave maps were widely available, and interpretations lacked the benefit of diverse field experience. With no consensus, it seemed that little solid ground had been gained.

Continental Europeans, with their long tradition in cave science, were astonished by the many contradictory American models for cave origin. The well-known French speleologist Bernard Gèze once said (translated loosely from Trombe, 1952), "It seems that the Americans are trying to reinvent speleology right from square one." But at the same time, western Europeans made almost no

reference to the vast amount of contemporary work accomplished in eastern Europe. This insular attitude can be clearly traced to the barriers of language, geography, and politics. The field is much more cosmopolitan today.

The growth of science within the NSS is clear from the first 10–20 years of the *Bulletin of the National Speleological Society* (now the *Journal of Cave and Karst Studies*). *NSS Bulletin* No. 1 was published by the short-lived precursor of the NSS, the Speleological Society of the District of Columbia. Its cover includes a cartoon of a group of cavers scrambling over stalagmites, with one team member burning the seat of the person ahead with his carbide lamp. The issue contains mainly trip reports, and although each shows a well-defined purpose, there is no coordinated scientific focus. Interest in science grew, however, and within a few years scientific articles dominated the *Bulletin*. Several of the early champions of cave geology, including Malott, Swinnerton, and Bretz, were made honorary NSS members, and they responded favorably by contributing articles. American studies of speleogenesis began gradually to rebuild. In 1949 the *Bulletin* included papers on the subject by Ralph Stone and Clyde Malott. In 1950, Allyn Swinnerton contributed a paper on cave mapping, but he did not pursue his ideas on cave origin.

#### A FORK IN THE ROAD

There may be a reason for Swinnerton's diminished interest in speleogenesis. In 1940, one of the greatest figures in petroleum geology and hydrology, M. King Hubbert, published a seminal paper, *The theory of groundwater motion*, in the *Journal of Geology*, in which he developed the principles of hydraulic potential and the influence of potential fields on ground-water motion. In it, he explicitly criticized Swinnerton's diagrams of cave origin for being incompatible with potential theory and violating the law of conservation of mass. Although Hubbert was not entirely wrong, he failed to take into account the distortion of laminar ground-water patterns by conduit growth (Hubbert, 1940).

Hubbert's paper was hardly noticed by speleologists at that time, but it was a turning point for ground-water hydrologists. For many, ground water became a technical field that relied as much on mathematics and physics as on geology. Today Hubbert is best remembered for his concept of peak oil, but his legacy in hydrology also lives on.

Although no one realized it at the time, this was the third and greatest obstacle faced by cave geologists during the early years of the NSS. Since the turning of hydrology in mathematical directions, speleology has been dismissed as hardly a science at all by most hydrologists, the very people who could benefit the most from cave geology.

#### A FRESH START

By the 1950s, several NSS members emerged as leaders in cave geology. Ralph Stone (former State Geologist of Pennsylvania) contributed an entire *NSS Bulletin* on Caves of Pennsylvania (Stone, 1953) an update of work that he had prepared earlier for the State Geological Survey, and which includes considerable geologic detail. William Davies, of the U.S. Geological Survey, wrote books on the caves of Maryland (Davies, 1950) and of West Virginia (Davies, 1959). He also advanced the study of speleogenesis with observations of cave levels and their correlation with river terraces (e.g., Davies, 1957). Both he and Stone served as NSS president. Bretz wrote a book on caves of Missouri (Bretz, 1956) and co-authored another on the caves of Illinois (Bretz and Harris, 1961). E.R. Pohl, long-time Kentucky geologist and one of the founders of the Cave Research Foundation, contributed important work on the origin of vertical shafts in limestone caves (e.g., Pohl, 1955).

George Moore, of the U.S. Geological Survey, recognized that it was time for American speleologists to review the status of speleogenesis. In 1959, he convened a symposium on cave origin, sponsored jointly by the NSS and the Geological Society of America. The proceedings were published as *NSS Bulletin* 22, No. 1 (Moore, 1960). This was probably the most important point in NSS history in terms of advancing the field of speleogenesis. Besides Moore, participants included Bretz, Davies, Rane Curl, George Deike, William Halliday, Arthur Lange, John Thraillkill, and William White. Bretz and Davies were already well known in the field, and each of the others also went on to make substantial contributions to speleogenesis. Some are still active in cave geology today.

