

Proceedings

of
Mammoth Cave National Park's
Eighth Science Conference



October 5-6, 2000



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Table of Contents

Pursuing Health in Mammoth Cave	9
<i>Stanley D. Sides, M.D., F. A. C. P.</i>	
Update on Paleontological Inventory of Caves of Mammoth Cave National Park, Kentucky, USA	21
<i>Rickard S. Toomey III, Mona L. Colburn, Rick Olson, and Blaine Schubert</i>	
An Important Interglacial Fauna from Sediments of the Frozen Niagara Entrance, Mammoth Cave National Park – A Preliminary Report	23
<i>Mona L. Colburn, Rickard S. Toomey III, Rick Olson, and Jeff Dorale</i>	
Geophysical Techniques for Locating and Mapping Caves from the Ground Surface: Microgravity Subsurface Investigation of the Egypt Parking Lot, Western Kentucky University	25
<i>Nicholas C. Crawford, Shane E. Fryer, and Craig A. Calkins</i>	
Investigation of Gasoline Vapors Rising from a Karst Aquifer into Greenwood Park Church of Christ and the Foundation Christian Academy, Bowling Green, Kentucky	37
<i>Nicholas C. Crawford, Thomas B. Brackman, Robby G. Barker, William A. Curry, David A. Ek, Raina N. Larsen, George G. Ryan, John M. Gossett, Johnny Meredith, and Denny L. Huffines</i>	
Sites Originally Proposed for the Southcentral Kentucky Trimodal Transpark: A Wake-Up Call for Everyone Concerned About the Protection of Mammoth Cave National Park	51
<i>Nicholas C. Crawford, Ph.D.</i>	
Antipredator Behavior of the Cave Cricket (<i>Hadenoeus</i> <i>subterraneus</i>) in Response to Predation Risk by White-Footed Mice (<i>Peromyscus leucopus</i>)	55
<i>Kurt Helf</i>	
Microbial Ecology of Conduit Stream Sediment Interstitial Fluids of the South Central Kentucky Karst Aquifer: Impacts on Aquifer Development	57
<i>Larry Elliott, Shannon Wright, Tricia Coakley, and Chris Groves</i>	

A Vegetation Map of Mammoth Cave National Park Using Satellite Remote Sensing Data	61
<i>Rick Olson, Michael Franz, and Geoff Gitter</i>	
The Girkin Formation of Western Kentucky	69
<i>Walter K. Johnson and Don Coons</i>	
Mammoth Cave Cartographic Program- A multi-step program consisting of Surveying, Data Processing and Management and Map Production	73
<i>Bob Osburn</i>	
Hydrologically Valid Delineation of Watershed Boundaries in Kentucky's Karst Terrane	75
<i>Joseph A. Ray, Peter T. Goodmann, and Joe Meiman</i>	
Update on Dye-Tracing Efforts at Mammoth Cave National Park	77
<i>Joe Meiman, Chris Groves, and Shannon Herstein</i>	
Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky	89
<i>Rhonda Pfaff, Chris Groves, Alan Glennon, John Fry and Joe Meiman</i>	
Threats to Surface and Karst Groundwater of Mammoth Cave National Park from the Arthur Oil Field, Kentucky	101
<i>David Ek, Chris Groves, Alan Glennon, Rhonda Pfaff, and Joe Meiman</i>	
A Historiography of Archaeological Research in the Mammoth Cave Area of Kentucky: 1824-2000	105
<i>Kenneth C. Carstens, Ph.D.</i>	
The NPS/Earthwatch Archeological Project in Mammoth Cave	125
<i>George M. Crothers, Charles A. Swedlund, and Robert H. Ward</i>	
Rethinking the Prehistoric Archeology of Salts Cave and Mammoth Cave	127
<i>Patty Jo Watson</i>	
Regional Atmospheric Carbon Sink Within the South Central Kentucky Karst	131
<i>Chris Groves and Joe Meiman</i>	
Acidic Bog Drainage and Limestone Dissolution, Mammoth Cave National Park	143
<i>Jeff Timmons, Chris Groves, and Joe Meiman</i>	
Carbonate Chemistry Variations in Showerbath Spring, Mammoth Cave, Kentucky	145
<i>Johnny Meredith, Chris Groves, and Joe Meiman</i>	

MAMMOTH CAVE NATIONAL PARK'S EIGHTH SCIENCE CONFERENCE

Sponsored by:

***Mammoth Cave National Park
And
The Cave Research Foundation***

***Thursday, October 5, 2000
Mammoth Cave National Park Training Center***

Welcome

- 8:00 Ron Switzer, Superintendent, Mammoth Cave National Park
- 8:15 Jerry O'Neal, Chief Natural Resources and Technical Assistance, Southeast Regional Office
- 8:30 Pat Kambesis, President, Cave Research Foundation

History and Paleontology Session

- 8:45 Stan Sides: *Pursuing Health In Mammoth Cave*
- 9:15 Rick Toomey III: *Paleontology of Mammoth Cave*
- 9:45 Rick Toomey III: *Paleontology of Frozen Niagara*
- 10:15 Group Discussion
- 10:30 Break

Karst Hydrogeology Session I

10:45 Nick Crawford*, Shane Fryer and Craig Calkins: *Geophysical Techniques for Locating and Mapping Caves from the Ground Surface*

11:15 Nick Crawford*, Thomas Brackman, Bobby Barker, William Curry, David Ek, Raina Larsen, George Ryan, John Gossett, Johnny Meredith and Denny Huffines: *Investigation of Gasoline Vapors Rising from a Karst Aquifer into Greenwood Park Church of Christ and the Foundation Christian Academy, Bowling Green, Kentucky*

11:45 Nick Crawford, *Preliminary evaluation of the three sites originally proposed for the Southcentral Kentucky Trimodal Transpark: A wake-up call for everyone concerned about the protection of Mammoth Cave National Park*

12:15 Group Discussion

12:30 Lunch Break

Ecology and Biology Session

1:45 Kurt Helf: *Antipredator behavior of the cave cricket (Hadenoeus subterraneus) in response to predation risk by white-footed mice (Peromyscus leucopus)*

2:15 Larry Elliot, Shannon Wright, Tricia Coakley*, and Chris Groves: *Microbial Ecology of Conduit Stream Sediment Interstitial Fluids of the South Central Kentucky Karst Aquifer: Impacts on Aquifer Development*

2:45 Rick Olson, Michael Franz, and Geoff Ghitter: *A Vegetation Map of Mammoth Cave National Park Based Upon Satellite Spectral Data*

3:00 Group Discussion

3:15 Break

Geology Session

3:30 Walter Johnson: *The Girkin Formation of Western Kentucky*

4:00 Group Discussion

4:15 End of first day presentations

Friday, October 6, 2000
Mammoth Cave National Park Training Center

Cave and Karst Management Session

- 8:00 Don Coons: *Digital Data Base Project of the Cave Research Foundation*
- 8:30 Bob Osburn: *Mammoth Cave Cartographic Program - A Multi Step Program Consisting of Surveying, Data Processing and Management and Map Production*
- 9:00 Joe Ray*, Peter Goodman, and Joe Meiman: *Hydrologically Valid Delineation of Watershed Boundaries in Kentucky's Karst Terrane*
- 9:30 Joe Meiman*, Chris Groves, and Shannon Herstein: *Update on Recent Dye-Tracing Efforts at Mammoth Cave*
- 10:00 Group Discussion
- 10:15 Break

Karst Hydrogeology and GIS Session

- 10:30 Rhonda Pfaff*, Alan Glennon, Chris Groves, Joe Meiman, and John Fry: *Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky*
- 11:00 David Ek*, Chris Groves, Alan Glennon, and Joe Meiman: *Threats to Surface and Karst Groundwater of Mammoth Cave National Park from the Arthur Oil Field, Kentucky*
- 11:30 Group Discussion
- 11:45 Lunch Break

Archeology Session

1:00 Ken Carstens: *A Historiography of Archeological Research in the Mammoth Cave Area of Kentucky: 1824-2000*

1:30 George Crothers*, Charles Swedlund, Bob Ward: *The NPS/Earthwatch Archeological Project in Mammoth Cave*

2:00 Patty Jo Watson: *Rethinking the Prehistoric Archeology of Salts Cave and Mammoth Cave*

2:30 Group Discussion

2:45 Break

Karst Hydrogeology Session II

3:00 Chris Groves* and Joe Meiman: *Regional Atmospheric Carbon Sink Within the South Central Kentucky Karst*

3:30 Jeff Timmons*, Chris Groves, and Joe Meiman: *Acidic Bog Drainage and Limestone Dissolution, Mammoth Cave National Park*

4:00 Johnny Meredith*, Chris Groves, and Joe Meiman: *Carbonate Chemistry Variations in Showerbath Spring, Mammoth Cave, Kentucky*

4:30 Group Discussion

4:45 End of second day presentations

6:00 Conference Social at Hamilton Valley



Pursuing Health in Mammoth Cave

Stanley D. Sides, M.D., F. A. C. P.
Cave Research Foundation

Abstract: In 1842, Mammoth Cave owner Dr. John Croghan (1790-1849) used the cave as a residence for individuals with presumed pulmonary tuberculosis. The practice failed to improve survival of the patients who braved living in the cave, and the experiment was widely criticized in the medical literature. The only comprehensive review of the Mammoth Cave tuberculosis treatment experience was published in the Bulletin of the History of Medicine by Stanley D. Sides and Harold Meloy (1913-1985) in 1971. In the past 29 years, several articles have been published, and obscure references found, that shed new light on John Croghan's "hospital in the cave." This report will summarize this more recent information, and speculate on the conditions at Mammoth Cave and in the United States that led to the famed experiment in treating tuberculosis nearly 40 years before the infectious nature of the disease was discovered.

In 1971, Harold Meloy and I published an article on the tuberculosis victims that resided in Mammoth Cave entitled, "The Pursuit of Health in the Mammoth Cave." I was a resident physician studying internal medicine at the A. B. Chandler Medical Center of the University of Kentucky and had free access to the extensive reference resources of the King Library and Medical Library. Although I received many reprint requests, Harold and I learned very little new information on the nature of the cave experiment or the identities of more of the participants. Since this time, access to information collected on the Croghan Family at Locust Grove, Kentucky, research by National Park Service guide Scott Sallee, newly discovered newspaper references, medical research, and personal correspondence have yielded new information.

Research on *Mycobacterium tuberculosis* has offered new insights. Pulmonary tuberculosis (TB) or pulmonary consumption was a major cause of death in the 19th century and remains a world wide problem today. The infectious cause of the disease was not known until Koch discovered the tubercle bacillus in 1882, long after the invalids entered the cave in 1842 (Sides and Meloy, 1971).

In the United States, the vast majority of TB cases are caused by *Mycobacterium tuberculosis*, sometimes referred to as the tubercle bacillus. *M. tuberculosis* and three very closely related mycobacterial species (*M. bovis*, *M. africanum*, and *M. microti*) can cause tuberculous disease, and they compose what is known as the *M. tuberculosis* complex.

TB is spread from person to person through the air. When a person with pulmonary or laryngeal TB coughs, sneezes, speaks, or sings, droplet nuclei containing *M. tuberculosis* are expelled in the air. Depending on the environment, these tiny particles (1-5 microns in diameter) can remain suspended in the air for several hours. Persons with the highest risk of becoming infected with *M. tuberculosis* are close contacts—persons who had prolonged, frequent, or

intense contact with a person with infectious TB. Data collected by CDC (Communicable Disease Center) since 1987 show that infection rates have been relatively stable, ranging from 21% to 23% for the contacts of infectious TB patients.

When droplet nuclei are inhaled, most of the larger particles become lodged in the upper respiratory tract, where infection is unlikely to develop. However, smaller droplet nuclei containing the tubercle bacilli may reach alveoli, where infection begins. The tubercle bacilli that reach the alveoli are ingested by alveolar macrophages; the majority of these bacilli are destroyed or inhibited. A small number multiply intracellularly and are released when the macrophages die. These bacilli can spread through the lymphatic channels to regional lymph nodes and then through the bloodstream to more distant tissues and organs, including areas in which TB disease is most likely to develop: the apices of the lungs, the kidneys, the brain, and bone (Anon., 2000).

Dr. Croghan purchased Mammoth Cave from attorney and friend, Franklin Gorin (1798-1877), on October 8, 1839. He wrote his brother-in-law, General Thomas Sidney Jesup (1788-1860) the following:

Here, I remarked to one of the guides, Mr. (William Scott) Miller (1815-1880), you ought to have a Hotel, well supplied with refreshments of all kinds, chambers on one side for the ladies and the other for gentlemen, a handsomely furnished parlor, reading room, and dining room, all brilliantly illuminated. The idea of such an establishment was novel to him, its appropriateness immediately flashed upon his mind, and he wondered that such a thing had never been thought of before, for said he "I would charge a little higher and make three times as much from the Tavern within as that above ground." The distance to this spot is between 5 and 6 miles, and Mr. Gorin writes me that an excellent carriage road can be made the entire way for an expense of from \$50 to \$100. An Hotel under ground at the distance of 5 or 6 miles, and a stage to convey passengers thereto, is in itself so unique, that, I think uncommon with all whom I have heard speak as the subject, it would be a means of increasing greatly the number of visitors. Be this as it may I do not feel inclined to make the trial; but I am convinced I will have applications enough for the situation. The ensuing 4th of July I will have celebrated at the Cave. On this occasion I will have the main branch of the Cave to the Cataract (three or four miles within I suppose) illuminated, suitable refreshments, and a band of music stationed at the Cataract, the total expense will not much exceed \$300, and in the opinion of all, by giving due notice, the number of visitors will be several 1000. This is at a \$1 entrance, independent of what will be paid for refreshments, will amount to a large sum. Owing to the uniformity of temperature throughout the year 60 Faht. the dryness of the atmosphere and the continual purification thereof by the constant formation of salt petre, I have no doubt there is no where to be found a spot so desirable for persons laboring under pulmonary affections, chronic Rheumatism, diseases of the eye, etc., etc. Divesting myself of all selfish

consideration I have no hesitation in affirming that for enjoyment, for the gratification of ones curiosity - for the restoration and preservation of health it stands unrivaled and in fine is worth all the Niagara's and watering places in the Union put together. I but recently got this place of Mr. Gorin at his own offer, he has since written to me and made a proposition to obtain one half and remarked that "if I accede to his proposition he will remain there with his family and give to the Cave his undivided attention" (Croghan to Jesup, November 15, 1839).

In the 19th century, most who developed pulmonary consumption, another name for pulmonary tuberculosis, had no idea of the concept of aerosol transmission of bacterial disease. Dr. John Croghan knew a prominent Louisville physician, Dr. William Adair McDowell (1795-1853). McDowell published a popular book in 1843 entitled *A Demonstration of the Curability of Pulmonary Consumption in All Its Stages*. He advocated the prevention of TB as follows: Alterations of temperature are deemed among the most frequent causes of phthisis. Hence it is incumbent on the cachectic, as much as practicable, to avoid exposure to such influences, which may be accomplished, first, by changes of climate; secondly, by judicious construction of dwellings; thirdly, by proper adaptation of clothing (McDowell, 1843).

Those afflicted with TB thought winter was the time most deaths occurred. If a way could be found to survive the cold months, there was hope of prolonged survival or recovery from the disease. The thought of overwintering in the constant atmosphere of the cave was an appealing prospect to those with a disease with no effective treatment.

Correspondence by John Croghan to General Jesup in 1841 reveals that Dr. McDowell was wanting to send an invalid to the Mammoth Cave for care:

I hired Harriett again to Mrs. Clark; but, before the expiration of the quarter she was sent here with a Note stating that "her physician said she had the consumption and ought to be in the country." Tubercles had formed in her lungs before I heard of her sickness, and although I do all I can for her, yet she is fast declining. Although it may appear absurd, yet if an opportunity were to occur I would send her to the Cave, sincerely believing that it is the only chance she had for recovery. Next month D(r.) McDowel(l) intended that Mrs. (Mary Eliza Churchill) Thruston (1804-1842) should go to the Cave, but he has postponed it too long. She could not I think, ride 20 miles even in a carriage (Croghan to Jesup, May 15, 1841).

The cave did not generate revenue as Dr. Croghan expected. He wrote Jesup in 1842: I spend most of my time now at the M(ammoth) Cave, where I have been compelled to erect large buildings in order to accommodate the visitors. All things will be completed in three months and after that I will draw in rapidly all my outlays (Croghan to Jesup, May 9, 1842). I have necessarily been subjected in furnishing the Hotel at the Cave. I am now more pushed for money than at any former period of my life; if, however, there be as many visitors at the

Cave this summer & fall as is expected I will soon be free from embarrassment (Croghan to Jesup, May 20, 1842).

On September 15, 1842 John (G.) Wesley Harper was the first consumptive to enter the cave. Croghan wrote two weeks later:

A number of visitors were at the Cave this fall, many of whom were your friends. Next year the crowd will be great; and then I will be more repaid for my expenditures. I leave here tomorrow, in company with the Col. For the Cave, in order to make suitable provisions for the invalids who intend spending this winter in the Cave. Mr. Miller writes, that from what he learns 100 will be there by the 1st. Novr (Croghan to Jesup, October 2, 1842).

One letter in the Huntington Library, San Marino, California, was written by Harper while at the cave:

I have just received a letter from Mr. Bates, informing me that he had placed under your care, to be forwarded to me at this place a package of medicine, requesting it to be sent by the first wagon. As I stand in urgent need of these medicines, I will be obliged to you to forward them by stage, to the care of Mr. Bell, "Three Forks P.O. Edmonson County - for G. W. Harper Mammoth Cave." If you will let Dr. Croghan know that you have forwarded them, he will repay you the expense you have incurred in the charges of the stage fare &c (Harper to Trabue, October 18, 1842).

An issue has been to what extent Dr. Croghan functioned as personal physician to the invalids. The following correspondence sheds light on this subject, written as the first invalids were dying at the cave:

Mr. Grimes, who formerly kept the Olympian Springs and more recently the Missouri hotel of St. Louis, has proposed to me to rent to him the Hotel at the Mammoth Cave. The offer, in writing, subject to my agreement, \$1200 for the first year in quarterly payments, to furnish 20 servants of his own, also \$2000 worth of furniture, to return at the expiration of the year all things belonging to me in good order and allow me all the entrance money to the Cave. According to the present arrangement the Cave occupies my attention to the exclusion of almost everything else. This is more especially the case now since it has become a resort for invalids. In order that I may have some time of my own I will accept the offer of Mr. Grimes if he give approved security. There are now from 15-20 invalids in the Cave. I am convinced they would all return to the "land above with greatly improved healths, but for three considerations. 1st, the want of attention to diet, 2, their indiscriminate use of medicines and lastly smoke. Whenever the temperature within the

Cave corresponds with that without, smoke collects about the chambers, irritating the lungs, destroys measureably the good resulting from the uniformity of the Cave climate and the peculiarity of its air. By sinking a shaft in the vicinity of the "invalids village" (as Judge Tompkins styles it) this may be obviated.

The life I lead when here is anything but pleasant, having no company I read and write until I am fatigued, then walk over the farm and ever & anon pay a visit to Louisville. I wish all of you could come on and spend a year or two here (Croghan to Jesup, January 13, 1843).

The number of invalids in the cave never reached Croghan's expectations. Two were accompanied by their wives, and one by his young daughter. Parker Willis wrote:

The equable air, and the good health of the miners, who were at one time employed in digging saltpetre from near the entrance, started an idea, some time since, that a hospital for consumptive patients might be profitably established in the cave. Stone huts were accordingly constructed, in the dark halls beyond the reach of external air, and, among those who tried the experiment, were two consumptive gentlemen, who, with their two healthy wives, passed six weeks in hideous seclusion from daylight. One of the gentlemen died there, and the other received no benefit—but the devotion of those voluntarily buried wives should chronicle their names in the cave's history (Willis, 1853).

The following individuals have been associated with the underground colony:

Oliver Hazard Perry Anderson. Born October 10, 1813 Elkhart, Franklin County, Kentucky, son of Rueben and Sarah Anderson. Entered cave October 20, 1842 29 years old, and resided 100 feet deeper in the cave near the Great Bend (Acute Angle), avoiding tours that would descend deeper in the cave at Giant's Coffin. Because of the smoke from the residents near Star Chamber, Dr. Croghan constructed him a hut in Pensacola Avenue, beyond Bottomless Pit. He left the cave January 11, 1843 and died May 17, 1845 at Frankfort, Kentucky, 31 years old.

Anderson wrote a letter on January 12, 1843 to Henry Wingate, from Three Forks, which is today Park City. "I left the cave yesterday under an impression that I would be better out than in as my lungs were constantly irritated with smoke and my nose offended by a disagreeable effluvia, the necessary consequence of its being tenanted without ventilation... Others will leave the cave soon I think; two recently died. I am the 5th person who has left" (Anderson, 1843).

Oliver H. P. Blair. Born May 14, 1814. From Pittsburg, Pennsylvania. Died March 2, 1843 28 years old. Buried in Old Guides Cemetery. (Obituary is in Pittsburgh *The Advocate and Advertiser*).

John Wesley Harper, Esquire. From South Carolina. Entered cave September 15, 1842 and resided in a wooden hut at Wandering Willie's Spring. Died January 18, 1843 at Mammoth Cave, and is buried in Old Guides Cemetery.

Charles Marshall. Oswego County, New York. Died February 1, 1843 at Mammoth Cave, and is buried in Old Guides Cemetery. Mrs. Charles Marshall accompanied him. They may have been parents of the four-year old child said to reside in the cave (Sallee, personal communication, 1998). The following was written of Marshall:

Having mentioned the name of Marshall, the guide informed me that he was employed then as now when Marshall came to the cave. At my request he conducted me to the spot where the shanty was erected for his accommodation. It is situated a little more than a mile from the entrance. Here the poor invalid, with his devoted wife, took up his abode, with a hope that the peculiar atmosphere of the place would restore him to health. Vain Hope! His Master said: 'Come up higher'—and he passed from the darkness of this living tomb, to the glories of the upper paradise. Here the affectionate wife watched by the couch of her afflicted husband, leaving him only once a day (as the guide informed me), and then only for a short time, to enjoy the light and sunshine of the outer world above. Portions of this little cabin still remain. I lingered around the spot with melancholy pleasure... The body of Marshall lies near the hotel, in an unassuming grave, unnoticed by the pleasure-seeking throng, who here congregate to squander away their precious time in idleness and dissipation (*Anon.*, 1848).

Joseph Khleber Miller. Born July 28, 1818 in Sumner County, Tennessee. Presumably left Mammoth Cave and died April 4, 1843 24 years old, and is buried in the Gallatin Cemetery, Gallatin, Tennessee. He was accompanied in the cave by Mary (Mollie) Franklin Miller and a negro slave, Peter. The cabin he occupied was pointed out to cave visitors as the "Mollie Miller Cabin" (Sallee, 1996).

Benjamin R. Mitchell. Mobile, Alabama. Entered Mammoth Cave December 28, 1842 (and resided in Audubon Avenue?). He was the first of the patients to die on January 9, 1843 in Houchins Narrows attempting to leave the cave.

Dr. William J. Mitchell. Glasgow, Kentucky. Entered cave May 23, 1842 and left June 25, 1842 "very much relieved." He resided in a hut constructed 100 yards in Audubon Avenue. "Unfortunately for the reputation of the new and infallible remedy, Dr. M. died the following winter—having been married in September preceding" (*Anon.*, 1844).

The *Newark Daily Advertiser*, June 5, 1843 on page 2 entitled, "The Mammoth Cave—Consumptives," stated:

The following extracts of a letter from a gentleman who is said to have the best means of information of the subject, appears in the Journal of Com-

merce this morning, in reply to the paragraph which recently went the rounds stating that Dr. Mitchell and other consumptives derived no benefit from the Mammoth Cave in Kentucky:

Louisville, May 21, 1843. A more extraordinary instance of the salutary influence of climate on a diseased frame cannot be cited than that of the air of the Mammoth Cave on Dr. Mitchell. When he left this city for the Cave, many persons thought his reaching there doubtful; yet so extraordinary was his improvement, (although he remained in the Cave only about two months,) that he was enabled to ride about, either for business or pleasure, and actually married, some four or five months after leaving his subterranean abode. Dr Mitchell, it is true, died some time during the last winter, but enough is known in respect to his case to demonstrate the extraordinary curative properties of the Mammoth Cave atmosphere. Dr. Mitchell was a resident of Kentucky; no man stood higher for candor and veracity; and those who wish to obtain correct information respecting the Cave air on pulmonary diseases, are referred to his published letter on this subject. It is stated in the paragraph just quoted, that out of 13 (there was, by and by, a greater number) who resorted to the Cave last winter, five died there and two after leaving there.

Now, of the number reported to have died, two never entered the Cave, but died in the hotel *above* ground; and the others were in the last stages of consumption, and as soon might it be expected that the air of the Cave would restore them to health, as to restore an amputated limb. Dr. Mitchell states that he does not think the Cave air will cure the advanced stages of consumption; it is those persons who labor under the incipient forms of the disease, whom he recommends to make a trial of its climate. There was no fair test of the virtues of the Cave in the cure of pulmonary diseases last winter; no physician resided there (Dr. Croghan, the proprietor, being in Louisville,) to regulate the diet of the Invalids, or prescribe medicines in case of need; and, again, the smoke, which accumulated about the rooms of the sick when the external and internal temperature was the same, would greatly irritate the lungs, and counteract all the good which a month's residence would produce. Remedy this evil, which can be easily done; get a physician to reside *in* the Cave with the invalids; make a good road in the main avenue to a distance of two or three miles, so as to admit of horse exercise, or, if necessary, carriages, and I will venture to predict that there will be a greater number of persons resorting to the Cave for health, than any other spot on this continent; and that their relief will be as great as could be anticipated. The above remarks are made not with a view to induce invalids to resort to the Cave, but merely to prevent erroneous impressions.

Unidentified patient, died before January 12. Referred to in O. H. P. Anderson letter.

Anne Marie Rose Parsons (Fraser, Baker, possible Grubbs or Briggs). Patient in the cave and died of tuberculosis. She was apparently alive when leaving the cave, but died shortly afterward. Family members reported her as "white as a ghost, and not able to stand sunlight or bright light." She was in her mid-to-late 20's, and when she emerged from the cave "her hair was snow-white." From Cincinnati originally, she was living in Philadelphia before she "went into the cave" (Constance D. French, personal communication, 1991).

A presumably fictional interview of a female invalid, probably not Anne Marie Rose, was published in *The Philadelphia Inquirer* in 1867:

The sick room lies round the Great Bend, an underworld hospital for those next to the sepulchre, who must choose between a living grave or the common narrow house... A row of pine cabins stand here, strange reminders of the outer world, and in them live the consumptive patients, with a doctor amidst them, breathing the mild, equitable cavern air. It is always dark except when the torches are lighted, and then so fantastic are the shadows and lights that it seems a perpetual theatre.

"Do you enjoy yourself?" I said to a lady who had been buried here many months. "Oh! Yes; it is a dreary, desperate life after the sunshine that one recollects; but when I venture out where it seems so beautiful I am torn to pieces with coughing. Then I come back to this darkness, my breast relieved, but my enjoyment of sight all lost, and I read and talk and sew, till in the yellow lustre of the pitch pine torches my eyes almost cry out for day. Sometimes I sing to myself; but the echoes are like my own voice calling for help, and I think I am buried alive."

"You have visitors?"

"Almost every day in the pleasant season. Again, for weeks we only see those who are connected with the hotel and the Cure. Some of these affect to envy our quiet, subterranean life; but when they stop with us longer than 24 hours we see them yawn and grow weary. It is so unreal that all shrink from it when the novelty is over. We lose our interest in terrestrial concerns" (Anon., 1867).

John Croghan begins to discuss his failing health, presumably due to pulmonary tuberculosis in correspondence to Jesup, writing from Locust Grove on November 20, 1843. Croghan believes the coming winter will provide more revenue, perhaps believing more invalids will enter the cave. He wrote:\

If I were to leave this place (Locust Grove) for three months, I would go to ruin. Negroes are not now what they were five years ago, and not one overseer in 20 is worth having. Owing to the reduced price of produce I realize but small profits, and so far from enjoying myself the care & atten-

tion which devolves on me in managing this place is a source of constant trouble and anxiety. I am literally tire down here & I have to make a partial sacrifice of my happiness merely to keep things here together & prevent the place from going to destruction. Again in order to prevent George from what I dreaded, public exposure, I obtained for him, through the Bank considerable sums of money, and this as well as the sums which I had necessarily to expend in buildings, furniture &c at the Mammoth Cave has somewhat embarrassed me. This would not have been the case had I have had my ordinary health; but being too unwell to attend to business I lost many debts which ought to have been saved... The buildings, furniture and all things at the Mammoth Cave are paid for, it is the most valuable property in the Union. And if I mistake not I will realize from this source the ensuing season enough to discharge nearly every debt I owe. My health is improving (Croghan to Jesup 1843).

Soon, John Croghan himself remained confined in the winter. From Locust Grove he wrote his sister:

"I am exceedingly feeble, but in other respects better than I have been. I am still confined to my room, and have been every day since you left here except one. ...I have not heard from the cave for some time" (Croghan to Ann Jesup, 1845).

February 10, 1846 he wrote:

I have also rented Throgmorton the cave. He has gone to New Orleans to purchase the necessary supply or groceries &c. He is expected in Louisville tomorrow, & immediately on his return the Col (George Croghan); & myself accompany him to the Cave. We will go in a steam boat. From what I hear there will be three times as many persons at the Cave as can be accommodated... My health is improved; but I am yet very feeble and suffer not a little from difficulty of breathing & cough (Croghan to Jesup, 1846a).

Cave visitation must have been very slow between February and April. George Croghan wrote his brother, John, from Mammoth Cave on April 19, 1846; "There have been 28 visitors since we were here with Throckmorton" (Croghan to Croghan, 1846).

By summer, visitation had improved. Croghan spent nearly all of his time at Locust Grove. "I returned from the Cave on Saturday. All things are looking well there. The number of visitors (including the Professors & students from Franklin College) was about 100. ...My health is improved, but I never will regain my former strength or capacity for business. It is very lonely here..." (Croghan to Jesup, 1846b).

Croghan had a small cabin built at the entrance of the cave for his health. Rather than seeking comfort and treatment of his TB within the cave, he sought benefit from the cool cave air

outside the cave's confines. There is no correspondence to guide us as to when Croghan built the cabin. In 1852, Dr. Joseph Parrish, M.D. commented: "In walking down its stony path (to the cave entrance), we come suddenly upon a neat frame, unoccupied cottage, left open for the amusement of the traveller..."

Charles C. Jones, Jr. visited Mammoth Cave in 1854. Croghan's cabin was still standing. "Opposite the mouth of the cave, at a distance of not more than 30 feet, stands the residence of Dr. Croghan, whose heirs now own the cave. It is situated in an artificial atmosphere, the wind constantly issuing from the cave being many degrees cooler than that which moves upon the surface of the earth. It was, however, found an unhealthy location and has been for several years deserted" (Jones, 1991).

Dr. Croghan also died at Locust Grove in the winter of 1849 of tuberculosis, six years after the death of the consumptives in Mammoth Cave. Croghan's cousin, George Clark Gwathmey (1790-1850) wrote Jesup:

You will have been informed by Telegraphic dispatch and from other sources of the death of Doct. Croghan which occurred on the Morning of the 11th inst. A messenger reached me at four oclock on Monday - from the Doctor, requesting me to go out. I got to him at dusk and found him as I thought dying, he ...lived until 35 minutes after six on Thursday morning. I left him at half past four believing him to be decidedly better. Although as himself, he certainly slept better than he had for some nights previous. I had gotten to sleep however before Judge Brown came up into my room to announce his death. The Judge informed me that after I left the Doctor he rested very well until half after six, he then (illegible) the judge taking a bed in the room and as he was getting to bed the Doctor called his Boy, Isaac who was asleep in a chair at the fire place. The judge got up and sent the Boy to his Master - just as he got to the bed side, the Doctor was seen to throw up his hands and before the judge got to him he was no more, Every proper attention was (illegible) to his remains and on Friday the 12th he was buried in the family burying ground (Gwathmey to Jesup, 1849).

References cited:

Anon. 1844. *Boston Medical and Surgical Journal*, 31(2): 43.

Anon. 1843. *Newark Daily Advertiser*, June 5, 1843, p 2.

Anon. 1867. From Philadelphia to Mammoth Cave. *The Philadelphia Inquirer*, Thursday, September 12. p. 2

Anon. 1848. *Sears Pictorial Description of the United States*, p. 480

Anon. 2000. Core Curriculum on Tuberculosis. Department of Health and Human Services; Centers for Disease Control and Prevention, Atlanta, Fourth edition. 139 pp.

Oliver Hazard Perry Anderson (1843). Letter January 12, 1843. Mammoth Cave National Park Library TB file

Croghan, George to Dr. John Croghan. Huntington Library microfilm, April 19, 1846.

Croghan, John to Major T.S. Jesup, Q.M. General. U.S. Army, Washington, D.C., Library of Congress. Locust Grove, November 15, 1839. . Copies of correspondence of members of the Croghan family were compiled and edited by Dr. Samuel W. Thomas in a manuscript at Locust Grove. In 1988, Philip J. DiBlasi kindly provided copies of many letters that referred to Mammoth Cave.

Ibid. May 15, 1841.

Ibid. May 9, 1842.

Ibid. October 2, 1842.

Ibid. January 13, 1843.

Ibid. November 20, 1843.

Croghan, John to Mrs. Ann Jesup, Washington, D.C., Library of Congress. Locust Grove, December 17, 1845.

Croghan, John to Major T.S. Jesup, Q.M. General. U.S. Army, Washington, D.C., Library of Congress. Locust Grove, February 10, 1846a.

Ibid. July 1, 1846b.

Gwathmey, George C. to Major Thomas S. Jesup, Q.M. General. U.S. Army, Washington, D.C., Library of Congress. Louisville, January 18, 1849.

Harper, G.W. to Garvis Trabue and lord. Huntington Library microfilm. Mammoth Cave
October 18, 1842.

Jones, Charles C. Jr. 1991. "An 1854 Visit to Mammoth Cave." *Journal of Spelean History*, 25:2,
p 27.

McDowell, William A. 1843. *A Demonstration of the Curability of Pulmonary Consumption is All its
Stages*. Prentice and Weissinger, Louisville, 347 pp.

Parrish, Joseph, M.D. 1852. *The Mammoth Cave of Kentucky*, Burlington, N.J., p. 4.

Sallee, Scott E. 1996. "For a Short Period, 1842-1843, Mammoth Cave Became TB Hospital."
Kentucky Explorer, 11, pp. 22-24.

Sides, Stanley D., and Harold Meloy. 1971. "The Pursuit of Health in the Mammoth Cave."
Bulletin of the History of Medicine, XLV, pp. 367-379.

Willis, N. Parker. 1853. *Health Trip to the Tropics*. Scribner, New York, p. 156.

Update on Paleontological Inventory of Caves of Mammoth Cave National Park, Kentucky, USA

Rickard S. Toomey III¹, Mona L. Colburn¹, Rick Olson² and Blaine Schubert¹

The Mammoth Cave Paleontological Inventory is a cooperative study of the vertebrate paleontological remains and deposits in caves of the Mammoth Cave National Park being conducted by The Illinois State Museum, the National Park Service and the Cave Research Foundation. The project is in its third year. We have found such a large array of remains that we have recently extended the project to a fourth year.

Over the past two years we have examined additional sites, both in Mammoth Cave and in other caves in the park, to determine if they have paleontological significance. One area that was highly significant was the Frozen Niagara Entrance area. Significant deposits from this area will be discussed separately during the Science Conference.

One of the most significant results of the continued field work has been to allow us to develop a better model for the types of paleontological contexts in which bone occurs in Mammoth Cave. Within Mammoth Cave, significant and potentially significant paleontological remains and deposits occur within four general contexts: (1) Relatively recent (<4000 year old) remains on the surface in the cave; (2) Relictual deposits representing the cave surface that had accumulated before the time humans began using the cave; (3) Older surface deposits (such as guano accumulations). These are often found preserved under large fall blocks and sometimes under grain-fall accumulation deposits; and (4) Very old (hundreds of thousands to millions of years) deposits associated with primary, water lain sediments in the cave. These contexts have been identified in the main Mammoth Cave trunk (Audubon Avenue, Broadway, and Main Cave to Ultima Thule). However, they have also been identified in side passages, such as Blue Spring Branch, Blackall Avenue, Gothic Avenue, and Backsliders Alley). Gothic Avenue, notably, contains deposits representing all of the contexts.

Previous work (reported on at previous Science Conferences) showed that guano deposits associated with free-tailed bats (*Tadarida* sp.) are found over an extensive area of Main Cave (probably from Wright's Rotunda to near Ultima Thule). More recent work indicates that free-tailed bats also roosted in Blue Springs Branch and probably Blackall Avenue. In addition, the identification of several sub-adult *Tadarida* bones solidifies the idea that at least some of the colonies were nursery colonies.

Field work and laboratory analysis are continuing in several smaller caves in the Park. We have completed preliminary field work in Bat Cave and Dixon Cave. Both are significant bat roosts with large accumulations of bone. Field work is partially complete in Long Cave, but much still remains. In addition, a large, ancient gray bat (*Myotis grisescens*) roost has been identified in the main trunk of Proctor Cave. Several pit caves that appeared to have potential from a paleontological standpoint were examined; however, none of them shows significant promise as a result of the field work.

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An Important Interglacial Fauna from Sediments of the Frozen Niagara Entrance, Mammoth Cave National Park — A Preliminary Report

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Recent work on paleontological remains contained in sediments at the Frozen Niagara Entrance of Mammoth Cave indicates that the area contains a fauna from the Sangamonian Interglacial. The diversity and taxonomic range of the fauna, combined with the ability to accurately date the deposit, indicate that this may be one of the most important Sangamon Episode (i.e. Sangamonian Age) sites in the central United States.

Discovery of the bone-bearing deposit was fortuitous. During the Cave Research Foundation's Thanksgiving 1999 Expedition, Toomey went on a trip into the Frozen Niagara Entrance area as a party member on a trip supporting the CRF-NPS Digital Video Project. The party leader and project director Mike Yocum loaned Toomey one of the video lights to examine sediments while Yocum set up the video shots. While examining travertine and sediment banks along the trail, Toomey identified several areas with small bones. Later Olson located several more bone areas while evaluating potential impacts of scheduled trail improvements. Toomey, Colburn, and Olson sampled the deposits for bone in January 2000 to evaluate the deposits before any possible impact. In addition they collected samples of flowstone for Uranium-series dating. As expected, the new construction had no impact on the deposits, but the results of the sampling indicate that the deposits are very significant.

The sampled deposits consist of sediment and travertine that are exposed on both sides of the paved tourist trail; they extend from approximately the bottom of the entrance steps to about 35 meters into the cave. The sediments and travertines that make up the deposit are exposed where they have been cut through during trail construction. The exposed section is about 1.5 meters thick, but this may only represent the top of a much thicker sediment and travertine deposit. Together the travertines and sediments represent a mass that was deposited near an ancient natural entrance of the cave system. During the 1920s the area was artificially re-opened, exposing the ancient sediments along the trail. The sediments consist mainly of red clay-rich matrix with abundant chert pebbles and small bones. The travertine consists of masses of cave popcorn and thin to massive carbonate crusts. Overall, the section is dominated by the travertines, with sediments occurring mainly in pockets in the travertine mass. The generally fine-grained sediments, the small size of bones and bone fragments, and the amount of travertine suggest that the entrance in the area was probably small.

Some of the clay-rich sediment pockets had abundant bone, while others had little to no bone. Analysis of the bone is only in a preliminary stage; however, a few comments are possible. The bone represents a wide taxonomic range; amphibians (both frog and salamander), reptiles (turtle, snake, and lizard), birds, and mammals are all represented in the

deposits. Most of the animals represented are small, with bats and rodents dominating the assemblage. Several larger animals are also present including include deer (*Odocoileus* sp.), raccoon (*Procyon lotor*), flat-headed peccary (*Platygonus* sp.), and beautiful armadillo (*Dasypus bellus*). Of greatest interest are the extralimital species (extant animals not found in the area today) that are found in the deposit. Pocket gopher (*Geomys* sp.), for example, does not occur in Kentucky today, but it is very abundant in the deposits. Pocket gophers indicate open habitats in the area. One of the most interesting rodents in the deposit is the water rat (*Neofiber* sp.). At this time we are not able to identify whether the water rat represents an extinct species or the modern one. However, modern water rats are sub-tropical animals, found only in Florida and extreme southern Georgia. The presence of *Neofiber* provides strong evidence that the deposit represents an interglacial assemblage. Their presence indicates marshy habitats in the area.

Uranium-series dating of the carbonate crust that seals the top of the deposit provides information on which interglacial is represented by the deposit. Initial analysis of this carbonate provides an age of 125,000-126,000 years. If this carbonate represents a flowstone layer that formed at about the same time as the bone-bearing portion of the deposit, it indicates that the deposit formed during the last interglacial (the Sangamon Interglacial).

If the fauna is indeed Sangamonian in age, the deposit is potentially very important from a paleontological standpoint. Relatively few well-dated Sangamonian faunas exist in the central United States. In addition, none has the diversity and taxonomic range exhibited in the Frozen Niagara fauna.

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Geophysical Techniques for Locating and Mapping Caves from the Ground Surface: Microgravity Subsurface Investigation of the Egypt Parking Lot, Western Kentucky University

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ABSTRACT

The Center for Cave and Karst Studies has been using geophysical techniques to locate caves from the ground surface since 1985. Although several geophysical techniques have been employed, the best results have been obtained using microgravity. The general trend of the cave is estimated by using a combination of lineament analysis, dye traces and potentiometric surface mapping. Microgravity is then measured at a ten-foot interval along traverses established perpendicular to the hypothesized general trend of the cave.

Once a low-gravity anomaly has been confirmed to be a cave, usually by an exploratory boring, the general route of the cave passage can be determined by proceeding in a "leap frog" fashion with short parallel traverses. A spring or a known section of cave can also be used as the starting point for the "leap frog" traverses. This technique is particularly useful in well-developed karst, where the caves are relatively large and shallow.

This paper discusses the use of the technique to locate a large cave under a large sinkhole basin that has a history of frequent flooding for over 40 years. The site receives storm water runoff from most of Western Kentucky University's campus and the flood waters impact the Egypt Parking Lot and also floods the railroad underpass for Route 68/80 and Route 231. During the Summer 2000, a six-inch diameter well was drilled into a microgravity low anomaly detected under the site. The well intersected a large cave which may have the capacity to reduce or eliminate the flooding problem. The Center for Cave and Karst Studies proposes that the existing, inadequate storm water retention basin be converted into a wetland treatment facility for the "first flush" of storm water runoff. An urban nonpoint source

pollution study by Crawford indicates that most of the oil and grease, metals and other urban runoff contaminants are in the "first flush". As the storm water rises however, the later runoff would be directed into a five or six foot diameter well drilled into the cave. Hopefully, this plan will reduce or eliminate a serious flooding problem while also improving the water quality presently sinking into the karst aquifer.