White (1959) had already published a discussion of speleogenesis in his local grotto newsletter. He reviewed the classic papers of the 1930s and early 1940s and came to the conclusion that no one agreed on anything. But it was made clear during the 1959 symposium that much of the confusion was only a matter of conflicting terminology. In the words of Halliday (1960),

There seems to be less and less divergence of basic concepts, and more and more argument over classification and terminology, which can be carried to the point that two authorities holding similar views are unable to recognize their agreement.

This warning applies as well today as it did in 1959. But at that time, field experience and cave data were growing rapidly, and the answers to many fundamental questions in speleogenesis seemed within reach. Little did the symposium participants realize how far they had to go.

#### PHYSICS AND CHEMISTRY ENTER THE PICTURE

An understanding of speleogenesis requires as much knowledge of hydraulics and chemical kinetics as it does of

geology. Laboratory experiments by non-speleologists Kaye (1957) and Weyl (1958) showed that the rate of limestone dissolution depends on the velocity of acidic water. This approach promised to solve some of the basic questions about cave origin, but they used hydrochloric acid, which behaves differently from carbonic acid, which is involved in most cave development, and so the results were not as helpful as they once seemed. They did, however, point the way. From his experiments, Weyl estimated that acidic water could not penetrate very far along a typical fracture in limestone before losing most of its solutional capacity.

On the basis of this research, William White and Judith Longyear concluded that none of the previous conceptual models of cave origin were incorrect, but that they were all irrelevant. In each model, caves were tied to their position relative to the water table, whereas, in fact, they form wherever the ground-water flow is greatest (White and Longyear, 1962). White and Longyear also predicted a substantial jump in dissolution rate when the flow changes from laminar to turbulent as the conduit grows.

Alan Howard applied chemistry and hydraulics to cave origin and estimated that the laminar-turbulent transition would increase the solution rate by a few times (Howard, 1964a). This estimate was much smaller than White and Longyear's, but more accurate. Several other projects and academic dissertations by NSS members were devoted to pursuing the kinetics of carbonate dissolution, with the specific goal of clarifying rates of cave origin (e.g., Howard and Howard, 1967; Rauch and White, 1970; Herman and White, 1985).

The idea of a threshold in cave development was expanded further by White (1977). He noted that as a cave grows and its flow becomes turbulent, the water also acquires the ability to transport sediment at nearly the same time. From then on, sinkholes open more rapidly, and abrasion can augment the dissolution rate in caves. White also applied experimental data from Plummer and Wigley (1976) to show that, in a typical cave, the dissolution rate of calcite increases abruptly at about the same time as the onset of turbulence and sediment transport. All three processes enhance the growth rate of caves at more or less the same point in a cave's evolution.

Rane Curl, since the late 1950s, had been concerned with the origin of solutional scallops in the bedrock surfaces of caves. By applying hydraulics and dimensional analysis, he showed how it is possible to determine past flow velocities from scallop lengths. This gave a great boost to the interpretation of cave paleohydraulics. His latest paper on the topic (Curl, 1974) is the most accessible.

Curl also investigated the statistical aspects of cave distribution and morphology. By quantifying these variables, the processes that form caves can be discriminated. He continued to pursue these topics for several decades (e.g., Curl, 1986). This approach is useful to scientists, such as petroleum geologists, who need to predict the distribution of porosity.

Similar advances were taking place simultaneously in Europe. It is worth noting how bursts of activity often take place almost simultaneously around the world under the direction of a few leading researchers, as suggested by Davies (1966). Today, with rapid worldwide communication, this tendency is even more prevalent.

#### ACADEMIC ALLIANCES

William White became a professor at Pennsylvania State University, where he nurtured a long string of graduate students with interests in cave geology and hydrology, as he continues to do today in semi-retirement. Speleogenesis was gradually becoming inseparable from karst hydrology. One by one, he and his students tackled the fundamental problems in these fields.

In the early 1960s, Derek Ford arrived in North America from Britain and soon joined the faculty at McMaster University (Hamilton, Ontario). He threw himself into exploring and interpreting the karst of his vast new homeland and almost singlehandedly put Canada on the map of important karst regions. He joined the NSS and began publishing in the *Bulletin*. A large number of talented graduate students obtained their training under his direction, and the list continues to grow today.

A steady stream of karst scientists from overseas began to pass through both McMaster University and the Pennsylvania State University to observe the research programs at these schools and often to linger as visiting scholars. Inevitably, the two groups began to meet periodically to combine socializing and science. Karst geology and speleogenesis were among the main topics of discussion. These occasional meetings were so successful that other karst scientists began to take part from all over the continent. Soon some of the meetings were held at other locations. In 1974, at a meeting at the University of West Virginia, the still-informal group acquired the name Friends of Karst. There were no rules, no official membership, officers, dues, or newsletter. Since then, many FOK meetings have been held throughout North America, as well as in Puerto Rico, San Salvador, and Romania.

Meanwhile, several Penn State and McMaster students went on to establish their own academic programs in karst or related fields, while similar programs at other universities sprouted from different seeds. A spirit of camaraderie bound them all together, as it still does today, partly owing to the eclectic nature of cave science. It is difficult to retain one's professional dignity while crawling through mud. Some of the unity also stemmed from the impression that few other people seemed to care about caves.

#### DEVELOPMENTS IN CAVE GEOLOGY

Early studies of speleogenesis were hampered by the paucity of field data on cave geology. In the first half of the 20<sup>th</sup> century there was almost no quantitative information

on the relation between caves and their surrounding geology, beyond visual and non-systematic observations. At that time, the situation was more favorable in Europe, where standards of cave mapping were more advanced. By the late 1940s, American geologists began to relate cave patterns to details in the surrounding geology. Such studies were most numerous in the Appalachians (E.L. Krinitzky, 1947; Davies, 1959, 1960; Deike, 1960), and in Mammoth Cave, Kentucky (Deike, 1967). In the Black Hills of South Dakota, Deal (1962) and Howard (1964b) related Jewel Cave and Wind Cave to their complex geologic and hydrologic settings.

In the 1960s, Richard Powell, of the Indiana Geological Survey, developed hand-leveling techniques to map the subtle geologic structure of caves in strata with dips so gentle that they cannot be distinguished by eye. His work at Wyandotte Cave, Indiana, was perhaps the first of its type (Powell, 1968, 1976). His associates, Arthur and Margaret Palmer, extended the technique to caves elsewhere in the country (e.g., Palmer, 1972, 1989). Recently, Roy Jameson has used the leveling method to obtain even greater detail through an analysis of the individual segments in each cave passage (Jameson, 1985, 2006).

This work showed that even in places of almost negligible dip, the trends of many cave passages are controlled by local structures that are too subtle to appear on geologic maps based on surface exposures. Such details provide the necessary criteria for distinguishing whether cave levels (i.e., stories, or tiers) are controlled by geomorphic events, by geologic structure, or by favorable stratigraphy. Earlier studies, such as those of Davies (1957) showed a general relationship between cave elevations and river terraces. Detailed geologic mapping makes it possible to validate the relationship between cave levels and former base levels in some caves (e.g., Powell, 1970) and to reject the relationship in others (e.g., Palmer and Palmer, 1989). As a complication, stress release around entrenched surface valleys helps to localize cave development (Sasowsky and White, 1994). As the dating of cave deposits becomes more sophisticated, caves that are convincingly related to base-level history can be used to interpret the drainage history of entire drainage basins (e.g., Granger et al., 2001; see details below).

Specialized topics in cave geology have emerged. In cave mineralogy, for example, Moore (1952) promoted the word *speleothem* to refer to secondary mineral deposits in caves. The literature on the subject is so vast that readers are referred simply to the massive summary by Hill and Forti (1997). By comparison, detrital cave sediments have received little attention, even though they are integral features of caves and important to cave development. Studies by William Davies and E.C.T. Chao at Mammoth Cave showed how it was possible to interpret source areas for cave sediments (Davies and Chao, 1959). Elizabeth and William White described the dynamics of sediment transport through caves and the relationship between sediments and cave origin (White and White, 1968). Current

knowledge on cave deposits, both mechanical and chemical, is summarized in a book edited by Sasowsky and Mylroie (2004).