Introduction

Storm water runoff from most of Western Kentucky University's campus has been directed into a large sinkhole basin that contains the Egypt Parking Lot, so named because it floods so frequently. Also within the sinkhole is a railroad underpass for Route 68/80 and Route 231. This sinkhole flooding problem has existed for more than forty years and on one occasion delayed fire trucks from reaching an apartment fire. On April 16, 1998, eighty student cars parked on the Egypt Lot were inundated. In 1999, the Center for Cave and Karst Studies at Western Kentucky University received a grant from the City of Bowling Green to use microgravity to investigate the flooding problem. The Center has used microgravity to locate caves from the ground surface since 1985 (Figure 1) and had already located a large cave near the Egypt Lot. Three wells drilled into a low-gravity anomaly along Creason Street revealed a large cave at least 15 feet high and over 50 feet wide. (Figure 2).

Site Geology

The area surrounding the Egypt Parking Lot is part of the Lost River Ground Water Basin. The study area overlies Mississippian aged limestones which strike to the northeast and dip gently to the northwest, the two primary directions of subsurface flow. The limestones contain two important chert layers. The flow of water in the subsurface is primarily perched upon the upper Lost River Chert Bed or the lower Corrydon Chert Member of the St. Louis Limestone.

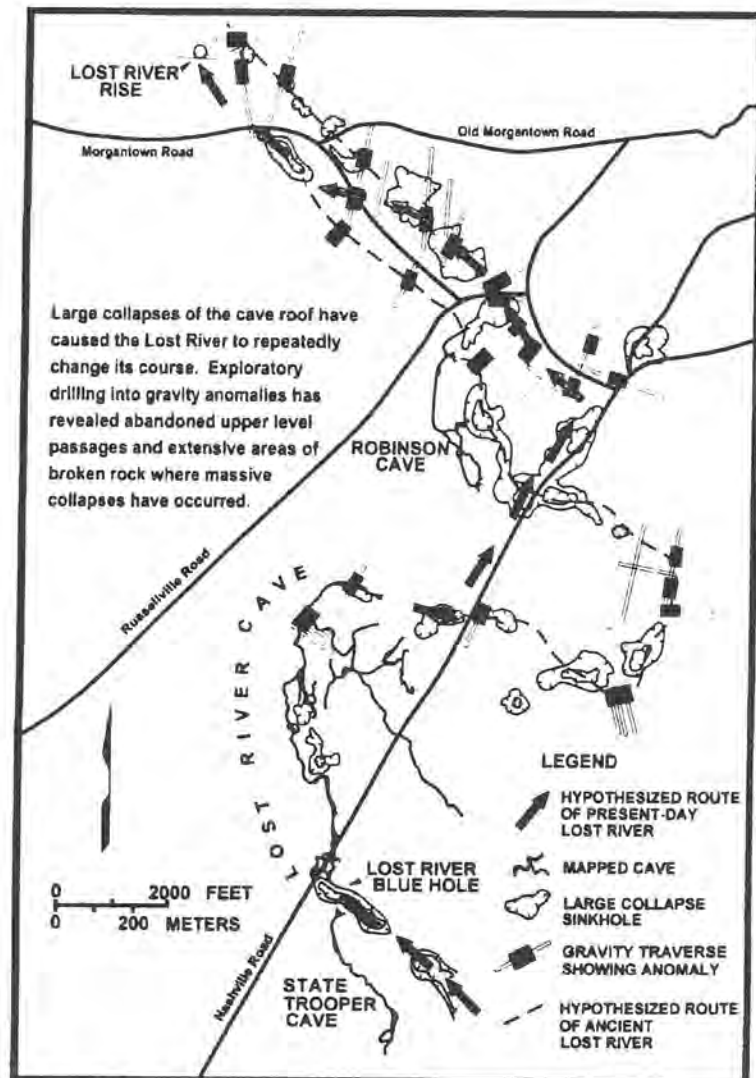


Figure 1- Mapped portions of Lost River Cave and hypothesized present-day and ancient routes as determined by microgravity (Crawford, 1986).

A stream in Robinson Cave (Figure 3), lies to the southwest of the study area. Water in Robinson Cave flows upon the Lost River Chert until it breaks through the chert and then sumps as it approaches the study area. Based on the depth, approximately 70 feet, of a known void intersected by wells along Creason Street (Figure 2), it is believed that ground water flow beneath the Egypt Parking Lot is perched upon the Corrydon Chert at that same depth. Dye traces indicate that the ground water beneath the study area emerges about one mile to the northwest at the Lost River Rise.

Microgravity Techniques

Microgravity Research Procedure

The Scintrex CG-3M Autograv microgravity meter used for the research underwent a 48-hour stabilization period prior to field use. Field calibration was performed on the instrument which consisted of a long-term drift correction and temperature compensation adjustment. The following corrections were calculated for each gravity measurement:

- Instrument Drift (short term)
- Earth Tides
- Reference Ellipsoid (latitude)
- Free-Air Effect (elevation)
- Bouguer Slab Density

A base station was established at the survey site between the lines of Traverse A and Traverse B. Gravity was repeatedly measured at this base station at approximately a one-hour interval while the meter was in use in order to derive instrument drift. A base station derived instrument drift curve was interpolated to the time of each survey station reading and each station reading was then corrected for instrument drift.

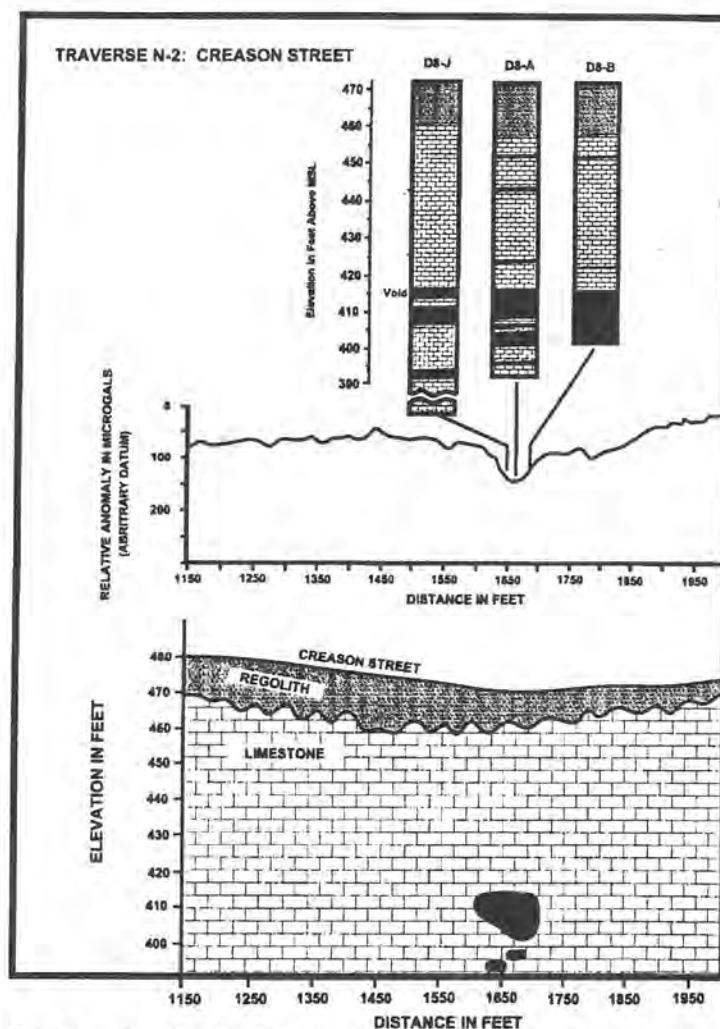


Figure 2. Three borings into this microgravity anomaly intersected a water-filled cave over 15 feet deep and 50 feet wide.

Earth tide corrections are based on the latitude and longitude of the survey station and the gravitational effect of the sun and moon at any given point in time. This correction was made for each gravity reading using latitude and longitude derived from a 7.5-minute topographic map and determined by recording date and time for each instrument reading (converted to UTC for calculations). The reference ellipsoid correction refers to the fact that the earth is an imperfect sphere with gravitational variation as a function of latitude. Differences in elevation between each survey station and the base station were compensated for using free-air correction calculations. The free-air effect compensates for the decrease in gravity with elevation due to increasing distance from the center of the earth. Elevation for each microgravity survey station were sighted to the nearest hundredth of a foot using a TOPCON RL-HA Rotating Laser Level and instrument height was measured to the nearest 1/8 of an inch at each station.

Theoretical gravity is modified to obtain Simple Bouguer Gravity by applying the Bouguer slab effect correction. This correction refers to the attraction of the slab of material, which is caused by a variation in density, between the station elevation and sealevel. Topographic relief across the survey site did not require terrain corrections to be applied to the data set.

In most karst areas, the following average density values are assumed:

Air = 0 g/cm^3

Water = 1.0 g/cm^3

Silt-clay sediments or regolith = $1.5\text{-}2.21 \text{ g/cm}^3$

Limestone = 2.67 g/cm^3

Therefore, density contrasts of -1.0 to -2.67 g/cm^3 are anticipated for any subsurface cavity, depending on whether the cavity is filled with air, water or silt-clay sediments. For the purpose of the Egypt Parking Lot survey, the density value of 2.67 g/cm^3 was used for interpreting Simple Bouguer Gravity because target features were located within limestone bedrock.

Detection of Subsurface Features in Karst Terrain

Bouguer gravity can identify locations on the earth's surface that have relatively higher or lower gravity caused by lateral variations in subsurface density. The Center for Cave and Karst Studies has used microgravity extensively to locate bedrock caves from the ground surface since 1985. The lower densities of the air, water, or mud within a cave compared to the surrounding carbonate rock results in a low gravity anomaly. The Center has also used microgravity to locate voids in the regolith (unconsolidated material above bedrock) which are potential sinkhole collapses. Since regolith is less dense than limestone bedrock, Bouguer gravity can also identify variations in depth to bedrock. In limestone areas, depth to bedrock is often very irregular with limestone pinnacles that protrude upward and cutters that extend downward. Cutters are V-shaped regolith-filled crevices formed by solution of the limestone by soil water as it percolates down to the karst aquifer. Regolith arches form as regolith spalls into solutionally enlarged voids in the bedrock. In some cases regolith may then be carried off by a cave stream. For these reasons, low-gravity anomalies indicate bedrock caves, voids

in the regolith or places where depth to bedrock is abruptly greater, which is often indicative of places where regolith may be descending into bedrock crevices.

Microgravity Used to Detect Bedrock Caves

Several researchers have demonstrated that gravity can be used to detect large bedrock caves (Omnes, G 1976, Kirk, K.G. and E. Warner, 1981, Butler, D.K. 1983, and Smith, D.L. and G.L. Smith, 1987). Although some studies had identified anomalies that were hypothesized to be caves, few, if any wells had been drilled prior to research performed by the Center in 1985. Crawford has drilled over sixty wells into caves detected by low-gravity anomalies.

Egypt Parking Lot Microgravity Investigation

Research Procedures

The microgravity study of the Egypt Parking Lot consisted of four parts:

1. Traverse A (330-foot survey over known cave on Creason Street alongside McNeil School).
2. Traverse B (320-foot survey in the Egypt Parking Lot)
3. Traverse C (430-foot survey in the Egypt Parking Lot)
4. Traverse D (300-foot survey in the Egypt Parking Lot)

The location of each traverse is indicated on Figures 3 and 4.

Field Method

A 10-foot station increment was used for each segment of the microgravity study. A base station for the survey was established between Traverse A and Traverse B. The base station was used to measure instrument drift at approximately one-hour intervals. The arbitrary reference datum of 979,950 mGals absolute gravity was used at the base station for subsequent data reduction. The Scintrex CG-3M Autograv microgravity meter used for the survey provided the following on-board data corrections.

1. Continuous Tilt Correction – for instrument level
2. Seismic Filter – for interference caused by vibration
3. Auto-Reject- for statistical rejection of anomalous readings

At each measuring station the instrument was manually leveled to within ± 10 arcseconds. Instrument height was measured to the nearest 1/8 inch for each station. Measurement readtime on the Scintrex CG-3M Autograv was programmed for 120 seconds (one reading per second for resultant average). The time of measurement (HH/MM) was accurately recorded for each measurement.

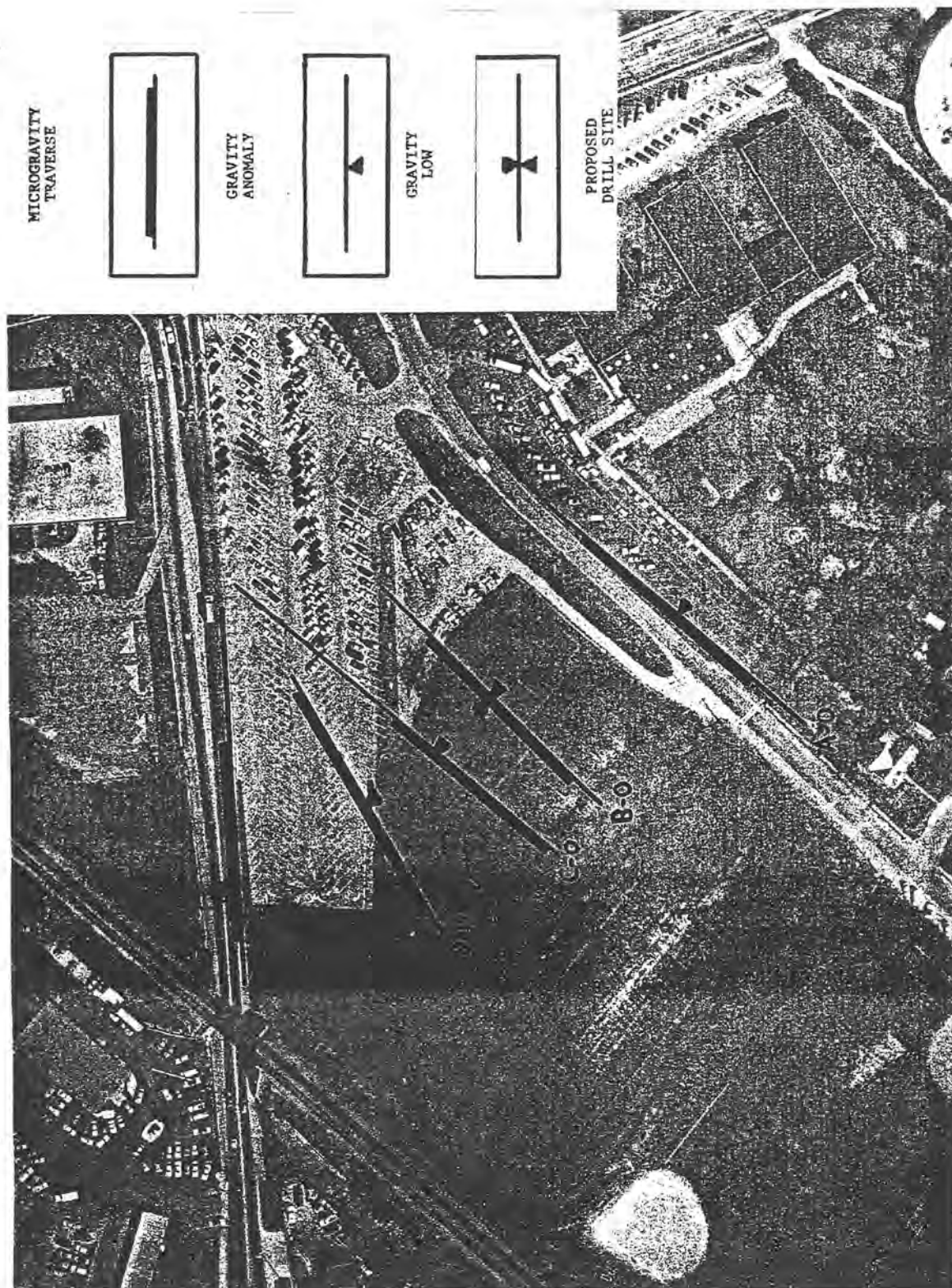
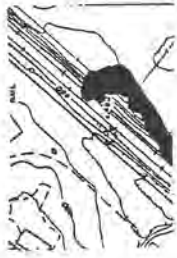
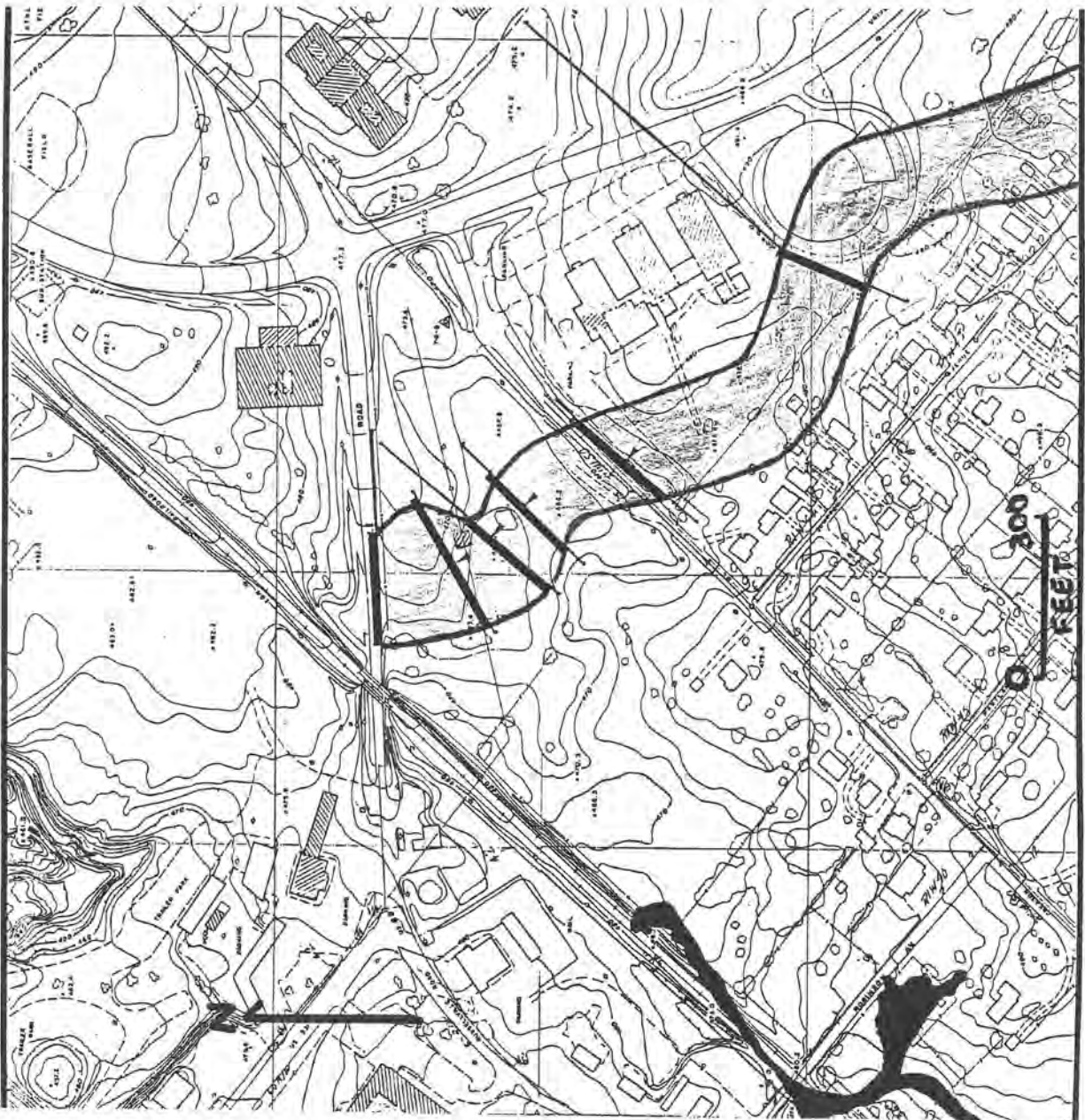


Figure 3. Air photo of Egypt Parking Lot and Route 68/80 and Route 231 railroad underpasses sinkhole flooding area showing microgravity Traverses A, B, C, and D with low-gravity anomalies indicated.



ROBINSON CAVE



MICROGRAVITY TRAVERSE



PROPOSED PATH
of CAVE

Figure 4. Study Area (topographic map)

Data Reduction

Elevations for each measurement station were surveyed by the Center for Cave and Karst Studies and data reduction was facilitated by the computer program GRAVPAC which included the following corrections:

1. Instrument Drift
2. Reference Ellipsoid (a function of latitude)
3. Earth Tide
4. Free Air Effect (elevation)
5. Bouguer Slab Effect (density)

Traverse A

A 1985 microgravity study conducted by the Center indicated the presence of a low-gravity anomaly along Creason Street by McNeil School (Figure 2). Three wells were drilled which successfully intercepted a cave over 15 feet deep and 50 feet wide. For this research 330 feet of this traverse were retraced, 165 feet to either side of the known cave, to establish a standard to compare findings. The gravity vs. distance chart for Traverse A (Figure 5) displayed a large, but poorly defined low-gravity anomaly of 150 microGals that extends approximately 230 feet. Within this anomaly is a more sharply defined low-gravity anomaly that extends approximately 50 feet. This well-defined anomaly is centered around the known void at station A-180. The patter of a sharply defined anomaly within a broader more general anomaly was mimicked in Traverse B and Traverse C, while Traverse D displayed only a large, less defined anomaly.

Traverse B

Traverse B was located in the Egypt Parking Lot trending SW to NE, roughly parallel to Traverse A. The gravity vs. distance chart for Traverse B (Figure 6) indicates a broad low-gravity anomaly of 170 microGals that extends approximately 220 feet. Within the broad anomaly is a more sharply defined low-gravity anomaly of 70 microGals that extends approximately 90 feet. The well defined anomaly is centered around station B-65.

Traverse C

Traverse C was located in the Egypt Parking Lot trending SW to NE, roughly parallel to Traverses A and B. The gravity vs. distance chart for Traverse C (Figure 7) indicates a broad low-gravity anomaly of 170 microGals that extends approximately 310 feet. Within the broad low gravity anomaly is a more sharply defined low-gravity anomaly of 70 microGals that extends approximately 80 feet. The well defined anomaly is centered around station C-70.

Traverse D

Traverse D was located in the Egypt Parking Lot trending WSW to ENE. The gravity vs. distance chart for Traverse D (Figure 8) indicates a broad low gravity anomaly of 140 microGals that extends approximately 280 feet. Traverse D lacks a smaller more sharply defined anomaly.

Figure 5. Creason St. Microgravity Traverse A

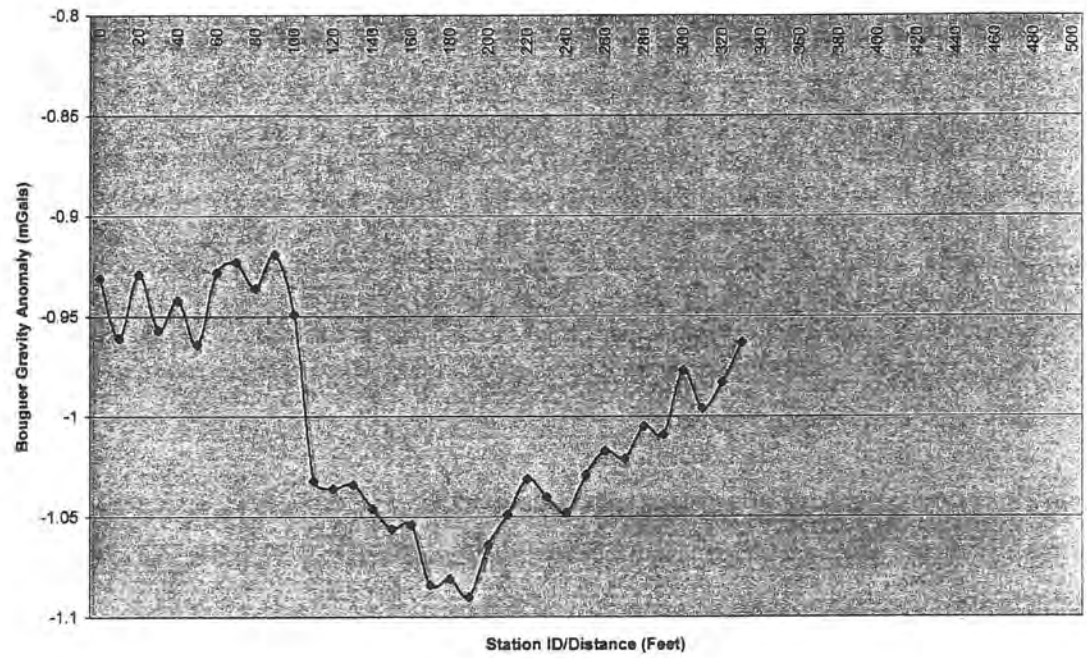


Figure 6. Egypt Lot Microgravity Traverse B

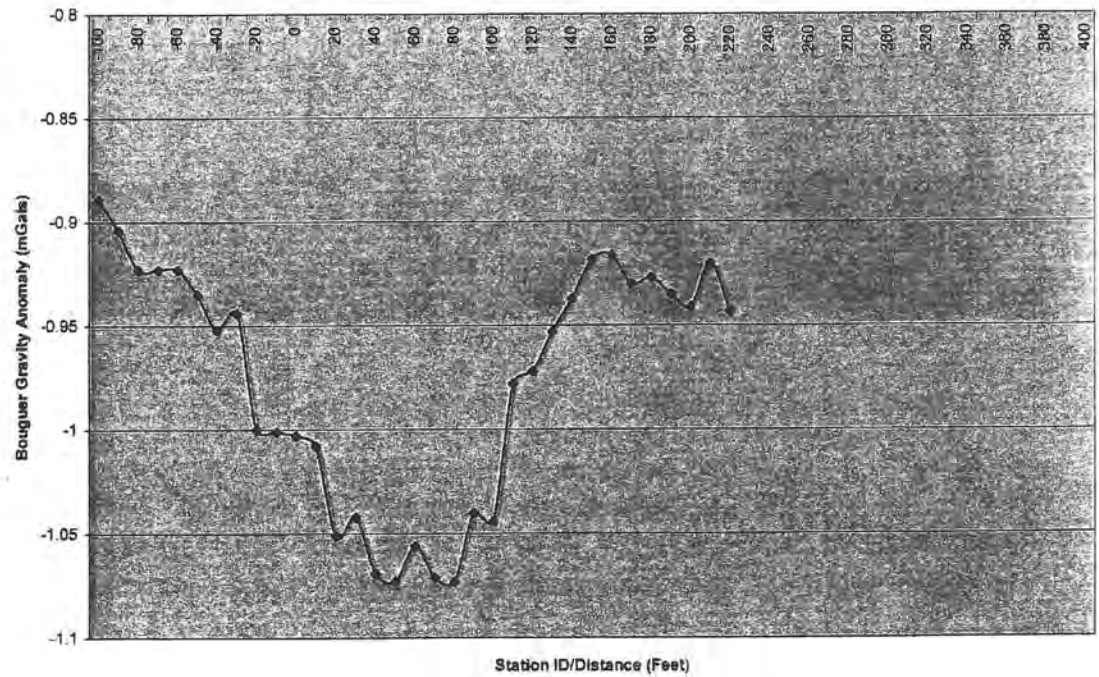


Figure 7. Egypt Lot Microgravity Traverse C

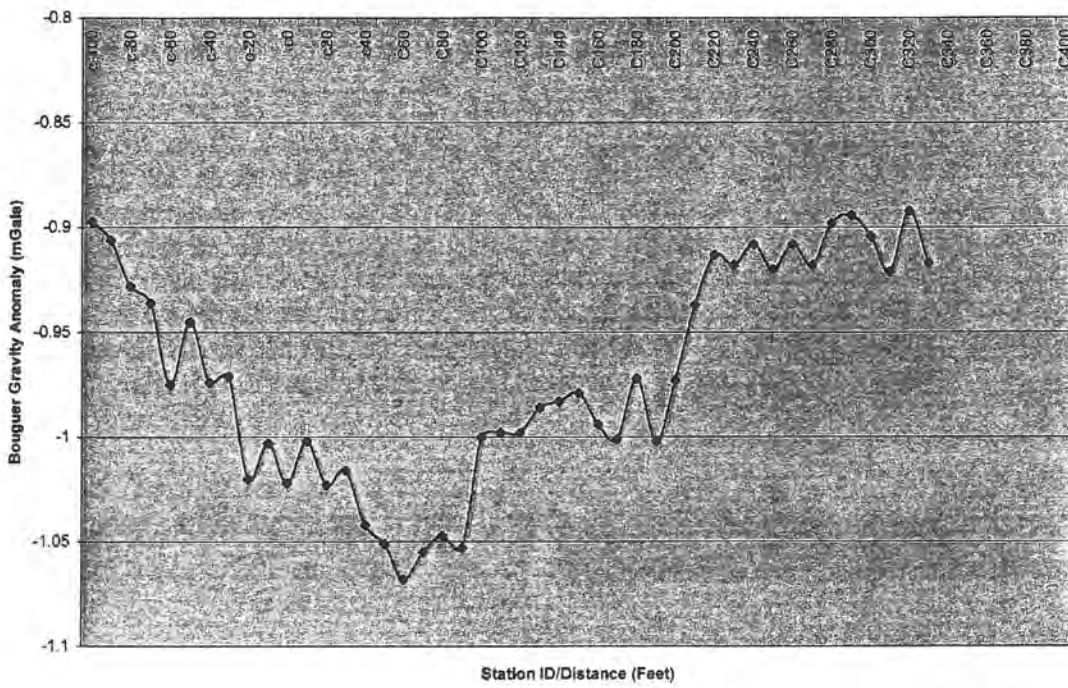
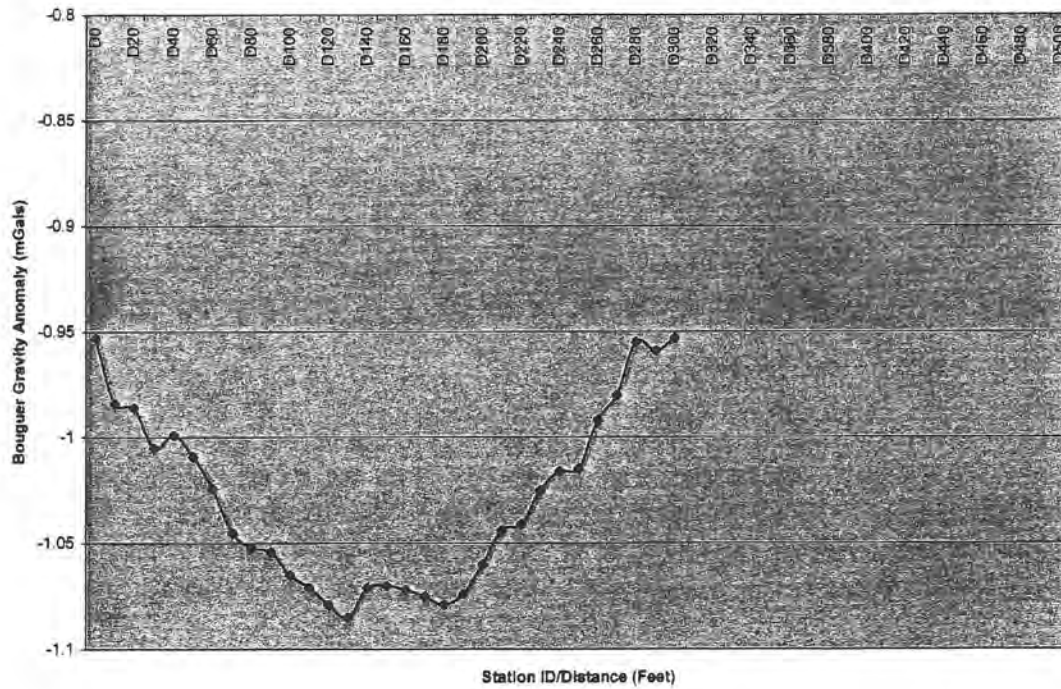


Figure 8. Egypt Lot Microgravity Traverse D



Exploratory Boring

A six-inch diameter well was drilled into the center of the large low-gravity anomaly at station 65 of Traverse B (Figure 6) during the Summer of 2000. The exploratory boring intersected a large cave forty feet below the surface.

The Center's down-hole camera revealed that the cave had three feet of air, two feet of water and twelve feet of silt. The diameter of the passage could not be estimated because the light on the camera could not expose the cave walls. Obviously, it is a wide cave passage.

Proposed Solution

Pressure transducers will be installed into a well in the cave stream and also on the surface at the bottom of the sinkhole in order to compare water levels during floods. The variation in water levels during floods will be used to evaluate the cave's capacity to accept additional storm water runoff. If the research indicates that the cave has the capacity to receive additional runoff during floods, the Center will propose that a five to six foot diameter well be drilled to permit storm water to drain rapidly into the large Lost River Cave and thus reduce or eliminate the flooding problem. Research by the Center and other agencies has revealed that the "first flush" of storm water runoff contains most of the oil and grease, metals and other contaminants associated with urban storm water runoff. Presently, there are several drainage wells and even exposed bedrock crevices in the Egypt Lot and railroad underpass. Therefore, the "first flush" is presently going directly into the karst aquifer. As the capacities of these wells are exceeded it is the cleaner storm water that fills the sinkhole during floods. The Center intends to design a wetland treatment system so that the "first flush" would flow into a constructed wetland at the bottom of the sinkhole basin. As the water rises, the later runoff would then spill over into the large diameter well. Therefore, the proposed mitigation would reduce or eliminate the flooding problem while also reducing the storm water runoff contaminant load that is presently flowing into the karst aquifer.

References

- Butler, D.D. (1983). "Microgravimetric and magnetic surveys, Medford Cave Site, Florida, "Cavity Detection Research Report 1, Tech. Rep GL-83-1. Vicksburg, MS: Army Engineer Waterways Station p.92.
- Crawford, N.C.; M.A. Lewis, S.A. Winter and J.A. Webster (1999). Microgravity Techniques for Subsurface Investigations of Sinkhole Collapses and for Detection of Groundwater Flow Paths Through Karst Aquifers, in Beck, Pettit, and Herring (eds). *Hydrogeology and Engineering Geology of Sinkholes and Karst*, Proceedings of the Seventh International Sinkhole Conference. Harrisburg, PA, Balkema, Rotterdam, pp. 203-218.
- Crawford, N.C., C. Calkins and S. Fryer (1999). *Microgravity Subsurface Investigation: Egypt Parking Lot, Western Kentucky University, Bowling Green, Kentucky*. Report prepared by Center for Cave and Karst Studies, WKU, for City of Bowling Green, Kentucky, p. 62.
- Crawford, N.C., J.W. Webster, and G. Veni, (1980). Sinkhole collapse problems in Warren County, in Crawford, (ed) *The Karst Landscape of Warren County*, prepared for Bowling Green-Warren County Planning and Zoning Commission, Center for Local Government. Western Kentucky University, Bowling Green, Kentucky , pp. 71-115.
- Crawford, N.C., J.W. Webster, and S.A. Winter, (1989). Detection of caves from the surface by microgravity followed by exploratory drilling. Lost River Groundwater Basin, Bowling Green, Kentucky, prepared for the City of Bowling Green, Municipal Order No. 85-83.
- Kirk, K.G. (1974). "Resistivity and gravity surveys applied to karst research, *Proceedings of the 4th Conference on Karst Geology and Hydrology*. West Virginia Geological Survey, pp. 61-71.
- Omnes, G. (1976). "High accuracy gravity applied to the detection of karstic cavities. *Karst Hydrogeology*, ed J.S. Tolson and F.L. Doyle UAH, Huntsville, Alabama. International Association of Hydrogeology. V.12 pp. 273-284.
- Smith D.L. and G.L. Smith (1997). Use of vertical gravity gradient analyses to detect near-surface dissolution voids in karst terrains, *2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst*, Beck, and Wilson, (eds). pp. 205-209.

Investigation of Gasoline Vapors Rising from a Karst Aquifer into Greenwood Park Church of Christ and the Foundation Christian Academy, Bowling Green, Kentucky

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ABSTRACT

On numerous occasions Bowling Green, Kentucky has had problems with explosive and/or toxic vapors rising from the karst aquifer under the city into homes and buildings. In the 1980's there were two USEPA Superfund Emergencies in Bowling Green because of toxic and explosive vapors rising from the contaminated karst aquifer. In March 1985, the U.S. Centers for Disease Control issued a Health Advisory for the Bowling Green area because of the problem. The Center for Cave and Karst Studies played a major role in assisting USEPA in finding the sources of the contamination and in improvising methods for preventing the vapors from rising into surface structures. Only a few minor problems have occurred during the past decade, but in the Fall of 1999, gasoline vapors rising from the karst aquifer became a serious problem for the Greenwood Park Church of Christ and the Foundation Christian Academy. Again, the Center assisted with the problem by providing advice on ridding the building of gasoline vapors, by performing a microgravity investigation to identify places for ventilation wells to be drilled and by performing dye traces to determine if other areas of the city were at risk.

INTRODUCTION

The entire city of Bowling Green is located upon a sinkhole plain in the karst of Southcentral Kentucky. The landscape consists primarily of closed depressions called sinkholes which effectively direct all surface water into caves in the underlying limestone. The Barren River is virtually the only surface-flowing stream in the entire city. Karst areas are extremely vulnerable to ground water pollution; anything capable of percolating through the soil or of being transported by storm water runoff directly into cave streams may contaminate the underlying aquifer. Carried along by underground streams. Contaminants may be transported several miles in only a few hours.

Contamination problems are particularly serious when they involve toxic or explosive liquids. Not only are these chemicals a threat to water supplies and aquatic life, but upon vaporizing they may produce hazardous vapors in caves which may then rise into homes and buildings on the surface. Natural gas from leaking or ruptured gas lines may also travel through caves and rise into crawl spaces and basements. An example of what can happen when explosive levels of gasoline vapors fill cave passages occurred in Pennsylvania in 1970 when a water well exploded (Gold, et al., 1970). The explosion may have been due to lightning or a spark from the pump motor. It demolished a concrete pump house and excavated a crater 25 feet across. Debris was thrown hundreds of feet into the air and the 200 lb. pump was thrown over trees and landed 179 feet away. The explosion caused considerable damage to the house and adjacent buildings. The time of the explosion is known precisely because it was recorded at the Seismic Observatory at Pennsylvania State University 12.5 miles away. Analysis of the crater and debris revealed a release of energy of 5×10^{13} erg, which could have been achieved by the combustion of only 2.5 gallons of gasoline! (White, 1988). The source was apparently a farmer's storage tank used to supply gasoline for farm machinery.

The magnitude of a potential explosion under Bowling Green may not be comprehensible when one considers that on seven occasions, 1,000-10,000 gallons of gasoline have leaked into the karst aquifer within 24 hours. These were cases that were reported. Many smaller leaks and spills probably were not even reported.

HISTORY OF THE PROBLEM IN BOWLING GREEN

In 1969 and again in 1981 residents of several homes in the Riverwood area were evacuated because explosive levels of fumes were detected in their basements and crawl spaces. In 1981 a trench was dug in an attempt to find the cave stream and obtain a sample of the gasoline. Since the backhoe excavated many large blocks of Lost river Chert (a light gray flint resembling limestone) mixed with the soil, it is fortunate that the cave and gasoline were not located! A survey of storm water drainage wells in the vicinity revealed high readings on a portable combustion meter for two drainage wells in the nearby Fairview Plaza shopping center parking lot. If someone had discarded a cigarette near one of the wells, it is conceivable that the explosion could have traveled through the cave system destroying houses some distance away. An underground explosion in the sewer system of Louisville, Kentucky in 1981

A Historiography of Archaeological Research in the Mammoth Cave Area of Kentucky: 1824-2000

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ABSTRACT

Archaeological interest in the Mammoth Cave area of Kentucky has been on-going since the early 19th century, primarily because of the unique preservation offered at the underground cave sites. In this paper I examine almost two hundred years of archaeological research conducted in the Mammoth Cave area. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and later by Willey and Sabloff (1993).

An examination of the history of archaeological study in the Mammoth Cave region of south-central Kentucky reflects parallel development with the growth of archaeology in North America (Schwartz 1967; Willey and Sabloff 1973), but it also demonstrates why additional intensive and systematic archaeological study should to be conducted in this very significant archaeological region. In this paper I provide an historical overview of archaeological research that has taken place in and around Mammoth Cave National Park. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and expanded by Willey and Sabloff (1993).

THE SPECULATIVE PERIOD

One of the earliest archaeological records pertaining to the Central Kentucky Karst research area was written in 1824 by Constantine Samuel Rafinesque (1824). Rafinesque, a colleague of James Audubon, was deeply interested in prehistoric remains of the Ohio Valley (Stout and Lewis 1995:83-90). According to Col. Bennett Young (1910:18), Rafinesque claims to have located 148 ancient sites (settlements) and 505 monuments in a 41 county area of Kentucky, speculating as with other early nineteenth century naturalists about the origin of these "natural" curiosities. Rafinesque's entry for the Central Kentucky Karst lists "shell mounds along Green River and mummies in caves."

Following Rafinesque's initial inquiry into Kentucky's prehistory, there appears to be an absence of related literature about the antiquities of the area. This is not to say that interest in antiquities had died; it had not. According to Col. Bennet Young (1910), increased farming activity, and in general, disruption of the land due to population growth, caused an escalation

in the amount of destruction and looting of prehistoric sites. By 1870, the collecting, selling, and smuggling of antiquities in Kentucky was a major profession. Although known mostly for its large cave system, the archaeological contents of the Mammoth Cave area offered a variety of artifacts and desiccated human remains for collecting and selling. Finds, such as Fawn Hoof in 1813, Scudder's Mummy in 1814, Little Al(ice)¹ in 1875, and Lost John in 1935, helped make the Mammoth Cave area famous (Meloy 1971). During the mid-nineteenth and early twentieth centuries, many individuals explored nearby cave systems looking for mummies and Indian relics to sell (see Young 1910). Unfortunately, this dilettantic pastime stopped only in those caves that came under the protection of the National Park Service after 1940 (e.g., Salts, Mammoth, Longs, Bedquilt, and Lee caves), and even then, infrequent looting of caves within the National Park still occurred.

The earliest historic date known from inside Salts Cave is 1809 (Watson 1969:7). Dates and names upon various signature rocks in Mammoth and Salts caves indicate that the majority of historic caving dates "from the last quarter or so of the 19th century to the first quarter of the 20th century" (Watson 1969:7; see also Watson ed., 1974:21-23). The vegetal antiquities (e.g., textile bags, cordages, sandals) that could be found within the dry caves were not normally preserved in surface or "open" sites. Hence, those items were especially sought for collecting, smuggling, and looting. As an example of smuggling, in 1874 or 1875, Louis Vial and some friends explored extensively in Salts Cave using a "new side entrance known only to themselves" (Watson 1969:7). During one of those cave trips they found the "Salts Cave Mummy," nicknamed incorrectly "Little Alice" (Robbins 1971; Tankersley et al. 1994; Watson 1969:7). More recent examinations by the late Louise Robbins (1971:200-206) identified the sex and age of this individual to be those of a nine-year-old male.