A common topic at meetings is the regional approach to karst and cave science, in which all aspects of the subject are discussed within a given geomorphic province. An example is the Appalachian Karst Symposium, held at Radford University, Virginia, with proceedings edited by Kastning and Kastning (1991).

In recent decades, cave scientists have begun to apply their knowledge to other fields not generally associated with caves. Examples include the relationship of caves to petroleum geology and mining (Furman, 1993; Hill, 1995), dolomitization (Thrailkill, 1971), the evolution of porosity in carbonate rocks (Queen, 1973, 1994), and the interpretation of tectonic history from the distribution of caves (DuChene and Cunningham, 2006). Other examples of how caves can provide information about the geologic history of the surrounding region are described below.

#### CONCEPTUAL MODELS OF CAVE ORIGIN

Devising conceptual models of cave origin continues to be a common goal of American speleologists. The tangled web left from earlier decades has finally been sorted out, so that the disparate interpretations finally made sense. None of the early work has been discarded. Instead it is periodically re-examined in the light of new knowledge and incorporated into new models where appropriate. Over the past few decades, several conceptual models have been proposed in an attempt to explain the origin of all caves with a single model.

#### RELATION TO AQUIFER TYPE

William White described karst aquifers according to their hydrogeologic settings and noted the types of caves that were most typical in each (White, 1969 and later). Diffuse-flow aquifers contain few caves, and they tend to be small and irregular. Free-flow aquifers may or may not be overlain by an insoluble cap-rock. Sinkholes are the main water inputs in the exposed type, and short caves with high sediment load are common. Capped aquifers are fed by vertical shafts around the eroded perimeters of the cap-rock, and long integrated caves extend beneath the cap-rock. Confined aquifers in which impermeable beds force water to flow below the regional base level tend to contain inclined three-dimensional mazes, and the sandwich variety of confined aquifer, which is confined between thin impermeable beds, contains horizontal two-dimensional mazes.

#### RELATION TO FISSURE FREQUENCY

Derek Ford proposed a model of cave patterns based on the evolution of fissure frequency (spatial density) within an aquifer (Ford, 1971). Fissure frequency is low at first but increases with time as erosion and cave development proceed. The result is a four-state model: (1) At low fissure

frequency only a few phreatic loops develop, which extend well below the water table and rise in their downstream ends. (2) With increasing fissure frequency, loops become more abundant but shallower. The water table drops as the permeability increases. (3) Eventually a mixture of phreatic and water-table cave segments develops. (4) Fissure frequency may become so great that phreatic loops cannot form, and cave passages develop almost entirely along the water table. Many caves exhibit more than one state, or they may bypass one or more of them. Two other conditions are possible (Ford, 1988): state 0, in which no fissures at all are present and caves cannot develop; and state 5, in which there are so many small openings that ground water is too diffuse to form significant caves. Artesian conditions are considered a special case in which maze caves form by slow, lengthy dissolution.

#### LINKAGE OF CAVE PASSAGES

Ralph Ewers demonstrated how individual cave passages link together to form complex caves (Ewers, 1982). Given various inputs at different distances from an outlet, those with the shortest paths are the first to form cave passages. Incipient caves fed by multiple inputs compete with each other, and the first to break through to a spring outlet becomes the main conduit. As the head decreases in the main passage, the flow from more remote inputs is drawn toward it to form tributaries. To develop these concepts, Ewers used models constructed of gypsum, plaster, and salt, into which he injected water under pressure along artificially prepared fissures. In some the water was injected along the flat bottom of the soluble block and viewed from below through a transparent bladder pressed against the block. The linkage mechanism is so robust that there was little or no interference caused by the contrasts in hydraulic gradient and dissolution kinetics between the models and real karst aquifers. As these ideas developed, they were combined with those of Ford in a single paper (Ford and Ewers, 1978).

#### ORIGIN OF CAVE PATTERNS

Arthur Palmer attributed branchwork caves to recharge through karst surfaces (e.g., through sinkholes and minor sinking streams) (Palmer, 1975). In contrast, he considered that maze caves form either by intense floodwaters (e.g., by recharge from major sinking streams) or by diffuse recharge such as seepage into soluble rock through overlying or underlying insoluble rocks. The model was later expanded (Palmer, 1991) by combining hydraulics and chemical kinetics, with the aid of earlier measurements of limestone dissolution rate (e.g., Plummer et al., 1978): Early cave enlargement depends on the ratio of discharge  $Q$  to flow length  $L$  ( $Q/L$ ). The enlargement rate increases with  $Q$ , but only up to a certain limit. Further increase in  $Q$  raises the enlargement rate only slightly. For a flow path to grow into a cave, its discharge must increase with time. Only a few of the original flow paths reach cave size, as is

typical of branchwork caves. The exception is where all openings grow at high rates from the beginning, to form maze caves, in which many alternate routes have large  $Q/L$ . Examples include recharge through an adjacent insoluble rock (small  $L$ ), or periodic floodwaters (large  $Q$ ). Aggressiveness produced by mixing, oxidation of sulfides, or cooling of thermal water also tends to produce mazes. Fully confined artesian conditions are not sufficient by themselves to form maze caves. The time required to form a cave increases with flow distance and temperature, and decreases with initial fissure width, hydraulic gradient, and  $\text{CO}_2$  concentration.

#### VERTICAL LAYOUT OF CAVES

Stephen Worthington, as an outgrowth of his 1991 Ph.D. dissertation at McMaster University, contributed two important papers on the vertical distribution of cave passages (Worthington, 2004, 2005). He notes that most large springs draining regional karst aquifers have high sulfate concentrations, and that the caves being initiated within them must encounter soluble gypsum or anhydrite beds. Maximum cave depth below the original water table is related to the extent of the cave from headwaters to spring. He re-interpreted cave levels, not in terms of successive stages of valley entrenchment, but instead as being part of the natural evolution of a cave. He based his idea on the fact that warm water at depth has a lower viscosity than cold water and is able to flow faster under a given hydraulic gradient. Utilizing a large personal database on caves from around the world, he devised empirical formulas for cave depth in relation to end-to-end length and other variables. Because of its reliance on field data, it is a rare example of a predictive model.

These constitute the main speleogenetic models developed in America in recent decades. Others have been offered by European speleologists (see Klimchouk et al., 2000). Despite the different approaches, all of these ideas are complementary. Each author is acquainted with the work of the others and has a lengthy familiarity with caves. There is still healthy debate about details, but one hopes that this always remains the case.

Besides the general models for cave origin described above, there have been several more tangible advances in cave geology. Additional styles of bedrock dissolution have been documented, beyond the typical carbonic acid reaction in meteoric water. New methods have been developed for determination of cave ages and paleoclimates. Digital models of cave growth have been devised. Cave information has been widely applied to the interpretation of regional geologic history. These topics are discussed in detail below.

#### SEACOAST CAVES

Studies in the 1970s by the U.S. Geological Survey (e.g., Plummer, 1975; Back et al., 1984) established that

carbonate dissolution could be caused by mixing between fresh water and seawater along limestone coasts. This process was accepted without debate by speleologists, especially by scuba divers, but it was not until the late 1980s that full attention was given to the topic. The leaders in the field have been John Mylroie and James Carew, both of whom were former New Yorkers capable of facing the rigors of research on tropical beaches. Their studies in the Bahamas (e.g., Mylroie and Carew, 1990) clarify the origin, distribution, and ages of caves in carbonate islands, as well as their relation to present and former sea levels. The topic is summarized in the carbonate island cave model (Mylroie and Vacher, 1999). The result of this work has been embraced by a diverse group including sedimentologists, geochronologists, paleoclimatologists, and petroleum geologists. Cave studies are most welcome where they help to address problems in other fields.