During the 1890s men such as F.W. Putnam of the Peabody Museum, as well as local Kentuckians such as Colonel Bennett Young, T. F. Hazen, and W.D. Cutliff, made extensive collections and/or purchased prehistoric material from Salts and Mammoth caves. Young (1910:300, 305) states:

In 1893 Mr. Theodore F. Hazen...opened a new entrance into Salts Cave..." [and] "we obtained many interesting relics..." about the present entrance [Salts Sink], numerous spalls, flakes of flint, pestles, axes, awls, and other implements have been found...

Young goes on to describe many artifacts taken from within Salts and Mammoth Caves, such as cords of bark, hemp, cattail leaves, and grass; basketwork; half-burned cane torches; corn cobs (probably modern); an aboriginal ladder; wooden digging implements; cups, dishes, bowls and water bottles made from gourds and squash rinds; tobacco leaves and seed pods (also probably modern), as well as many chert implements. The large collection of antiquities Young acquired was sold to the Museum of the American Indian, Heye Foundation, New York (Schwartz 1958e; Watson 1974: 167). Later, John M. Nelson, who was a cave guide from 1894-1907, extensively collected antiquities both from the caves and from surrounding surface sites (Carey 1942; Schwartz 1958f:3; Watson 1969, 1974). With the exception of the John M. Nelson

collection, the other large private collections were either given or sold to the American Museum of Natural History, Smithsonian Institution, or the Peabody Museum of Archaeology and Ethnology. It was the Mammoth Cave Estates collection, donated to the American Museum of Natural History in 1913, that prompted Nels C. Nelson (no relation to John M. Nelson) to engage in the “only scientific archaeological investigations” (Schwartz 1958d) of the Mammoth Cave area up to that time and usher in the Classificatory-Historical Period of archaeological work (Schwartz 1967; Willey and Sabloff 1993).

The Speculative Period focused initially upon discovery, with only meager attempts to offer explanations of derivation of the discovered sites. Once discovered and made known, sites were vandalized and exploited for private purposes, whether pots, “arrowheads” or “mummies”—the market for trafficking in North American antiquities had begun. But it was from the seeds of site destruction that the first museum acquisitions were made that ushered in professional archaeological work of the Classificatory Period.

THE CLASSIFICATORY PERIOD, 1916-1960

Nels C. Nelson worked in Mammoth Cave National Park during May and November of 1916 as an archaeological representative of the American Museum of Natural History. Nelson’s 1917 report describes the materials found during his surface and cave reconnaissances and excavations within the Mammoth Cave area. Specifically Nelson describes and compares his surface finds from the Mammoth Cave and Eaton Valley fields to similar bifacial chipped stone materials then being found in the French Paleolithic (Nelson 1917:16-19). In total Nelson examined, through excavation and/or other study, six of nine cave sites, six of seven open surface sites, and one of four rockshelters (Nelson 1917: 11). The latter number refers to the category of site types he reported for the Mammoth Cave area. Douglas W. Schwartz (1958d:1-2) states that Nelson’s main contribution was to “scientifically document the presence in the caves of some classes of material previously only reported by amateurs.” Nelson also drew substantial conclusions from his materials, despite the lack of published reports concerning antiquities of the area and the role of plant domestication (he found large quantities of charred sunflower seeds in his Mammoth Cave Vestibule excavations) in the Central Kentucky region. Nelson concluded that the Flint-Mammoth Cave system had an economic importance to the Native Americans, e.g., the quarrying of flint (e.g., from Flint Alley in Mammoth Cave, which has since been questioned [Munson et al. 1989, Prentice 1993]); Nelson was not aware that the Native Americans also exploited the caves for minerals (e.g., mirabilite, gypsum, satin spar and selenite; see Munson et al. 1989 and Tankersley 1996).

Nelson’s archaeological excavations inside the Vestibule of Mammoth Cave is his major work in the Mammoth Cave area. Although this excavation was exploratory, it was extremely extensive and thorough. Nelson sank a series of 10 test trenches that revealed midden in two places. One was near the west wall of the entrance while the other, some 40 feet from the first, extended 50 feet back over the entire entrance area. Although Nelson’s notes are at times ambiguous, he demonstrated a strong concern for the temporal and spatial location of

artifacts excavated (personal observation in April, 1975 of Nelson's catalog record on file with the American Museum of Natural History, New York).

Nelson excavated almost all of the Vestibule entrance, but the number of artifacts found was few. Douglas W. Schwartz (1958d) explains that this was probably the result of extensive looting that had occurred earlier, throughout the nineteenth century. It also may be the result of Nelson's recovery methods (no screens were used), and/or extensive subsurface alterations resulting from cave commercialization or previous salt petre mining operations during the War of 1812 (Meloy 1968). Any of these reasons may explain the paucity of artifacts recovered from the Mammoth Cave Vestibule. Nelson did find and recognize evidence of prehistoric diet in the form of animal bone, sunflower seeds, and fresh water molluscs (Nelson 1917; Watson 1974:212). He also found prehistoric tools such as bone awls, bone flakers, antler points, tubes, stone projectile points, scrapers, ground stone implements, and items for personal adornment. Most importantly, Nelson (1917:69) concluded that two different cultures could be distinguished within his Vestibule excavations. The lower, or more "primitive" group was identified by Nelson as what archeologists would define two decades later (e.g., Ritchie 1933) as the Archaic culture (Schwartz 1960:133).

Only one other reference to Mammoth Cave area prehistory appeared in print during the first two decades of the twentieth century. This was a fleeting mention of a series of rockshelter sites near what is now the western boundary of Mammoth Cave National Park. The reference was made by C.B. Moore who visited the Indian Hill rockshelter complex in 1915 (Moore 1916). Fortunately, shallow water conditions on Green River forced Moore to terminate his plunderous Green River expedition near Indian Hill as his boat, The Gopher, was too large to continue the journey upstream.

In 1935, a newly discovered desiccated burial within Mammoth Cave, known to the cave guides as "Lost John," brought additional archaeological publicity to the area (Pond 1935, 1937). Alonzo Pond and George Neumann's analysis of Lost John (Neumann 1938), constituted the only professional archaeological inquiry in the Mammoth Cave area between N.C. Nelson's 1916 work and the formation of Mammoth Cave National Park in 1940 (although several additional references to caves and rockshelter sites in and around the present boundary of MCNP appeared in print intermittently (e.g., Fowke 1922; Funkhouser and Webb 1932). With the final acquisition of lands by the federal government on April 25, 1940, it became a federal offense to remove materials from cave interiors within Mammoth Cave National Park.

During the formation of MCNP, the Mammoth Cave National Park Association purchased from John M. Nelson, a collection of prehistoric, historic, and geological specimens that were subsequently donated to Mammoth Cave National Park on January 15, 1942 (Carey 1942:1). Henry A. Carey, then of the Archaeology Department at the University of Kentucky, was placed in charge of cataloging the Park's new acquisitions. He was assisted by a new National Park Service employee, Jesse D. Jennings (Carey 1942). Unfortunately, the majority of the 25,000 specimens in the John M. Nelson collection was without provenience. Items in the collection had been bought from the local area with no note made as to the exact collecting

location. Furthermore, Nelson kept only "mental notes" for his more unusual specimens. From the John M. Nelson collection, Henry Carey concludes: (1) the Mammoth Cave National Park area was utilized for an extensive period of time by aboriginal peoples; (2) a typological sequence could be worked out for the area using the collection, but that extreme caution should be used in drawing definitive conclusions due to the lack of controlled locational data; and (3) that scientific archaeological excavations should be started, inside the caves and at selected surface sites, immediately. Unfortunately, due to the start of World War II, the Mammoth Cave collections heralded for study by Carey were not examined again until 1957 when Douglas W. Schwartz, at the University of Kentucky examined the John M. Nelson materials and attempted to relocate some of the surface sites from which John Nelson had made his collections (Schwartz 1958f). Schwartz also brought systematization to the study of Native American sites in MCNP and visited several major museums in the East to study collections acquired from the Mammoth Cave area at the turn of the century (Schwartz 1958a-h). These activities culminated in a series of valuable descriptive reports (Schwartz 1958a-h) and other interpretive and popular accounts about the archaeology of the area (Schwartz 1960; 1965).

The Classificatory Period brought a logical, scientific inquiry to the archaeology of the Mammoth Cave area. With the first work of Nelson in 1916, to the discovery of an exsiccated individual (Lost John) in 1935, to the systematic reporting of archaeological sites above ground and below by Douglas Schwartz during the late 1950s/early 1960s, the archaeology of the Mammoth Cave area yielded ever-so-slowly, evidence of very significant information about prehistoric cultural adaptations and cultural processes. These later studies served as the foundation for investigations by Patty Jo Watson, the Cave Research Foundation, the National Park Service, and the Illinois State Museum (Watson 1969) during the next period of archaeological development.

THE EXPLANATORY/INTERDISCIPLINARY PERIOD, 1960-PRESENT

In 1942, Henry Carey emphasized the need for further surface investigations and excavations in Mammoth Cave National Park, but little was accomplished until the recent research efforts by Patty Jo Watson and her associates (Carstens 1974, 1975, 1976 1980; Carstens and Watson 1996; Marquardt 1974; Robbins 1971; Wagner 1976; Watson 1969; 1974). Whether you call it explanatory archaeology, processual archaeology, or even post-processual archaeology, the post-1960 era of interdisciplinary archaeological research in the Central Kentucky Karst began to answer many questions about the area's prehistory and the avenues of cultural change and adaptation through time and space.

Watson's archaeological work in Mammoth Cave National Park began in 1962 when, in conjunction with the Cave Research Foundation, the Illinois State Museum, and Mammoth Cave National Park, she initiated an archaeological reconnaissance of the large caves within the Flint Mammoth Cave system (Carstens and Watson 1996; Watson 1969:v). Watson's initial work was carried out primarily in Salts Cave, but later research expanded into other caves (e.g., Mammoth, Lee, and Bluff), and to archaeological surface reconnaissance (Carstens 1974, 1980). Watson's reason for studying the cultural materials from within the caves was that data

derived from those materials was highly relevant to the discovery of dietary practices during the early agricultural Late Archaic-Early Woodland period. Watson's research was expanded in April, 1969, to include, "excavation in Salts Cave Vestibule, a search for and testing of possible surface sites near Salts Sink, and recording of prehistoric remains in other caves within the Park" (Watson 1969:v). Between 1973 and 1980, Watson and her colleagues initiated comparative studies at caves outside the Park (e.g., Wyandotte Cave, Indiana, and Wolf River or Jaguar Cave, Tennessee) (Crothers 1986; P. Munson and C. Munson 1990; Robbins, Wilson, and Watson 1981; Tankersley, P. Munson, C. Munson, Shaffer, and Lieniger 1990). She also obtained a more complete radiocarbon sequence from Salts and Mammoth caves, excavated and floated a stratigraphic column from Salts Cave Vestibule; obtained pollen and parasitological analyses from human paleofecal specimens found within the cave, and took pollen core samples from nearby sinkhole ponds.

Aided in her research by scientists from many different fields of study, Watson was able to approach the archaeological problems of the Mammoth Cave National Park area in a scientifically-integrated manner, a methodological approach she had learned as a University of Chicago graduate participating in Robert Braidwood's interdisciplinary studies of agricultural origins in the Near East. This approach led to some answers, and to many new questions, particularly with respect to environmental changes and their possible effects on the prehistoric inhabitants of the study area. Watson and her colleagues (e.g., Munson et al. 1989; Tankersley 1985, 1996) documented that prehistoric people using the cave were mining the cave for minerals (e.g., mirabilite, gypsum, selenite, and satin spar) and were simply exploring the cave system. She noted similar patterns of cultural activities in portions of other caves located inside (Lee and Bluff) and outside the Park boundaries (e.g., Wyandotte Cave in Indiana, and Big Bone and Jaguar caves in Tennessee; Crothers 1986; Munson and Munson 1990; Watson 1986:109-116). Although Lee, Bluff, Wyandotte, and Jaguar caves are not comparable in size to either Salts or Mammoth Cave, the data collected by Watson and her colleagues clearly indicate that cave mining and exploration were widespread activities in this karstic region that probably began during the Late Archaic (Watson 1974:221-232; Watson 1986; Munson et al. 1989). The 50+ radiocarbon dates now available for the Mammoth Cave project clearly demonstrate the widespread prehistoric use of caves over a very important and similar time horizon (Kennedy, 1996): that of early agriculture in the Late Archaic-Early Woodland period (ca., 4,000 to 2,000 B.P.).

Watson's research between 1962 and 1980 in the Mammoth Cave region is unique for two reasons: (1) it is the first time such scientifically-integrated archaeological deep-cave research has been attempted in the eastern United States; and (2) it provides an aspect of prehistoric culture process that was extremely important (i.e., the domestication of native plants, evidence for which was not then being found in "open" surface sites in the eastern U.S.). Watson's research continues in the Mammoth Cave region.

As a part of the Watson research team between 1973 and 1975, my job was to document the culture history evident in a sample of 83 surface sites in and around MCNP, examining the

techno-economies of several of those sites diachronically, and presenting a cultural historical context within which the surface dwellers of the Central Kentucky Karst explored and exploited the large caves (Carstens 1980).

Between 1977 and 1987, MCNP witnessed only intermittent archaeological research on the Park's surface archaeology. Most of the work accomplished included small, unrelated cultural resource management surveys (e.g., Beditz 1979, 1981; Carstens 1977, 1978). Between 1981 and 1989, few archaeological projects were conducted on the surface of Mammoth Cave National Park. Exceptions are the work of Philip J. DiBlasi, who investigated the 1920s home-
stead of Floyd Collins (DiBlasi 1987a), a famous local cave explorer, and George Crothers, who documented material left in Sand Cave where Collins died in 1925 (Crothers 1981, 1983). DiBlasi (1987b, 1996), working with the Cave Research Foundation, also found, in Salts Cave, a series of prehistoric pictographs and glyphs previously undocumented. Other studies concerning the human use of the cave system, and of the people who were using the cave, focused on determining the exact nature of prehistoric mineral procurement (Tankersley et al. 1985), forensic examinations of the historic findspots of mummies (K. Tankersley et al. 1994; S. Tankersley 1993), and a new and exciting search for pathogenic microorganisms in prehistoric and historic human feces and bodily fluids (Ruppert 1994; Tankersley 1993).

The most systematic undertaking to inventory a representative sample of the Park for both historic and prehistoric cultural resources was directed by NPS archeologist Guy Prentice (1993). Although much of Prentice's prehistory is a summary of Nelson (1917), Schwartz (1958a-g), Carstens (1980), and Watson and Carstens' (1982) site inventories, Prentice adds new prehistoric and historic sites to the overall resource inventory of the Park. As a result, Prentice (1994, 1996) was able to offer a settlement synopsis of MCNP for his doctoral dissertation that includes a hypothetical seasonal round between the Big Bend shell mound area and the Mammoth Cave area.

In 1993, the Science and Resource Management Division at Mammoth Cave National Park began a long-term cultural resource inventory of all artifacts (historic and prehistoric) within the Main Cave in Mammoth Cave. This project is co-sponsored by the NPS and Earthwatch; the field work for this project has been directed by Ken Tankersley, Mary Kennedy, George Crothers, Christine Hensley, and Bob Ward (Kennedy 1993; Crothers and Ward 1995). Using an Electronic Distance Measurement (EDM) system, the Earthwatch team records the exact location of every artifact noted within the surveyed areas of the cave system. This makes it possible to prepare density plots of aboriginal activity within the cave system, and to determine prehistoric use areas within the cave despite 200 years of historic cave use and cave disturbance to the aboriginal materials in Mammoth Cave.

In 1992, Patty Jo Watson, Mary Kennedy, Kristen Gremillion, and Kristin Sobolik began a new study in Mammoth and Salts cave. This new arena emphasized the collection of human paleofecal samples for radiocarbon dating, parasitological analysis, macro- and microethnobotanical studies, and biochemical (hormonal) analysis. These studies would

allow prehistoric fecal specimens to be sexed and thereby enable a better understanding about specific individuals who explored and mined prehistoric Mammoth Cave (Watson 1992; Watson and Kennedy 1993).

In 1994, Christine Hensley and Tom Sussenbach, while working for the National Park Service in Mammoth Cave National Park, conducted excavations at the Stairway Rockshelter (Hensley 1995, 1996). The three radiocarbon samples from Hensley's excavations of Feature 1 consistently place the site's occupation in the Early Woodland period, ca., 2170 to 2570 B.P., a date range that is quite comparable to the majority of aboriginal use of Mammoth and Salts caves (Hensley 1995: 24, Table 1; Kennedy 1990, 1996). Further, Paul Gardner identified more than 5,000 seeds of domestic, semi-domestic, and wild chenopodium from the living floor of the rockshelter (Hensley 1995, 1996). Similar contractual archaeological studies continue today through the supervision of Bob Ward, cultural resource specialist at Mammoth Cave National Park and the assistance of Darlene Appelgate, archaeologist at Western Kentucky University (Appelgate, personal communication email to Carstens, July 1, 2000).

Analytically, the Explanatory/Interdisciplinary (post-1960) era of archaeological research has answered many questions about the Native Americans who explored and exploited the environment and resources above and below ground in the Central Kentucky Karst. Initial studies by Watson and her colleagues in the early 1960s through 1980s focused upon time-space and environmental reconstruction sequences, then turned to more processual issues while unraveling the prehistory of the Mammoth Cave area. That work inspired other archeologists in Tennessee and Indiana to test several of Watson's observations and conclusions about the prehistory of Mammoth Cave specifically, and prehistoric cultural processes in general, finding that prehistoric aboriginal mining and exploration was a wide-spread cultural phenomenon; it was not limited solely to Mammoth Cave National Park nor only to the Late Archaic-Early Woodland transition (e.g., Faulkner 1986). Furthermore, not only had Watson and her associates confirmed and expanded N.C. Nelson's initial observations about the importance of plant cultivation in the Mammoth Cave area, but also Watson's research teams went far beyond, examining human paleofeces for parasites and micro-organisms and determining whether prehistoric caving activities were carried out by both sexes, thereby helping to engender, and more accurately describe, Mammoth Cave prehistory.

RETROSPECT AND PROSPECT

The history of archaeology in the Mammoth Cave area closely parallels the growth and development of archaeological trends in North America. From the Speculative to the Classificatory to the Explanatory and Interdisciplinary periods, archaeological inquiry in the Central Kentucky Karst has demonstrated that the uncommon preservation characteristics of the cave environment provides unique insight into human behavior (prehistoric and historic) that may be more accessible than from open "surface" sites. Table 1 also reflects that, along with an increase in the intensity of cave archaeological investigation, a greater sophistication began once interdisciplinary research was initiated at the Park (post-1960). That work was initiated

by Patty Jo Watson and her associates and colleagues.

Early turn-of-the century interests in cave archaeology, primarily atheoretical, prompted work at surface sites in the Mammoth Cave area and led to speculation about the origins of prehistoric cultural materials, sometimes comparing them to the better-understood European record (e.g., Nelson 1917; Young 1910). Assessing significance of and attempting to order archaeological sites from within the Park area, both above ground and below, and assessing Mammoth Cave collections held outside the Park, were the foci of the Classificatory Period between 1916 and 1970, culminating in the summaries of Douglas W. Schwartz (1958a-h, 1960a,b, 1965). More recent work by Watson and her colleagues brought a theoretical and interdisciplinary framework to the

Speculative

Rafinesque (1824), Young (1910)
pre-1915

Classificatory

Carey (1942), Hanson (1960), Fowkes 1916-1970 (1922), Funkhouser and Webb (1932), Meloy (1968), Moore (1916), Nelson (1917), Neumann (1938), Pond (1935, 1938), Schwartz (1958a-h; 1960a,b, 1965, 1967), Schwartz and Hanson (1961), Schwartz and Sloan (1958, 1960a,b), Schwartz and Sloan and Hanson (1960)

Explanatory

*Beditz (1979, 1981), Carstens (1974, 1975, 1976, 1977, 1978, 1980), Carstens and 1971-Present**

Interdisciplinary

Watson (1996), Crothers (1981, 1983), Crothers and Ward (1995), DiBlasi (1987a,b, 1996), Duffield (1974), Hensley (1995, 1996), Kennedy (1990, 1993, 1996), Marquardt (1974), Molnar and Ward (1974), Munson et al. (1989), Prentice (1993, 1994, 1996), Robbins (1971, 1974, 1980), Robbins et al. (1981), Ruppert (1994), Schoenwetter (1974), K. Tankersley et al. (1994), K. Tankersley et al. (1990), K. Tankersley et al. (1985), S. Tankersley (1993), Wagner (1976), Watson (1969, 1974, 1986, 1992), Watson and Carstens (1975, 1982), Watson and Kennedy (1993)

Table 1: Archaeological research in the area of Mammoth Cave National Park, 1824-Present (*not an exhaustive list).

archaeology of the Park often reflecting various themes prominent in the "New Archaeology." Within the last decade cave art studies (DiBlasi 1996) have added a cognitive, or post-processualist research slant to the efforts begun by Watson's group. However, additional research is still needed in the Mammoth Cave area, above ground and below. Only the tip of

the proverbial iceberg at Mammoth Cave has been studied, whereas artifacts from surface sites and from within the caves continue to be damaged or stolen in spite of the security efforts of the National Park Service. New insights and new energies are needed in the 1990s to carry on the fascinating study of the aboriginal and Euro-American people who explored and exploited the Kentucky underworld.

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References

- Appelgate, Darlene
2000 Fax to Kenneth C. Carstens, July 1, 2000.
- Barnes, Shelley
1974 Analysis of Three Bt-5 Burials. Unpublished Manuscript. Department of Anthropology, Washington University, St. Louis.
- Beditz, Lindsay C.
1979 Archaeological Reconnaissance and Testing of Alternative JCCCC Sites in Mammoth Cave National Park. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.
- 1981 Mammoth Cave National Park, Kentucky: Bluffline Survey of the Childress Farm/Great Onyx Job Corps Civilian Conservation Center Property. Manuscript on file, National Park Service Southeast Archaeological Center, Tallahassee.
- Brown, Jeffrey
1977 The Elmore Surface Collection Site: A Paleo-Archaic Lithic Assemblage. Senior Honors Thesis, Department of Anthropology, Washington University, St. Louis.
- Carey, Henry A.
1942 Report on John M. Nelson Collection. U.S. Department of the Interior, National Park Service, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
- Carstens, Kenneth C.
1974 Archaeological Surface Reconnaissance of Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis.
- 1975 Surface Archaeology in Mammoth Cave National Park, Kentucky. Paper Presented to the 40th Annual Meeting of the Society for American Archaeology, Dallas.
- 1976 Recent Investigations in the Central Kentucky Karst: A Preliminary Temporal Ordering of Several Surface Sites in the Mammoth Cave Area, Kentucky. Paper Presented to the 55th Annual Meeting of the Central States Anthropological Society, St. Louis.
- 1977 Three Springs Pumphouse: An Assessment of Damage. Manuscript on file, Mammoth Cave National Park, Kentucky.
- 1978 Mammoth Cave National Park: Archaeological Survey of Proposed Water Lines and Sewers. Manuscript on file, Southeast Archaeological Center, Tallahassee.

1980 Archaeological Investigations in the Central Kentucky Karst. Doctoral Dissertation, Department of Anthropology, Washington University, St. Louis.

Carstens, Kenneth C., and Patty Jo Watson (editors)

1996 Of Caves and Shell Mounds. University of Alabama Press, Tuscaloosa.

Cleland, Charles E.

1976 The Focal-Diffuse Model: An Evolutionary Perspective on the Prehistoric Cultural Adaptations of the Eastern United States. Midcontinental Journal of Archaeology, Vol. 1, No. 1.

Crothers, George M.

1981 Archaeological Investigations in Sand Cave, Kentucky. Eighth International Congress of Speleology, Proceedings, Vol. 1, Pp. 374-376.

1983 Archaeological Investigations in Sand Cave, Kentucky. National Speleological Society Bulletin, Vol. 45, Pp. 19-33.

1986 Final Report on the Survey and Assessment of the Prehistoric and Historic Archaeological Remains in Big Bone Cave, Van Buren County, Tennessee. University of Tennessee, Knoxville.

Crothers, George, and Robert Ward

1995 The NPS/Earthwatch Cultural Resource Survey: Discerning Patterns of Prehistoric Activity in Main Cave Despite 200 Years of Historic Use. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave.

DiBlasi, Philip J.

1987a Archaeological Monitoring of the Water Pipeline at the Floyd Collins Complex. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.

1987b Drawings Found in Salts Cave. CRF Newsletter, Vol. 15, No. 4, Pp. 1-2.

1996 Prehistoric Expressions from the Central Kentucky Karst. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, University of Alabama Press, Tuscaloosa.

Duffield, Lathel

1966 The Robert Dugeon Site. National Park Service, Richmond, Virginia.

1974 Nonhuman Vertebrate Remains from Salts Cave Vestibule. Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp., 123-133, Academic Press.

Faulkner, Charles H. (editor)

1986 The Prehistoric Native American Art of Mud Glyph Cave. University of Tennessee Press, Knoxville.

Fowke, Gerald

1922 Archaeological Investigations. Part I. Cave Explorations in the Ozark Region of Central Missouri. Part II. Cave Explorations in Other States. Bureau of American Ethnology, Bulletin 76. Washington, D.C.

Funkhouser, William D., and William S. Webb

1928 Ancient Life in Kentucky. Kentucky Geological Survey, Geologic Reports, Series 6, Vol. 34.

1929 The So-Called "Ash Caves" in Lee County, Kentucky. University of Kentucky Reports in Anthropology and Archaeology, Vol. 1, No. 2.

1930 Rock Shelters in Wolfe and Powell Counties, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 1, No. 4, Lexington.

1932 Archaeological Survey in Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 2, Lexington.

1936 Rock Shelters in Menifee County, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 3, No. 4, Lexington.

Gilmore, M.R.

1931 Vegetal Remains of the Ozark Bluff-shelter Culture. Michigan Academy of Science, Arts and Letters, Vol. 14, Ann Arbor.

Griffin, James B., editor

1952 Archaeology of Eastern United States. University of Chicago Press, Chicago.

Hagg, William

1939 Mulberry Creek Cord-Marked. Southeastern Archaeological Conference Newsletter, Vol. 1, No. 1, Lexington.

Hanson, Lee

1960 The Analysis, Distribution and Seriation of Pottery from the Green River Drainage as a Basis for an Archaeological Sequence of that Area. Unpublished Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Hensley, Christine

1995 Archaeological Investigations at the Stairway Rockshelter. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave, Kentucky.

1996 The Stairway Shelter (15Ed303), Mammoth Cave National Park. Paper presented at the 13th Annual Kentucky Heritage Council Archaeological Conference, March 1996, Louisville, Kentucky.

Jones, Volney

1936 The Vegetal Remains of Newt Kash Hollow Shelter. In *Rockshelters in Menifee County, Kentucky* by William S. Webb and W.D. Funkhouser. University of Kentucky Reports in Archaeology and Anthropology, Vol. 3, No. 4, Lexington.

Kennedy, Mary C.

1990 An Analysis of the Radiocarbon Dates from Salts and Mammoth Caves, Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis, Missouri.

1993 NPS and Earthwatch Cultural Resource Inventory of Mammoth Cave. In Cave Research Foundation Newsletter, Vol. 21, No. 4, Pg. 15.

1996 Radiocarbon Dates from Salts and Mammoth Caves. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 48-81, University of Alabama Press, Tuscaloosa.

Lewis, R. Barry

1996 The Archaeology of Kentucky. University of Kentucky Press, Lexington, in press.

Marquardt, William

1972a Recent Investigations in a Western Kentucky Shell Mound. A Research Report Read May 4, 1972 at the Annual Meeting, Society for American Archaeology, Miami Beach, Florida.

1972b Research Report on Excavations at the Carlston Annis Mound. Southeastern Archaeological Conference Newsletter, Vol. 16, No. 2.

1974 A Statistical Analysis of Constituents in Human Paleofecal Specimens from Mammoth Cave. In Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 193-209. Academic Press, New York.

Marquardt, William and Patty Jo Watson

1974 The Green River, Kentucky, Shellmound Archaeological Project. Paper Presented to the 73rd Annual Meeting of the American Anthropological Association, Mexico City.

1976 Excavation and Recovery of Biological Remains from Two Archaic Shell Middens in Western Kentucky. Paper Presented in the Symposium, "The Research Potential of Shell Middens: Methodological and Analytical Considerations," organized by Thomas Ryan. Southeastern Archaeological Conference, Tuscaloosa, Alabama. Copy of manuscript in possession of author.

- 1983 The Shell Mound Archaic of Western Kentucky. In Archaic Hunters and Gatherers in the American Midwest, edited by James L. Phillips and James A. Brown, pp. 323-39, Academic Press, New York.
- Marquardt, William, Patty Jo Watson, Mary Kennedy (editors)
1996 Archaeology of the Middle Green River, Kentucky, Kent State University Press.
- Meloy, Harold
1968 Mummies of Mammoth Cave. Shelbyville, Indiana: Micron.
- Molnar, Stephen, and Stephen Ward
1974 Dental Remains from Salts Cave Vestibule. In The Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 163-166, Academic Press.
- Moore, Clarence B.
1916 Some Aboriginal Sites on Green River, Kentucky: Certain Aboriginal Sites on Lower Ohio River. Academy of Natural Sciences of Philadelphia, Journal, 2nd Series, Vol. 16, No. 3. Philadelphia.
- Morse, Dan
1967 The Robinson Site and Shell Mound Archaic Culture in the Middle South. Doctoral Dissertation, Department of Anthropology, University of Michigan, Ann Arbor.
- Munson, Patrick J., and Cheryl Ann Munson
1990 The Prehistoric and Early Historic Archaeology of Wyandotte Cave and Other Caves in Southern Indiana. Indiana Historical Society, Prehistoric Research Series, Indianapolis.
- Munson, Patrick J., Kenneth B. Tankersley, Cheryl Ann Munson, and Patty Jo Watson
1989 Prehistoric Selenite and Satinspar Mining in the Mammoth Cave System, Kentucky. In Midcontinental Journal of Archaeology, 14(2):119-145.
- Nelson, Nels C.
1917 Contributions to the Archaeology of Mammoth Cave and Vicinity, Kentucky. Anthropological Papers, American Museum of Natural History, Vol. 22, Part I. New York.
- 1923 Kentucky: Mammoth Cave and Vicinity. Unpublished manuscript on file at the American Museum of Natural History, New York.
- Neumann, Georg K.
1938 The Human Remains from Mammoth Cave. American Antiquity, Vol. 3.
- Pollack, David (editor)
1990 The Archaeology of Kentucky: Past Accomplishments and Future Directions, Vol. 1. Kentucky Heritage Council State Historic Preservation Comprehensive Plan Report No. 1, Frankfort.

Digital Database Project of the Cave Research Foundation

Don Coons

ABSTRACT

The beginning of the new millennium marks the end of the forty fourth year that the Cave Research Foundation has been collecting cave survey data in and around the Mammoth Cave area. Beginning with the Ohio Grotto efforts during the NSS sponsored Collins Crystal Cave epic, the grid of ever increasing survey lines has expanded outward to include Unknown, Salts, Colossal, and finally the link to Mammoth Cave. Ongoing efforts now include Proctor, Lee, Logsdon-Hawkins River and most of the smaller caves within the park boundaries. Together with the efforts of the Central Kentucky Karst Coalition in Roppel, this work now includes more miles of connected survey within a single cave than any other caving area in the world. More than three fold longer than the nearest competitor.

In total more than 4500 individual survey books have been generated in this effort to document the worlds longest cave. With an average of 35 stations per book, the total estimated number of individual survey points within the system has passed the 150,000 mark. Managing a data base as large as this one has become a truly monumental effort. It was realized several decades ago that using paper as an archival medium was quickly going to become an unwieldy proposition.

In the early 70's Will Crowther and Bill Mann pioneered the effort to begin entering this mountain of material into the large mainframe computers available to them at the time. Original efforts were stored on punch cards. Since that time the technology has progressed from large format magnetic tapes, to 5.5 inch floppy discs, 3.5 inch floppy discs and on today to zip discs and CD Roms. CRF volunteers have made a valiant effort for nearly four decades now to keep pace with these changing technologies. Through the efforts of Lynn Brucker, Dave Hanson, Mel Park, Paul Hauck, Richard Zopf, Scott House, Bob Osburn and many others much of the CRF data generated throughout this ongoing effort has been entered into a computer base.

One problem arising as a result of the changing technologies has been the inconsistency in programming and hardware available to the successive generations of CRF cartographers. Over the years they have worked in at least twelve different software formats on an untold number of ever more sophisticated machines. It has only been the advent of the Pentium class PC's coupled with today's software developments that has finally brought the technology to a level that is capable of handling the entirety of the Mammoth Cave System on a single home computer.

The current phase of CRF digital data development is, then, an effort to combine this accumulated work of the past forty years. The first step was to find all of the individual copies of data archives, find equipment and programs to read them, and begin the process of converting everything into a single compatible format. The program chosen for this effort is named COMPASS. It's primary features of

robust dependability, readily available support, and ease of conversion to other formats have proven it to be a very successful platform for this effort. This original phase of the project has now been completed. Everything ever entered is now running in the COMPASS base.

The next step was creating an index to list all of the information that is running and, more importantly, all the information that is still sitting in the original survey books and has never been entered into any program. File Maker Pro was chosen as the format for this information in order to be compatible with the CRF trip report data base. This index is now complete and reveals that nearly 85% of the entire data collection is now running in a computer format. Data entry is currently being lead by a team of CRF volunteers. Completion of the remaining 700 or so books is expected by the end of the year 2001. This presentation is a demonstration of the capabilities of the virtual reality cave map that this ongoing effort has produced.

Mammoth Cave Cartographic Program-

A multi-step program consisting of Surveying, Data Processing and Management and Map Production

**Bob Osburn,
Chief Cartographer
CRF Eastern Operations Area**

ABSTRACT

Mammoth Cave and other large systems present a challenge to cave cartographers. It is a thrill to do one of the big ones but from the practical side the project becomes so large that the major job becomes project management rather than drafting. CRF's Mammoth Cave project has a long history and some notable accomplishments. It has surveyed more than 350 miles of cave and produces a variety of maps from that survey including the "Postcard" Map, "Poster" Map, and the Flint Ridge Folio among others. All of the early system wide maps are small scale. Expectations as to how much detail a cave map should show had increased by the 1980's and a project was begun to produce detailed maps of the entire system at as large of scale as was practical. It was judged that this scale was 1:600. This project continues today as a major part of CRF cartographic effort. Reports were given on this project at the 1996 and 1997 Mammoth Cave Science Conferences. This report provides an updated overview of this project and a discussion of changing conditions and the ways the project will or might react.

The Mammoth system is divided into approximately 50 map areas or sheets. Individual cartographers oversee work on one or more map sheets. Most of the work is carried out by standard methods. Survey is accomplished with Suunto compasses and clinometers and fiberglass survey tapes. CRF is slightly more rigorous than many projects in that we make two measurements, a fore and back shot, for each survey vector to eliminate blunders. Data are processed by reducing survey vector data to Cartesian coordinates based on a 0,0,0 point at Walker benchmark TT8W at the Violet City Entrance. A planar grid is used rather than a mathematically more complex map projection. Data processing is accomplished entirely by computer. At the time of the last report the program SMAPS was extensively used but it has largely been supplanted by WALLS or COMPASS. Survey and data processing are the quick part of any cave cartography process. Actual map drafting requires a higher skill level and commitment of large amounts of time after the exciting "in cave" stage. About 150 people regularly participate in Mammoth surveying but fewer than 10 manage sheets and regularly draw maps. The "Area" maps are drafted on 42 inch wide mylar of variable length to fit the morphology of the cave. An initial pencil working draft is maintained on gridded mylar until the area is finished. The working map is then overlaid with plain mylar and the final draft traced in ink. Completing the 1:600 series of maps will take several more years even at maximum effort.

In addition to the "Area" maps, several newer projects are moving forward due to the innovation and energy of individual Cartographers. Mike Yocum is devising methods to transfer survey lines and maps

into GIS systems and Don Coons has compiled most of the hundreds of miles of Mammoth Cave survey into a single data set. These projects are reported on separately at this meeting. Further, experimentation with drawing cave maps on the computer as vector graphic files shows good potential, perhaps even to the extent that some of the 1:600 Area maps will be drawn that way. Computers as map making tools hold great promise. GIS systems allow production of maps in minutes that would have taken years by other methods if they were ever undertaken at all. This also represents a danger in that maps easily made may not be thought out as well as ones requiring more labor. Secondly, as amply demonstrated by the recording industry recently, intellectual title to electrons is a lot harder to maintain than title to a 8 foot long piece of mylar. No cartographer wants to spend years crafting a map only to have it or the derivative maps published by someone else.

Hydrologically Valid Delineation of Watershed Boundaries in Kentucky's Karst Terrane

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EXTENDED ABSTRACT

The delineation of valid hydrologic boundaries in soluble-rock terrane requires tracer-testing of the karst aquifer. The well-known karst aquifers of Kentucky are composed of contiguous groundwater drainage basins which commonly do not coincide with surface watershed configurations.

Hydrologic Unit Code (HUC) watershed maps in karst areas of Kentucky have been delineated by the US Geologic Survey and cooperating agencies (1997) based on surface drainage criteria without consideration of subsurface conduit hydrology. Published groundwater maps and data illustrating trunk groundwater flow paths were not used in the HUC project. In order to represent true hydrologic units, a region's karst groundwater drainage must be considered. The fact that *groundwater divides in soluble rock terranes do not always coincide with topographic divides*, has not been adequately evaluated in the production of these important maps.

The HUC delineation project used the concept of "non-contributing areas", which is defined as "areas that do not flow toward the outlet of the hydrologic unit". A "non-contributing area" on the boundary between two or more hydrologic units was included in the hydrologic unit adjacent to the lowest point of the "non-contributing area" boundary. A karst area's subsurface drainage was effectively ignored by its designation as a non-contributing area. Drainage from large surface watersheds may deviate, through a karst conduit, beneath a topographic divide to an adjacent basin. Consequently, the unfortunate designation of "non-contributing areas" has inevitably resulted in several cases of the hydrology of certain karst watersheds being attributed to the wrong river basin.

A comparison of tracer-delineated groundwater drainage basins with these topographic basins reveals that a significant percentage of the HUC basins in karst regions fails to coincide with actual hydrologic basins on two levels:

- 1) The HUC boundaries are incorrect where they attribute drainage of an area to the wrong watershed (under all flow conditions). [Although HUC boundaries do not distinguish between flow conditions, karst groundwater flow elevations and directions may change due to varying hydrologic conditions, and therefore must be considered when mapping karst drainage.]
- 2) The HUC boundaries are inaccurate when they attribute drainage to the wrong watershed, even though some portion of high-flow discharge does intermittently follow surface channels or overflow springs to the attributed basin.

For example, a large karst watershed, located in Barren and Edmonson counties of the Green River basin, is hydrologically mismapped where an 8-digit Cataloging Unit boundary incorrectly attributes about 85 mi² of the Green River basin to the Barren River. This error exaggerates the latter's basin by nearly 4%. Base-flow and high-flow drainage from this 85 mi² area has been traced by fluorescent dyes to large springs on the Green River rather than the Barren River. These traced groundwater basins were originally published by Quinlan and Ray (1981) and have been republished at scale of 1:100,000 (Ray and Currens, 1998).

Additionally, in Christian and Trigg counties within the Cumberland River basin, an 11-digit Hydrologic Unit boundary inaccurately attributes about 22 mi² of the Little River basin to the Sinking Fork basin. The Sinking Fork watershed does receive a portion of this basin's high-flow drainage via overflow springs and channels, but it's summer base flow drains exclusively to the largest spring on the Little River. Similar inaccuracies involving six karst drainage basins have been determined for about 40 mi² in Meade and Breckinridge counties.

To date, the actual hydrology of about 250 mi² of three different karst areas of the Mississippian Plateau, or about 15-20% of the mapped karst aquifer, varies from HUC topographic watersheds. Individually, however, the majority of a karst watershed could be incorrectly attributed. For example, about 75% of the Green River's Turnhole Spring karst watershed is included in the Barren River basin.

A basic principle of karst watersheds has been ignored since the HUC maps signify hydrologic rather than mere topographic divisions. If environmental-protection work, land and water-resource management activities, hydrologic balance calculations, flood-control structure-design calculations, or water-supply planning assessments in karst terrane were based on existing HUC maps, serious errors could result.

Although topographic divides are often used when estimating karst-basin boundaries, an important practice is the illustration of these inferred karst divides with broken lines, which more accurately reflects their imprecise nature. At a minimum, topographic divides in karst terrane should be depicted on HUC maps with *dashed or dotted lines* where the true nature of perennial stream flow and groundwater drainage is unknown. Traced groundwater-basin delineations should be utilized where available. Also, a *caveat*, alerting the user to the potential noncongruity between topographic basins and karst watersheds, should be prominently displayed in the karst regions of these maps. One must recognize, and advise the user of HUC maps, that topographic divides are unreliable when mapping valid hydrologic units in karst terrane.

Update on Dye-Tracing Efforts at Mammoth Cave National Park

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INTRODUCTION

Since the first dye-trace was performed at Mammoth Cave in 1925 – Anderson, working for Louisville Gas and Electric, conducted several traces, including Three Springs to Echo River Spring, to demonstrate that groundwater can travel through adjacent ridges which would pose engineering problems for a proposed high-dam on the Green River near Pike Spring (Brown, 1966) – dye-tracing has been used as the primary investigative tool for understanding, and thus, protecting the karst aquifer. A tremendous effort was directed by Dr. Jim Quinlan in the mid 1970's through the early 1980's, and resulted in the excellent and much used map "Groundwater Basins in the Mammoth Cave Region, Kentucky (Quinlan and Ray 1981, 1989). During the early 1990's Meiman and Ryan concentrated dye tracing efforts to the north side of the Green River where 16 groundwater basins were defined (1992). There have been many "specialized" traces over the past ten years, including a series of quantitative traces by Ryan (1992), flow-velocity traces by Murphy (1992), flood pulse tagging Hall (1994) and Ryan and Meiman (1996), and traces along Interstate 65 by Meiman and Capps (1995). It cannot be overstated that without these works we would know very little about the overall hydrogeology of the Mammoth Cave karst aquifer. It should be noted that the current work is by no means designed to refute the findings of these earlier studies, but to merely improve and expand our knowledge base.

Within the past year there has been a renewed interest in dye tracing at Mammoth Cave, as evident by 15 dye injections since late May of 1999. While at first glance it might appear that

the groundwater basin definition gained by these earlier studies have provided all the information needed to fully delineate karst groundwater basins in and around Mammoth Cave National Park, we have found it necessary to further these efforts with additional tracing.

The foremost reason is a matter of scale and resolution; as the areal distribution of traces, which define the groundwater basins, is quite lacking in detail proximal to many basin divides (Figure 1). In some cases there are several kilometers between injection sites with basin divides drawn somewhere in between, and in large part based upon groundwater potentiometric data. In areas where this condition exists in combination of potential threats to groundwater quality (primarily urban and transportation areas) additional tracing is needed to know the flow paths of individual recharge points. This situation is best represented in the Cave City area where the boundary between the Turnhole Spring groundwater basin (which drains northwestward into the park) and the Gorin Mill groundwater basin (which drains to the east through Hidden River Cave). This three-kilometer portion of boundary, through the ever-developing section of Cave City, is defined by three dye traces.

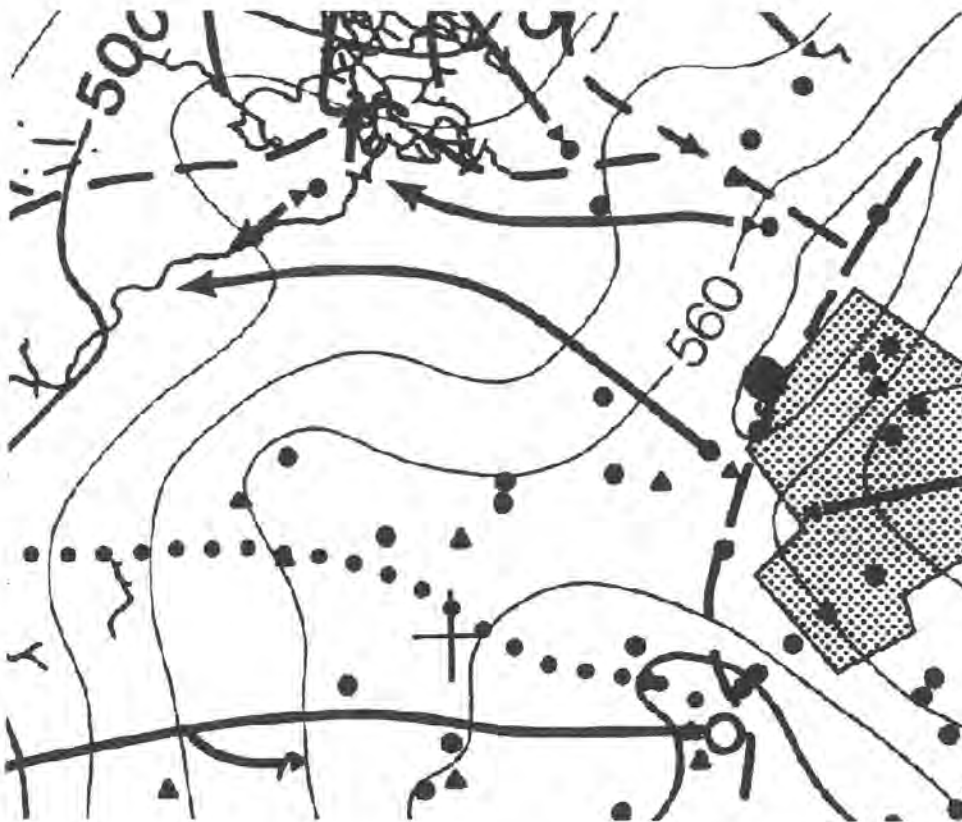


Figure 1. A portion of the 1:138,000 scale map "Groundwater Basins in the Mammoth Cave Region, Kentucky", Quinlan and Ray (1989).

A secondary reason for additional traces, is to increase our understanding of the plumbing of active conduits through the karst aquifer. For the most part past tracing efforts have focused on surface injection points and spring recovery points. We know, for example, that if a dye is introduced into a sinkpoint on the surface, and emerges at a spring, that the dye course has traversed active flow cave conduits. It would be very helpful, in respect to examining cave evolution and development, if a more detailed picture of the flow routes were described. As one could imagine this type of dye tracing is logistically demanding (requires visits to cave dye recovery locations), it can be very rewarding. This in-cave tracing will be the main focus of this paper.

NEW DATA WITHIN PREVIOUSLY DESCRIBED GROUNDWATER BASINS

Turnhole Spring Groundwater Basin

The 244 km² groundwater basin, by far the largest contributing flow into the park, has been the focus of scores of studies and water quality initiatives over the past 25 years. It is divided into the Mill Hole, Proctor, Cave City and Patoka Creek sub-basins. Each sub-basin is drained by a main trunk conduit: the Mill Hole stream, Hawkins River (Red River in Whigpistle Cave) Logsdon River, and Hawkins River, respectively. The vast majority of the sub-basins are wonderfully under-represented by accessible cave streams. We know that there is active cave passages within these areas, but, for the most part, cannot gain access — usually due to passage collapse or sumps.

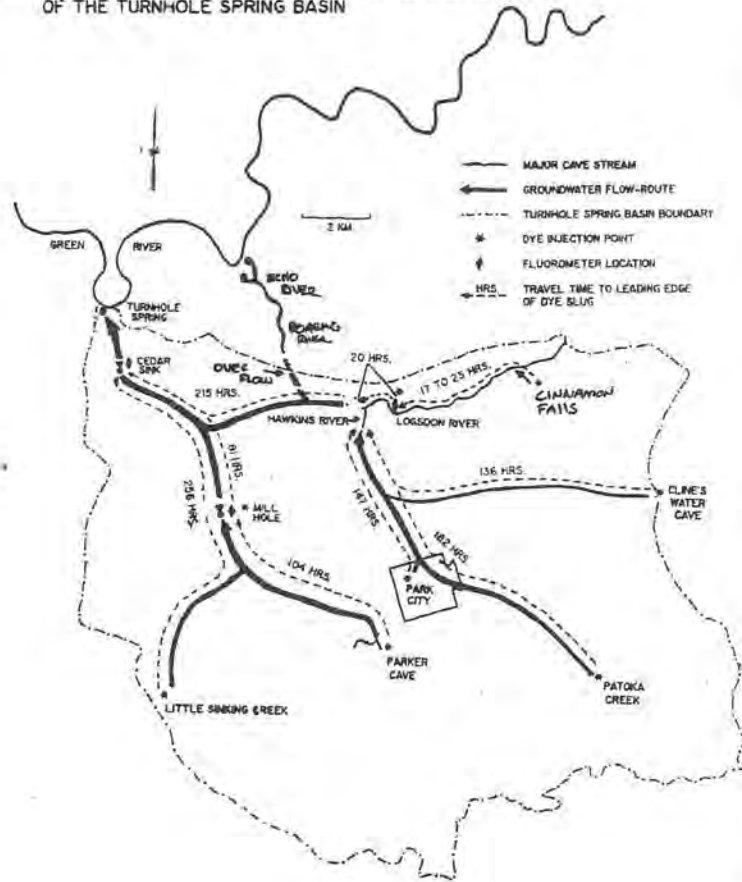
Denial River

The portion of the Cave City sub-basin adjacent to the boundary of the Pike Spring basin within Roppel Cave presents a refreshingly atypical situation, as many active flow passages are present. Near the upstream termination of Logsdon River at the S-188 Sump lies a complex tangle of small stream passages, one of which is called Denial River. This upstream portion of Logsdon River is also geological compelling as Logsdon is apparently perched atop the Corydon Chert for much of its eight kilometer traverse downstream to P. Strange Falls. There have been numerous air-filled stream passages found at elevations above and below Logsdon River in this area. Denial River seemed like a good place to start to unravel this picture. Previous traces show that lower streams in this area, the flow from the Western Kentucky Parkway for example, drains northwards to Pike Spring. On October 19, 1999 approximately 0.5 kg of power eoscin dye was injected into Denial River, which receives flow from a series of vertical shafts. Dye was recovered within two weeks at P. Strange Falls and not at Pike Spring, showing that Denial River is a tributary of Logsdon River. This was the first in a series of traces from this area of the cave and many more traces will be necessary to fully understand its complex plumbing.

Turnhole-Roaring/Echo Overflow

During the flurry of dye tracing in the late 1970's and early 1980's, Jim Quinlan and Joe Ray discovered the existence of a high level overflow route linking the main trunk of the Proctor sub-basin (Hawkins River, to which Logsdon is a tributary) to the Echo River Spring groundwater basin (Quinlan and Ray, 1981 and 1989). This overflow junction is inaccessible due to sumps in all river passages leading to it. Meiman and Ryan injected dye into Logsdon River on the recession limb of floods and demonstrated that this overflow route – taking a portion

ASE-FLOW TRAVEL TIMES THROUGH VARIOUS SEGMENTS OF THE TURNHOLE SPRING BASIN



of Hawkins River, which flows to Turnhole Spring during low flow conditions, and reassuming its original route into the head of Roaring River during overflow conditions– is active when the stage of Logsdon River near its confluence with Hawkins exceeds three meters over base flow stage (Figure 2) (Meiman and Ryan, 1993). This was important information as the Echo River groundwater basin, which is almost exclusively within park boundaries during low flow times and harbors the endangered Mammoth Cave Shrimp, receives flow from nearly 100 km² of lands beyond the park boundary when Logsdon River stage is greater than three meters. Stage excesses of three meters is quite common. A reconstruction of float level records between 1984 and 1988 shows that this horizon was exceeded 38 times; periods when the aquatic ecosystem of Roaring and Echo Rivers were recharged largely by non-park lands.

Figure 2. Hydrogeology of inter-basinal overflow, with base-flow groundwater travel velocities tossed in for good measure (Murphy, 1992).

Some discoveries are unintentional. On April 24, 2000, in support of a pesticide flood pulse-sampling effort, approximately two kg of powder fluorescein dye was injected into the Big Clifty/Girkin contact swallet at Cinnamon Falls. Under almost any other circumstances rational investigators would not use such a copious quantity of dye. However, this trace, injected

on the leading edge of a forecasted large rainfall event, was designed to place a sufficient amount of dye to "tag" a flood pulse and to detect in grab samples some five kilometers downstream in Logsdon River. Rainfall was intense during the injection, however within minutes after the dye was underground the rain event stopped. It did not rain again for weeks. We now had 2 kg of fluorescein slowly coursing through base-flow cave streams. Ouch! The flood pulse sampling operation was aborted. Two weeks later, while collecting dye receptors along the Green River, the Echo River Spring site exhibited a very strong presence of fluorescein. The highest stage in Logsdon River since the injection was approximately 0.5 meters above base level. A subsequent dye receptor recovery at the First Landing of Roaring River (upstream portion) also showed a strong positive. Dye (thus water) is leaking into Roaring/Echo Rivers from Logsdon/Hawkins Rivers during base flow. We believe that this flow route was not observed by previous investigators because, until now, no one had made the mistake of using far too much dye during base flow conditions, as "normal" quantities of dye would dilute into Roaring/Echo Rivers in concentrations below detection limits.

What does this mean? One possible explanation, relative to speleogenesis, is that we are witnessing the earliest stages of groundwater basin piracy. For many years Hawkins and Logsdon Rivers were the upstream portion of Roaring/Echo Rivers. At some point – perhaps due to a retreating nick-point in the Green River passing the Turnhole Bend – a more efficient route was established pirating flow from Hawkins River to Turnhole Bend Spring. Over time, as this piracy became the dominant flow route, the original route into Roaring/Echo was only used during high-flow periods as an overflow. It may be possible that this low-level "leak" marks the beginning of Roaring/Echo taking its flow back. Another explanation may be that the present overflow route, although a large, higher conduit, is simply wrought with many small "leaks" at lower elevations.

It is also possible for dye introduced into Logsdon River to find a secondary route before it even reaches the confluence of Hawkins River and the downstream sump and overflow area (first thoughts that the dye may enter Roaring/Echo via Mystic River, however that idea was discounted as dye receptor at the First Landing, which is far upstream of the confluence of Mystic, was positive). It remains possible, however, that the dye is taking an unknown route to the upstream segment of Roaring River. In order to put this mystery to rest, later this autumn we will introduce dye; at base-flow conditions, into Cinnamon Falls and immediately upstream of the Hawkins River sump.

Aside from a hydrogeologic curiosity, what relevance does this have to cave management and protection? The discovery of the overflow route brought about major changes to conservation efforts of park managers, as it was proven that the sewer-less community of Park City flowed directly into endangered species habitat of the main active flow trunk of Mammoth Cave. This discovery was extremely important to the realization of the regional sewer system. Until now, we thought at least Roaring/Echo River would be spared contamination events during low flow. Not anymore.

Crystal Cave

Perhaps because Cooper and Collins Springs (both Haney Limestone springs perched upon the Big Clifty Sandstone) are well within the delineated bounds of the Pike Spring groundwater basin they, as far as we can tell, have never been traced. With the assistance of Art and Peg Palmer, we placed dye receptors at six locations within Crystal Cave and introduced dye into the Big Clifty/Girkin contact swallets of Cooper and Collins Springs. Both dyes appeared at Pike Spring as suspected. Although the trace from Cooper Spring (located near the intersection of Collins and Flint Ridge Roads) was not found in the waters of Crystal, the trace from Collins Spring (located 900 m north of Cooper) was detected in a strong positive at the C-3 Waterfall Campsite. We have not given up on finding and in-cave recovery point for Cooper Spring. This fall we plan on setting a dye receptor in the western stream of Sides Cave and run the trace again.

Outward Bound

In support of a Western Kentucky University's Hoffman Environmental Research Institute study of land use delineation for the US Fish and Wildlife Service a trace was initiated from the eastern-most known stream in Roppel Cave, therefore, the eastern most stream in the Mammoth System. It seemed very possible that this stream recharged the proximal Suds Spring along the Green River. If so, this would mean that the Mammoth Cave System span seven groundwater basins and sub-basins – perhaps adding additional relevance and protection to the Suds Spring basin. Just to let the reader know that not all traces we perform produce spectacular and shocking results, the Outward Bound trace flowed to Pike Spring, nonetheless, adding new hydrogeologic information.

Three Springs

As mentioned in the introduction, the first dye trace in the Mammoth Cave area was performed at Three Springs. Quinlan and Ray traced this perched Haney Spring to Styx Spring. Meiman and Ryan found both Echo River Spring and River Styx Spring to receive flow from Three Springs. During the late fall of 1999 dye was again introduced into the Big Clifty/Girkin contact swallet of Three Springs, except this time, in addition to placing receptors at Echo and Styx Springs, we also monitored eight locations along River Styx in the cave. All receptors were positive – from the First Arch to the Dead Sea in the Cave, as well as Echo and Styx Springs. Although the Styx/Echo conduits were not experiencing a flow reversal event (water from the Green River entering Styx Spring, running through the cave and exiting at Echo River Spring), the system was not quite at base-flow levels. The flow conduit from Three Springs may enter the Echo/Styx Rivers upstream from the flow bifurcation of Echo River (see the next trace description to further examine the relationship between Echo and Styx). Additional tracing is needed, with receptors placed in Roaring and Mystic Rivers to pin-down its location.

An additional curiosity was found last autumn when Park Ecologist Rick Olson removed a visitor-constructed rock dam at Styx Spring. The removal of this dam, which increased the pool elevation of Styx Spring by several centimeters, did not register with the stage monitoring probe in the Dead Sea (which can resolve stage changes of 0.01 mm). This may indicate that there exists a free-surface segment of River Styx between its sump, as the change in stage was not propagated to the Dead Sea from Styx Spring.

Service Station

All parking lots within Mammoth Cave National Park drain into the cave system. The lot surrounding the service station near the main campground is no exception. During the fall of 1999 we injected dye into the Big Clifty/Girkin contact swallet behind the service station after placing receptors throughout the River Styx area on the cave. It should be noted that five Mammoth Cave Shrimp were observed while placing receptors in the Hades section of River Styx. The highest elevation that dye was recovered was Shaller's Brook (a shaft drain off of Gratz Avenue). From there, after dropping through Lee's Cistern, the dye appeared at Hades, River Styx, the Dead Sea, and Styx and Echo River Springs. The park will soon begin construction of oil separation filters on all major parking lots within the park.

The fact that dye which entered River Styx via the Hades lead – which is at the downstream end of Styx near the Dead Sea and well downstream of the Echo-Styx split – was also detected at Echo River is perplexing. Recall that the trace from Three Springs also appeared in Styx and Echo Springs, although that injection site was well distal and upstream of the Echo-Styx bifurcation. The service station trace was also conducted under “normal” flow conditions, that is to say, low-flow and no flow-reversal. Is it possible that a second conduit exists between River Styx and Echo River downstream of the River Styx sump? A rather simple trace will be performed (dumping dye into the Styx sump) this year.

NEW DATA WITHIN PREVIOUSLY UN-DESCRIBED GROUNDWATER BASINS

Floating Mill Hollow

Upon close inspection of the map “Groundwater Basins of the Mammoth Cave Region, Kentucky” (Quinlan and Ray, 1989) one might find a few apparently minor springs along the Green River for which their recharge area is unknown. Upon a field inspection, you may find an occasional small spring along the Green that does not appear on this or any other map. One such spring was found near the mouth of Floating Mill Hollow. Most of the time this spring does not appear to flow, as like Running Branch, Mary Parker and other small springs, base-flow is discharged into the riverbed through alluvial filled under-flow spring. Basically, the surface springs orifice, where the dye receptors were placed, acts as an overflow discharge.

In the late spring of 1999 we placed receptors in all known springs from the upstream park boundary to Echo River Spring in preparation for a trace from Candlelight River, a small shaft drain stream along the famous Flint Ridge-Mammoth Cave connection route of 1972. According to the aforementioned map, Candlelight River should drain to Pike Spring. A few CRF “old-timers” also had opinions on the spring that receives water from Candlelight – either Pike or Echo River Spring (“Everyone knows that all streams before the “Tight Tube” drains to Pike”, or “What? All that water heads to Echo”). If nothing else, dye-tracing came be a humbling enterprise: the dye appeared at neither Pike nor Echo, rather the newly discovered Floating Mill Hollow Spring (Figure 3). A new watershed was being defined.

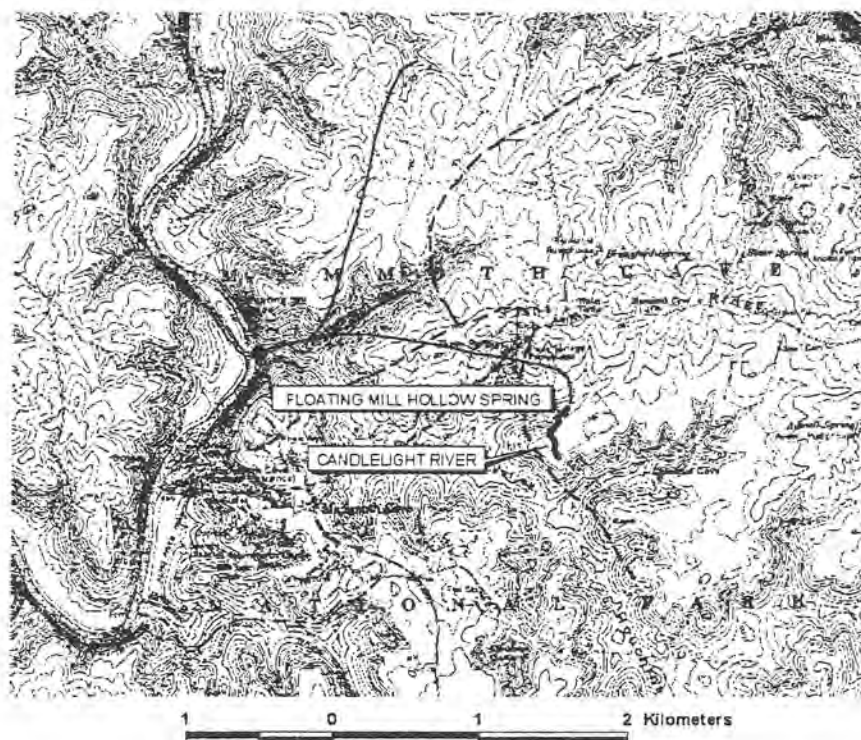


Figure 3. Dye traces to Floating Mill Hollow Spring. Dashed lines, Quinlan and Ray (1989) groundwater basin boundaries; dashed line to Styx Spring, Quinlan and Ray (1989) hypothesized flow route; solid lines, hypothesized flow routes from recent traces.

The fact that Candlelight River, which was originally placed within the Pike Spring basin, drains to Floating Mill Hollow Spring is of particular interest as in order to reach Floating Mill Hollow Spring it must either pass over, under, or around the Three Springs portion of the Echo River basin. Although we do not have direct evidence for any of these three possibilities, it will not present a deterrent from hypothesizing. It seems quite possible that the flow route from Candlelight River actually passes over the conduit draining Three Springs. As far as we know the shaft complexes beneath such large Haney springs such as Three Springs have not been discovered – if a cave explorer is interested in finding the largest vertical shafts in the Mammoth Cave System we have some ideas on where to look. The fact that they exist should

not be an issue, as even non-descript sink-points can produce large shafts (Bottomless Pit is a good example). Given that a shaft exists beneath Three Springs, it is very likely that it is very large and deep, as it receives perennial flow from Three Springs in addition to runoff from rainfall events. It is possible that such a shaft cuts deep to base-level, ignoring lithologic changes. Conversely, a small shaft drain as Candlelight River is perched upon local resistant lithologies. This perching can cause a small stream to run horizontally for several hundred meters before it falls towards base-level.

The discovery of a new groundwater basin led to two additional traces. Receptors were placed at Bögli Shafts and the river springs for a trace originating from the Big Clifty/Girkin contact swallet above the shafts. This trace was also recovered at Floating Mill Hollow Spring, however the receptors at Bögli Shafts were negative. It is very possible that individual shafts have such specific inputs that it is difficult to always make a connection.

A third trace was recovered at Floating Mill Hollow Spring from a trace initiated from the Big Clifty/Girkin contact swallet of Holton Hollow (the sinkpoint approximately 2.25 km north-northeast of the spring). Additional traces are planned for Rigdon, Taylor Coats, and an unnamed hollow, all which lie between Holton and Floating Mill Hollows.

Great Onyx

The small springs, one an underflow and one an overflow, at the mouth of Great Onyx Hollow were also blank areas on our hydrogeologic maps. During the spring of 2000 two dye traces were performed at Big Clifty/Girkin contact swallets about 800 and 400 meters south of the Green River (Figure 4). Both traces were recovered at the overflow spring (the underflow spring is used as a low-flow monitoring site). Additional traces are planned for this basin.

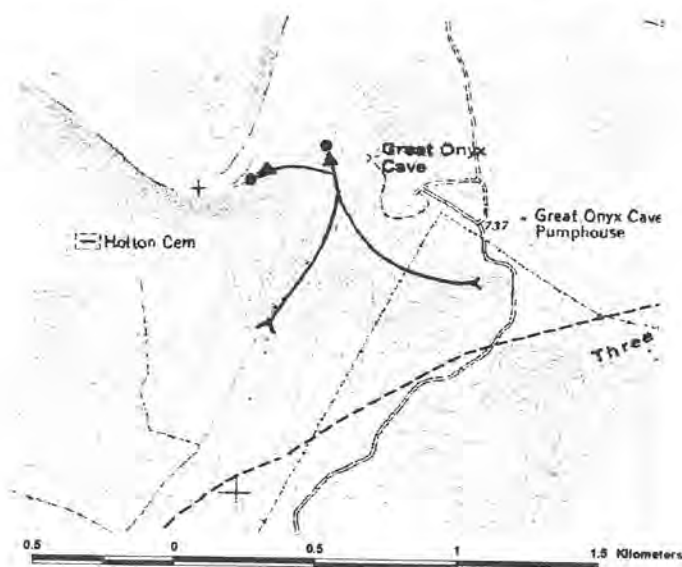


Figure 4. Dye traces within the Great Onyx Spring groundwater basin.

CONCLUSIONS

The past year has been used as a trial to gauge the success of in-cave dye tracing. As predicted, such work is strenuous and rewarding. We now know much more than a year ago, both in terms of cave hydrogeology and cave conservation and protection. Over the course of the next few years we plan many additional traces along these same lines. In addition to the future traces described above, we also plan on focusing on refining groundwater basin boundaries on the Pennyroyal Plateau, especially within developed portions of the watershed.

Another aspect of karst hydrogeology is becoming readily apparent from detailed in-cave dye tracing, especially proximal to basin boundaries: the complex three-dimensional nature of basin divides. This actually comes as no surprise as mature cave systems, such as the Mammoth Cave System, display intricate three-dimensional relationships between cave conduits, and therefore, groundwater basin boundaries are governed by flow routes. The problem is in the map display of these 3-D basin divides. At this time we have not decided on the best way to show these divides.

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References Cited

- Anderson, R.B., 1925, Investigation of a proposed dam site in the vicinity of Mammoth Cave, Kentucky, *cited in* Brown, R.F., 1966, Hydrology of the cavernous limestones of the Mammoth Cave area, Kentucky: U.S. Geological Survey Water-Supply Paper 1837, 64 p.
- Hall, C.L., 1996, Water quality variations and contaminant mass flux signatures relative to quick-flow recharge within the Turnhole Spring Groundwater Basin: M.S. Thesis, Eastern Kentucky University, 206 p.
- Meiman, J., and Ryan, M.T., 1992, Unpublished groundwater tracing data: Mammoth Cave National Park, Kentucky.
- Meiman, J., and Ryan, M.T., 1993, The Echo River-Turnhole Bend overflow route: *Cave Research Foundation Newsletter*, v. 21, no. 1, p. 1, 16-18.
- Meiman, J. and Capps, A.S., 1995, Unpublished dye tracing data: Mammoth Cave National Park.
- Murphy, J.D., 1992, Determining the hydrology of the Turnhole Spring Groundwater Basin of Mammoth Cave National Park, Kentucky using quantitative dye tracing: B.S. Thesis, University of Durham, 51 p.
- Quinlan, J.F., and Ray, J.A., 1981 and 1989, Groundwater basins in the Mammoth Cave Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky
- Ryan, M.T., 1992, Using newly-developed quantitative dye tracing techniques to determine the karst hydrogeology of the Buffalo Spring Groundwater Basin of Mammoth Cave National Park, Kentucky: M.S. Thesis, Eastern Kentucky University, 123 p.
- Ryan, M.T. and Meiman, J., 1996, An examination of short-term variations in water quality at a karst spring in Kentucky: *Ground Water*, vol. 34, no. 1, pp. 23-30.

Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky

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ABSTRACT

Threats to the health of karst ecosystems, including the Mammoth Cave Karst Aquifer, come from a variety of agricultural, urban, and transportation land use practices. For the Mammoth Cave Karst Aquifer, the US Fish and Wildlife Service has funded the Hoffman Environmental Research Institute to: 1) classify land use, 2) perform a dye-trace investigation to determine if the hydrologic network of the eastern end of the Mammoth Cave System extends into a fourth major drainage basin, 3) develop a GIS (Geographic Information System) as a data storage and retrieval tool, and 4) investigate potential protection strategies for these areas.

We conducted Anderson Level III land use classification at 1:24,000 scale for 383 km² comprising the Turnhole Bend Basin, Echo River Basin, Pike Spring Basin, Mile 205.7 Spring Basin, Suds Basin, and intermediate drainage areas. Within the Mammoth Cave Karst Aquifer, broad categories of land use include:

*17.4 km² of Urban and Built-up land
156.6 km² of Agricultural land
0.5 km² of Rangeland/Grassland
159.2 km² of Forestland
1.7 km² of Water
<0.1 km² of Wetland
1.0 km² of Barren land*

A series of dye traces was undertaken with this project. A dye trace in the northeast portion of the Mammoth Cave System, near the Kahn Entrance, emerged at Pike Spring. A dye trace near Candlelight River conducted within this study emerged at Floating Mill Hollow Spring, thus identifying a new spring basin that communicates with known passages in the Mammoth Cave System. ArcView GIS was used to catalog and analyze the results of the land use classification.

INTRODUCTION

Western Kentucky University received funding from the U.S. Fish and Wildlife Service in 1998 to investigate land use in the groundwater recharge area draining to Kentucky's Mammoth Cave karst aquifer. This area, which represents one of the most spectacularly developed of the world's karst landscape/aquifer/ecosystems, includes the world's longest known cave, the 500+ km-long Mammoth Cave System. Due to the globally significant nature of both the cave and its aquatic ecosystem, the area has been designated as a National Park, a World Heritage Site, and an International Biosphere Reserve. The park is home to at least nine federally endangered species, including the Kentucky Cave Shrimp (*Paleamonias ganteri*). In addition, the south-central Kentucky karst was recently selected by the Karst Waters Institute as one of ten of the world's karst ecosystems in most critical need of protection (Springston, 1998).

The quality of much of the water that flows through the Mammoth Cave karst aquifer has been impaired, and continues to be threatened, by agricultural, urban, and transportation land use activities within the aquifer's recharge area, much of which is outside the protective boundaries of the National Park. The intimate relationship between land use and groundwater quality in the well-developed karst areas of the Green River Basin occurs due to the rapid groundwater velocities, as high as several km per day, which can allow contaminants to travel into, and through, the aquifer in a short time with little attenuation. A toxic spill along I65 or the CSX railroad in the recharge area, for example, could potentially have rapid and devastating impacts on the habitats of numerous species. Bacteria from human and animal waste also present a particularly serious problem in water quality degradation.

PROJECT GOALS

The primary goals of this study were to complete a quantitative land use analysis of the recharge area that contributes water to the Mammoth Cave karst aquifer, along with a hydrogeologic fieldwork component by which we further defined the appropriate boundaries of the groundwater basins. This work represents a first step in developing a land use strategy designed to protect this globally significant karst ecosystem by defining a critical boundary condition on the physical structure of that ecosystem. The recharge zone is comprised of those groundwater catchments that have been shown to drain to conduits of the Mammoth Cave System, including the Turnhole Bend, Echo River, and Pike Basins. Partial development of a Geographic Information Systems (GIS) database for Turnhole Bend basin land use was completed by scientists at Mammoth Cave National Park in the mid-1990's; the current U.S. Fish and Wildlife Service (USFWS) funding allowed completion of the task for the entire Mammoth Cave aquifer as currently defined. In addition, analysis was completed for two other major adjacent basins (Suds and Mile 205.7 Spring Basins), and seven other smaller basins and interbasin areas that are likely to be included in the future as cave exploration, dye tracing, and hydrogeologic analysis continue to reveal the nature of the landscape/aquifer system and in particular, the full extent of the Mammoth Cave System. The areas for which land use was analyzed for this project include 336.4 km² of the Mammoth Cave karst aquifer and 46.4 km² in Suds, 205.7 Spring, and smaller basins, for a total of 382.8 km².

HYDROLOGY AND RECHARGE OF THE STUDY AREA

The Mammoth Cave karst aquifer is located within the broad karst region that extends through the Interior Low Plateaus of the southeastern United States, and is among the most extensively developed, well explored, and intensively studied of the world's karst landscape/aquifer systems (White *et al.*, 1970; Hess, 1974; White and White, 1989). The aquifer contains the Mammoth Cave System, which, with a currently explored length of over 500 km, is the world's longest known cave. Additionally, several hundred km of active groundwater conduits in the area have been identified by groundwater dye tracing (Quinlan and Ray, 1989; Crawford, 1985; Ray and Currens, 1998). The aquifer extends across several interrelated groundwater basins, all of which drain from large, alluviated springs along the south side of the Green River, the major base level stream for the area.

The Mammoth Cave karst aquifer is developed within a 160 m thick section of nearly horizontal, Upper Mississippian limestones of the St. Louis, Ste. Genevieve, and Girkin Formations (Pohl, 1970; White *et al.*, 1970; Palmer, 1981). The limestones are intermixed with minor chert and dolomite layers, and in the northern part of the study area, are covered by flat-lying clastic caprocks (primarily the Big Clifty Sandstone) that form the dissected Mammoth Cave Plateau. The southern parts of the study area extend onto the Pennyroyal Plateau, on which one of the world's most extensive sinkhole plains is developed. Regionally, the area lies on the flank between the Cincinnati Arch and Illinois Basin, with beds generally dipping towards the northwest at very gentle gradients of a few m per km (Deike, 1967; White *et al.*, 1970). Gentle local structures also influence the development of both landscape features and groundwater flow paths (Howard, 1963, 1964; Palmer, 1981, 1984, 1991), and Deike (1967) concluded that although two major joint sets are present, cave passage orientation, and thus groundwater flow, is controlled primarily by bedding structures. Surface elevations in the karst area range from about 127 m at local base level on the Green River, to nearly 300 m on the sandstone capped ridges of the southern Mammoth Cave Plateau.

There are three main sources of recharge to the Mammoth Cave karst aquifer, the majority of which is a large area of direct rainfall onto an extensive sinkhole plain developed within the St. Louis and Ste. Genevieve Limestones (Palmer, 1981; Richards, 1964; Haynes, 1962 and 1964a, b, and c; Klemic, 1963). Recharge derived from non-carbonate headwater areas also enters the aquifer at discrete swallets (sinking surface streams) from the argillaceous limestones and shales of the lower St. Louis along the southern margin of the sinkhole plain (the Glasgow Upland), as well as sinking streams flowing into the Girkin Limestone from the overlying clastic rocks of the of the highly dissected Mammoth Cave Plateau in the northern part of the catchment (Quinlan and Ewers, 1981). The recharge area has mean-annual precipitation of 1,264 mm, and the mean-annual temperature is 13°C (Hess, 1974). Precipitation is spread out throughout the year, although the late summer and early fall are drier than other months. Using the empirical methods of Thornthwaite (1948), Hess (1974) determined that mean-annual potential evaporation is 800 mm, varying from near zero in the winter to over 100 mm/mo during the warm season months.

AQUATIC RESOURCES

Although in many areas one would consider both surface and groundwater supplies in describing aquatic resources of a region, a feature of well developed karst systems such as this is that integrated surface drainage can be almost wholly lacking. Within much of the study area most flow is in the subsurface, where enlarged conduits in the limestone carry streams in a tributary fashion somewhat analogous to the organization of drainage systems on the surface in non-karst areas.

Within the Glasgow Upland region in the southern end of the study the headwaters of numerous small stream flow on the relatively impervious shales and argillaceous limestones of the lower part of the St. Louis Limestone. However, as these streams flow northwards they soon encounter the purer limestones of the upper St. Louis and Ste. Genevieve Formations, and sink into the subsurface as recharge to the Mammoth Cave karst aquifer. There are also small streams that flow upon the non-carbonate rocks of the Big Clifty sandstone and other clastic rocks that overlie the main karst-forming limestones in the northern part of the study area, but these too disappear into the subsurface upon reaching the limestones to become part of the groundwater supply.

The sinkhole plain areas of the surface also contain numerous small farm ponds that form in closed depressions (sinkholes) that become plugged with relatively impervious clays and silts either intentionally by farmers or by being compacted by livestock. Many of these tend to be ephemeral features over long timescales, and indeed in the sinkhole plain areas it is not uncommon to hear stories of some that have become unplugged and drained rapidly into the cave system below after years or even decades of holding water.

There are also wetland areas developed on the sandstones and possibly cherts within the study area, although these tend to be variable in extent depending on seasonal weather conditions. The few wetlands that we mapped in our land use analysis reflected those that were recognizable at the time that the infrared photos were taken March 20, 1990.

The resources that the various waters within the study area supply are primarily of importance because of the unique aquatic ecosystem that exists within the subsurface of the karst aquifer and the impact that these waters have on the aquatic health of the Green River. Except for water wells in some of the more remote areas where water supply infrastructure has not been developed, groundwater is not used for human consumption. This is largely a direct result of agricultural land use, which has made the groundwater unusable for drinking due to high levels of bacteria from animal and human waste. In some cases fecal coliform concentrations have been measured to exceed several *tens of thousands* of colonies per ml of groundwater (Quinlan and Rowe, 1978; Joe Meiman, personal communication). Increased attention in the area is also being directed towards potential threats to groundwater quality from agricultural chemicals, especially pesticides.

The aquatic ecosystem within the Mammoth Cave karst aquifer is among the most diverse known of any karst system. It is home to the endangered Kentucky Cave Shrimp (*Palaemonias ganteri*) as well as numerous other sensitive species, including two species of eyeless cavefish, *Typhlichthys subterraneus* and *Amblyopsis spelaea*. As the aquifer's waters ultimately discharge at major springs along the south side of the Green River, their quality also impacts the environment of surface river species, which include six endangered freshwater mussels in section of river along which the aquifer discharges. Two species of federally endangered bats also live within the vadose, or air-filled, part of the aquifer. The direct connection between land use and groundwater quality in the karst area poses a major threat to the health of the aquatic ecosystem.

STUDY RESULTS

Two related components were required to achieve the objectives of this study:

1. *Verification of the recharge area contributing to the Mammoth Cave aquifer.* In addition to the three major groundwater basins mentioned above, during the last decade exploration in the far eastern end of the Mammoth Cave system has suggested that the recharge area of the aquifer may extend eastward beyond the boundary of the Pike Spring Basin, although this had not been verified. It appears, on small-scale drainage basin maps of the area, to approach the three-way boundary junction of Pike, Suds Spring, and Lawler Bluehole groundwater drainage basins (Quinlan and Ray, 1984), but the mapped boundary in the region is a coarse estimate, and a direct groundwater trace from within the cave was required to verify which basin contains this section of the cave system. Using standard karst groundwater tracing techniques, we performed three fluorescent dye traces to clarify uncertain boundaries of the aquifer recharge zone.
2. *Land use classification at a scale of 1:24,000 using analysis of color infrared images, with field verification of ambiguous units.* This information was digitized and compiled into an ArcView GIS database. The information from the analysis provides a quantitative evaluation of the current land use practices impacting water quality in the Mammoth Cave aquifer.

VERIFICATION OF CONTRIBUTING RECHARGE AREA

The major question to be answered by hydrologic fieldwork for the project was whether the recharge area for the Mammoth Cave aquifer should include Suds, Mile 205.7 Spring, or Lawler Bluehole basins, in addition to the currently accepted Turnhole Bend, Pike, and Echo River basins. Since the Mammoth Cave System and its associated ecosystem has historically provided the basis for the region's political designation as a globally significant ecosystem, the Mammoth Cave aquifer is defined in this study as the recharge area of those basins that contribute flow to the 500+ km-long cave system. Recently discovered passages within Mammoth Cave, and in particular a cave stream passage named "Outward Bound", have extended to the area of the triple junction of the boundaries of Pike, 205.7 Spring, and Lawler

Blue Hole Basins. The first dye trace completed for this project was from the Outward Bound Stream, which showed that this portion of the flow system drains to Pike Spring. Thus, this part of the cave system is still within the confines of the traditionally defined Mammoth Cave karst aquifer, and the Suds, Mile 205.7 Spring, and Lawler Bluehole Basins were not shown to contribute flow to the aquifer system. However, we nonetheless completed land use analysis for Suds and Mile 205.7 Spring basins. Cave exploration in the area continues, and it seems likely that several large cave systems nearby within the two basins, including the Fisher Ridge and Vinegar Ridge Caves, may one day connect to Mammoth Cave. Thus, the definition of the recharge area of the Mammoth Cave system and aquifer depend on an anthropomorphic view of the current state of knowledge of the system, which is likely to change as time passes. For this reason we chose to complete land use analysis in the project for areas not only currently known to be included within the aquifer's recharge area, but also those areas that are likely to be contributing areas based on hydrogeologically reasonable interpretation, and which were feasible within the resources of the study.

Due to the extensive nature of the passages of Fisher Ridge Cave (150+ km), much of which is developed within the Lawler Bluehole Basin to the east of Suds, there is some chance that further exploration may show that the Mammoth Cave System extends into that Basin. However, land use analysis for this large basin was not feasible within the resources of the current project. While there is also some chance that in the future the cave system may be found to extend into the Bear Wallow Basin, even further to the east and still within the Green River Basin's area of significant cave development, none of the currently known significant cave systems are situated to suggest that connections to the Mammoth Cave System are imminent, and thus there is considerably less probability that this basin will be included as part of the Mammoth Cave karst aquifer in the foreseeable future.

In addition, beyond the original goals of the project, in June 1999 we identified by dye tracing another significant catchment that was not previously known to be included in the Mammoth Cave aquifer recharge zone. This catchment, the Floating Mill Hollow Spring Basin, lies in a triangular region of several square km bounded by Pike Basin, the Echo River Basin, and the Green River. Rhodamine WT dye traveled over 2 km from the Candlelight River area of Mammoth Cave to Floating Mill Hollow Spring. Previous estimates of the basin boundary (Quinlan and Ray, 1984) had mapped Candlelight River within the Echo River Basin. A third trace from the surface above Bögli Shafts area of Mammoth Cave also went to Floating Mill Hollow Spring, further defining the exact location of the boundary. This work is making it clear to us that this type of detailed, in-cave hydrologic work, while physically demanding and time consuming, is providing us with a new level in precision for the boundary delineation so critical for recharge zone evaluation and source water protection programs.

It should be emphasized that the criteria with which we have defined which basins are pertinent to the study are somewhat arbitrary, and have been done so in order to prioritize which ones are in most immediate need of analysis and study due the recognized global significance of those basins associated with the Mammoth Cave System. However, in ecological terms *all*

areas of the much larger karst area between the Green and Barren Rivers within the Green River Basin have both high potential for significance and high vulnerability from the same types of agricultural and other land use pressures that we are identifying the Mammoth Cave area. As resources become available similar delineation work and land use analysis would be a prudent first step in protecting these important karst areas.

LAND USE ANALYSIS

The land use analysis employed the Anderson land use classification (Anderson, *et al.* 1976). This hierarchical system is divided into three levels, with a higher level representing a greater level of detail. A one digit number represents seven broad categories of Level I land use, including agriculture, urban development, rangeland, water, wetlands, barren land, and forest-land. Level II is broken into 29 categories that are depicted by a two-digit number. Level III is most detailed, with a three or more digit number representing over 100 land-use types. The Mammoth Cave Karst Aquifer and adjacent study areas (Suds Spring Basin, Mile 205.7 Spring Basin, and several intermediate and undelineated minor basins) have 94 different Level III land use types in 7,944 land use parcels. The total area of the Mammoth Cave Karst Aquifer and adjacent study area covers 382.8 km².

Anderson Level III land use classification at 1:24,000 scale was conducted for the 382.8 km² comprising the Turnhole Bend Basin, Echo River Basin, Pike Spring Basin, Mile 205.7 Spring Basin, Suds Basin, Floating Mill Hollow Basin and intermediate drainage areas. A base map for land use parcels was constructed in an ArcView project contained on the compact disks that accompanies this report. The base map consisted of 1:12,000 digital orthophoto quarter quadrangles (DOQQ's) in the Universal Transmercator North American Datum 1927, Zone 16 coordinate system. Parcel shapes and land use codes interpreted from the color infrared images were then transposed to the base map. For some of the study area, Mammoth Cave National Park had previously classified land use for part of the study area and placed parcels and codes on mylar sheets. Since we had access to newer DOQQ's (developed from photos taken in March, 1993) compared to images used by the Mammoth Cave scientists for areas previously classified, we completely redigitized the land use parcels for the primary ArcView land use database.