### SULFURIC ACID CAVES

In the 1970s, when it seemed that the main controversies in speleogenesis were finally being ironed out, an unexpected mode of cave origin was revealed. In a preview of things to come, David Morehouse suggested that sulfuric acid from pyrite oxidation could account for certain caves in eastern Iowa (Morehouse, 1968). Soon afterward, Stephen Egemeier, for his dissertation at Stanford University, chose to study a group of caves in Wyoming's Bighorn valley (such as the Kane Caves), which smelled strongly of hydrogen sulfide. He soon realized that the caves were still in the process of forming by sulfuric acid produced by the oxidation of  $H_2S$ , both in the cave stream and on the walls and ceilings above (Egemeier, 1973, 1981). Sulfuric acid attack of the bedrock left a rind of gypsum, which occasionally spalled off, fell to the floor, and was carried away in solution by cave streams. Egemeier briefly visited Carlsbad Cavern (New Mexico) and noted similarities to what he had observed in Wyoming.

This was not the first time sulfuric acid had been linked to cave origin. As early as the 1930s, researchers in Italy, Russia, Hungary independently proposed the process, but their studies were neither detailed nor well publicized.

The idea of sulfuric acid speleogenesis took hold among several western speleologists (e.g., Davis, 1980). Meanwhile, David Jagnow recognized the role of sulfuric acid in the origin of caves in the Guadalupe Mountains, New Mexico, but attributed them to oxidation of pyrite in overlying beds (Jagnow, 1977). Independently, J. Michael Queen noted gypsum replacement in the walls of caves in the Guadalupe Mountains of New Mexico and interpreted the cave inception to mixing between fresh water and underlying sulfate-rich brine (Queen, 1973).

Carol Hill measured sulfur isotopes in the Carlsbad gypsum and found a light isotopic ratio that suggested biological redox reactions, and that the original  $H_2S$  must have come from reduction of deep-seated sulfates, followed

by oxidation to sulfuric acid where the  $H_2S$  rose to the water table in the adjacent limestone mountains (Hill, 1981). By the time she published her full study (Hill, 1987), the concept of sulfuric acid speleogenesis was well accepted by most speleologists. The topic is covered thoroughly in a special issue of the *Journal of Cave and Karst Studies* (DuChene and Hill, 2000).

The Guadalupe cave studies were hampered by the fact that the caves are inactive relics. Evidence to support a sulfuric acid origin is circumstantial. Eventually NSS researchers become aware of an  $H_2S$  cave far more active than the ones Egemeier had studied. In the late 1980s, James Pisarowicz and Warren Netherton were apparently the first Americans to enter Cueva de Villa Luz, in Tabasco, Mexico. It contains sickeningly high  $H_2S$  concentrations, as well as gypsum crusts, long microbial filaments with highly acidic drips, and many features resembling those of the Guadalupe. A combined team of geologists and biologists examined the cave and gave support to the interpretations of cave origin and modification that had been developed in the Guadalupe (Hose et al., 2000). Although Villa Luz is much more potent than the Kane Caves, re-visits to the Kane Caves showed that they contain many of the same features (e.g., Engel et al., 2004).

The recognition of sulfuric acid speleogenesis opened the door to other types of deep-seated cave origin. This was a field well known in eastern Europe but barely recognized in America until the mid-1980s (e.g., Bakalowicz et al., 1987). In one of the clearest examples, Fred Luiszer combined a study of cave sediments with geochemical analysis of nearby springs to show that Colorado's Cave of the Winds is the product of mixing between deep high- $CO_2$  water and shallow low- $CO_2$  water (Luiszer, 1994).

A promising new tool in hydrology is the use of rare elements, including helium isotope ratios, to identify water that has risen from deep igneous sources. Michael Spilde et al. (Spilde et al., 2005) have used this technique to determine that about 6% of the water in Cueva de Villa Luz comes from these deep sources.