Land use was identified from 1:24,000 color infrared aerial photographs taken by the Tennessee Valley Authority on March 20, 1990. The images consisted of nine-inch color positive film, which were viewed under magnification on a light table. Most polygons were drawn at 1:4,000, unless one particular land-use large area. This mainly occurred in the case of a continuous forest of the same type and thickness. Observing color patterns on the color infrared images using standard techniques and transposing the patterns into polygons in Environmental Systems Research Institute's (ESRI) ArcView GIS program created parcel polygons. For example, on infrared photography analysis, reds and greens are types of vegetation and farmland; purple trees are pines or evergreens; and reddish brown trees are cedars. These color patterns and observable features on the infrared images (cultural features and livestock,

for example) allowed classification of the levels (I, II, and III) of the Anderson scheme. Additionally, field checking was conducted to classify vague areas in more detail and verify quality. Quality control field checks of 84 randomly selected parcels found that classification for this project was above Anderson's standard 85% accuracy guideline. Using the query ability of the GIS database, an Anderson Level I land use table was generated for both the Mammoth Cave Karst Aquifer and total study area (Table 1).

Table 1: Anderson Level I land use within the Mammoth Cave Karst Aquifer and the total study area

	Mammoth Cave Karst Aquifer	Study Area and Adjacent Basins	Total
Urban/Built-Up (km ²)	17.4	1.7	19.1
Agricultural (km ²)	156.6	14.1	170.7
Rangeland/Grassland (km ²)	0.5	0.1	0.6
Forestland (km ²)	159.2	30.3	189.5
Water (km ²)	1.7	0.2	1.9
Wetland (km ²)	<0.1	<0.1	<0.1
Barren (km ²)	1.0	0.0	1.0
Total (km ²)	336.4	46.4	382.8

ECOSYSTEM PROTECTION AND FUTURE RESEARCH

With the established significance of this karst aquifer and ecosystem, there has for a number of years been a focus on water quality and ecosystem health within the Mammoth Cave karst aquifer. The major contribution of the current study, therefore, has not been to identify any particular new threats to water quality or immediate solutions to those threats. However, this work represents the first detailed quantitative evaluation of the land use practices that provide the primary threats to the system. The GIS format provides a flexible, queryable tool for the storage, analysis, and visualization of these data.

There are several strategies for remediation protection of the ecosystem supported by the results of this analysis:

- 1) The database provides a baseline with which to quantitatively evaluate and compare measured water quality changes that may result from future land use changes, in particular the implementation of various Best Management Practices (BMP's) of land management. In the study area water quality threats come from a variety of agricultural, transportation, and urban land use practices that may be amenable to BMP strategies. This detailed GIS database provides an excellent tool to record the temporal and spatial implementation of these strategies, as well as other land use changes that will take place for other reasons, driven by social and cultural influences, but nonetheless may impact ecosystem quality.
- 2) The database serves as a key component for the development of quantitative, predictive models that relate present and future land use strategies to groundwater quality and thus ecosystem health. These could allow simulation of various land use changes, with model results describing the resulting modifications in water quality at key points in the system such as springs and various cave habitats. While developing such models is a necessarily complex operation requiring significant assumptions about flow system structure, they can possibly provide useful information on trends or relative magnitudes of groundwater impacts resulting from various land use scenarios.

There are a variety of obvious and useful directions for further research related to this project and study of the ecosystem health of the Mammoth Cave karst aquifer and surrounding areas. The most immediate are to extend the two main components of the current work, including hydrogeologic study to further delineate the complex geometries of the karst groundwater basins and particularly their boundaries, and to extend the detailed land use analysis and GIS development to other areas of the south central Kentucky karst area which potentially contain both fragile and significant subsurface ecosystems.

For information about obtaining the ArcView GIS database for this project, please contact the Hoffman Environmental Research Institute at Western Kentucky University.

References

- Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976, *A Land Use and Land Cover Classification System for Use With Remote Sensor Data*. Washington, D.C.: U.S. geological Survey Circular 671, 28. P.
- Crawford, N.C., 1985, *Hydrologic Hazards in Karst Terrain*. U.S. Geological Survey Water Fact Sheet, 2.
- Deike, G.H. III, 1967, *The Development of Caverns of the Mammoth Cave Region*, Ph.D. Dissertation, The Pennsylvania State University, 235 p.
- Haynes, D. D., 1962, Geology of the Park City quadrangle, Kentucky. U.S. Geological Survey. *Geologic Quadrangle Map* GQ-183.
- Haynes, D.D., 1964a, Geology of the Glasgow North quadrangle, U.S. Geological Survey, *Geologic Quadrangle Map* GQ-339.
- Haynes, D.D., 1964b, Geology of the Horse Cave quadrangle, U.S. Geological Survey, *Geological Quadrangle Map* GQ-558.
- Haynes, D. D., 1964c, Geology of the Mammoth Cave quadrangle, Kentucky. U.S. Geological Survey. *Geologic Quadrangle Map* GQ-351.
- Hess, J.W., 1974, *Hydrochemical investigation of the central Kentucky karst aquifer system*, Ph.D. Dissertation, Geology, The Pennsylvania State University, 218 p.
- Howard, Alan D., 1963, The development of karst features. *National Speleological Society Bulletin*, vol. 25, no. 2, p. 45-65.
- Howard, Alan D., 1964, Process of limestone cave development. *International Journal of Speleology*, vol. 1, p. 47-60.
- Klemic, H., 1963, Geology of the Rhoda quadrangle, U.S. Geological Survey. *Geologic Quadrangle Map*. GQ-219.
- Palmer, A. N., 1981, *A Geologic Guide to Mammoth Cave National Park*. Zephyrus Press. Teaneck, New Jersey: 210 p.
- Palmer, A.N., 1984, Geomorphic interpretation of karst features, in *Groundwater as a Geomorphic Agent*, R.G. LaFleur, (editor) (Allen and Unwin, London), pp.173-209.
- Palmer, A. N., 1991, The origin and morphology of limestone caves. *Geological Society of America Bulletin*, vol. 103, pp. 1-21.

- Pohl, E.R., 1970, Upper Mississippian deposits of south-central Kentucky, *Kentucky Acad. Sci. Trans.*, vol.1, pp.1-15.
- Quinlan, J. F. & Ewers, R. O., 1981, Hydrogeology of the Mammoth Cave region, Kentucky. in *GSA Cincinnati '81 Field Trip Guidebook 3*, Roberts, T.G. (editor). American Geological Institute, Falls Church, Virginia, pp. 457-506.
- Quinlan, J.F., and J.A. Ray, 1989, *Groundwater Basins in the Mammoth Cave Area, Kentucky*. Friends of Karst, Occasional Publication 1 (revision of 1984).
- Quinlan, J.F., and R. Rowe, 1978, Hydrology and water quality in the central Kentucky karst: *Water Resources Institute, University of Kentucky, Research, Report 109*, 42 p.
- Ray, J.A., and J.C. Currens, 1998, *Mapped Karst Ground-Water Basins in the Beaver Dam 30 x 60 Minute Quadrangle, scale 1:100,000*. Kentucky Geological Survey, Map and Chart Series 19 (11).
- Richards, P.W., 1964, Geology of the Smiths Grove quadrangle, Kentucky, U.S. Geological Survey, *Geologic Quadrangle Map GQ-357*.
- Springston, B., 1998, Karst Waters Institute Lists top 10 endangered karst ecosystems. *American Caves*, vol. 11, p. 7.
- Thornwaite, C.W., 1948, An approach towards a rational classification of climate. *Geographic Review*, vol. 38, pp. 55-89.
- White, W.B., R.A. Watson, E.R. Pohl, and R. Brucker, 1970, The central Kentucky karst. *Geograph. Rev.* vol. 60, pp. 88-115.
- White, W. B. and E.L. White, 1989, *Karst Hydrology: Concepts from the Mammoth Cave Area*. Van Nostrand Reinhold. New York: 346 p.

Threats to Surface and Karst Groundwater of Mammoth Cave National Park from the Arthur Oil Field, Kentucky

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INTRODUCTION

In the early 1990s a small oil boom began in Edmonson County, Kentucky. Today, oil production continues and a number of wells have been drilled on properties adjacent to the southwestern edge of Mammoth Cave National Park. While steps have been taken to reduce the chance of oil spills and the potential contamination of karst aquifers of Mammoth Cave National Park, accidents can happen. Therefore, in order to be proactive, research efforts are not only lessening the possibility of an oil spill, but are also preparing contingency plans in the event that one occurs.

This potential threat was demonstrated in January 1997, when a fitting in one Arthur well ruptured and spilled 2,000 liters of crude oil, which flowed on the surface into the park. Only a quick and coordinated effort prevented the oil from sinking into and contaminating the primary karst aquifer. This spill clearly demonstrated the inherent threat posed by the area's numerous wells and petroleum facilities, while it also emphasized the need for a better understanding of the karst hydrogeology of this region of the park.

In order to prepare for potential threats in this area, scientists and students of Western Kentucky University and the National Park Service are cooperating in the development of a Geographic Information System (GIS) database. When completed, this database will depict the hydrogeology, oil well location data, karst features, access roads, and in particular, surface and subsurface flow routes adjacent to these oil facilities. The database, including a summary map for use during emergencies, will then be distributed to the various agencies, organizations, and response personnel to better plan future efforts.

GEOLOGIC SETTING OF ARTHUR AREA

Dry Branch is an ephemeral stream located just to the west of the Mammoth Cave System. While most of the Dry Branch drainage area lies within Mammoth Cave National Park, it is west of the recharge area for the Mammoth Cave karst aquifer. The "Arthur Oil Field" is primarily located in and just to the south of Dry Branch. Unlike the Mammoth Cave aquifer,

the Dry Branch aquifer is not believed to be connected to the Sinkhole Plain recharge area. Consequently, the springs within Dry Branch are small, and the karst is not well developed. Dry Branch empties into the Green River near Houchin's Ferry. Dry Branch drains approximately 644 hectares. Geologically, the surface on which Dry Branch flows is composed of 48% carbonate rocks and 52% noncarbonates. The carbonates are three distinct Mississippian limestones: the Glen Dean, the Haney, and the Girkin Limestones. The Girkin Limestone is the uppermost limestone unit comprising the main Mammoth Cave aquifer. The Girkin Limestone is only exposed within 2% of the Dry Branch basin. Separating the Girkin and Haney limestones, as well as the Haney Limestone and the Glen Dean Limestone, are fairly impermeable sandstone layers. Sandstone and shale caps much of the Glen Dean Limestone. This configuration of the bedding layers results in the hydrology resembling stair-steps. Storm events produce surface runoff on uppermost sandstones and shales, which empty into sinkholes near the upper contact with the Glen Dean Limestone. This water reappears at small springs located at the contact with the next lower sandstone layer. This runoff then drains on the surface again, only to sink into the Haney Limestone. The Haney Limestone springs are usually located at the lowest part of the limestone, near the contact with the lowest sandstone layer. Below this sandstone layer is the Girkin Limestone; however, there is no appreciable karst development known in the Girkin Limestone of Dry Branch. This is due mostly to the fact that the Girkin Limestone in this region is near the base level elevation of the Green River, thereby restricting karst development.

The stratigraphy of the Dry Branch basin lends itself to containment of potential contaminants. The Haney and Glen Dean aquifers of Dry Branch are not known to be hydrologically connected outside of the Dry Branch catchment region. Therefore, they are relatively self-contained units.

METHODS

The project consists of several parts. Dye tracing studies (Figure 1) are underway to determine the subsurface flow routes that a potential spill may take. Well sites, oil tanks and other facilities are being inventoried using a global positioning system (GPS) and aerial photography. Access roads and other features are also being inventoried and mapped, as well as basic geology and stratigraphy. This information is being used to develop a detailed ArcView GIS-based map and database of the region that park staff and response personnel can use for both developing emergency procedures and responding in the event of a spill.

CONCLUSION

This project represents an important tool for the protection of water resources for the plateau and ravine karst section of Mammoth Cave National Park, as well as the Green River below Houchins Ferry. Oil development to the south of the park boundary continues to put potential pressures to aquatic ecology and water quality in the area.

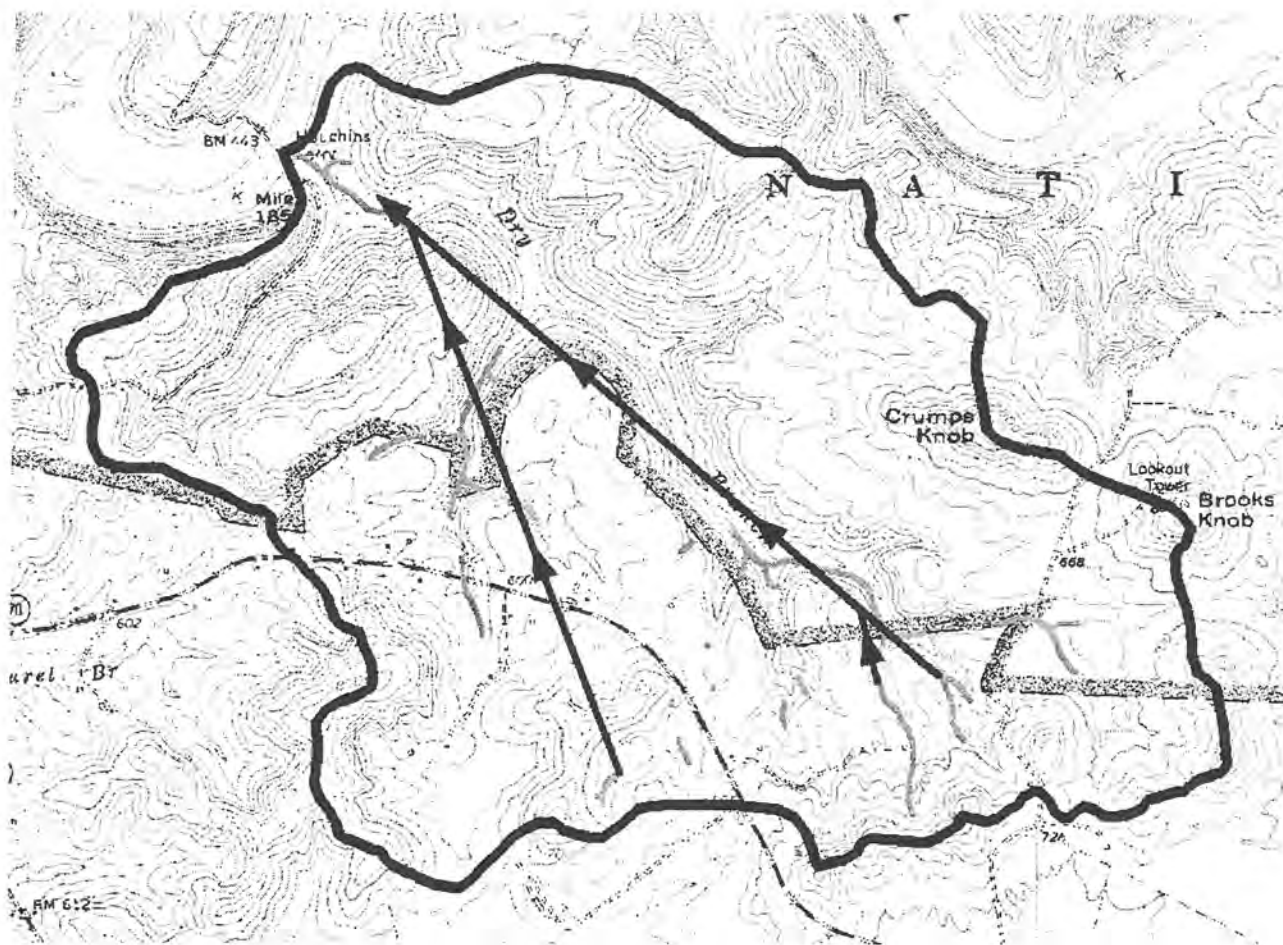


Figure 1. Drainage area and completed dye tracing for the Dry Branch catchment in the vicinity of the Arthur Oil Field. The area of potential oil contamination lies in the southern part of the catchment, to the south of Mammoth Cave National Park.

However, the best landuse strategy overall for the area requires a simultaneous need to strike a balance between the ecological, cultural, and economic needs of the area and its residents. With the construction of such a database and map, along with the preparation of emergency preparedness procedures, we will most be able to protect these resources in the case of an accidental spill from oil production activities.

There are many potential threats to cave, karst, water, and ecological resources. Each area has its own unique situation and potential problems. However, with thorough inventory, assessment, and coordinated preplanning and preparedness efforts, resource managers can responsibly maintain the ecological health of surface and karst water resources of the boundary areas of Mammoth Cave National Park.

A Historiography of Archaeological Research in the Mammoth Cave Area of Kentucky: 1824-2000

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ABSTRACT

Archaeological interest in the the Mammoth Cave area of Kentucky has been on-going since the early 19th century, primarily because of the unique preservation offered at the underground cave sites. In this paper I examine almost two hundred years of archaeological research conducted in the Mammoth Cave area. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and later by Willey and Sablof (1993).

An examination of the history of archaeological study in the Mammoth Cave region of south-central Kentucky reflects parallel development with the growth of archaeology in North America (Schwartz 1967; Willey and Sabloff 1973), but it also demonstrates why additional intensive and systematic archaeological study should to be conducted in this very significant archaeological region. In this paper I provide an historical overview of archaeological research that has taken place in and around Mammoth Cave National Park. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and expanded by Willey and Sabloff (1993).

THE SPECULATIVE PERIOD

One of the earliest archaeological records pertaining to the Central Kentucky Karst research area was written in 1824 by Constantine Samuel Rafinesque (1824). Rafinesque, a colleague of James Audubon, was deeply interested in prehistoric remains of the Ohio Valley (Stout and Lewis 1995:83-90). According to Col. Bennett Young (1910:18), Rafinesque claims to have located 148 ancient sites (settlements) and 505 monuments in a 41 county area of Kentucky, speculating as with other early nineteenth century naturalists about the origin of these "natural" curiosities. Rafinesque's entry for the Central Kentucky Karst lists "shell mounds along Green River and mummies in caves."

Following Rafinesque's initial inquiry into Kentucky's prehistory, there appears to be an absence of related literature about the antiquities of the area. This is not to say that interest in antiquities had died; it had not. According to Col. Bennet Young (1910), increased farming activity, and in general, disruption of the land due to population growth, caused an escalation

in the amount of destruction and looting of prehistoric sites. By 1870, the collecting, selling, and smuggling of antiquities in Kentucky was a major profession. Although known mostly for its large cave system, the archaeological contents of the Mammoth Cave area offered a variety of artifacts and desiccated human remains for collecting and selling. Finds, such as Fawn Hoof in 1813, Scudder's Mummy in 1814, Little Al(ice)¹ in 1875, and Lost John in 1935, helped make the Mammoth Cave area famous (Meloy 1971). During the mid-nineteenth and early twentieth centuries, many individuals explored nearby cave systems looking for mummies and Indian relics to sell (see Young 1910). Unfortunately, this dilettantic pastime stopped only in those caves that came under the protection of the National Park Service after 1940 (e.g., Salts, Mammoth, Longs, Bedquilt, and Lee caves), and even then, infrequent looting of caves within the National Park still occurred.

The earliest historic date known from inside Salts Cave is 1809 (Watson 1969:7). Dates and names upon various signature rocks in Mammoth and Salts caves indicate that the majority of historic caving dates "from the last quarter or so of the 19th century to the first quarter of the 20th century" (Watson 1969:7; see also Watson ed., 1974:21-23). The vegetal antiquities (e.g., textile bags, cordages, sandals) that could be found within the dry caves were not normally preserved in surface or "open" sites. Hence, those items were especially sought for collecting, smuggling, and looting. As an example of smuggling, in 1874 or 1875, Louis Vial and some friends explored extensively in Salts Cave using a "new side entrance known only to themselves" (Watson 1969:7). During one of those cave trips they found the "Salts Cave Mummy," nicknamed incorrectly "Little Alice" (Robbins 1971; Tankersley et al. 1994; Watson 1969:7). More recent examinations by the late Louise Robbins (1971:200-206) identified the sex and age of this individual to be those of a nine-year-old male.

During the 1890s men such as F.W. Putnam of the Peabody Museum, as well as local Kentuckians such as Colonel Bennett Young, T. F. Hazen, and W.D. Cutliff, made extensive collections and/or purchased prehistoric material from Salts and Mammoth caves. Young (1910:300, 305) states:

In 1893 Mr. Theodore F. Hazen...opened a new entrance into Salts Cave..." [and] "we obtained many interesting relics..." about the present entrance [Salts Sink], numerous spalls, flakes of flint, pestles, axes, awls, and other implements have been found...

Young goes on to describe many artifacts taken from within Salts and Mammoth Caves, such as cords of bark, hemp, cattail leaves, and grass; basketwork; half-burned cane torches; corn cobs (probably modern); an aboriginal ladder; wooden digging implements; cups, dishes, bowls and water bottles made from gourds and squash rinds; tobacco leaves and seed pods (also probably modern), as well as many chert implements. The large collection of antiquities Young acquired was sold to the Museum of the American Indian, Heye Foundation, New York (Schwartz 1958e; Watson 1974: 167). Later, John M. Nelson, who was a cave guide from 1894-1907, extensively collected antiquities both from the caves and from surrounding surface sites (Carey 1942; Schwartz 1958f:3; Watson 1969, 1974). With the exception of the John M. Nelson

collection, the other large private collections were either given or sold to the American Museum of Natural History, Smithsonian Institution, or the Peabody Museum of Archaeology and Ethnology. It was the Mammoth Cave Estates collection, donated to the American Museum of Natural History in 1913, that prompted Nels C. Nelson (no relation to John M. Nelson) to engage in the “only scientific archaeological investigations” (Schwartz 1958d) of the Mammoth Cave area up to that time and usher in the Classificatory-Historical Period of archaeological work (Schwartz 1967; Willey and Sabloff 1993).

The Speculative Period focused initially upon discovery, with only meager attempts to offer explanations of derivation of the discovered sites. Once discovered and made known, sites were vandalized and exploited for private purposes, whether pots, “arrowheads” or “mummies”—the market for trafficking in North American antiquities had begun. But it was from the seeds of site destruction that the first museum acquisitions were made that ushered in professional archaeological work of the Classificatory Period.

THE CLASSIFICATORY PERIOD, 1916-1960

Nels C. Nelson worked in Mammoth Cave National Park during May and November of 1916 as an archaeological representative of the American Museum of Natural History. Nelson’s 1917 report describes the materials found during his surface and cave reconnaissances and excavations within the Mammoth Cave area. Specifically Nelson describes and compares his surface finds from the Mammoth Cave and Eaton Valley fields to similar bifacial chipped stone materials then being found in the French Paleolithic (Nelson 1917:16-19). In total Nelson examined, through excavation and/or other study, six of nine cave sites, six of seven open surface sites, and one of four rockshelters (Nelson 1917: 11). The latter number refers to the category of site types he reported for the Mammoth Cave area. Douglas W. Schwartz (1958d:1-2) states that Nelson’s main contribution was to “scientifically document the presence in the caves of some classes of material previously only reported by amateurs.” Nelson also drew substantial conclusions from his materials, despite the lack of published reports concerning antiquities of the area and the role of plant domestication (he found large quantities of charred sunflower seeds in his Mammoth Cave Vestibule excavations) in the Central Kentucky region. Nelson concluded that the Flint-Mammoth Cave system had an economic importance to the Native Americans, e.g., the quarrying of flint (e.g., from Flint Alley in Mammoth Cave, which has since been questioned [Munson et al. 1989, Prentice 1993]); Nelson was not aware that the Native Americans also exploited the caves for minerals (e.g., mirabilite, gypsum, satin spar and selenite; see Munson et al. 1989 and Tankersley 1996).

Nelson’s archaeological excavations inside the Vestibule of Mammoth Cave is his major work in the Mammoth Cave area. Although this excavation was exploratory, it was extremely extensive and thorough. Nelson sank a series of 10 test trenches that revealed midden in two places. One was near the west wall of the entrance while the other, some 40 feet from the first, extended 50 feet back over the entire entrance area. Although Nelson’s notes are at times ambiguous, he demonstrated a strong concern for the temporal and spatial location of

artifacts excavated (personal observation in April, 1975 of Nelson's catalog record on file with the American Museum of Natural History, New York).

Nelson excavated almost all of the Vestibule entrance, but the number of artifacts found was few. Douglas W. Schwartz (1958d) explains that this was probably the result of extensive looting that had occurred earlier, throughout the nineteenth century. It also may be the result of Nelson's recovery methods (no screens were used), and/or extensive subsurface alterations resulting from cave commercialization or previous salt petre mining operations during the War of 1812 (Meloy 1968). Any of these reasons may explain the paucity of artifacts recovered from the Mammoth Cave Vestibule. Nelson did find and recognize evidence of prehistoric diet in the form of animal bone, sunflower seeds, and fresh water molluscs (Nelson 1917; Watson 1974:212). He also found prehistoric tools such as bone awls, bone flakers, antler points, tubes, stone projectile points, scrapers, ground stone implements, and items for personal adornment. Most importantly, Nelson (1917:69) concluded that two different cultures could be distinguished within his Vestibule excavations. The lower, or more "primitive" group was identified by Nelson as what archeologists would define two decades later (e.g., Ritchie 1933) as the Archaic culture (Schwartz 1960:133).

Only one other reference to Mammoth Cave area prehistory appeared in print during the first two decades of the twentieth century. This was a fleeting mention of a series of rockshelter sites near what is now the western boundary of Mammoth Cave National Park. The reference was made by C.B. Moore who visited the Indian Hill rockshelter complex in 1915 (Moore 1916). Fortunately, shallow water conditions on Green River forced Moore to terminate his plunderous Green River expedition near Indian Hill as his boat, The Gopher, was too large to continue the journey upstream.

In 1935, a newly discovered desiccated burial within Mammoth Cave, known to the cave guides as "Lost John," brought additional archaeological publicity to the area (Pond 1935, 1937). Alonzo Pond and George Neumann's analysis of Lost John (Neumann 1938), constituted the only professional archaeological inquiry in the Mammoth Cave area between N.C. Nelson's 1916 work and the formation of Mammoth Cave National Park in 1940 (although several additional references to caves and rockshelter sites in and around the present boundary of MCNP appeared in print intermittently (e.g., Fowke 1922; Funkhouser and Webb 1932). With the final acquisition of lands by the federal government on April 25, 1940, it became a federal offense to remove materials from cave interiors within Mammoth Cave National Park.

During the formation of MCNP, the Mammoth Cave National Park Association purchased from John M. Nelson, a collection of prehistoric, historic, and geological specimens that were subsequently donated to Mammoth Cave National Park on January 15, 1942 (Carey 1942:1). Henry A. Carey, then of the Archaeology Department at the University of Kentucky, was placed in charge of cataloging the Park's new acquisitions. He was assisted by a new National Park Service employee, Jesse D. Jennings (Carey 1942). Unfortunately, the majority of the 25,000 specimens in the John M. Nelson collection was without provenience. Items in the collection had been bought from the local area with no note made as to the exact collecting

location. Furthermore, Nelson kept only "mental notes" for his more unusual specimens. From the John M. Nelson collection, Henry Carey concludes: (1) the Mammoth Cave National Park area was utilized for an extensive period of time by aboriginal peoples; (2) a typological sequence could be worked out for the area using the collection, but that extreme caution should be used in drawing definitive conclusions due to the lack of controlled locational data; and (3) that scientific archaeological excavations should be started, inside the caves and at selected surface sites, immediately. Unfortunately, due to the start of World War II, the Mammoth Cave collections heralded for study by Carey were not examined again until 1957 when Douglas W. Schwartz, at the University of Kentucky examined the John M. Nelson materials and attempted to relocate some of the surface sites from which John Nelson had made his collections (Schwartz 1958f). Schwartz also brought systematization to the study of Native American sites in MCNP and visited several major museums in the East to study collections acquired from the Mammoth Cave area at the turn of the century (Schwartz 1958a-h). These activities culminated in a series of valuable descriptive reports (Schwartz 1958a-h) and other interpretive and popular accounts about the archaeology of the area (Schwartz 1960; 1965).

The Classificatory Period brought a logical, scientific inquiry to the archaeology of the Mammoth Cave area. With the first work of Nelson in 1916, to the discovery of an exsiccated individual (Lost John) in 1935, to the systematic reporting of archaeological sites above ground and below by Douglas Schwartz during the late 1950s/early 1960s, the archaeology of the Mammoth Cave area yielded ever-so-slowly, evidence of very significant information about prehistoric cultural adaptations and cultural processes. These later studies served as the foundation for investigations by Patty Jo Watson, the Cave Research Foundation, the National Park Service, and the Illinois State Museum (Watson 1969) during the next period of archaeological development.

THE EXPLANATORY/INTERDISCIPLINARY PERIOD, 1960-PRESENT

In 1942, Henry Carey emphasized the need for further surface investigations and excavations in Mammoth Cave National Park, but little was accomplished until the recent research efforts by Patty Jo Watson and her associates (Carstens 1974, 1975, 1976 1980; Carstens and Watson 1996; Marquardt 1974; Robbins 1971; Wagner 1976; Watson 1969; 1974). Whether you call it explanatory archaeology, processual archaeology, or even post-processual archaeology, the post-1960 era of interdisciplinary archaeological research in the Central Kentucky Karst began to answer many questions about the area's prehistory and the avenues of cultural change and adaptation through time and space.

Watson's archaeological work in Mammoth Cave National Park began in 1962 when, in conjunction with the Cave Research Foundation, the Illinois State Museum, and Mammoth Cave National Park, she initiated an archaeological reconnaissance of the large caves within the Flint Mammoth Cave system (Carstens and Watson 1996; Watson 1969:v). Watson's initial work was carried out primarily in Salts Cave, but later research expanded into other caves (e.g., Mammoth, Lee, and Bluff), and to archaeological surface reconnaissance (Carstens 1974, 1980). Watson's reason for studying the cultural materials from within the caves was that data

derived from those materials was highly relevant to the discovery of dietary practices during the early agricultural Late Archaic-Early Woodland period. Watson's research was expanded in April, 1969, to include, "excavation in Salts Cave Vestibule, a search for and testing of possible surface sites near Salts Sink, and recording of prehistoric remains in other caves within the Park" (Watson 1969:v). Between 1973 and 1980, Watson and her colleagues initiated comparative studies at caves outside the Park (e.g., Wyandotte Cave, Indiana, and Wolf River or Jaguar Cave, Tennessee) (Crothers 1986; P. Munson and C. Munson 1990; Robbins, Wilson, and Watson 1981; Tankersley, P. Munson, C. Munson, Shaffer, and Lieniger 1990). She also obtained a more complete radiocarbon sequence from Salts and Mammoth caves, excavated and floated a stratigraphic column from Salts Cave Vestibule; obtained pollen and parasitological analyses from human paleofecal specimens found within the cave, and took pollen core samples from nearby sinkhole ponds.

Aided in her research by scientists from many different fields of study, Watson was able to approach the archaeological problems of the Mammoth Cave National Park area in a scientifically-integrated manner, a methodological approach she had learned as a University of Chicago graduate participating in Robert Braidwood's interdisciplinary studies of agricultural origins in the Near East. This approach led to some answers, and to many new questions, particularly with respect to environmental changes and their possible effects on the prehistoric inhabitants of the study area. Watson and her colleagues (e.g., Munson et al. 1989; Tankersley 1985, 1996) documented that prehistoric people using the cave were mining the cave for minerals (e.g., mirabilite, gypsum, selenite, and satin spar) and were simply exploring the cave system. She noted similar patterns of cultural activities in portions of other caves located inside (Lee and Bluff) and outside the Park boundaries (e.g., Wyandotte Cave in Indiana, and Big Bone and Jaguar caves in Tennessee; Crothers 1986; Munson and Munson 1990; Watson 1986:109-116). Although Lee, Bluff, Wyandotte, and Jaguar caves are not comparable in size to either Salts or Mammoth Cave, the data collected by Watson and her colleagues clearly indicate that cave mining and exploration were widespread activities in this karstic region that probably began during the Late Archaic (Watson 1974:221-232; Watson 1986; Munson et al. 1989). The 50+ radiocarbon dates now available for the Mammoth Cave project clearly demonstrate the widespread prehistoric use of caves over a very important and similar time horizon (Kennedy, 1996): that of early agriculture in the Late Archaic-Early Woodland period (ca., 4,000 to 2,000 B.P.).

Watson's research between 1962 and 1980 in the Mammoth Cave region is unique for two reasons: (1) it is the first time such scientifically-integrated archaeological deep-cave research has been attempted in the eastern United States; and (2) it provides an aspect of prehistoric culture process that was extremely important (i.e., the domestication of native plants, evidence for which was not then being found in "open" surface sites in the eastern U.S.). Watson's research continues in the Mammoth Cave region.

As a part of the Watson research team between 1973 and 1975, my job was to document the culture history evident in a sample of 83 surface sites in and around MCNP, examining the

techno-economies of several of those sites diachronically, and presenting a cultural historical context within which the surface dwellers of the Central Kentucky Karst explored and exploited the large caves (Carstens 1980).

Between 1977 and 1987, MCNP witnessed only intermittent archaeological research on the Park's surface archaeology. Most of the work accomplished included small, unrelated cultural resource management surveys (e.g., Beditz 1979, 1981; Carstens 1977, 1978). Between 1981 and 1989, few archaeological projects were conducted on the surface of Mammoth Cave National Park. Exceptions are the work of Philip J. DiBlasi, who investigated the 1920s home-
stead of Floyd Collins (DiBlasi 1987a), a famous local cave explorer, and George Crothers, who documented material left in Sand Cave where Collins died in 1925 (Crothers 1981, 1983). DiBlasi (1987b, 1996), working with the Cave Research Foundation, also found, in Salts Cave, a series of prehistoric pictographs and glyphs previously undocumented. Other studies concerning the human use of the cave system, and of the people who were using the cave, focused on determining the exact nature of prehistoric mineral procurement (Tankersley et al. 1985), forensic examinations of the historic findspots of mummies (K. Tankersley et al. 1994; S. Tankersley 1993), and a new and exciting search for pathogenic microorganisms in prehistoric and historic human feces and bodily fluids (Ruppert 1994; Tankersley 1993).

The most systematic undertaking to inventory a representative sample of the Park for both historic and prehistoric cultural resources was directed by NPS archeologist Guy Prentice (1993). Although much of Prentice's prehistory is a summary of Nelson (1917), Schwartz (1958a-g), Carstens (1980), and Watson and Carstens' (1982) site inventories, Prentice adds new prehistoric and historic sites to the overall resource inventory of the Park. As a result, Prentice (1994, 1996) was able to offer a settlement synopsis of MCNP for his doctoral dissertation that includes a hypothetical seasonal round between the Big Bend shell mound area and the Mammoth Cave area.

In 1993, the Science and Resource Management Division at Mammoth Cave National Park began a long-term cultural resource inventory of all artifacts (historic and prehistoric) within the Main Cave in Mammoth Cave. This project is co-sponsored by the NPS and Earthwatch; the field work for this project has been directed by Ken Tankersley, Mary Kennedy, George Crothers, Christine Hensley, and Bob Ward (Kennedy 1993; Crothers and Ward 1995). Using an Electronic Distance Measurement (EDM) system, the Earthwatch team records the exact location of every artifact noted within the surveyed areas of the cave system. This makes it possible to prepare density plots of aboriginal activity within the cave system, and to determine prehistoric use areas within the cave despite 200 years of historic cave use and cave disturbance to the aboriginal materials in Mammoth Cave.

In 1992, Patty Jo Watson, Mary Kennedy, Kristen Gremillion, and Kristin Sobolik began a new study in Mammoth and Salts cave. This new arena emphasized the collection of human paleofecal samples for radiocarbon dating, parasitological analysis, macro- and microethnobotanical studies, and biochemical (hormonal) analysis. These studies would

allow prehistoric fecal specimens to be sexed and thereby enable a better understanding about specific individuals who explored and mined prehistoric Mammoth Cave (Watson 1992; Watson and Kennedy 1993).

In 1994, Christine Hensley and Tom Sussenbach, while working for the National Park Service in Mammoth Cave National Park, conducted excavations at the Stairway Rockshelter (Hensley 1995, 1996). The three radiocarbon samples from Hensley's excavations of Feature 1 consistently place the site's occupation in the Early Woodland period, ca., 2170 to 2570 B.P., a date range that is quite comparable to the majority of aboriginal use of Mammoth and Salts caves (Hensley 1995: 24, Table 1; Kennedy 1990, 1996). Further, Paul Gardner identified more than 5,000 seeds of domestic, semi-domestic, and wild chenopodium from the living floor of the rockshelter (Hensley 1995, 1996). Similar contractual archaeological studies continue today through the supervision of Bob Ward, cultural resource specialist at Mammoth Cave National Park and the assistance of Darlene Appelgate, archaeologist at Western Kentucky University (Appelgate, personal communication email to Carstens, July 1, 2000).

Analytically, the Explanatory/Interdisciplinary (post-1960) era of archaeological research has answered many questions about the Native Americans who explored and exploited the environment and resources above and below ground in the Central Kentucky Karst. Initial studies by Watson and her colleagues in the early 1960s through 1980s focused upon time-space and environmental reconstruction sequences, then turned to more processual issues while unraveling the prehistory of the Mammoth Cave area. That work inspired other archeologists in Tennessee and Indiana to test several of Watson's observations and conclusions about the prehistory of Mammoth Cave specifically, and prehistoric cultural processes in general, finding that prehistoric aboriginal mining and exploration was a wide-spread cultural phenomenon; it was not limited solely to Mammoth Cave National Park nor only to the Late Archaic-Early Woodland transition (e.g., Faulkner 1986). Furthermore, not only had Watson and her associates confirmed and expanded N.C. Nelson's initial observations about the importance of plant cultivation in the Mammoth Cave area, but also Watson's research teams went far beyond, examining human paleofeces for parasites and micro-organisms and determining whether prehistoric caving activities were carried out by both sexes, thereby helping to engender, and more accurately describe, Mammoth Cave prehistory.

RETROSPECT AND PROSPECT

The history of archaeology in the Mammoth Cave area closely parallels the growth and development of archaeological trends in North America. From the Speculative to the Classificatory to the Explanatory and Interdisciplinary periods, archaeological inquiry in the Central Kentucky Karst has demonstrated that the uncommon preservation characteristics of the cave environment provides unique insight into human behavior (prehistoric and historic) that may be more accessible than from open "surface" sites. Table 1 also reflects that, along with an increase in the intensity of cave archaeological investigation, a greater sophistication began once interdisciplinary research was initiated at the Park (post-1960). That work was initiated

by Patty Jo Watson and her associates and colleagues.

Early turn-of-the century interests in cave archaeology, primarily atheoretical, prompted work at surface sites in the Mammoth Cave area and led to speculation about the origins of prehistoric cultural materials, sometimes comparing them to the better-understood European record (e.g., Nelson 1917; Young 1910). Assessing significance of and attempting to order archaeological sites from within the Park area, both above ground and below, and assessing Mammoth Cave collections held outside the Park, were the foci of the Classificatory Period between 1916 and 1970, culminating in the summaries of Douglas W. Schwartz (1958a-h, 1960a,b, 1965). More recent work by Watson and her colleagues brought a theoretical and interdisciplinary framework to the

Speculative

Rafinesque (1824), Young (1910)
pre-1915

Classificatory

Carey (1942), Hanson (1960), Fowkes 1916-1970 (1922), Funkhouser and Webb (1932), Meloy (1968), Moore (1916), Nelson (1917), Neumann (1938), Pond (1935, 1938), Schwartz (1958a-h; 1960a,b, 1965, 1967), Schwartz and Hanson (1961), Schwartz and Sloan (1958, 1960a,b), Schwartz and Sloan and Hanson (1960)

Explanatory

*Beditz (1979, 1981), Carstens (1974, 1975, 1976, 1977, 1978, 1980), Carstens and 1971-Present**

Interdisciplinary

Watson (1996), Crothers (1981, 1983), Crothers and Ward (1995), DiBlasi (1987a,b, 1996), Duffield (1974), Hensley (1995, 1996), Kennedy (1990, 1993, 1996), Marquardt (1974), Molnar and Ward (1974), Munson et al. (1989), Prentice (1993, 1994, 1996), Robbins (1971, 1974, 1980), Robbins et al. (1981), Ruppert (1994), Schoenwetter (1974), K. Tankersley et al. (1994), K. Tankersley et al. (1990), K. Tankersley et al. (1985), S. Tankersley (1993), Wagner (1976), Watson (1969, 1974, 1986, 1992), Watson and Carstens (1975, 1982), Watson and Kennedy (1993)

Table 1: Archaeological research in the area of Mammoth Cave National Park, 1824-Present (*not an exhaustive list).

archaeology of the Park often reflecting various themes prominent in the "New Archaeology." Within the last decade cave art studies (DiBlasi 1996) have added a cognitive, or post-processualist research slant to the efforts begun by Watson's group. However, additional research is still needed in the Mammoth Cave area, above ground and below. Only the tip of

the proverbial iceberg at Mammoth Cave has been studied, whereas artifacts from surface sites and from within the caves continue to be damaged or stolen in spite of the security efforts of the National Park Service. New insights and new energies are needed in the 1990s to carry on the fascinating study of the aboriginal and Euro-American people who explored and exploited the Kentucky underworld.

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References

- Appelgate, Darlene
2000 Fax to Kenneth C. Carstens, July 1, 2000.
- Barnes, Shelley
1974 Analysis of Three Bt-5 Burials. Unpublished Manuscript. Department of Anthropology, Washington University, St. Louis.
- Beditz, Lindsay C.
1979 Archaeological Reconnaissance and Testing of Alternative JCCCC Sites in Mammoth Cave National Park. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.
- 1981 Mammoth Cave National Park, Kentucky: Bluffline Survey of the Childress Farm/Great Onyx Job Corps Civilian Conservation Center Property. Manuscript on file, National Park Service Southeast Archaeological Center, Tallahassee.
- Brown, Jeffrey
1977 The Elmore Surface Collection Site: A Paleo-Archaic Lithic Assemblage. Senior Honors Thesis, Department of Anthropology, Washington University, St. Louis.
- Carey, Henry A.
1942 Report on John M. Nelson Collection. U.S. Department of the Interior, National Park Service, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
- Carstens, Kenneth C.
1974 Archaeological Surface Reconnaissance of Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis.
- 1975 Surface Archaeology in Mammoth Cave National Park, Kentucky. Paper Presented to the 40th Annual Meeting of the Society for American Archaeology, Dallas.
- 1976 Recent Investigations in the Central Kentucky Karst: A Preliminary Temporal Ordering of Several Surface Sites in the Mammoth Cave Area, Kentucky. Paper Presented to the 55th Annual Meeting of the Central States Anthropological Society, St. Louis.
- 1977 Three Springs Pumphouse: An Assessment of Damage. Manuscript on file, Mammoth Cave National Park, Kentucky.
- 1978 Mammoth Cave National Park: Archaeological Survey of Proposed Water Lines and Sewers. Manuscript on file, Southeast Archaeological Center, Tallahassee.

1980 Archaeological Investigations in the Central Kentucky Karst. Doctoral Dissertation, Department of Anthropology, Washington University, St. Louis.

Carstens, Kenneth C., and Patty Jo Watson (editors)

1996 Of Caves and Shell Mounds. University of Alabama Press, Tuscaloosa.

Cleland, Charles E.

1976 The Focal-Diffuse Model: An Evolutionary Perspective on the Prehistoric Cultural Adaptations of the Eastern United States. Midcontinental Journal of Archaeology, Vol. 1, No. 1.

Crothers, George M.

1981 Archaeological Investigations in Sand Cave, Kentucky. Eighth International Congress of Speleology, Proceedings, Vol. 1, Pp. 374-376.

1983 Archaeological Investigations in Sand Cave, Kentucky. National Speleological Society Bulletin, Vol. 45, Pp. 19-33.

1986 Final Report on the Survey and Assessment of the Prehistoric and Historic Archaeological Remains in Big Bone Cave, Van Buren County, Tennessee. University of Tennessee, Knoxville.

Crothers, George, and Robert Ward

1995 The NPS/Earthwatch Cultural Resource Survey: Discerning Patterns of Prehistoric Activity in Main Cave Despite 200 Years of Historic Use. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave.

DiBlasi, Philip J.

1987a Archaeological Monitoring of the Water Pipeline as the Floyd Collins Complex. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.

1987b Drawings Found in Salts Cave. CRF Newsletter, Vol. 15, No. 4, Pp. 1-2.

1996 Prehistoric Expressions from the Central Kentucky Karst. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, University of Alabama Press, Tuscaloosa.

Duffield, Lathel

1966 The Robert Dugeon Site. National Park Service, Richmond, Virginia.

1974 Nonhuman Vertebrate Remains from Salts Cave Vestibule. Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp., 123-133, Academic Press.

Faulkner, Charles H. (editor)

1986 The Prehistoric Native American Art of Mud Glyph Cave. University of Tennessee Press, Knoxville.

Fowke, Gerald

1922 Archaeological Investigations. Part I. Cave Explorations in the Ozark Region of Central Missouri. Part II. Cave Explorations in Other States. Bureau of American Ethnology, Bulletin 76. Washington, D.C.

Funkhouser, William D., and William S. Webb

1928 Ancient Life in Kentucky. Kentucky Geological Survey, Geologic Reports, Series 6, Vol. 34.

1929 The So-Called "Ash Caves" in Lee County, Kentucky. University of Kentucky Reports in Anthropology and Archaeology, Vol. 1, No. 2.

1930 Rock Shelters in Wolfe and Powell Counties, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 1, No. 4, Lexington.

1932 Archaeological Survey in Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 2, Lexington.

1936 Rock Shelters in Menifee County, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 3, No. 4, Lexington.

Gilmore, M.R.

1931 Vegetal Remains of the Ozark Bluff-shelter Culture. Michigan Academy of Science, Arts and Letters, Vol. 14, Ann Arbor.

Griffin, James B., editor

1952 Archaeology of Eastern United States. University of Chicago Press, Chicago.

Hagg, William

1939 Mulberry Creek Cord-Marked. Southeastern Archaeological Conference Newsletter, Vol. 1, No. 1, Lexington.

Hanson, Lee

1960 The Analysis, Distribution and Seriation of Pottery from the Green River Drainage as a Basis for an Archaeological Sequence of that Area. Unpublished Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Hensley, Christine

1995 Archaeological Investigations at the Stairway Rockshelter. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave, Kentucky.

1996 The Stairway Shelter (15Ed303), Mammoth Cave National Park. Paper presented at the 13th Annual Kentucky Heritage Council Archaeological Conference, March 1996, Louisville, Kentucky.

Jones, Volney

1936 The Vegetal Remains of Newt Kash Hollow Shelter. In *Rockshelters in Menifee County, Kentucky* by William S. Webb and W.D. Funkhouser. University of Kentucky Reports in Archaeology and Anthropology, Vol. 3, No. 4, Lexington.

Kennedy, Mary C.

1990 An Analysis of the Radiocarbon Dates from Salts and Mammoth Caves, Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis, Missouri.

1993 NPS and Earthwatch Cultural Resource Inventory of Mammoth Cave. In Cave Research Foundation Newsletter, Vol. 21, No. 4, Pg. 15.

1996 Radiocarbon Dates from Salts and Mammoth Caves. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 48-81, University of Alabama Press, Tuscaloosa.

Lewis, R. Barry

1996 The Archaeology of Kentucky. University of Kentucky Press, Lexington, in press.

Marquardt, William

1972a Recent Investigations in a Western Kentucky Shell Mound. A Research Report Read May 4, 1972 at the Annual Meeting, Society for American Archaeology, Miami Beach, Florida.

1972b Research Report on Excavations at the Carlston Annis Mound. Southeastern Archaeological Conference Newsletter, Vol. 16, No. 2.

1974 A Statistical Analysis of Constituents in Human Paleofecal Specimens from Mammoth Cave. In Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 193-209. Academic Press, New York.

Marquardt, William and Patty Jo Watson

1974 The Green River, Kentucky, Shellmound Archaeological Project. Paper Presented to the 73rd Annual Meeting of the American Anthropological Association, Mexico City.

1976 Excavation and Recovery of Biological Remains from Two Archaic Shell Middens in Western Kentucky. Paper Presented in the Symposium, "The Research Potential of Shell Middens: Methodological and Analytical Considerations," organized by Thomas Ryan. Southeastern Archaeological Conference, Tuscaloosa, Alabama. Copy of manuscript in possession of author.

- 1983 The Shell Mound Archaic of Western Kentucky. In Archaic Hunters and Gatherers in the American Midwest, edited by James L. Phillips and James A. Brown, pp. 323-39, Academic Press, New York.
- Marquardt, William, Patty Jo Watson, Mary Kennedy (editors)
1996 Archaeology of the Middle Green River, Kentucky, Kent State University Press.
- Meloy, Harold
1968 Mummies of Mammoth Cave. Shelbyville, Indiana: Micron.
- Molnar, Stephen, and Stephen Ward
1974 Dental Remains from Salts Cave Vestibule. In The Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 163-166, Academic Press.
- Moore, Clarence B.
1916 Some Aboriginal Sites on Green River, Kentucky: Certain Aboriginal Sites on Lower Ohio River. Academy of Natural Sciences of Philadelphia, Journal, 2nd Series, Vol. 16, No. 3. Philadelphia.
- Morse, Dan
1967 The Robinson Site and Shell Mound Archaic Culture in the Middle South. Doctoral Dissertation, Department of Anthropology, University of Michigan, Ann Arbor.
- Munson, Patrick J., and Cheryl Ann Munson
1990 The Prehistoric and Early Historic Archaeology of Wyandotte Cave and Other Caves in Southern Indiana. Indiana Historical Society, Prehistoric Research Series, Indianapolis.
- Munson, Patrick J., Kenneth B. Tankersley, Cheryl Ann Munson, and Patty Jo Watson
1989 Prehistoric Selenite and Satinspar Mining in the Mammoth Cave System, Kentucky. In Midcontinental Journal of Archaeology, 14(2):119-145.
- Nelson, Nels C.
1917 Contributions to the Archaeology of Mammoth Cave and Vicinity, Kentucky. Anthropological Papers, American Museum of Natural History, Vol. 22, Part I. New York.
- 1923 Kentucky: Mammoth Cave and Vicinity. Unpublished manuscript on file at the American Museum of Natural History, New York.
- Neumann, Georg K.
1938 The Human Remains from Mammoth Cave. American Antiquity, Vol. 3.
- Pollack, David (editor)
1990 The Archaeology of Kentucky: Past Accomplishments and Future Directions, Vol. 1. Kentucky Heritage Council State Historic Preservation Comprehensive Plan Report No. 1, Frankfort.

-
- Pond, Alonzo
1935 Report of Preliminary Survey of Important Archaeological Discovery at Mammoth Cave, Kentucky. Wisconsin Archeologist, Vol. 15.
- 1937 Lost John of Mummy Ledge. Natural History, Vol. 39.
- Prentice, Guy
1993 Mammoth Cave National Park: Overview and Assessment, Vols. I and II. Southeast Archaeological Center, National Park Service Tallahassee, Florida.
- 1994 A Settlement Pattern Analysis of Prehistoric Sites in Mammoth Cave National Park, Kentucky. Doctoral Dissertation, Department of Anthropology, University of Florida, Gainesville.
- 1996 Site Distribution Modeling for Mammoth Cave. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 12-32, University of Alabama Press, Tuscaloosa.
- Rafinesque, Samuel Constantine
1824 Ancient History, or Annals of Kentucky: Introduction to the History and Antiquities of the State of Kentucky. Frankfort.
- Ritchie, William
1933 The Lamoka Lake Site. Researches and Transactions of the New York State Archaeological Association, Lewis H. Morgan Chapter, Vol. 7, No. 4.
- Robbins, Louise
1971 A Woodland "Mummy" from Salts Cave, Kentucky. American Antiquity, Vol. 36:200-206.
- 1974 Prehistoric People of the Mammoth Cave Area. Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp. 137-162, Academic Press, New York.
- 1980 Appendix V: Report on Blue Spring Hollow Burial. In: Archaeological Investigations in the Central Kentucky Karst by Kenneth C. Carstens, Doctoral Dissertation, Department of Anthropology, Washington University, St. Louis.
- Robbins, Louise M., Ronald C. Wilson, and Patty Jo Watson
1981 Paleontology and Archaeology of Jaguar Cave, Tennessee. In, Proceedings of the VIIIth International Congress of Speleology, Volume I, B. Beck editor, pp. 377-380.
- Rolinson, Martha
1967 Temporal Perspective on the Archaic Cultures of the Middle Green River Region, Kentucky. Doctoral Dissertation, Department of Anthropology, University of Michigan, Ann Arbor.

Ruppert, Lisa Karen

1994 Evidence for the Endoparasite *Giardia lamblia* in Human Paleofeces from Salts Cave, Mammoth Cave National Park, Kentucky. MA thesis, Department of Anthropology, Western Michigan University, Kalamazoo.

Schoenwetter, James

1974 Pollen Analysis of Human Paleofeces from Upper Salts Cave. In Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp. 97-105, Academic Press, New York.

Schwartz, Douglas

1958a Sandals and Textiles from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958b Archaeological Report on Materials in the John M. Nelson Collection from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958c An Archaeological Report on Physical Remains from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958d Summary and Evaluation of the 1916 American Museum Archaeological Work in Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958e Description and Analysis of Museum Materials from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958f Archaeological Survey of Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958g Report on Two Radiocarbon Dates from Mammoth Cave, Kentucky. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1958h The Archaeology of Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

1960a Prehistoric Man in Mammoth Cave. Scientific American, Vol. 203.

1960b Archaeological Survey of the Nolin River Reservoir. Manuscript, Museum of Anthropology, University of Kentucky, Lexington.

1965 Prehistoric Man in Mammoth Cave. Eastern National Park and Monument Association. Interpretive Series, No. 2.

1967 Conceptions of Kentucky Prehistory: A Case Study in the History of Archaeology. Studies in Anthropology, No. 6, University of Kentucky Press, Lexington.

Schwartz, Douglas and Lee Hanson

1961 Archaeological Excavation in the Nolin Basin - 1961. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Schwartz, Douglas, and Tacoma Sloan

1958 Excavation of the Rough River Site, Grayson County 12, Kentucky. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

1960a Archaeological Survey of the Barren Reservoir. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

1960b Archaeological Survey of Twenty-Two Small Federal Projects in Kentucky. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Schwartz, Douglas W., Tacoma Sloan, and Lee Hanson

1960 Test Excavations in the Nolin Basin - 1960. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Sides, Stan

1971 Early Cave Exploration in Flint Ridge, Kentucky: Colossal Cave and the Colossal Cavern Company. Journal of Spelean History, Vol. 4, No. 4.

Stout, Charles, and R. Barry Lewis

1995 Constantine Rafinesque and the Canton Site, a Mississippian town in Trigg County, Kentucky. Southeastern Archaeology, 14(1):83-90.

Tankersley, Kenneth

1996 Prehistoric Mining in Mammoth Cave. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 33-39, University of Alabama Press, Tuscaloosa.

Tankersley, Kenneth B., John Bassett and Samuel Frushour

1985 A Gourd Bowl from Salts Cave Kentucky. Tennessee Anthropologist 10:95-104.

Tankersley, Kenneth B., S.S. Frushour, F. Nagy, S.L. Tankersley

1994 The Archaeology of Mummy Valley, Salts Cave, Mammoth Cave National Park, Kentucky. North American Archaeologist, Vol. 15, Number 2, Pp. 129-145.

Tankersley, Stephen L.

1993 Detection and Recovery of Anthropogenic Introduced Pathogenic Microorganisms in Mammoth Cave, Mammoth Cave National Park, Kentucky. Unpublished MA thesis, Department of Anatomy, Wright State University, Dayton.

Wagner, Gail E.

1976 An Archeobotanical Analysis of Five Sites in the Mammoth Cave Area. Master's Thesis, Department of Anthropology, Washington University, St. Louis.

Watson, Patty Jo

1986 Prehistoric Cavers of the Eastern Woodlands. In: The Prehistoric Native American Art of Mud Glyph Cave, edited by Charles H. Faulkner, University of Tennessee Press, Knoxville.

1992 Cave Research Archaeological Project. Cave Research Foundation Annual Report, Pp. 46-47, Memphis.

Watson, Patty Jo (editor)

1974 Archaeology of the Mammoth Cave Area. Studies in Archaeology, Academic Press, New York.

Watson, Patty Jo, Richard A. Yarnell, Harold Meloy, William S. Benninghoff, Eric O. Callen, Adian Cockburn, Hugh Cutler, Paul W. Parmalee, Lionel Prescott, William B. White

1969 The Prehistory of Salts Cave, Kentucky. Illinois State Museum, Reports of Investigations, No. 16, Springfield.

Watson, Patty Jo, and Kenneth C. Carstens

1975 Archaeological Resources of Mammoth Cave National Park: A Brief Summary. Report Prepared for the National Park Service, July, Tallahassee.

1982 Archaeological Survey and Testing, Mammoth Cave National Park. An archaeological contract (#CX5000080976) between the Cave Research Foundation and the National Park Service. Southeast Archaeological Center, National Park Service, Tallahassee.

Watson, Patty Jo and Mary C. Kennedy

1993 Cave Research Foundation Archaeological Project, 1993. Cave Research Foundation Annual Report, Pp. 49-50, Memphis.

Webb, William S.

1946 Indian Knoll, Site Oh2, Ohio County, Kentucky. The University of Kentucky Reports in Anthropology and Archaeology, Vol. 4, No. 3., Lexington.

1950a The Carls[t]on Annis Mound, Site 5, Butler County, Kentucky. University of Kentucky Reports in Anthropology, Vol. 7, No. 4. Lexington.

1950b The Read Shell Midden, Site 10, Butler County, Kentucky. University of Kentucky Reports in Anthropology, Vol. 7, No. 5, Lexington.

William S., and David L. DeJarnette

1942 An Archaeological Survey of Pickwick Basin. Bulletin 129, Bureau of American Ethnology, Washington, D.C.

Webb, William, and William D. Funkhouser

1936 Rock Shelters in Menifee County. *Reports in Anthropology and Archaeology*, Vol. 3, No. 4, Pp. 105-167.

Webb, William, and William Haag

1939 The Chiggerville Site, Site 1, Ohio County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 4, No. 1, Lexington.

1940 Cypress Creek Village, Sites 11 and 12, McClean County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 4, No. 2, Lexington.

1947 Archaic Sites in McLean County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 7, No. 1, Lexington.

Webb, William, and Charles G. Wilder

1951 *An Archaeological Survey of Guntersville Basin on the Tennessee River in Northern Alabama*. University of Kentucky Press, Lexington.

Wiley, Gordon R., and Jeremy A. Sabloff

1993 *A History of American Archaeology*, 3rd Edition, W. H. Freeman & Company, San Francisco.

Winters, Howard

1968 Value Systems and Trade Cycles of the Late Archaic in the Midwest. In *New Perspective in Archaeology*, edited by S.R. Binford and L.R. Binford, pp. 175-221, Aldine Publishing Company.

1969 *The Riverton Culture: A Second Millenium Occupation in the Central Wabash Valley*. Published Jointly by the Illinois State Museum, *Reports of Investigations*, No. 13, and the

1974 Introduction. In: *Indian Knoll* (William S. Webb, 1946) Reprinted by the University of Tennessee Press, Knoxville.
Illinois Archaeological Survey.

Young, Col. Bennett

1910 *The Prehistoric Men of Kentucky*. Filson Club Publications, No. 25. Louisville: John P. Morton.

¹Initially called Little Alice, forensic examinations by Louis Robbins (Watson, ed., 1974) clearly demonstrated that the gender of Little "Al(ice)" was male, hence the corrected named, "Little Al."

The NPS/Earthwatch Archeological Project in Mammoth Cave

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ABSTRACT

We are in the eighth year of an ongoing systematic archaeological survey of the upper trunk passage in Mammoth Cave. The survey area is three-quarters complete, and greater than 9000 historic and prehistoric items have been located and recorded. Progress of this long-term project is updated and some preliminary results discussed. For example, it is now clear from the distribution of prehistoric remains that the location of mineral salts (predominately mirabilite) was an important focal point of prehistoric activity in the cave. The distribution of mid-nineteenth century historic artifacts and wood construction debris can be used to identify the locations of several of the TB patients' residential huts built in 1841-42 for Dr. Croghan's medical experiment. The survey should be completed in 2001 or 2002 including those portions of the cave most heavily impacted by saltpetre mining. Future survey teams should help delineate features of the saltpetre operation that have been dismantled or obscured by later modifications to the cave.

Rethinking the Prehistoric Archeology of Salts Cave and Mammoth Cave

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EXTENDED ABSTRACT

The CRF Archeological Project was initiated to investigate prehistoric cultural remains in Salts Cave, Mammoth Cave, and nearby caves and rockshelters. The research was developed during the heyday of the New Archaeology (1960s-1970s) when ecological, environmental, economic foci were dominant. As Director of this CRF Project, my own interest in agricultural origins combined with that disciplinary-wide emphasis meant a heavy stress on the economic aspects of cave mineral mining and even more on the importance of plant and animal remains (subsistence and paleoenvironment). The plant remains from Salts Cave and Mammoth Cave were especially interesting with regard to the burgeoning concern about agricultural origins in Eastern North America during the 1970s and 1980s. Flotation-recovery of charred botanical material together with the well-preserved remains in thousands of human paleofecal deposits established that the caves of the Mammoth Cave System contained the most detailed and best preserved evidence yet known anywhere for an early agricultural complex (Kennedy and Watson 1998; Watson ed. 1969, 1974, 1997). We are still following that research trajectory with a recently proposed attempt (by Kristin Sobolik, University of Maine) to isolate DNA from some of the paleofecal material.

A very different theme has recently been introduced into all this, however. Over the past several years I have been convinced by slowly accumulating evidence and by persistent colleagues (George Crothers and Phil DiBlasi are chief among them) that there was much more to ancient activities in parts of the world's longest cave than I had previously conceived of. We now know about Archaic period (3000 years old or more) pictographs and petroglyphs in Salts and Fisher Ridge Caves, mud glyphs in Adair Cave, and petroglyphs in 3rd Unnamed Cave (Crothers in press; Crothers et al. in press; DiBlasi 1996; Simek et al. 1998). We do not know with any certainty what these graphic renderings on cave walls, floors, and ceilings meant to the people who created them, but there is a very large literature on what is broadly termed "rock art", some of which may be partially relevant to thinking about these cave graphics in the Midsouth and Southeast.

In MesoAmerica and North America, there is widespread belief in a layered universe. Caves are thought to be entry and exit points between the surface layer where humans and other animals live, and the layers below that surface world. Whoever enters the lower levels must be prepared to encounter not only total darkness, total lack of food (at least of food that humans ordinarily eat), and quite possibly lack of water as well. A person entering these lower levels would have had (as documented ethnographically and inferred for prehistoric people) vivid and detailed expectations about who or what was down there. In much of

ethnographically known North America, for example, one of the main inhabitants of the subterranean dark zone was the earth-serpent/water panther Longtail monster, known as Uktena in the Southeast and Meshipishew in the Northeast. This fearsome creature ordinarily attacked humans who disturbed it, but those who succeeded in eluding the Uktena, or in negotiating with it, might be able to return to the surface world with a scale dislodged from the Uktena's hide, or with some moist clay rubbed off its body. Such a person was then equipped to be a seer, healer, wisdom keeper, or shaman in league – however tenuously – with the Uktena.

A frequent motif in the prehistoric cave graphics referred to above is a lattice-work or checkerboard design. In the Great Lakes region, this kind of sign apparently “represented both a spiritual bridge between cosmic layers and a level or degree of sacred society membership. ...Mishi Bizi and his cohort were particularly accessible at places where two material realms or levels of reality met, for example where rock faces met water. The pictures of Mishi Bizi were found at cliffs, or in caves, and the manitou was logically associated with blindness..” (Martin 1999: 206).

What if anything does the above discussion have to do with the fact that approximately 30% of the human bone fragments in Salts Cave Vestibule are burned, cut, or otherwise modified (Robbins 1974)? Is this pattern the result of charnel house ceremonies performed on the mortal remains of loved ones? Does it reflect ritual or other cannibalism? (Turner and Turner 1999; White 1992). Are these the remains resulting from mutilation and dismemberment of enemies? To begin answering such questions with some degree of confidence, experts must reanalyze the unusual bone assemblage from the prehistoric cultural deposits in Salts Cave with modern techniques including Scanning Electron Microscopy.

Pending that and other future work, I conclude with two final comments:

- (1) An individual scientist's theoretical orientation, early training, and past experience markedly affect that individual's research designs as well as their implementation. NEVERTHELESS, science works: what philosopher of science Thomas Kuhn called the essential tension between expectations and observations, as well as the lively exchange of data and opinions within a healthy scientific community ensure that, sooner or later, the truth will out. That is, competition among advocates of alternative hypotheses will provide a diverse array of data illuminating the subject matter far more comprehensively than does monolithic, narrowly channelled research of one person or of a single very focused research group.
- (2) After many decades of cave archaeology in parts of the Mammoth Cave System, we have learned a great deal, which is important and gratifying to those of us who work there, but equally significant is the fact that this cave system keeps delivering surprises to those who remain alert to the subtle complexities of that marvelous subterranean universe. The latest of those surprises is that clues to the cognitive worlds of ancient people who entered it seem to be subtly but undeniably preserved in the rooms and passageways of the world's longest cave.

NOTE: Carol Diaz-Granados and Jerome Jacobson kindly provided information on the water panther/Uktena monster (also see Hudson 1976), but are by no means responsible for anything I say about it here.

References Cited

- Crothers, George M.
In Press. Early Woodland Mineral Mining and Perishable Remains in Mammoth Cave, Kentucky. In P. Drooker, ed. Fleeting Identities: Perishable Material in Archaeological Research. Southern Illinois University Center for Archaeological Investigations, Occasional Papers.
- Crothers, George M., Charles H. Faulkner, Jan F. Simek, Patty Jo Watson, and P. Willey
In Press. Woodland Cave Archaeology in Eastern North America, In D. Anderson and R. Mainfort, eds. The Woodland Southeast. Tuscaloosa: University of Alabama Press.
- DiBlasi, Philip J.
1996 Prehistoric Expressions from the Central Kentucky Karst. In K. Carstens and P. Watson, eds. Of Caves and Shell Mounds, pp. 40-47. Tuscaloosa, AL: University of Alabama Press.
- Hudson, Charles
1976 The Southeastern Indians. Knoxville, TN: The University of Tennessee Press.
- Kennedy, M. C., and P.J. Watson
1997 The Chronology of Early Agriculture and Intensive Mineral Mining in the Salts Cave and Mammoth Cave Region, Mammoth Cave National Park, Kentucky. Journal of Cave and Karst Studies, National Speleological Society Bulletin 59, 1: 5-9.
- Martin, Susan R.
1999 Wonderful Power: the Story of Ancient Copper Working in the Lake Superior Basin. Detroit, MI: Wayne State University Press.
- Robbins, Louise M.
1974 Prehistoric People of the Mammoth Cave Area. In P.J. Watson, ed. Archeology of the Mammoth Cave Area, pp. 137-162. New York: Academic Press.
- Simek, Jan F., Jay D. Franklin, and Sarah C. Sherwood
1998 The Context of Early Southeastern Prehistoric Cave Art: a Report on the Archaeology of 3rd Unnamed Cave. American Antiquity 63: 663-677.
- Turner, Christy G., and Jacqueline A. Turner
1999 Man Corn: Cannibalism and Violence in the Prehistoric American Southwest. Salt Lake City, UT: The University of Utah Press.
- Watson, P.J., editor
1969 The Prehistory of Salts Cave, Kentucky. Illinois State Museum, Reports of Investigations No. 16. Springfield, IL: Illinois State Museum.
1974 Archeology of the Mammoth Cave Area. New York: Academic Press.
1997 Archeology of the Mammoth Cave Area, reprint of the 1974 edition with a new Foreword. St. Louis, MO: Cave Books.
- White, Tim D.
1992 Prehistoric Cannibalism at Mancos 5MTUMR-2346. Princeton, NJ: Princeton University Press.

Regional Atmospheric Carbon Sink Within the South Central Kentucky Karst

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ABSTRACT

Of the $7.8 \times 10^3 \pm 1.9 \times 10^3 \text{ kg ha}^{-1}$ of total inorganic carbon (TIC) leaving the 25 km² Cave City basin of the south central Kentucky karst aquifer over one year (May 1995-96), 1% entered the aquifer as recharge, 57% was derived from carbonate mineral dissolution, and 42% was produced by biological activities. The inorganic component of the atmospheric "young" CO₂ sink was $3.4 \times 10^3 \pm 8.5 \times 10^2 \text{ kg ha}^{-1} \text{ yr}^{-1}$.

Published estimates of regional and global carbonate mineral weathering sink terms typically assume that each mole of "old" mineral carbon reacts with a mole of young carbon as H₂CO₃. Examination of the elementary reactions of the CaCO₃-H₂O-CO₂ system, however, suggests that under geologically reasonable conditions reaction with H₂O and H⁺ can lower the young/old carbon ratio.*

INTRODUCTION

Limestone karst aquifer/landscape systems cover some 12% of the earth's land surface (Ford and Williams, 1989). In addition to the complex biogeochemical interactions that impact carbon transport and cycling in other geological terranes, in these areas carbon dynamics are further complicated by fluid/carbonate rock interactions (White, 1988; Ford and Williams, 1989). Numerous processes impact the evolution and transport of CO₂ within these environments. In addition to the typically low, ubiquitous atmospheric background levels, sources of carbon dioxide within carbonate karst systems include microbial respiration, oxidation of organic material, plant root respiration in the soil as well as carbonate mineral precipitation. Dissolution of limestone by H₂SO₄ can also liberate CO₂ (White, 1988). Atkinson (1977) and Wood and Petraitis (1984) found evidence of CO₂ production within the vadose zones of both carbonate and noncarbonate aquifers, presumably by oxidation of organic material washed down from the soil zone. The primary sinks include diffusive loss to the atmosphere, uptake by infiltrating recharge waters, and dissolution of carbonate minerals in CO₂-H₂O solutions.

Understanding and quantifying CO₂ landscape/atmosphere interactions is increasingly relevant with the recognition that rising atmospheric CO₂ levels have the potential to impact rates of global climate change (Keeling *et al.*, 1982 and 1995; Baes *et al.*, 1977; Houghton and Woodell, 1989; IPCC, 1990, 1992, 1994, and 1995). Weathering of carbonate rock has been recognized as a sink term for atmospheric CO₂ at the continent scale (Bernier *et al.*, 1983; Meybeck, 1987; Probst *et al.*, 1994; Amiotte Suchet and Probst, 1993, 1995; Liu *et al.*, 1998).

The broad, global estimates of large-scale carbon pool size and structure, however, are still subject to considerable uncertainty. The global "missing carbon sink", estimated at 1.2 to $1.8 \times 10^{15} \pm 1.5 \times 10^{15}$ g C yr⁻¹ (Siegenthaler and Oeschger, 1978; Broecker, *et al.*, 1979; IPCC, 1994; Joos, 1994; Hesshaimer, *et al.*, 1994), and which has remained unsolved through more than a decade of intense scrutiny, highlights this problem. The answer lies in a clearer quantitative description of cycle dynamics. Along with broad-scale "box" cycle models, detailed process/rate studies are required to develop sufficiently precise quantitative evaluation of reservoir dynamics, and to understand how pools with different sizes, residence times, and exchange rates interact.

This paper reports on results of a one year (May 17, 1995 to May 16, 1996) calibrated hydrochemical modeling program designed to study detailed inorganic carbon dynamics within the 25 km² Cave City Groundwater Basin of the humid-subtropical south central Kentucky karst aquifer. Like in other well-developed karst flow systems, fluid flow and chemical changes within the Cave City Basin can be extremely rapid, and the new, high temporal resolution methods presented here use two minute-resolution to encompass all significant features of storm-scale and seasonal variations. In this paper we report estimates of the magnitudes of mineral, atmospheric, and biological sources of the total inorganic carbon (TIC) flux from the catchment and an estimate of the inorganic component of the regional atmospheric CO₂ sink term resulting from carbonate mineral weathering. This represents a step toward quantitative evaluation of the atmosphere/landscape interaction for well-developed karst landscapes in humid-subtropical climates, which cover large areas of the southeastern U.S. as well as extensive regions of southern Asia (Köppen and Geiger, 1936).

Although not considered in this paper, field observations suggest that the transport of both dissolved and particulate organic carbon, in forms ranging from simple acids and sugars to complex humic substances (Moore, 1997; Anthony, 1988; Vaughan, 1998), also participate in aquifer carbon budgeting. Further study of organic carbon and microbial ecology within the Cave City Basin and the nearby Echo River Basin are underway (Vaughan, 1998; Elliott *et al.* 2000).

AQUIFER INORGANIC CARBON BALANCE

In our analysis we assume that there are three classes of sources for total inorganic carbon, TIC (MT⁻¹), leaving a limestone or dolomite karst groundwater basin:

- a. dissolved inorganic carbon in precipitation, in equilibrium with the atmospheric background CO_2 pressure, entering the aquifer as recharge, C_a (MT^{-1}),
- b. biological processes that produce gaseous CO_2 in the soil, vadose, and saturated zones, including microbial respiration, oxidation of organic material, and plant root respiration, C_b (MT^{-1}), and
- c. carbonate mineral dissolution, C_m (MT^{-1}).

Thus over a specified time interval t (T),

$$\int_0^t \text{TIC} dt = \int_0^t C_a dt + \int_0^t C_b dt + \int_0^t C_m dt. \quad (1)$$

Since C_a and C_b originate in the atmosphere as CO_2 gas, and leave the karst system as dissolved inorganic carbon species, we define the inorganic component of the CO_2 sink, x ($\text{MT}^{-1} \text{L}^{-2}$) due to flow and biogeochemical processes within the karst landscape/aquifer system:

$$\xi = (\int_0^t C_a dt + \int_0^t C_b dt) / tA \quad (2)$$

where t is the length of the sampling period (T), and A is drainage basin area (L^2).

C_a is estimated by calculating a carbon mass flux leaving the basin, using measured river discharge and assuming TIC in equilibrium with a constant representative atmospheric CO_2 pressure, nominally set at 360 parts per million over the study period, where

$$\text{TIC} = [\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{H}_2\text{CO}_3^*] \quad (3)$$

with activities denoted by square brackets and where $(\text{H}_2\text{CO}_3^*)$ is the sum of H_2CO_3^0 and aqueous CO_2 (Stumm and Morgan, 1981). In the current study, input data with two-minute resolution of chemical and flow conditions within the river are able to encompass all significant features of storm-scale and seasonal variations, so that close estimates of the appropriate integrals can be obtained.

To obtain both C_m and C_p , we make use of the fact that during dissolution of limestone or dolomite one mole of C is released from the mineral for each mole of $\text{Ca}^{2+} + \text{Mg}^{2+}$, regardless of the elementary reaction involved (Berner *et al.*, 1983; Plummer *et al.*, 1978; Busenberg and Plummer, 1982), so that

$$\int_0^t C_m dt = \int_0^t (Ca^{2+} + Mg^{2+}) dt, \quad (4)$$

and by substituting (4) into (1) and rearranging,

$$\int_0^t C_b dt = \int_0^t TIC dt - \left(\int_0^t (Ca^{2+} + Mg^{2+}) dt + \int_0^t C_a dt \right). \quad (5)$$

Finally, having determined C_a and C_b , we can obtain a value for the inorganic carbon sink term using (2).

FIELD SITE

The geology and hydrogeology of the south central Kentucky karst has been reviewed by numerous authors including Hess and White (1988, 1989) and Palmer (1991), and Quinlan and Ray, (1983). Logsdon River is one of the major underground streams of the south central Kentucky karst. Within the Proctor Cave section of the system, near the southwestern currently explored edge of Mammoth Cave, Logsdon River converges with Hawkins River, which drains about 75 km² near Park City, Kentucky. The Logsdon River drains the 25 km² Cave City groundwater basin. Within Logsdon River, about 100 m upstream from the confluence of the two rivers, are two 15-cm diameter, 145-m deep observation wells intersecting the river. One well is equipped with a compressor-driven pump for collecting water samples from the surface, and through the other electronic probes deliver high-resolution (two-minute) data on stage, velocity, temperature, and specific conductance. The bottoms of the wells can be reached underground (for pump and probe installation and maintenance) through the Doyel Valley Entrance to Mammoth Cave, requiring a 3-km round-trip through the cave. The conduit at the Logsdon River well site is about 3 m tall and 7 m wide, and lies near the downstream end of one of the world's longest known sections of accessible underground river passage, continuously traversable for over 8 km.

FIELD AND LABORATORY METHODS

The primary objective of the research has been to collect sufficient high-resolution data on both flow and chemical characteristics of the river to quantitatively evaluate the magnitudes and rates of change of carbonate chemistry and water/rock interactions at a variety of time scales. Four probes are installed through the wells into each stream, including temperature, specific conductance, river stage, and velocity. A Campbell 21X multichannel data logger queries the probes every thirty seconds, and averages these readings every two minutes. Data are recorded at varying intervals, from each two minutes during rapidly changing flow or chemical conditions in the rivers to hourly during static conditions. Using an accurately surveyed passage cross section at the well site, stage data were used to calculate flow cross-sectional and wetted perimeter for discharge calculations.

With data resolution varying from two minutes during storms to hourly during static conditions, these values were determined for 21,473 observations between May 5, 1995 to May 4, 1996. Equipment problems led to a loss of 19.9 days (5.4% of the period) of conductance data during the year. With the large number of conductance chemographs during storms available over the rest of our study period, however, we were able to closely estimate these missing periods using a procedure analogous to unit hydrograph analysis (Chow, 1964). In addition, electrical problems created offsets of the data (29.2 days, or 8.0%) that were corrected by calibration and translation.

We also used direct velocity measurements (with two minute resolution) to estimate discharge under open channel conditions, but these were limited by measurement at a single location in the center of the flow cross-section in each stream. To account for the vertical velocity distribution the velocity at 0.6 flow depth, which has been shown to be close to the mean velocity in the vertical profile, was related to the apparent velocity at the fixed-depth point of measurement assuming a logarithmic velocity distribution (Boyer, 1964). In order to correct for longitudinal velocity variations, discharge measurements were made on eight occasions using standard wading-rod gaging techniques and a 0.3 meter longitudinal spacing (Boyer, 1964), and the average ratio between mean and maximum velocity (assumed at the center of each channel, where the velocity sonde is located) was determined. The vertically corrected apparent velocity in each stream was then multiplied by this ratio (0.57). As this represents the highest relative uncertainty in the measurements, we report the actual mass flux values $\pm 25\%$.

Hourly water chemistry measurements have been made during storms of various magnitudes by sampling from the surface through the wells. Calcium has been measured with either titration or with a Varian Spectra 10/20 atomic absorption spectrophotometer (AA) at the Ogden Environmental Water Lab at Western Kentucky University, and magnesium has been measured exclusively with atomic absorption. Samples for calcium and magnesium AA analysis were filtered (0.45 μ m) and acidified. Conductivity and pH were measured immediately after sample collection. A gel filled combination electrode using two-point calibration was used to measure pH. Bicarbonate alkalinity was been measured by acid titration either immediately after collection, or in some cases samples were stored on ice, and the titrations were done at the Ogden Laboratory within 24 hours.

ANALYSIS

With this information we have used least-squares regression analysis (Draper and Smith, 1981) to relate high-resolution specific conductivity data from within the cave rivers to calcium, magnesium, and bicarbonate concentrations, as well as pH. These relationships, along with direct temperature measurement, then allow calculation of several important components of carbonate system behavior with high temporal resolution, including inorganic carbon (TIC) fluxes through the aquifer contributed from mineral, atmospheric, and biological sources.

Activities of Ca^{2+} , Mg^{2+} , and HCO_3^- are first obtained using the extended Debye-Hückel limiting law (Stumm and Morgan, 1981). Then activities of CO_3^{2-} and H_2CO_3^* are calculated, where

$$[\text{H}_2\text{CO}_3^*] = \frac{[\text{H}^+][\text{HCO}_3^-]}{K_1} \quad (8)$$

and

$$[\text{CO}_3^{2-}] = \frac{K_2[\text{HCO}_3^-]}{[\text{H}^+]} \quad (9)$$

These are then summed using (3) to obtain *TIC* for each observation. Along with calcium and magnesium activities, this is used to solve (4), (5), and (2) for C_m , C_b , and x , respectively. C_a is obtained from discharge and atmospheric CO_2 using appropriate equilibria. Our aqueous model assumes that the influence of ion pairing and complexation is negligible.

RESULTS

Flow and Chemistry Variations

Fifty-six storm events caused measurable changes in the flow or chemistry within the river during the study, with thirteen of the storms flooding the conduit to the ceiling. During the largest storm, on May 18, 1995, the water level reached a maximum height of 28.2 m, with a maximum rate of rise of 6.03 m/hr. The ceiling of the conduit under these conditions is about 25 m below the water table, and the conduit remained totally flooded for 114 hours. Based on observed flow characteristics, the year can be divided into a dry and wet season. After the May 1995 flood subsided, the conduit flooded only twice over the next 224 days, and one of those events was the remnants of a hurricane (Opal, study day 141, October 5), a relatively infrequent weather condition for Kentucky. In contrast, during the last 135 days of the study, beginning on Jan 2, 1996, floodwaters filled the conduit ten times, or an average of about once every two weeks.

The chemistry of the system also showed a seasonal signature, with the most highly concentrated fluids during the dry season, presumably reflecting a larger proportion of diffuse flow, in contrast to more diluted storm flow, with higher concentrations of dissolved limestone. A third-order regression curve of the 21,473 conductivity observations shows a sine-like form, apparently reflecting a higher frequency of storms during the winter which do not allow the river's waters to return to a "chemical baseflow" condition, in which river flow is completely maintained relatively concentrated diffuse flow waters. Conductivity, in contrast, continues to climb for several months between the infrequent rains of the dry summer period. This suggests that the full relaxation time for the waters to reach a "chemical baseflow" condition in the river is on the order of months, rather than days in the case of river stage.

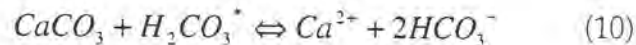
The minimum conductivities reached as a result of storms nearly all fell within a close range, suggesting a minimum bounding value of about 190 mS that, for sufficiently large rainfalls, is independent of season, rainfall amount, and antecedent moisture conditions. The one exception is the large May 1995 flood, where the conductivity reached a low of 167 mS.

Inorganic Carbon Flux

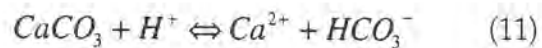
Of the $7.8 \times 10^3 \pm 1.9 \times 10^3$ kg ha⁻¹ of total inorganic carbon that left the Cave City basin during the year, 1% entered the aquifer as recharge, 57% was derived from carbonate mineral dissolution, and 42% was produced by biological activities. The inorganic component of the atmospheric "young" CO₂ sink was $3.4 \times 10^3 \pm 8.5 \times 10^2$ kg ha⁻¹ yr⁻¹, which includes that which came in as recharge plus the biologically produced inorganic carbon, which originally came from the atmosphere through plant and microbial processes.

DISCUSSION

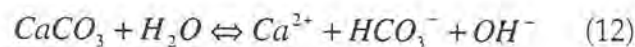
Regional and global carbon models that consider carbonate mineral weathering have generally assumed that for all of the riverine dissolved inorganic carbon leaving the continents, mostly as HCO₃⁻, the source has been one mole of mineral carbon reacting with one mole of atmospheric carbon as H₂CO₃^{*} (e.g. Berner *et al.*, 1983; Meybeck, 1987; Berner and Lasaga, 1989; Probst *et al.*, 1994; Amiotte Suchet and Probst, 1993, 1995; Liu *et al.*, 1998), through the reaction



Inspection of the elementary reactions of the CaCO₃-H₂O-CO₂ system, however (Plummer *et al.*, 1978, 1979), shows that in addition to the reaction of with H₂CO₃^{*}, calcite (and similarly, dolomite (Busenberg and Plummer, 1982)) simultaneously reacts with protons and water in the reactions



and



The roughly 57:43 ratio of "old" mineral C to "young" atmospheric C produced within the Cave City Basin can be explained by noting that to the extent that calcite dissolution occurs due to the elementary reactions (11) and (12), each mole of C produced comes from the "old" mineral source *without* an atmospheric contribution. This appears to be geologically reasonable, as the CO₂ pressures reported for a wide variety of geochemical environments within the south-central Kentucky karst [e.g. Miotke, 1974, 1975; Hess, 1974; Hess and White, 1988; Palmer,

1995, Anthony, 1998; Vaughan, 1998) range from atmospheric ($\sim 10^{-3.5}$ atm) to about $10^{-1.5}$ atm. Waters in equilibrium with the range of CO_2 pressures reported for the overall flow system may reach a pH of about 4.5 for the highest soil CO_2 levels, but within the aquifer, due to rapid buffering upon contact with calcite, they are generally above 6.5. Under these conditions the reaction with carbonic acid can be expected to dominate, with a smaller contribution from reaction (12), limited by the solubility of calcite in pure water, and perhaps reaction (11) where acidic soil solutions first meet the soil-bedrock interface.

Although the difference between the 50:50 ratio assumed in most carbonate mineral weathering sink term estimates and the 57:43 ratio shown by our data will not lead to a dramatic correction of this term with global carbon cycle estimates, it does point out the need for detailed process studies such as this to compliment the large scale global estimates. More importantly, these results show that the details of atmospheric CO_2 /carbonate mineral interactions have some dependence on the kinetics of the dissolution and precipitation reactions. Thus the overall balance between the continental CO_2 sink (from weathering of carbonate minerals) and the oceanic CO_2 source (from an equal amount of precipitation) assumed to exist (Berner and Lasaga, 1989), may not be in balance to the extent that the kinetics of the reactions vary.

Within global carbon cycle, while the general budget models and concepts can be straightforward, the geochemical details are in some ways complex. Additional, detailed work to describe these processes quantitatively at a variety of scales is required to ensure that our understanding of model dynamics is sufficiently precise to answer the hugely important questions posed by the carbon cycle and the potential for anthropomorphic influence on the rates global climate change.