### THE GEOMICROBIOLOGY OF CAVE ORIGIN

The study of active sulfuric acid speleogenesis led to an explosion of interest in cave geomicrobiology. Before 1990, reports of fossil bacterial filaments in paleokarst were met with skepticism. Were these simply a geologic aberration? Only a few years later, at a meeting of the Karst Waters Institute, at which biologists and geologists from many diverse fields were brought together, the idea suddenly gelled that microbiology is the key to many karst processes (see proceedings edited by Sasowsky and Palmer, 1994). The main importance to speleogenesis is that microbial mediation controls many karst-related redox reactions, including the production rate of  $H_2S$  and sulfuric acid (Cunningham et al., 1995; Northup et al., 2000). The quantitative effect of microbial mediation is still uncertain,

but no one questions its significance. Cave microbiology has branched off as a major field of cave biology. An intriguing offshoot of these studies is the idea that cave microbiology may provide a window to extraterrestrial life (Boston, 2000).

#### GEOCHRONOLOGY AND PALEOCLIMATOLOGY

Speleogenesis can be understood only in terms of geologic time, and quantitative methods of dating cave deposits have helped greatly to advance the field. Many of the techniques in radiometric dating of speleothems were developed at McMaster University by Derek Ford, Henry Schwarcz, and their students (e.g., Harmon et al., 1975). Most speleothem dating involves uranium-series methods, which yield fairly accurate results as far back as 600,000 years (ten times the range of C-14 methods). Recent advances in uranium-lead dating can theoretically reach back as far as Earth's origin, but the technique is fairly complex and does not work with all samples. An example of the technique is given by Lundberg et al. (2000).

The McMaster team was also among the first to apply oxygen and carbon isotopic signatures to the interpretation of paleoclimates and changes in overlying vegetation. This approach makes it possible to determine conditions on a precise local scale, whereas most other methods provide generalized global averages. In the past couple of decades this field has been taken up by many researchers who do not consider themselves to be speleologists.

Throughout geologic time, the magnetic field of the earth reverses itself periodically, and this change is recorded in a tiny residual magnetism locked in rocks and sediments. Victor Schmidt (Schmidt, 1982) measured the paleomagnetism of sediments in Mammoth Cave, Kentucky, and determined that the middle levels of the cave pre-date the last magnetic reversal, i.e., they are older than 780,000 years. This approach has been carried on by Ira Sasowsky and Greg Springer to clarify entrenchment rates in Tennessee and West Virginia (e.g., Sasowsky et al., 1995; Springer et al., 1997). Paleomagnetism can also be measured in many calcite speleothems (Latham et al., 1979), and, where it is also possible to date them radiometrically, the history of magnetic variations can be calibrated.

One problem with dating cave deposits is that the dates are inevitably younger (often much younger) than the caves that contain them. But some minerals are alteration products of sulfuric acid attack on clay and presumably date from the latest phase of sulfuric acid speleogenesis. Some, like alunite ( $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$ ) can be dated radiometrically. Victor Polyak and his co-researchers sampled this mineral in caves at various elevations in the Guadalupe Mountains and showed that their ages range from 12 million to 4 million years, from highest to lowest elevations (Polyak, et al., 1998). Many researchers assume that the decrease in cave age with decreasing altitude

indicates a gradual rise of the Guadalupe block with time, while the water table stayed fixed at approximately the same elevation. In contrast, DuChene and Cunningham (2006) suggest that a decline in the water table was caused by loss of the original catchment area by the foundering of fault blocks in the headwater regions. The alunite dating technique is now being applied elsewhere, such as Grand Canyon, in an attempt to determine the history of tectonic uplift and river entrenchment.

Quartz-rich sediment at the earth's surface is continually bombarded by cosmic radiation. Minute amounts of radioactive aluminum and beryllium isotopes ( $^{26}\text{Al}$  and  $^{10}\text{Be}$ ) are produced in a certain ratio. When the sediments are buried or carried underground, these isotopes are no longer replenished, and the remaining ones decay.  $^{26}\text{Al}$  decays faster than  $^{10}\text{Be}$ , so with time the  $^{26}\text{Al}/^{10}\text{Be}$  ratio decreases. By measuring this ratio, the age of the sediment burial can be estimated. Darryl Granger was the first to apply this technique to caves (e.g., Granger et al., 2001; Anthony and Granger, 2004). These studies have helped to sort out the evolution of the Ohio River drainage. After more than a century of explaining caves in terms of surface erosion, speleologists can now reverse the trend by using caves to explain the history of surface erosion.