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References

- Amiotte Suchet, P. and J.L. Probst, A global model for present day atmospheric/soil CO₂ consumption by chemical erosion of continental rocks (GEM-CO₂), *Tellus*, 47B, 273-280, 1995.
- Amiotte Suchet, P. and J.L. Probst, Modeling of atmospheric CO₂ consumption by chemical weathering of rocks: Application to the Garonne, Congo, and Amazon Basins. *Chem. Geol.*, 107, 205-210, 1993.
- Anthony, D.M., 1988, *Seasonal effects on the geochemical evolution of the Logsdon River, Mammoth Cave, Kentucky*. Unpublished MS. Thesis, Department of Geography and Geology, Western Kentucky University, 140 p.
- Atkinson, T.C., Carbon dioxide in the atmosphere of the unsaturated zone: An important control of groundwater hardness in limestones, *J. Hydrol.*, 35, 111-125.
- Baes, C.F. Jr., H.E. Goeller, J.S. Olson, and R.M. Rotty, *The Global Carbon Dioxide Problem*, 72 pp., Oak Ridge Natl. Lab. Report NTIS ORNL-5194, Oak Ridge, Tennessee, 1976.
- Berner, R.A. and A.C. Lasaga, Modeling the geochemical carbon cycle, *Scientific Am.*, 260, 74-81, 1989.
- Berner, R.A., Lasaga, A.C. and R.M. Garrels, The carbonate-silicate geochemical cycle and its effect on atmospheric CO₂, *Am. J. Sci.*, 283, 641-683, 1983.
- Broecker, W. S. *et al.*, Fate of fossil fuel carbon dioxide and the global carbon budget, *Science*, 206, 409-418, 1979.
- Busenberg, E. and L.N. Plummer, The kinetics of dissolution of dolomite in CO₂-H₂O systems at 1.5 to 65°C and 0 to 1 atm PCO₂, *Am. J. Sci.*, 282, 45-78, 1982.
- Draper, N. and H. Smith, *Applied Regression Analysis (3rd Edition)*, 706 pp., John Wiley & Sons, Inc., New York, 1981.
- Ford, D. C. and P. Williams, *Karst Geomorphology and Hydrology*, 601 pp., Unwin Hyman Ltd., Winchester, Massachusetts, 1989.
- Hess, J. and W. White, 1988, Storm response of the karstic carbonate aquifer of south-central Kentucky. *Journ. Hydrol.* 99, 235-252.
- Hess, J. and W. White, 1989, Chemical hydrology: in *Karst Hydrology: Concepts from the Mammoth Cave Area*, W.B and E.L White, eds., New York: Van Nostrand Reinhold, 346p.

- Hesshaimer V., M. Heimann and I. Levin, 1994: Radiocarbon evidence for a smaller oceanic carbon dioxide sink than previously believed, *Nature*, 370, 201-203, 1994
- Houghton, R.A. and G.M. Woodell, Global climate change, *Scientific Am.*, 260 (4), 36-44, 1989.
- IPCC (Intergovernmental Panel on Climate Change). *Climate Change: The IPCC Scientific Assessment*. J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.). Cambridge University Press, Cambridge, U.K., 1990.
- IPCC (Intergovernmental Panel on Climate Change), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, 200 pp., Cambridge Univ. Press, Cambridge, 1992.
- IPCC (Intergovernmental Panel on Climate Change), *Radiative Forcing of Climate Change: The 1994 Report of the Scientific Assessment Working Group of the IPCC*, Meteorological Office Marketing Communications Graphics Studio, Bracknell, United Kingdom, 1994a.
- IPCC (Intergovernmental Panel on Climate Change), *Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, edited by J. T. Houghton, L. G. Meria Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haïtes, N. Harris and K. Maskell, Cambridge University Press, Cambridge, Great Britain, 1994b.
- IPCC (Intergovernmental Panel on Climate Change), *IPCC Second Assessment - Climate Change 1995*, 64 pp., IPCC, WMO, Geneva, Switzerland, 1995.
- Joos F., Imbalance in the budget, *Nature*, 370, 181-182, 1994.
- Keeling C.D., R.B. Bacastow, and T.P. Whorf, Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii in *Carbon Dioxide Review: 1982.*, Edited by W.C. Clark, Oxford University Press, New York, 1982.
- Keeling C.D., T.P. Whorf, M. Wahlen, and J. van der Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature*, 375, 666-670, 1995
- Köppen, W. and R. Geiger, *Handbuch der Klimatologie*, 44 pp., Gebrüder Borntraeger, Berlin, 1936.
- Liu, Z., Y. Daoxiaoan, S. He, and J. Zhao, Contribution of carbonate rock weathering to the atmospheric CO₂ sink, *International Geological Correlation Program, Project 379: Karst Processes and the Carbon Cycle Newsletter* 1998, 27-34, 1998.
- Meybeck, M., Global chemical weathering of surficial rocks estimated from river dissolved load, *Amer. J. Sci.*, 287, 401-428, 1987.
- Miotke, F. -D., 1975, *Der Karst im zentralen Kentucky bei Mammoth Cave*, Jahrbuch der Geographischen Gesellschaft zu Hannover für 1973, 360p.

- Miotke, F. -D., 1974, Carbon dioxide and the soil atmosphere. *Karst u. Höhlenkunde, Abh. Ser. A, No. 9*, 1-49.
- Moore, T.R., Dissolved organic carbon: Sources, sinks, and fluxes and role in the soil carbon cycle, in *Soil Processes and the Carbon Cycle*, edited by R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart, pp. 281-292, CRC Press, New York, 1997.
- Palmer, A., *A Geological Guide to Mammoth Cave National Park*, 196 pp., Zephyrus Press, Teaneck, New Jersey, 196 p., 1981.
- Plummer, L.N., T.M.L. Wigley, and D.L. Parkhurst, The kinetics of calcite dissolution in CO_2 -water systems at 5 to 60°C and 0.0 to 1.0 atm CO_2 . *Am. J. Sci.*, 278, 179-216, 1978.
- Pohl E.R. and W.B. White, Sulfate minerals: Their origin in the central kentucky karst, *Am. Mineral.*, 50, 1461-1465, 1965.
- Probst, J.L., J. Mortatti, and Y. Tardy, Carbon river fluxes and global weathering CO_2 consumption in the Congo and Amazon River basins, *Appl. Geochem.*, 3, 1-13, 1994.
- Siegenthaler, U. and H. Oeschger, Predicting future atmospheric carbon dioxide levels, *Science*, 199, 388-395, 1978.
- Stumm, W. and J. Morgan, *Aquatic Chemistry An Introduction Emphasizing Chemical Equilibria in Natural Waters*, 780 pp., John Wiley and Sons, New York, 1981.
- Vaughan, K., 1998, *A quantitative analysis of interstitial fluid chemistry and limestone dissolution rates within the clastic sediment of a karst aquifer conduit, Mammoth Cave, Kentucky*. M.S. Thesis, Western Kentucky University, 128 p.
- White, W.B., *Geomorphology and Hydrology of Karst Terrains*, 464 pp., Oxford University Press, New York, 1988.
- Wood and Petraitis, Origin and distribution of carbon dioxide in the unsaturated zone of the southern High Plains, *Water Resour. Res.*, 20, 1193-1208, 1984.

Acidic Bog Drainage and Limestone Dissolution, Mammoth Cave National Park

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ABSTRACT

Stagnant ponds or bogs produce abundant amounts of humic material and organic acids. Organic acids are also produced on forest floors and by simpler organisms such as bacteria or lichens, thus accumulating in the upper horizon of the soil. The potential impact of these species on karst landscape development has received relatively little study. Organic acids have been found to promote mineral dissolution via two mechanisms, acidification and metal complex formation. In most natural settings, carbonic acid will be the predominant proton donor. The ability to form multifunctional complexes with cations, in addition to their acidic properties alone, allows these compounds to be effective at mineral dissolution.

Two small catchments in similar geologic settings within Mammoth Cave National Park are being examined to study the phenomenon. One of these drainage areas contains a large bog with abundant organic matter and a pH of that has been measured below 4. The control stream does not contain bog vegetation and typically has more circumneutral pH levels. An approach combining geochemical modeling with limestone tablet weight loss methods is underway to determine the effect of these organic acids on limestone dissolution, and thus potentially on landscape development. Preliminary results indicate significant differences in the geochemistry of the two streams. Conductivity measurements in the bog stream (often <20 microSiemens) are as low as any surface or groundwaters that we know of recorded in the Mammoth Cave area.

Carbonate Chemistry Variations in Showerbath Spring, Mammoth Cave, Kentucky

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ABSTRACT

Vertical shafts (often referred to as pits, domes, and domepits) are a common feature of the south central Kentucky karst. These features are created by water flowing vertically downward within the vadose zone. While they may be concentrated at caprock margins and especially where ephemeral caprock streams cross onto the carbonate sequence, they may occur at any location within the aquifer. They vary in size, up to 25 m in diameter and 60 m deep, and in plan view may have cylindrical or elongated shapes. Vertical shafts are important because they:

- 1) often represent the headwaters for subsurface streams,
- 2) form pathways for the rapid transport of pollution to the aquifer, and
- 3) are often closely related to the surface drainage topography.

Previous studies conducted on the genesis of horizontal river cave passageways in the Mammoth Cave area suggest that growth of the major base level conduits may be dominated by infrequent storm events. This project represents a pilot evaluation of temporal variations in water chemistry within Showerbath Spring, a perennially flowing vertical shaft in the Frozen Niagara section of Mammoth Cave. Weekly analyses of pH, temperature, bicarbonate, and calcium concentrations allow quantification of dissolution rates and CO₂ pressures. This in turn allows comparison of the temporal variation of these parameters with those of active, base level horizontal passages within the cave and their impacts on conduit development. During the year-long study the vertical shaft waters of Showerbath Spring were undersaturated at all times, and had a much smaller range of dissolution rates (~0.7-1.3 mm/yr) than those measured in Hawkins and Logsdon Rivers. Carbon dioxide pressures were generally low, in some cases less than atmospheric background levels.

traveled along the sewer system for eleven blocks with estimated damages exceeding forty-three million dollars.

In the fall of 1982, cave explorers encountered strong fumes and a reddish-gray scum on the water in Lost River Cave beneath the city. An investigation by the Kentucky Division of Water revealed the presence of benzene and methylene chloride and led to an emergency response action by the U.S. Environmental Protection Agency, USEPA Region IV in March, 1983. Dr. Nick Crawford, Director of the Center for Cave and Karst Studies at Western Kentucky University, was employed by USEPA as a consultant to assist in finding the source(s) of contamination. The task appeared to be extremely difficult since the Lost River flowed under the South Side Industrial Park, and there were thousands of sinkholes upstream into which contaminants could have been dumped. However, by checking various cave entrances for fumes and contaminated water, it was possible to trace the pollution upstream to a tributary of the Lost River. This action greatly reduced the potential source area and led to the investigation of a spring-fed farm pond south of the city. The owners had reported that their ducks were dying immediately after drinking from the pond. Samples taken from the spring revealed benzene, methylene chloride, trichloroethane, chlorobenzene, 1, 2 di-chloroethane, 1,2 di-chloroethene, toluene, 1,1,1 tri-chloroethane, methyl ethyl ketone, ethyl acetate, and xylene. The spring-fed pond continuously overflowed into a sinkhole, and a dye trace confirmed that it then flowed through the tributary cave stream into the Lost River. Treatment of the total discharge of the spring was initiated immediately by USEPA and resulted in the treatment of 1.9 million gallons over the next two months.

A search for the source of the chemicals issuing from the spring began by delimiting the area higher in elevation than the spring. A search of the area revealed two potential sources, a large factory and a small chemical company with several underground tanks. Dye was injected into the ground above the chemical company's buried tanks and the soil was then flushed with a garden hose overnight. Dye was detected at the spring in 47 hours. Several dye traces performed at the factory site all took different routes to Lost River Cave and proved that the factory was not a source of the contamination at the spring. As a result of this investigation, the chemical company removed all of its tanks and moved to a site near Nashville, Tennessee.

During the 1983 "Superfund" emergency response action by USEPA several important precedents were established for finding sources of contamination in karst aquifers. These precedents proved valuable in the following months. In January of 1984 fumes began to rise from contaminated cave streams into several homes and buildings in Bowling Green's Forest Park Subdivision. Initial investigations were made by the Bowling Green Fire Department and Kentucky Fire Marshal's Office. In May, 1984 Crawford was asked by the State Fire Marshal and by the Bowling Green City Commissioners to investigate and prepare a proposal for dealing with the problem. Crawford and his students (1984) identified the homes, buildings, drainage wells and sinkholes in the Forest Park area with fumes and recommended that the USEPA be asked to deal with the problem.

USEPA Region IV began a health investigation in cooperation with the U.S. Centers for Disease Control (CDC) in June, 1984. Air samples collected from bedrooms, crawl spaces, and basements of 125 homes in the Forest Park area were analyzed as were blood samples and urine samples of residents from twenty homes. During the investigation the fume problem continued to worsen as fumes forced the partial evacuation of Parker-Bennett Elementary School in November, 1984 and Dishman-McGinnis Elementary School in January, 1985. Fumes were reported in over fifty homes, three commercial buildings, two schools, one church, eighteen drainage wells, four sinkholes, and nine caves. The most severe problems were in the Forest Park area above the Lost River Ground Water Basin. Another area of concern was in the Parker-Bennett School area above the Double Springs Ground Water Basin.

After an extensive public health evaluation of the fumes by the CDC, a Health Advisory was issued in March, 1985 for the Bowling Green area. The advisory was issued on the grounds that explosive levels of fumes existed and that detectable levels of benzene, toluene, and xylene exceeded standards for "non-occupational settings". As a result of the Health Advisory, the USEPA, Region IV initiated a "Superfund" emergency response in April, 1985.

Again Crawford was hired by USEPA to assist with the problem as were a team of his graduate students that included Chris Groves, Tony Able, John Hoffelt, and Jim Webster. The Center for Cave and Karst Studies Team explored and mapped caves, excavated entrances into caves, directed the drilling of two 30-inch diameter wells into caves that were located by using microgravity and exploratory borings, exploratory borings, and with the help of the late Frank Reid and his magnetic induction transmission "cave radio", they directed the installation of monitoring wells into cave passages.

An extensive investigation to find the sources of the hazardous vapors was made by USEPA and the Kentucky Division of Water. A tank-testing program for underground storage tanks was initiated by USEPA and four gasoline tanks in the Forest Park area were found to be leaking. The Kentucky Division of Water, assisted by USEPA, made a systematic investigation of factories in the South Side Industrial Park and elsewhere. When violations were found, dye traces were performed by the Center for Cave and Karst Studies Team to determine the ground water flow route of any contaminant being discharged into the ground. Seven factories were cited for discharging into the karst aquifer without a permit. Several factories had drains within their buildings that were connected to storm sewers discharging into sinkholes, bedrock crevices or storm water injection wells. One factory was discharging their toxic waste directly into two wells it had drilled into the karst aquifer.

After the four leaking gasoline tanks were replaced and the factories stopped discharging toxic chemicals into the karst aquifer, the vapors rising into homes and buildings slowly decreased. However, it was noted that after large storm events the vapors would return at some of the homes. This led to some pioneering research concerning the movement of point source contaminants through karst aquifers.

An investigation of toxic organic chemicals in the Lost River Cave System beneath Bowling Green was made by Francis M. Cretella (1985) for his M.S. thesis in biology. The work was directed by Martin R. Houston, Ph.D. and Nicholas C. Crawford, Ph.D. Water samples were collected at three sites: 1) Keith Pond Spring, 2) Lost River Blue Hole Karst Window, and 3) Lost River Rise at Lampkin Park. The cave water samples were analyzed for volatile organic compounds during four separate storm events. The compounds detected were as follows:

- a. toluene
- b. 1, 1, 1-trichloroethane
- c. trans-1,2 – dichloroethylene
- d. methylene chloride
- e. 1,1- dichloroethane
- f. trichloroethylene
- g. tetrachloroethylene
- h. 1,1- dichloroethylene
- i. ethylbenzene

These compounds were detected in varying amounts at each of the three sampling sites during base flow conditions. However, during each storm event, the levels of each contaminant changed significantly at all three sites. The first change during each of four storm events studied was the dilution of the volatile organic compounds by storm water runoff. The second effect was a drastic increase in the level of all contaminants during and after the storm event (Cretella, 1985).

This research confirmed what Crawford (1984) had noted earlier. These volatile organic compounds (and others not studied) are in the soil at sites of previous leaks and spills. They are held by capillary attractions of soil particles and do not percolate down into the karst aquifer. However, during storm events the percolating soil water pushes these chemicals down into the cave streams. The liquid chemicals volatilize in the turbulent cave streams and fill the caves with vapors. The vapors then rise to the surface at: a) solutionally enlarged joints, b) where breakdown of the cave roof has reached the surface, c) sinkhole drains, and d) drainage wells. This research demonstrated why storm-event monitoring is necessary for most karst aquifers. Unfortunately, it is rarely required by regulatory agencies.

The problem of explosive and/or toxic vapors rising from the karst aquifers under Bowling Green appeared to have ended by the late 1980's. Fortunately, there were no explosions, no one died, no one's health was impaired, and no one sued anyone. With the institution of the Underground Storage Tank (UST) program, virtually all of the more than 500 underground gasoline tanks in the Bowling Green vicinity were replaced. It was hoped that the city would not have a recurrence of the problem. Unfortunately, it returned in August 1999 as gasoline vapors began to rise into Greenwood Park Church of Christ and Foundation Christian Academy.

GASOLINE VAPORS RISING INTO GREENWOOD PARK CHURCH OF CHRIST AND FOUNDATION CHRISTIAN ACADEMY

In August 1999, the Foundation Christian Academy had to be evacuated due to what appeared to be gasoline vapors rising into the building (Figure 1). The Bowling Green Fire Department responded and tested the basement, the part of the Greenwood Park Church of Christ used by the Foundation Christian Academy, with a combustibility meter. They found the levels were very low and well below the Lower Explosive Limit (LEL). However, the odor of what appeared to be gasoline remained quite strong and the basement could not be used. Nick Crawford was asked to assist in August 1999, and upon inspection advised that the problem was very serious since the explosive level might be reached after a rain and/or during a period when low barometer pressure outside caused increased cave air flow into the building. He advised that a fan with an explosion-proof motor be installed to pump air from the basement sump and vent it to the outside to create low pressure under the concrete floor of the basement and thus prevent soil and cave air from entering the building. This was essentially the technique used earlier to rid homes of gasoline vapors. Although, usually the technique used was to excavate to bedrock to expose a bedrock crevice adjacent to the home or building. A pipe and fan were then installed to vent the vapors into the atmosphere. Although the sump fan lowered the odor in the church basement, it did not eliminate it completely, and the basement school could not be used.

Crawford walked over the area in the vicinity of the church and discovered several potential sources but did not detect any product or odor in nearby drainage wells. Three weeks later, the Kentucky Division of Waste Management discovered that a nearby gasoline station had lost product from an underground tank. The gasoline station owners then assumed responsibility for the investigation and mitigation of the problem. The Center for Cave and Karst Studies then assisted their consulting firm in ridding the church of the potentially explosive vapors. Center personnel and students assisted with a microgravity investigation (Figure 4) and dye traces of nearby locations to determine groundwater flow. Wells drilled into a low microgravity anomaly along a traverse adjacent to the church intersected voids in the regolith above bedrock (Figure 5). These wells were connected to an outside fan that vented the vapors into the atmosphere (Figure 6). The combination of the sump fans and the outside fan connected to the wells eliminated the gasoline odor in the church basement and appears to have solved the problem.

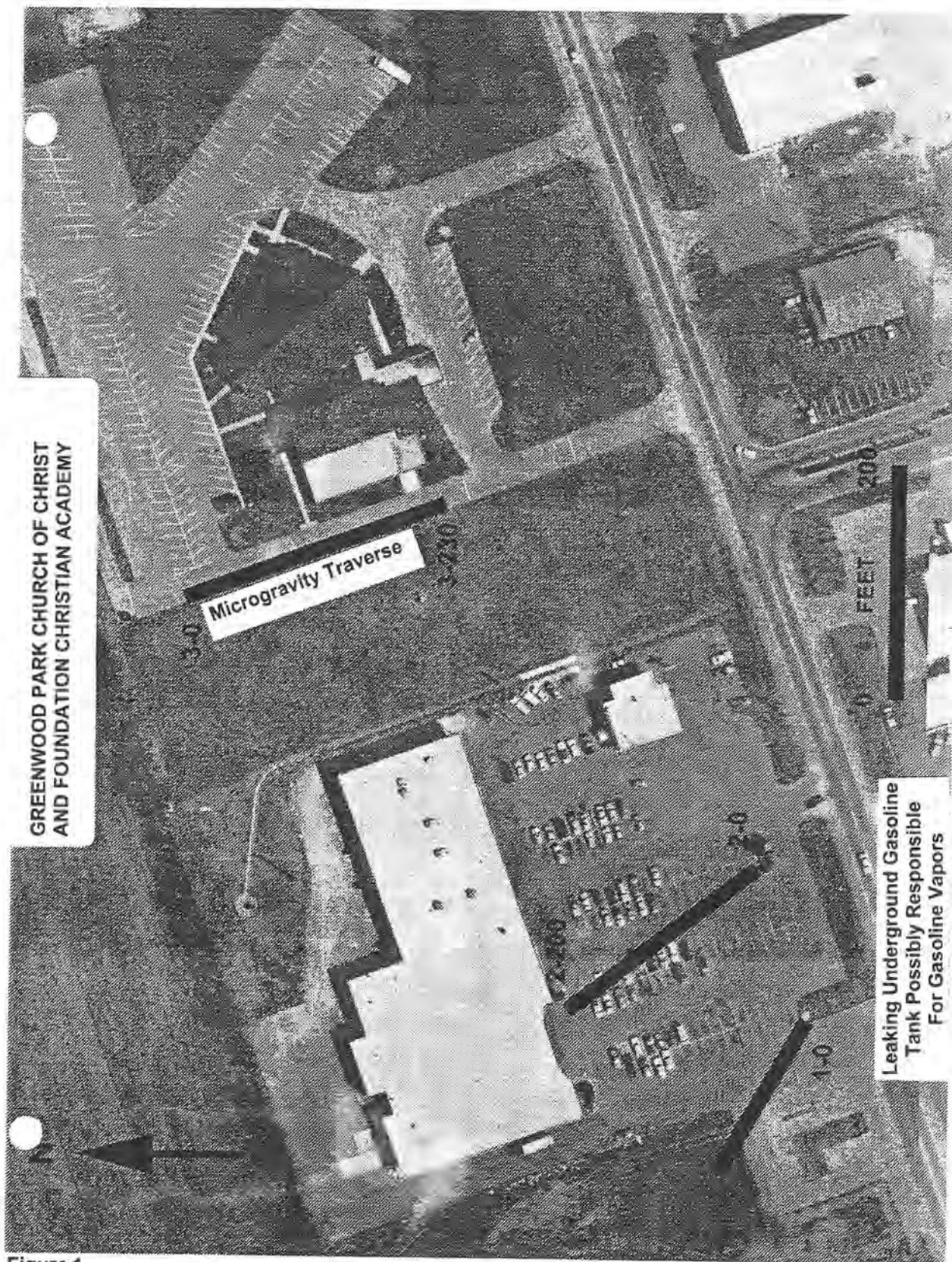


Figure 1

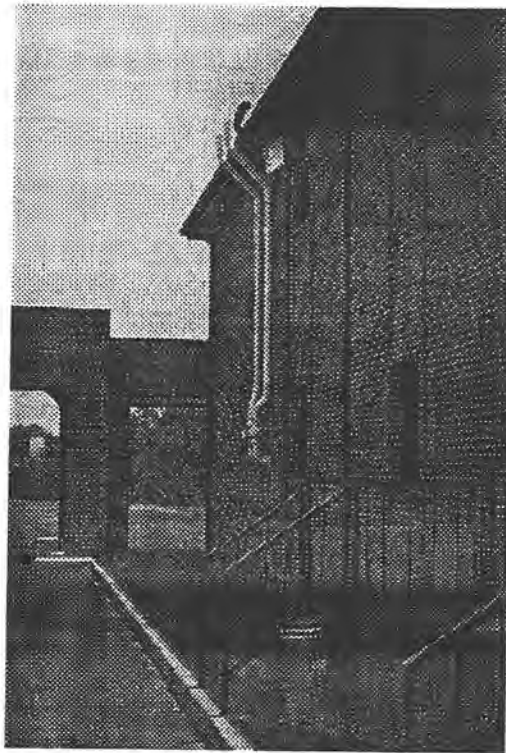


Figure 2. Fans in back church for removing gasoline vapors from basement sump.

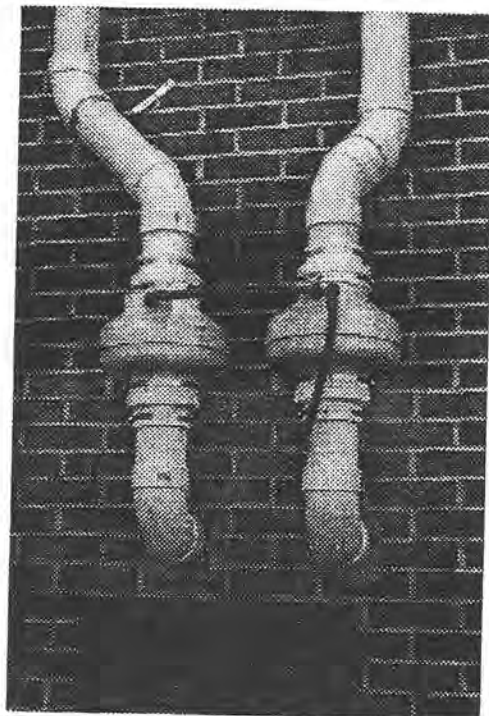


Figure 3. Fans in back of church removing gasoline vapors from basement sump. Fans have explosion-proof motors.



Figure 4. Microgravity traverse using the Scintrex CG-3M Microgravity Meter.

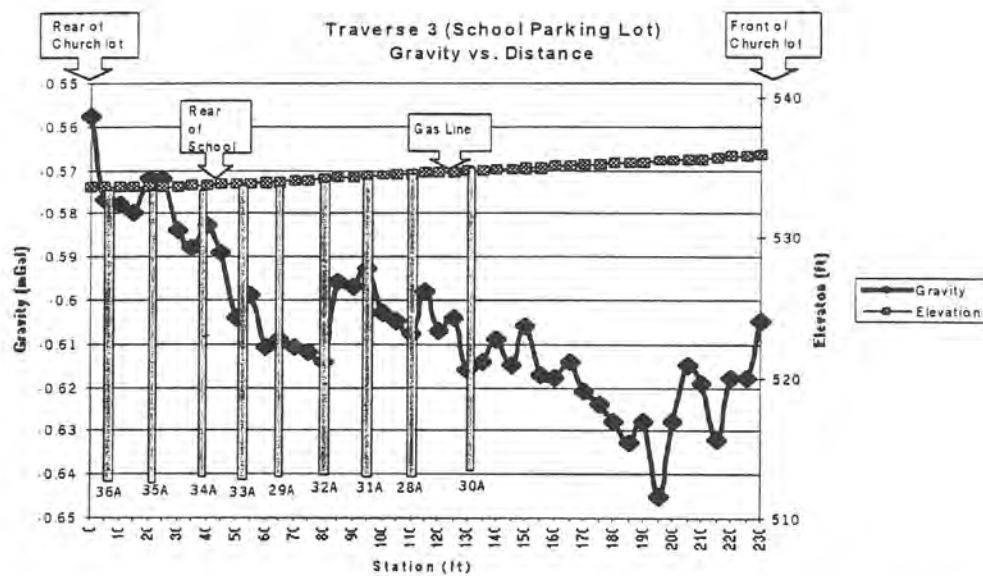


Figure 5. A) Low microgravity anomaly along traverse adjacent to church and school. B) Anomaly is adjacent to sinkhole over which the church and school were built. C) Borings 32A, 29A, and 33A intersected voids in regolith. The outside fan was installed to remove gasoline vapors from these bore holes.

CONCLUSIONS

1. Even though the UST program has reduced the risk, leaking underground tanks continue to be a serious problem for Bowling Green and other areas built upon karst terrain. Versailles, Kentucky is another town that has had problems with gasoline fumes rising into some of the downtown buildings within the past three years.

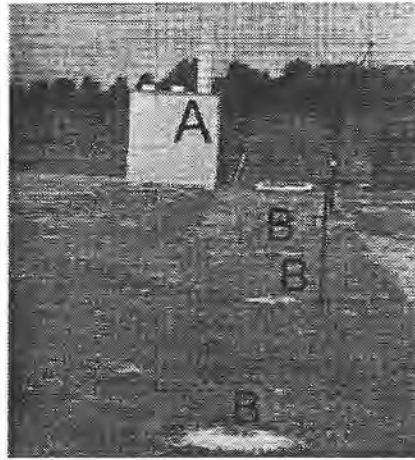


Figure 6. A) Fan for removing gasoline vapors from karst aquifer. B) Borings into subsurface void identified by low gravity anomaly.

2. Because of the potential for explosions, gasoline, and other liquid chemicals that produce explosive vapors, should be considered the most serious of all ground water contaminants. Although the potential for explosions exist in porous-media, laminar-flow aquifers also, it is much more serious for karst-conduit, turbulent-flow aquifers.

3. In dealing with ground water contamination problems under Bowling Green and elsewhere since the late 1970's, Crawford and his students at the Center for Cave and Karst Studies have made several significant discoveries concerning ground water contamination of karst aquifers. Most of the discoveries were made during the late 1970's and early 1980's and they include the following:

a) Dye traces to trace the flow of contaminants can be initiated by injecting the dye into a dye injection pit excavated into the soil with a backhoe at the site of the contamination and flushed through the soil into the underlying karst aquifer with potable water. Previous to this work, dyes were injected into sinking streams, sinkholes and, in a few cases, wells drilled into bedrock voids. This work demonstrated that one can inject dye at any location within a karst aquifer, not just at sinking streams and sinkholes that are directly connected to the karst conduit system.

b) Many point source contaminants are flushed from the soil down into the karst aquifers during storm events resulting in a higher concentration of the contaminant during high discharge. This is just the opposite of what one would expect – that point-source contaminants would be diluted in concentration during high discharge associated with storm events. This resulted in the Center performing storm-event monitoring at springs beginning in the Spring of 1983.

- c) If one removes the source of contamination by removing the contaminated soil, even severely contaminated caves will rapidly clean themselves of most contaminants by the constant flushing during storm events. Examples include the Lost River Cave under Bowling Green, contaminated with gasoline, fuel oil and other VOCs, and the Arnemann Spring Cave System in Simpson County, Kentucky, contaminated with PCBs.
- d) Although, microgravity had been used to demonstrate that it could detect known caves, by Dwain Butler (1983) and others, the Center in 1985 was the first to apply microgravity as a tool to locate and even map the route of caves from the ground surface so that monitoring wells could be installed directly into cave streams (Crawford, Lewis, Winter and Webster, 1999).
- e) The Center discovered a method of ridding homes and buildings of explosive and/or toxic vapors in 1985 by excavation to expose bedrock crevices and then installing a fan to vent the vapors into the atmosphere. This technique was first applied to the George Demond home, the Parker Bennett Elementary School and the Dishman McGinnis Elementary School in 1984-1985.
- f) The Center first developed emergency response techniques and procedures for dealing with leaks and spills of hazardous liquids upon karst terrain and the Center was the first to demonstrate that miscible liquid contaminants could be flushed from karst aquifers during emergencies.
- g) The Center was the first to systematically measure homes for radon gas in karst aquifers in 1986-1987 and proved that karst areas have some of the highest radon levels in homes in the United States (Webster and Crawford, 1989). A fact that USEPA has only recently accepted.
- h) The Center has made numerous advances in the use of fluorescent dyes as tracers, such as, in the use of multiple dyes and using non-linear curve-fitting computer programs to facilitate dye detection.
- i) The Center has hosted many scientific meetings, established the Karst Field Studies Program and offered numerous workshops for USEPA and State environmental agencies on karst environmental problems.

Many of the lessons learned and discoveries made by the Center while working on karst environmental problems in Bowling Green and elsewhere are now considered common knowledge by those dealing with karst environmental problems. At a time when most karst scientist were exploring and mapping caves, and performing important basic research about caves, a group of professors and students located only twenty miles from Mammoth Cave, chose to work with very unpleasant caves and to engage in applied research to solve serious karst environmental problems, sometimes even risking their lives and health to do so. The lessons learned have not only benefited Bowling Green but all karst areas vulnerable to ground water contamination and other karst environmental problems.

References

1. Butler, D.K., (1983). Microgravimetric and Magnetic Surveys, Medford Cave Site, Florida, *Cavity Detection Research Report 1. Tech. Rep GL-83-1*. Vicksburg, MS: Army Engineer Waterways Station. P.92.
2. Crawford, N.C., (1982). *Hydrogeologic Problems Resulting from Development upon Karst Terrain, Bowling Green, KY*. Guidebook for U.S. Environmental Protection Agency Karst Hydrogeology Workshop, Nashville, TN, p.34.
3. Crawford, N.C. (1983), Dye Traces of Subsurface Flow Routes of Toxic Chemicals in the Vicinity of Keith Pond, Bowling Green, KY. Report to Emergency Response Section, U.S. Environmental Protection Agency, p. 21.
4. Crawford, N.C., (1984a). Toxic and Explosive Fumes Rising from Carbonate Aquifers: A Hazard for Residents of Sinkhole Plains. In: Beck, B.F. (ed) *Sinkholes: Their Geology, Engineering and Environmental Impact*. Proceedings, First Multidisciplinary Conference on Sinkholes, Orlando FL. A.A. Balkema, Rotterdam, Netherlands, pp.297-304.
5. Crawford, N.C., (1984b). Potentially Toxic and Explosive Fumes Rising from caves under Bowling Green, Kentucky. Report prepared for City Commissioner of Bowling Green, Kentucky. P.19.
6. Crawford, N.C., (1985). Map of Groundwater Flow Routes: Lost River Groundwater Basin, Warren County, Kentucky. Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, Kentucky.
7. Crawford, N.C., (1988). Karst Groundwater Contamination from Leaking Underground Storage Tanks: Prevention, Monitoring Techniques, Emergency Response Procedures, and Aquifer Restoration. *Proceedings, Second Conference on Environmental Problems in Karst Terranes and Their Solutions*, National Water Well Association, Nashville, TN.
8. Crawford, N.C., (1989). Groundwater Contamination in Warren County, Kentucky: Toxic and Explosive Fumes Rising from Contaminated Groundwater Flowing Through Caves Under Bowling Green, in Crawford (ed) *Karst Landscape Analysis*, Warren County Comprehensive Plan Technical Report, pp. 117-143.
9. Crawford, N.C.,; M.A. Lewis; S.A. Winter; and J.A. Webster, (1999). Microgravity Techniques for Subsurface Investigations of Sinkhole Collapses and for Detection of Groundwater Flow Paths through Karst Aquifers, in Beck, Pettit and Herring (eds) *Hydrogeology and Engineering Geology of Sinkholes and Karst*. Proceedings, Seventh Multidisciplinary Conference on Sinkholes, Harrisburg, PA, Balkema, Rotterdam, pp. 203-218.

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10. Gold, D.P., R.R. Parizek and T. Giddings, (1970). Water Well Explosions: An Environmental Hazard. The Pennsylvania State University, 40, pp. 17-21.
 11. Stroud, F.B., J. Gilbert, G.W. Powell, N.C. Crawford, M.J. Rigatti and P.C. Johnston, (1986). Role of U.S. Environmental Protection Agency Emergency Response to Toxic Fumes and Contaminated Groundwater in Karst Topography: A Case Study. *Karst Environmental Problems in Karst Terranes and Their Solution Conference, Proceedings*, National Water Well Association, Western Kentucky University, Bowling Green, KY, pp. 197-225.
 12. Webster, J.W. and N.C. Crawford (1989). Radon Levels in the Homes and Caves of Bowling Green, Warren County, Kentucky. Warren County Comprehensive Plan Technical Report, p.15.
 13. White, W.B., (1988). *Geomorphology and Hydrology of Karst Terrains*. Oxford University Press. New York. p. 464.

Sites Originally Proposed for the Southcentral Kentucky Trimodal Transpark: A Wake-Up Call for Everyone Concerned About the Protection of Mammoth Cave National Park

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ABSTRACT

Three potential sites were originally selected for the proposed Southcentral Kentucky Trimodal Transpark. One of the three sites for the Transpark, originally called the "Airpark" because it will consist of a large industrial park built around an airport, was along the boundary between Warren, Edmonson and Barren Counties. This site is located where the Cumberland Parkway joins Interstate 65, a site that is within the headwaters of the streams that flow into and through Mammoth Cave National Park, the streams that have created the world's longest cave. Crawford was very critical of this site in his comments in the original site selection report submitted by the primary consulting firm responsible for site selection.

Although a site adjacent to Bowling Green (ten miles south of the Park and outside the drainage that flows into the Park) has been selected, concerns about development upstream from the Park remain. Within six years, Interstate 65 will be a six-lane highway, the Cumberland Parkway is being considered as a part of the proposed Interstate 66, and an industrial park has been established within this area near Park City. This paper recommends that planning for the rapid urban development that is going to occur adjacent to and upstream from the Park begin immediately to avoid possible negative impacts to the one karst area in the eastern U.S. that has been set aside as a National Park.

INTRODUCTION

One of the three proposed sites for the Southcentral Kentucky Trimodal Transpark was in the vicinity of the intersection of the Cumberland Parkway and Interstate 65 (Figure 1). This site is within the Turnhole Spring Ground Water Basin, and the headwaters for the streams that have created and continue to create the world's longest cave. Although a site adjacent to Bowling Green (ten miles south of the Park and outside the drainage that flows into the park) has been selected, concerns about development upstream from the Park remain.

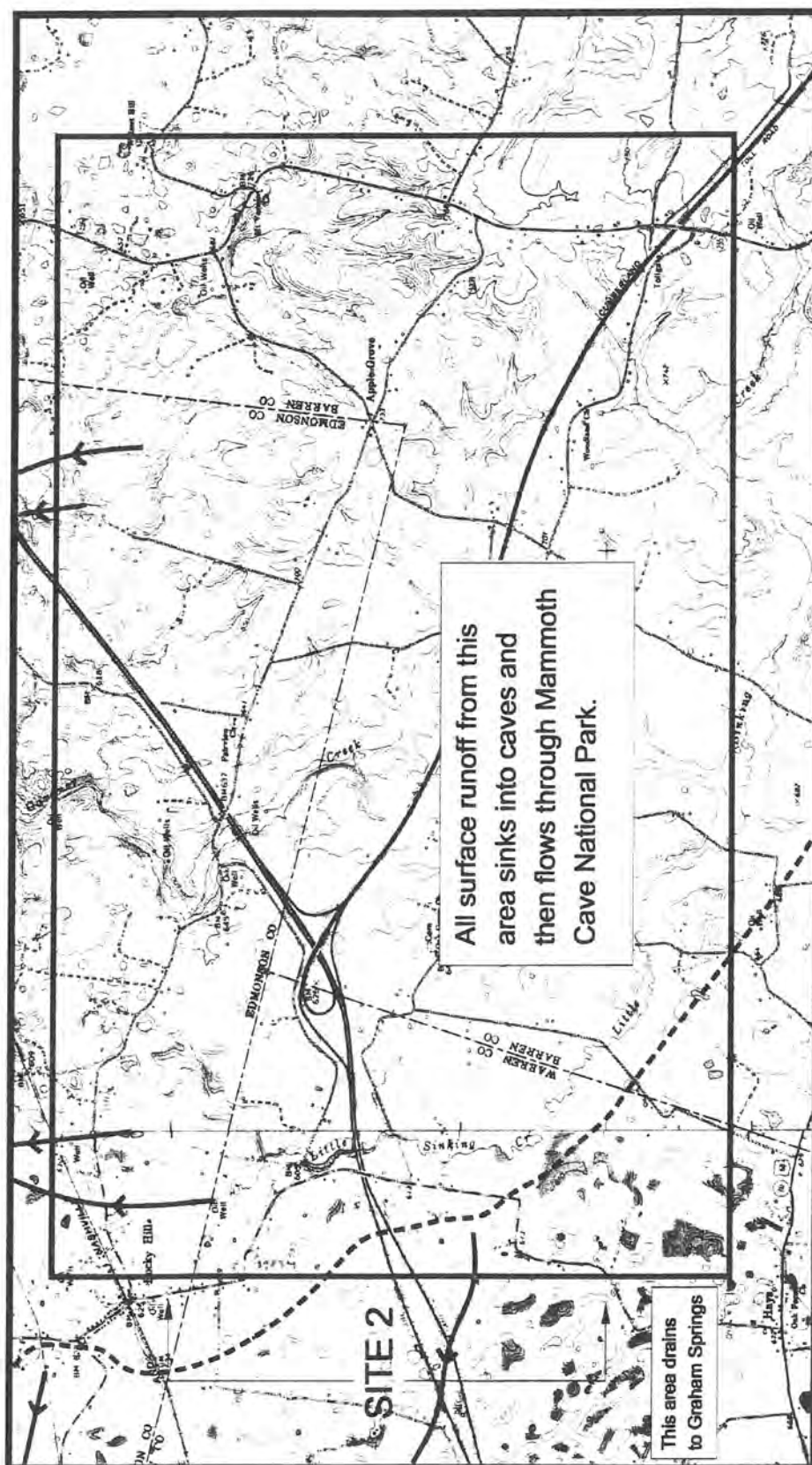


Figure 1. Topography of Site 2 showing surface streams, such as Little Sinking Creek and Gardner Creek, that sink and then flow into and through the caves of Mammoth Cave National Park.