#### DIGITAL MODELING

As computer technology has become more powerful and accessible over the past few decades, digital modeling of cave origin has become feasible. The first working models of limestone cave development were developed in the early 1980s by Arthur Palmer to determine the functional relationships among the variables involved in speleogenesis (initial fissure width, hydraulic gradient, flow distance, etc.). The results formed the basis for one of the conceptual models described above (Palmer, 1991). Chris Groves and Alan Howard developed similar models in two-dimensional grids but found that computer technology was not yet advanced enough for them to realize the full potential of the method (Groves and Howard, 1994; Howard and Groves, 1995). Groves reports that one model tied up the mainframe computer at Western Kentucky University for an entire night.

Soon afterward, as technology advanced, karst researchers in Germany and France developed computer models capable of solving complex two-dimensional problems of speleogenesis. Work in this field has progressed at a rapid pace. The results tend to support earlier conceptual models, but they also provide quantitative estimates of the relative importance of such processes as mixing between waters of different chemistry. Dreybrodt and his co-researchers have summarized the advances in the field in a book accompanied by an interactive compact disk. They and other European researchers are now the undisputed leaders in the digital modeling of karst (Dreybrodt et al., 2005).

## NON-SOLUTIONAL CAVES

Throughout the history of the NSS, there has been continued but low-level interest in non-solutional caves and pseudokarst, but in the past 15 years the study of lava caves has grown enormously (Halliday, 2004). Kazumura Cave, a 60-km-long lava cave in Hawai'i, is not only the world's longest explored lava cave, but also by far the deepest American cave of any kind (deep, that is, in greatest vertical extent, but not in depth below the surface). The Hawaiian Speleological Survey and Cave Conservancy of Hawai'i now involve many local researchers as well as frequent visitors from the mainland. New discoveries are made every year, especially on the big island of Hawai'i, and they provide a fresh perspective on cave origin.

## CURRENT ROLE OF THE NSS IN CAVE GEOLOGY

Today the NSS works closely with many other karst organizations, both in America and in other countries. Over the history of the NSS, many affiliated groups have branched off, but they have all complemented the goals of the Society and have many members in common. The scientific status of the NSS has been strengthened by this mutual cooperation.

The NSS has recently published the book *Speleogenesis: The evolution of karst aquifers*, edited by an international team (Klimchouk et al., 2000), which includes contributions from authors around the world. This book has provided a foundation for the Web site [www.speleogenesis.info](http://www.speleogenesis.info), which publishes articles in the field, both new and from related journals, and serves as a clearing-house for information about the topic. The *Journal of Cave and Karst Studies* includes reviews of all other major international karst journals, which helps to publicize work in speleology throughout the world. The NSS also offers several research grants, the largest and most prestigious of which is the Ralph Stone Graduate Fellowship in Cave and Karst Studies.

The status of geologic cave research in America has blossomed in recent years. For example, special sessions and symposia in the field are frequently sponsored by NSS members at annual and regional meetings of the Geological Society of America. At some recent national meetings, karst sessions outnumbered those in all but a handful of major fields in geology. In 2004, Derek Ford and William White were jointly honored by GSA for their lifetime contributions to karst (see commemorative volume edited by Harmon and Wicks, 2006).

The reasons for this explosion of interest are clear. Recent advances in dating, paleoclimatology, porosity evolution, and geomicrobiology have applications to many other fields. Several high-profile journal articles in cave geology and speleogenesis have brought widespread attention. Highly regarded books on karst hydrology and geomorphology have been produced by NSS members

(e.g., White, 1988; Ford and Williams, 1989; White and White, 1989). New academic centers of karst research have appeared in recent years, as a quick Web search can show.

An organization does not make scientific discoveries: individuals do. But the NSS as a whole has contributed to the field in a unique way. The Society provides a sense of shared purpose in which the scientists share common ground with explorers and mappers, without whose achievements the science would not be where it is today.

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