Mammoth Cave Biosphere Reserve Existing and Proposed Boundaries

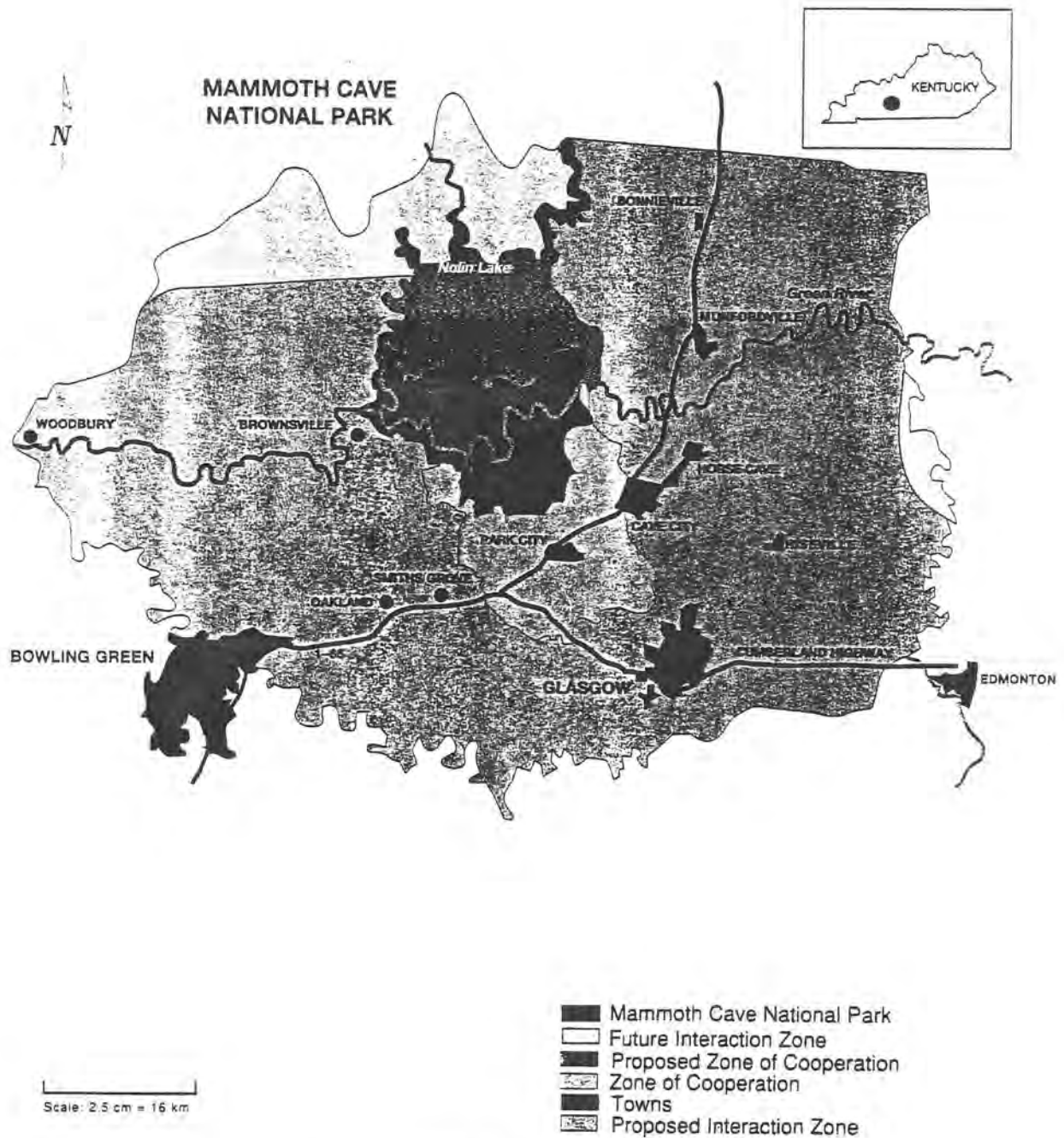


Figure 2.

The Cumberland Parkway will probably become part of the proposed Interstate 66. Interstate 65 will soon be a six-lane highway. The principal North-South route of the CSX Railroad extends through this area, and now there is access to sanitary sewer.

CONCLUSIONS

It does not take an Urban Geographer or City Planner to recognize that the headwaters to Mammoth Cave National Park will soon become the focus for rapid urban residential development, industrial development and commercial development, including truck stops and gasoline stations. As this area changes from primarily rural to primarily urban landuse, the headwaters for the Park must be protected. Designation of the area as an International Biosphere Reserve was a good first step, but it affords little protection (Figure 2). Hopefully, many of the lessons learned in Bowling Green about ground water contamination of karst aquifers and the research the Center for Cave and Karst Studies has in progress concerning treatment of urban storm water runoff by filtration and wetland treatment will be used for planning purposes before this very sensitive area changes from agricultural landuse to urban landuse.

Antipredator Behavior of the Cave Cricket (*Hadenoeus subterraneus*) in Response to Predation Risk by White-Footed Mice (*Peromyscus leucopus*)

Kurt Helf

ABSTRACT

The cave cricket (*Hadenoeus subterraneus*) feeding in its natural habitat has been effectively used as a model system to investigate foraging strategies of crickets under the influence of predation risk and in response to other features of their abiotic and biotic environment. We qualitatively measured cricket foraging responses using color-coded baits positioned at increasing distance from cave entrances where crickets exit to forage on the surface, and quantitatively using the technique of giving-up fullness (GUF). The GUF represents the percent amount of food consumed by a cricket relative to its crop-empty live weight. We hypothesized that the degree to which crickets 'fill up' is proportional to their foraging costs, e.g., metabolic costs and predation risk. To test our hypotheses that crickets can assess and respond to the risk of predation from white-footed mice around cave entrances, we used a combination of GUF and tethering experiments. We tethered crickets outside three cave entrances to determine variation in predation rates among caves and variability in predation as a function of distance from a cave entrance. At the same time, GUFs were collected at distances of 0, 5, and 15m from entrances (distances identified by color-coded food). While our analysis showed cave entrance had a significant effect on GUFs (ANOVA, $F_{2,1036} = 3.25$, $P = .039$), contrary to our predictions GUFs were highest (i.e. foraging costs lowest) at caves with the highest predation rates on tethered crickets. Though GUFs increased from 0 to 5m, consistent with our hypothesis of high density-dependent predation risk just outside cave entrances, predation rates on tethered crickets were not correlated with distance from cave entrances. Our data suggest crickets may not be responding primarily to the risk of predation while foraging outside of cave entrances. An alternative hypothesis is that resource competition is driving cricket behavior. Consistent with this hypothesis, we found (1) a negative correlation between GUFs and the number of crickets feeding at our bait patches, and (2) shifts in habitat use (distance from entrance) as a function of the number of feeding crickets. Future studies will be directed at multiple explanations of cricket behavior.

Microbial Ecology of Conduit Stream Sediment Interstitial Fluids of the South Central Kentucky Karst Aquifer: Impacts on Aquifer Development

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INTRODUCTION

A 1998 study of interstitial fluid geochemistry within the sediments beneath Charon's Cascade in the Echo River/River Styx area of the Mammoth Cave System (Vaughan, 1998; Vaughan *et al.*, 1998), found that carbon dioxide pressures were as much as an order of magnitude higher than the fluids of the cave stream itself. Modeling of both equilibrium chemistry and kinetics of the limestone dissolution showed that fluids were far undersaturated with respect to the mineral phase, and that dissolution rates were correspondingly high. This was confirmed by a limestone weight loss experiment, in which samples readily dissolved at various levels (30, 60 and 90 cm) below the streambed, in spite of the low fluid velocities there. The acidic conditions and high CO₂ pressures thus appear to significantly influence on both conduit dissolution rates and geometry. An obvious question relates to the source of the acids and elevated CO₂ pressures, which presumably result from the microbial degradation of organic material within the sediments.

To explore the relationship between the geochemical environment of these fluids and microbial ecology, additional fluid and sediment samples were collected in February 2000 from the same location beneath Charon's Cascade. A series of experiments is underway to better understand the relationships between microbial ecology and biochemistry, limestone dissolution kinetics, and karst aquifer evolution under geologically reasonable conditions within the Mammoth Cave System. The purpose of this paper is to describe results of this work so far.

METHODS

Isolation of Microbial Species

The water for bacteriological analysis was collected in the cave at Charon's Cascade in sterilized dilution bottles, while the sediment was collected in sterile 125 ml beakers. The water and air temperatures were taken at each site.

After thorough agitation of each water sample 1.0 ml of water was transferred into Bacto Brewer Thioglycollate Broth. One sample at each sampling site was incubated at 20°C and the other at 37°C. One gram of sediment from each site was also transferred to Bacto Brewer Thioglycollate Broth and incubated as just described. After 72 h the broths were checked for growth and pH. From the thioglycollate broth 0.5 ml of each sample was inoculated into Bacto-SIM melted, tempered medium and incubated at 37°C and checked daily for hydrogen sulfide production. From the thioglycollate broth, each sample was streaked for isolation on nutrient agar and incubated aerobically and anaerobically in GasPak jars at 37°C for 24-48 h. Gram stains were made from all inoculated thioglycollate broths and colonies from aerobic and anaerobic nutrient agar plates to gain a general indication of the possible flora.

Gram negative rods that were observed from the nutrient agar plates were picked and streaked for isolation on Levine's Eosin Methylene Blue Agar. These plates were incubated for 24 h at 37°C and the colony morphology of the various isolates noted. Each distinct colony from each plate was transferred to a nutrient agar slant and incubated for 24 h at 37°C. The resulting slant cultures were used for further testing.

Coliforms were identified by the MicroScan Walkaway Automated System. Eight isolates that had the ability to grow at 12°C were identified to species level.

Calcite Dissolution Experiment

Eight isolates which had been identified to the species level were tested to determine if they influenced the dissolution of calcite within broth/microbe/calcite mixtures. Each isolate was inoculated into 65 ml of thioglycollate broth with a calcite (Iceland spar) sample of known weight and surface area and incubated at the cave temperature of 12°C. Many bacteria, especially members of the family Enterobacteriaceae, carry on mixed acid fermentation which results in the excretion of a complex mixture of acids and the production of carbon dioxide.

The samples were left in the solutions for a total of 92 days, after which they were removed, cleaned and reweighed. Initial and final solution pH's were also compared. Samples were not stirred or otherwise agitated, and thus it is presumed that calcite dissolution kinetics were limited by diffusional transport through the mineral/fluid surface boundary layer.

RESULTS

Although aerobic, anaerobic, and facultatively anaerobic bacteria were identified from the sediments beneath Charon's Cascade, we have not yet focused on identification of anaerobic species. This work is underway. Of the bacteria we have identified (Table 1), five are members of *Enterobacteriaceae* and three were found to be oxidase positive, gram negative aerobic rods.

Due apparently to the fluid/rock interaction, the control sample dissolved at a rate of 4.5 mg cm⁻²yr⁻¹. Calcite in the presence of four of the incubating bacteria species dissolved more than the control, ranging up to 18.1 mg cm⁻²yr⁻¹ for *Escherichia Coli*. Although all media began

the experiment with a pH of 7.0, final pH's of all calcite and bacteria containing samples ranged from 8.5 to 8.8.

species	mass change (mg)	surface area (cm ²)	dissolution rate (mg/cm ² /yr)
<i>Enterobacter cloacae</i>	-11.1	13.7	3.2
<i>Klebsiella pneumoniae</i>	-14.7	12.6	4.5
<i>Serratia fonticola</i>	-9.2	10.4	3.5
<i>Escherichia coli</i>	-37.7	8.2	18.1
<i>Pseudomonas alcaligenes</i>	-6.7	12.0	2.2
<i>Serratia marcescens</i>	-13.1	5.7	9.0
<i>Alcaligenes sp.</i>	-8.2	12.8	2.5
<i>Pseudomonas fluorescens</i>	-15.4	9.3	6.5
control	-8.2	7.1	4.5

Table 1. Bacteria identified from sediments of Charon's Cascade in Mammoth Cave and associated experimental calcite dissolution rates.

These preliminary results suggest that in typical southeastern U.S. cave environments acid-producing bacteria within cave sediments may influence limestone dissolution and thus cave and aquifer development. These impacts may occur directly, with the microbial production of acids, or indirectly through production of carbon dioxide or hydrogen sulfide gasses. These effects on aquifer development are potentially very important in that they may impact dissolution of limestone bedrock beneath sediments under all flow conditions. If interstitial fluids were not capable of dissolution (which has commonly been assumed in speleogenetic models), most or all conduit growth would be restricted to periods of flooding, during which stream waters are in contact with the bare rock of cave walls and ceilings.

Further experiments are underway to further investigate these phenomena in four simultaneous areas: 1) replicate dissolution experiments in presence of bacteria using limestone samples, 2) examination of the geochemical evolution of bacteria solutions in the absence of limestone, and theoretical modeling of the impact of this evolution on limestone dissolution rates, 3) collection and isolation of bacteria species within other interstitial environments of Mammoth Cave, including within Pike Spring, Echo River, and Turnhole Spring Groundwater Basins, and 4) characterization of anaerobic bacteria from the cave sediments.

References

- Vaughan, K., 1998, *A quantitative analysis of interstitial fluid chemistry and limestone dissolution rates within the clastic sediment of a karst aquifer conduit, Mammoth Cave, Kentucky*. M.S. Thesis, Western Kentucky University, 128 p.
- Vaughan, K., C. Groves, and J. Meiman, 1998, "Carbonate Chemistry of Interstitial Fluids Within Cave Stream Sediments." *Proceedings of the International meeting of the International Geological Correlation Program, Project 379: "Karst Processes and the Global Carbon Cycle"*, Bowling Green, Kentucky.

A Vegetation Map of Mammoth Cave National Park Using Satellite Remote Sensing Data

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ABSTRACT

Landsat TM 5 imagery from May and October of 1995 were classified into broad Anderson level I and II categories (deciduous, coniferous, Ag/other) using an iterated-unsupervised classification routine. The data were then parsed into 100 spectral classes, and sent to the Division of Science and Resources Management at Mammoth Cave National Park for community level classification.

INTRODUCTION

The first vegetation field mapping in the park was completed by Ivan Ellsworth (1934), and included 47,348 acres within the minimum proposed boundary. In the resulting map, (Ellsworth 1936) seventeen categories were shown within four major forest types plus two categories of cleared areas. Much of these disturbed areas, now in middle succession can still be discerned today. Though aerial photographs were available at the time, he does not mention their use for vegetation mapping, which was accomplished by field teams armed with topographic maps. The next vegetation map was produced by Franklyn Hambly as part of the park's Resource Management Plan of the same year (1966). The map featured five forest cover types, and park biota were assigned to one or more of the cover types. No details of mapping methods were provided, but the map must have been considered fairly reliable as it was included in Guy Prentice's excellent Archaeological Overview and Assessment of Mammoth Cave National Park (1993). The third vegetation map of the park was produced by Adolf Faller and Marion Jackson (1975). They used 1966 panchromatic aerial photography (1:20,000) to establish individual mapping units. Seven major vegetation types were established with 18 "subunits characteristic of successional types on particular landforms." It was a thorough study, but the map sections had boundary discrepancies, which prevented assembly into one coherent map. The fourth vegetation map of the park was prepared by Kemuel Badger et.al.

(1997), and employed a stratified random field sampling approach within a variety of habitat types. Eight community types were delineated with GIS-based modeling, but significant discrepancies between field data and community types on the map persisted.

With the park's Fire Management Plan in development, a vegetation map was needed for classification of fuel types, and for delineation of Fire Management Units. Vegetation ecologist Mark Drew, and Remote sensing analyst Geoff Ghitter of the Mid-America Remote Sensing Center at Murray State University called to inquire about field checking a 25 category unsupervised classification derived from Landsat TM 5 satellite data of the park. Of course we were interested (!), and so began our collaboration. The unsupervised classification was not accurate enough to be used as a vegetation map, but it showed the promise of this approach.

Procedures

Landsat TM 5 scenes from May 1995 (leaf on) and October (leaf off) 1995 were used to create an unsupervised classification as part of the Kentucky Gap Analysis Program. The broad goal of the classification was to produce a classified image as input for the creation of an alliance level vegetation map for wildlife habitat mapping and biodiversity conservation analysis.

A two-tier iterated unsupervised classification procedure, using Erdas 'Imagine' software, designed to maximize the accuracy in identifying broad (Anderson level 1 and 2) classes was used to create the spectral classification. NAPP 1:40,000 color infrared photography (1992) was used in all stages to guide the classification procedure.

The satellite data were first geometrically corrected ($RMSE \pm 15$ meters) to ensure co-registration between the two images. Next, the leaf-off scene was classified and used to identify coniferous vegetation only. Once the classification was completed, a mask of those pixels was created and the pixels were removed from further analysis. With the coniferous vegetation masked out, the next step was to split deciduous vegetation from agricultural land. Unsupervised classifications using a combination of the leaf-off and leaf-on scenes were used to accomplish this task. By alternating the iterations of the unsupervised classification between these scenes, misclassification was minimized.

Finally, masks were created of each category (coniferous, deciduous, ag/other) and were used to parse the data into spectral classes, the leaf off data for the coniferous and the leaf on data for the deciduous and agricultural land. The deciduous and coniferous classifications were then sent to the Division of Science and Resources Management at Mammoth Cave National Park for biological community level classification.

The 100 spectral classes each of coniferous and deciduous vegetation were printed as histograms, spectral peak clusters were grouped by Rick, and these were displayed in Arc View by Michael. This rational approach unfortunately did not work, so Michael suggested individual evaluation of each spectral class. Sorting the 200 spectral classes took about two intensive weeks of work. An individual spectral class was given a bright color, and the distribution of pixels park-wide was studied against the park's Habitat Physical Attribute Classification

(Olson and Franz 1998). Based upon the pixel distribution in relation to this habitat model, the class was assigned to one of several spectral groups, which were viewed as emerging vegetation types.

As the vegetation map "picture" slowly developed, assignment of spectral classes became somewhat easier, especially when pixels were clearly embedded within a contiguous group of previously labeled pixels. Vegetation transect and permanent plot GIS data layers were valuable for "virtual ground truthing", and the same was true of 1:24,000 stereo aerial infrared transparencies (winter scene). In one case, these aerial photos enabled us to correct classification on some coniferous spectral data in a steep, remote, shaded area to deciduous.

RESULTS AND DISCUSSION

Spectral groups were ultimately assigned to one of seven vegetation cover types, creating a condensed vegetation map of the park (see Figure 1 and Table 1), which was completed in January of 1999. The vegetation classification was condensed in order to facilitate designation of fuel types for fire management. For example, the floodplain forest could potentially be spectrally differentiated from connecting mesic hollows, but they are the same fuel type. Discussion of vegetation types below follows the order in Table 1.

In subxeric deciduous forest, chestnut oak and chinkapin oak sort very distinctly with sandstone and limestone substrates respectively, whereas blackjack and post oaks are less selective. With periodic fire, these forest stands may have been a more open woodland or savanna in the past. On the map in Figure 1, both red and orange are shown for this vegetation type since the red spectral class most often indicates the presence of chestnut oak. There is an apparent illumination angle bias probably introduced by the October data since the Landsat satellite passes over at 10:00 AM, and the sun is low at that time of year.

Much of the relatively level plateau fragments, (locally called ridges) which will someday support oak-hickory forest and savanna, were in agricultural use prior to park establishment. Exceptions to this generality are the Big Woods Collie Ridge north of the Green River, and much of the Mammoth Cave Estate visible in Figure 1 as a prominent yellow area on Jim Lee and Mammoth Cave Ridges. Within these mesic upland oak-hickory forests, the chemical and hydrological influence of relatively thin limestone units (currently classified as calcareous subxeric habitat) interbedded with sandstone on the ridges is muted in comparison with the thick limestone beneath karst valleys. This is due to weathered sandstone residuum on top of the limestone, and the limited degree of karst development possible. Karst usually leads to drier surface conditions due to subsurface drainage, but (paradoxically) upland swamps perched on sandstone may have originated as sinkholes in these thinner units such as the Haney limestone. Unfortunately, these upland swamps with stands of pin oak, sweetgum, and red maple are too small to be mapped at the 30 meter resolution of Landsat imagery.

Table 1. Vegetation, habitat types, and typical species. Habitat type nomenclature was adapted from the Kentucky State Nature Preserves Commission system (Evans 1991). "Acid" refers to non-carbonate bedrock, which results in acid soil, and "calcareous" refers to carbonate bedrock, which results in more alkaline soil. Xeric refers to dry areas, mesic to moist, and alluvium to river lain sediments.

Vegetation	Habitat Type	Typical Species
1. Subxeric Deciduous Forest/Savanna	Acid Subxeric	Chestnut Oak Post Oak
	Calcareous SubXeric	Chinquapin Oak Blackjack Oak Post Oak
2. Mesic Upland Deciduous	Acid Mesic Calcareous Subxeric	White Oak Pignut Hickory Black Oak Tulip Poplar
3. Mesic Hollow/Floodplain Deciduous Forest	Calcareous Mesic Alluvium	Sugar Maple Beech Box Elder Sycamore
4/5. Mixed Deciduous/Coniferous Mixed Coniferous/Deciduous Forest	Acid Mesic Calcareous Subxeric Alluvium	Red Maple Tulip Poplar Dogwood Sweetgum Cedar/pine
6. Coniferous Forest	Acid Xeric to Mesic Calcareous Xeric to Subxeric	Virginia Pine Eastern Red Cedar
7. Prairie/Open Area	Calcareous Subxeric Acid Mesic	Native Grasses and Forbs Mown Grass

Mesic hollow forests are most prominent in ravines directly connected with the Green and Nolin River Valleys, but outliers exist in karst valleys in the bottoms of large sinkholes. In addition to beech and maple, black cherry, and black walnut can be locally prevalent. In exceptionally moist hollows mostly found in the northwest extremity of the park, relict stands of hemlock and yellow birch are found. These also are too small to map at 30 meters resolution. Floodplain forests are characterized by sycamore, silver maple, and river birch on river banks, and box elder slightly further from the water. Mesic hollows are relatively undisturbed due to the lack of flat ground, which cannot be said for the once heavily farmed floodplain. Being superbly adapted to the highly disturbance-prone gravel bar habitat, sycamore trees are also found wherever significant soil disturbance has occurred, such as along roads.

Mixed deciduous/coniferous (and vice versa) forests in the park are overwhelmingly successional after pre-park pasture and row crop use. These old fields are generally located in acid mesic habitats (with some interbedded limestones as discussed above) on relatively level uplands, in calcareous subxeric habitat found in karst valleys, and on floodplain alluvium. Mixed xeric communities such as cedar glades, and mixed old field communities could not be spectrally distinguished in this study. A refined, higher resolution habitat model used in conjunction with the satellite spectral data could potentially allow this differentiation. In these xeric habitat types, virginia pine is typically associated with chestnut oak, and eastern red cedar with chinkapin oak. Many of these stands appear to be virgin in contrast to the profoundly disturbed old fields. On xeric limestone sites, solutional features called rillenkarren indicate that the thin soil and exposed bedrock is not due to post settlement erosion. The successional trajectory for old field forests is reasonably clear on the uplands (oak-hickory forest/savanna), and the floodplain (sycamore-boxelder), but in the karst valleys pre-settlement vegetation types are not known. Shingle oak is largely restricted to karst valleys, so this species may have been prevalent, but the big questions are more fundamental: Was the vegetation dominated by prairie, as on similar habitat type on the sinkhole plain? Was it forest dominated? Or was it savanna, a blend of the two? Carbon and oxygen isotope studies of speleothems in cave passages underlying these karst valleys can provide information on major vegetation type and climate (Dorale et al. 1998), and these will be pursued in the future.

Coniferous forests in the park, like the mixed stands previously discussed, are overwhelmingly successional after pre-park agriculture. Stands in karst valleys are dominated by eastern red cedar, and those on sandstone are mostly virginia pine, but considerable mixing occurs. During the time frame of this study, we were unable to spectrally discriminate cedars and pines, but are of the opinion that it is possible. Whether the stands are cedar or pine, indications of ecological succession are visible on the map (Figure 1). Commonly on the uplands around a nucleus of coniferous forest, a zone of coniferous/deciduous forest is found, which is followed by a zone of deciduous/coniferous vegetation, transitional to oak-hickory forest. All elements are not present in each case, but it is certain that forest succession is clearly documented, which no previous vegetation map of the park has been able to show. In the big karst valleys, the current successional trajectory is less clear. In the absence of fire, the karst valleys could easily become a subxeric oak-hickory forest with mesic hollow species in the sink bottoms.

Prairie in the park is limited to small areas each no greater than 40 acres, and none can be considered actual remnants from presettlement times. Even so, these areas are rich in prairie grasses and forbs such as big bluestem, Indian grass, goldenrod, and tall coreopsis. They serve as refuges for species marginalized by conversion of former prairie on the sinkhole plain to agriculture, and by fire suppression within and beyond park boundaries (Seymour 1997). Other open areas in the park are largely mown roadsides, cemeteries, and lawns around developments maintained in fescue.

Accuracy of the map in Figure 1 was judged by field-checking boundaries between different vegetation types. Though some discrepancies exist, especially due to illumination angle bias,

the map is quite reliable and far exceeds the 80% accuracy standards of the National Vegetation Classification System (NVCS). Furthermore, this 80% standard applies at the Formation level (USFWS 2000), which is a physiognomic classification less detailed than the map in Figure 1. NVCS Formations in the park are:

* I., A., 8., N., b., and c. This string of code stands for closed canopy (I) evergreen forest (A), temperate or subpolar needle-leaved (8), natural/semi-natural (N), rounded-crowned temperate or sub-polar needle leaved (b), and conical crowned temperate or sub-polar needle leaved (c). This includes all coniferous forest in the park.

** I., B., 2., N., a., and d. This code stands for closed canopy (I) deciduous forest (B), cold-deciduous (8), natural/semi-natural (N), lowland or submontane cold-deciduous (a), and temporarily flooded cold-deciduous (d). This includes all broadleaf forests in the park.

*** I., C., 3., N. a. This code stands for closed canopy (I) mixed evergreen-deciduous forest (C), cold-deciduous (3), natural/semi-natural (N), mixed needle-leaved evergreen cold-deciduous (a). This includes all mixed forests in the park.

**** V., D., 2., N., a. This code stands for herbaceous vegetation (V), annual graminoid or forb vegetation (D), temperate or subpolar (2), natural/semi-natural (N), tall grassland dominated (a). This includes all prairie patches in the park, some of which may be locally dominated by forbs. Cultivated lawns would fall under C. instead of N., and a. for "annual close grown forbs and grasses, but this is a very minor portion of cover in the park.

CONCLUSION

In the field, the vegetation map produced has been used for the park's Fire Management Plan in the selection of prescribed fire management areas, and classification/delineation of fuel types. In the park's Fire Prevention Plan, hazard fuel zones were partially delineated on the basis of this map. As well, migratory songbird monitoring points were selected using the map in cooperation with the Kentucky Division of Fish and Wildlife Resources. If there is one thing we have learned, it is that vegetation mapping is an iterative process. Future efforts will seek to avoid illumination angle bias, and to achieve higher spatial resolution since plant communities often change on scales much smaller than 30 meters.

References

- Anderson, J., E. Hardy, J. Roach, and R. Whitmer. 1976. *A Land Use and Land Cover Classification System For Use With Remote Sensor Data*. USGS Professional Paper 964, U. S. Government Printing Office, Washington, D.C.
- Badger, K., Taylor, J., Jones, B., and M. Shell. 1997. *Mammoth Cave National Park Forest Vegetation Study*. Ball State University, Muncie, Indiana, p. 1-7, and map.
- Dorale, J., R. Edwards, E. Ito, and L. Gonzales 1998. *Climate and vegetation history of the midcontinent from 75 to 25 ka: a speleothem record from Crevice Cave, Missouri, USA*. *Science*, v. 282, p. 1871.
- Ellsworth, I. 1934. *Forest cover type map survey of proposed Mammoth Cave National Park*. United States Department of the Interior, Office of National Parks, Buildings and Reservations, p. 2.
- Ellsworth, I. 1936. *Forest cover type map of proposed Mammoth Cave National Park*. United States Department of the Interior, Office of National Parks, Buildings and Reservations
- Evans, M. 1991. *Kentucky ecological communities* (Draft). Kentucky State Nature Preserves Commission, Frankfort, KY.
- Faller, A. and M. Jackson. 1975. *The Plant Ecology of Mammoth Cave National Park, Kentucky*. Indiana State University, Terre Haute, Indiana, p. 41, 126.
- Hambly, F. 1966. *Mammoth Cave National Park Resources Management Plan*. p. 35, plus attached map stored in the park curatorial facility.
- Olson, R., and M. Franz. 1998. *A Vegetation Habitat Classification for Mammoth Cave National Park*. Proceedings of Mammoth Cave National Park's Seventh Science Conference, p. 19.
- Prentice, G. 1993. *Archaeological Overview and Assessment of Mammoth Cave National Park*. Volume I, Southeast Archaeological Center, National Park Service, Tallahassee, Florida, p. 8.
- Seymour, R. 1997. *Wildflowers of Mammoth Cave National Park*. University Press of Kentucky, Preface.
- USFWS. 2000. *GIS Vegetative Cover Mapping TEC7134*. U. S. Fish and Wildlife Service, National Conservation Training Center, Shepherdstown, WV, p. 141.

The Girkin Formation of Western Kentucky

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ABSTRACT

The Early Girkin Formation is a shallow-water, carbonate-dominated unit in west-central Kentucky in the southeastern part of the Eastern Interior basin. The Girkin lies between the Ste. Genevieve below and the Big Clifty Member of the Golconda Formation above. Carbonates in the Girkin are usually fossiliferous or oolitic calcarenites. Cyclic clastic-rich intervals are represented by thin shale and shaley carbonates; coarse-clastic sediments are rare. Beyond the occurrence of the Girkin Formation, the unit is split into a number of smaller formations as the cyclic clastic intervals thicken and coarsen. The Girkin at present is poorly defined and the interpretation of formation boundaries varies among authors. For purposes of this study, the Girkin Formation is informally divided into three members.

*The lower member of the Girkin comprises two major coarsening and shallowing-upward carbonate sequences overlain by paleosols, which locally contain clastics. Species of the crinoid *Talarocrinus* serve to differentiate the lower member from the lithologically similar Ste. Genevieve Formation.*

Beds in the middle member are predominantly carbonates, but several persistent clastic rich horizon are present near the middle. The carbonates in this interval reflect coarsening-upward sequences, but local fining-upward sequences are present. Oolitic beds are common. In places paleosols are present near the top of the member. Upper parts of the middle member may be absent due to pre-Big Clifty erosion.

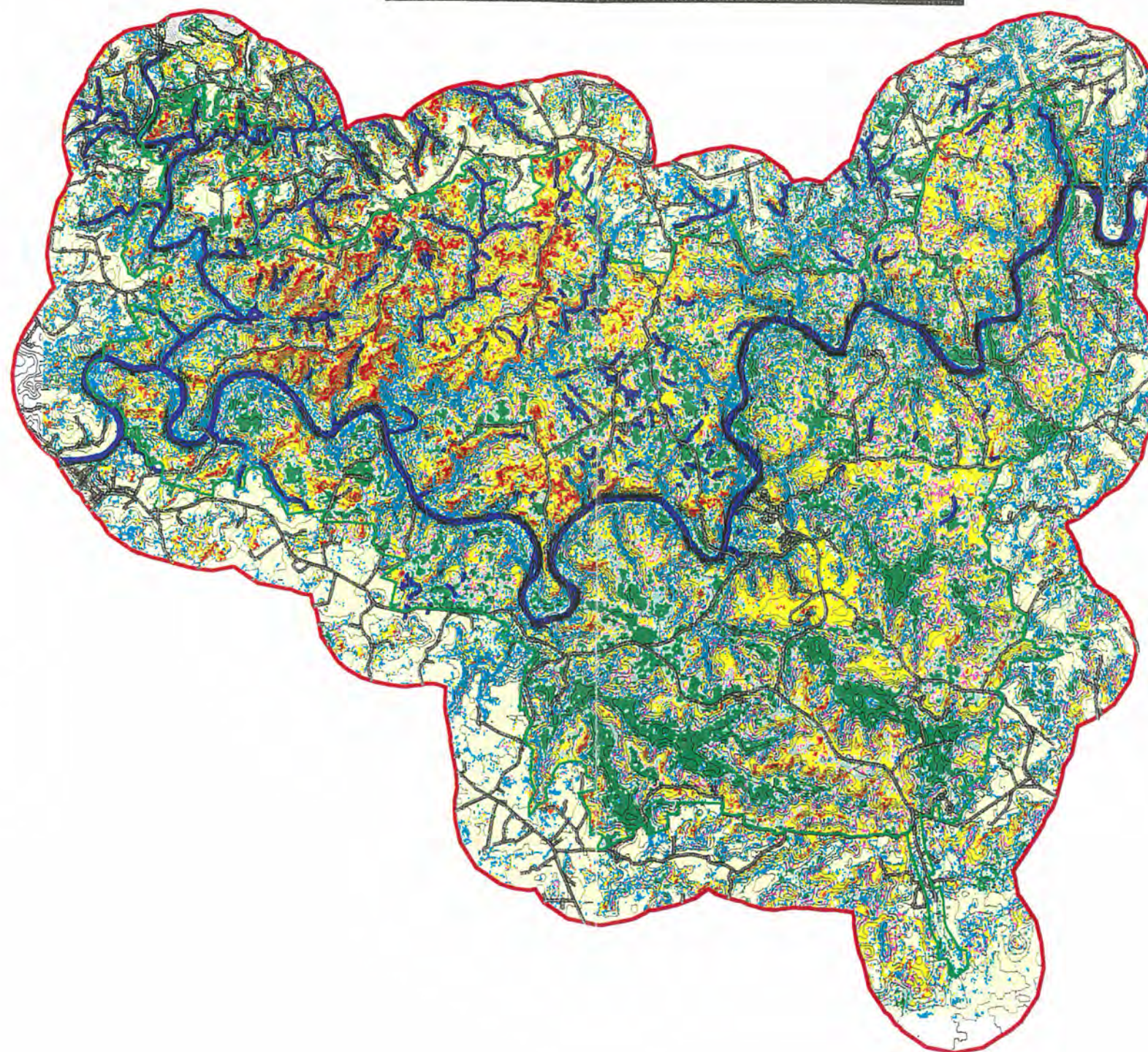
The upper member consists of a basal shale-rich horizon with locally developed paleosols and an upper, coarsening-upward, carbonate. Species of productid brachiopods are distinctive in both clastic and carbonates. Locally the upper member is partially or wholly absent due to pre-Big Clifty erosion, and locally the upper member is gradational with the shale and sandstone dominated Big Clifty Member of the Golconda Formation.

Facies and lithologic changes in the Girkin occur both perpendicular and parallel to basin strike. Changes are probably related to distance from source areas, and to syn- and post-depositional structural activity.

Figure 1. Condensed Vegetation Map
Mammoth Cave National Park
January 1999

Cover Type	Typical Species
SubXeric Deciduous Forest/Savanna	Chestnut Oak Post Oak Chinkapin Oak Blackjack Oak
Mesic Upland Deciduous Forest /Savanna	White Oak Pignut Hickory Black Oak Tulip Poplar
Mesic Hollow/Floodplain Deciduous Forest	Sugar Maple Beech Box Elder Sycamore
Mixed Deciduous/Coniferous Mixed Coniferous/Deciduous Forest	Red Maple Tulip Poplar Dogwood Sweetgum Cedar/Pine
Xeric - Mesic Coniferous Forest	Cedar/Pine

Note: At the 30 meter resolution of Landsat data, hemlock stands in deep hollows, and upland wetlands are marginally represented. Cedar stands within the park are mostly successional, but natural cedar-oak glades do occur on southerly slopes.



Legend

- Mammoth Cave National Park Boundary
 - MCNP Boundary Buffer (1 Mile)
 - MCNP Roads
 - Surface Hydrology
 - Contours (40 ft Interval)
- Cover Types**
- SubXeric Deciduous Forest/Savanna
 - "
 - Mesic Upland Deciduous Forest/Savanna
 - Mesic Hollow/Floodplain Deciduous Forest
 - Mixed Deciduous/Coniferous Forest
 - Mixed Coniferous/Deciduous Forest
 - Xeric - Mesic Coniferous Forest
 - Open Area/Prairie



1 0 1 2 Miles

Digital Database Project of the Cave Research Foundation

Don Coons

ABSTRACT

The beginning of the new millennium marks the end of the forty fourth year that the Cave Research Foundation has been collecting cave survey data in and around the Mammoth Cave area. Beginning with the Ohio Grotto efforts during the NSS sponsored Collins Crystal Cave epic, the grid of ever increasing survey lines has expanded outward to include Unknown, Salts, Colossal, and finally the link to Mammoth Cave. Ongoing efforts now include Proctor, Lee, Logsdon-Hawkins River and most of the smaller caves within the park boundaries. Together with the efforts of the Central Kentucky Karst Coalition in Roppel, this work now includes more miles of connected survey within a single cave than any other caving area in the world. More than three fold longer than the nearest competitor.

In total more than 4500 individual survey books have been generated in this effort to document the worlds longest cave. With an average of 35 stations per book, the total estimated number of individual survey points within the system has passed the 150,000 mark. Managing a data base as large as this one has become a truly monumental effort. It was realized several decades ago that using paper as an archival medium was quickly going to become an unwieldy proposition.

In the early 70's Will Crowther and Bill Mann pioneered the effort to begin entering this mountain of material into the large mainframe computers available to them at the time. Original efforts were stored on punch cards. Since that time the technology has progressed from large format magnetic tapes, to 5.5 inch floppy discs, 3.5 inch floppy discs and on today to zip discs and CD Roms. CRF volunteers have made a valiant effort for nearly four decades now to keep pace with these changing technologies. Through the efforts of Lynn Brucker, Dave Hanson, Mel Park, Paul Hauck, Richard Zopf, Scott House, Bob Osburn and many others much of the CRF data generated throughout this ongoing effort has been entered into a computer base.

One problem arising as a result of the changing technologies has been the inconsistency in programming and hardware available to the successive generations of CRF cartographers. Over the years they have worked in at least twelve different software formats on an untold number of ever more sophisticated machines. It has only been the advent of the Pentium class PC's coupled with today's software developments that has finally brought the technology to a level that is capable of handling the entirety of the Mammoth Cave System on a single home computer.

The current phase of CRF digital data development is, then, an effort to combine this accumulated work of the past forty years. The first step was to find all of the individual copies of data archives, find equipment and programs to read them, and begin the process of converting everything into a single compatible format. The program chosen for this effort is named COMPASS. It's primary features of

robust dependability, readily available support, and ease of conversion to other formats have proven it to be a very successful platform for this effort. This original phase of the project has now been completed. Everything ever entered is now running in the COMPASS base.

The next step was creating an index to list all of the information that is running and, more importantly, all the information that is still sitting in the original survey books and has never been entered into any program. File Maker Pro was chosen as the format for this information in order to be compatible with the CRF trip report data base. This index is now complete and reveals that nearly 85% of the entire data collection is now running in a computer format. Data entry is currently being lead by a team of CRF volunteers. Completion of the remaining 700 or so books is expected by the end of the year 2001. This presentation is a demonstration of the capabilities of the virtual reality cave map that this ongoing effort has produced.

Mammoth Cave Cartographic Program-

A multi-step program consisting of Surveying, Data Processing and Management and Map Production

**Bob Osburn,
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CRF Eastern Operations Area**

ABSTRACT

Mammoth Cave and other large systems present a challenge to cave cartographers. It is a thrill to do one of the big ones but from the practical side the project becomes so large that the major job becomes project management rather than drafting. CRF's Mammoth Cave project has a long history and some notable accomplishments. It has surveyed more than 350 miles of cave and produces a variety of maps from that survey including the "Postcard" Map, "Poster" Map, and the Flint Ridge Folio among others. All of the early system wide maps are small scale. Expectations as to how much detail a cave map should show had increased by the 1980's and a project was begun to produce detailed maps of the entire system at as large of scale as was practical. It was judged that this scale was 1:600. This project continues today as a major part of CRF cartographic effort. Reports were given on this project at the 1996 and 1997 Mammoth Cave Science Conferences. This report provides an updated overview of this project and a discussion of changing conditions and the ways the project will or might react.

The Mammoth system is divided into approximately 50 map areas or sheets. Individual cartographers oversee work on one or more map sheets. Most of the work is carried out by standard methods. Survey is accomplished with Suunto compasses and clinometers and fiberglass survey tapes. CRF is slightly more rigorous than many projects in that we make two measurements, a fore and back shot, for each survey vector to eliminate blunders. Data are processed by reducing survey vector data to Cartesian coordinates based on a 0,0,0 point at Walker benchmark TT8W at the Violet City Entrance. A planar grid is used rather than a mathematically more complex map projection. Data processing is accomplished entirely by computer. At the time of the last report the program SMAPS was extensively used but it has largely been supplanted by WALLS or COMPASS. Survey and data processing are the quick part of any cave cartography process. Actual map drafting requires a higher skill level and commitment of large amounts of time after the exciting "in cave" stage. About 150 people regularly participate in Mammoth surveying but fewer than 10 manage sheets and regularly draw maps. The "Area" maps are drafted on 42 inch wide mylar of variable length to fit the morphology of the cave. An initial pencil working draft is maintained on gridded mylar until the area is finished. The working map is then overlaid with plain mylar and the final draft traced in ink. Completing the 1:600 series of maps will take several more years even at maximum effort.

In addition to the "Area" maps, several newer projects are moving forward due to the innovation and energy of individual Cartographers. Mike Yocum is devising methods to transfer survey lines and maps

into GIS systems and Don Coons has compiled most of the hundreds of miles of Mammoth Cave survey into a single data set. These projects are reported on separately at this meeting. Further, experimentation with drawing cave maps on the computer as vector graphic files shows good potential, perhaps even to the extent that some of the 1:600 Area maps will be drawn that way. Computers as map making tools hold great promise. GIS systems allow production of maps in minutes that would have taken years by other methods if they were ever undertaken at all. This also represents a danger in that maps easily made may not be thought out as well as ones requiring more labor. Secondly, as amply demonstrated by the recording industry recently, intellectual title to electrons is a lot harder to maintain than title to a 8 foot long piece of mylar. No cartographer wants to spend years crafting a map only to have it or the derivative maps published by someone else.

Hydrologically Valid Delineation of Watershed Boundaries in Kentucky's Karst Terrane

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EXTENDED ABSTRACT

The delineation of valid hydrologic boundaries in soluble-rock terrane requires tracer-testing of the karst aquifer. The well-known karst aquifers of Kentucky are composed of contiguous groundwater drainage basins which commonly do not coincide with surface watershed configurations.

Hydrologic Unit Code (HUC) watershed maps in karst areas of Kentucky have been delineated by the US Geologic Survey and cooperating agencies (1997) based on surface drainage criteria without consideration of subsurface conduit hydrology. Published groundwater maps and data illustrating trunk groundwater flow paths were not used in the HUC project. In order to represent true hydrologic units, a region's karst groundwater drainage must be considered. The fact that *groundwater divides in soluble rock terranes do not always coincide with topographic divides*, has not been adequately evaluated in the production of these important maps.

The HUC delineation project used the concept of "non-contributing areas", which is defined as "areas that do not flow toward the outlet of the hydrologic unit". A "non-contributing area" on the boundary between two or more hydrologic units was included in the hydrologic unit adjacent to the lowest point of the "non-contributing area" boundary. A karst area's subsurface drainage was effectively ignored by its designation as a non-contributing area. Drainage from large surface watersheds may deviate, through a karst conduit, beneath a topographic divide to an adjacent basin. Consequently, the unfortunate designation of "non-contributing areas" has inevitably resulted in several cases of the hydrology of certain karst watersheds being attributed to the wrong river basin.

A comparison of tracer-delineated groundwater drainage basins with these topographic basins reveals that a significant percentage of the HUC basins in karst regions fails to coincide with actual hydrologic basins on two levels:

- 1) The HUC boundaries are incorrect where they attribute drainage of an area to the wrong watershed (under all flow conditions). [Although HUC boundaries do not distinguish between flow conditions, karst groundwater flow elevations and directions may change due to varying hydrologic conditions, and therefore must be considered when mapping karst drainage.]
- 2) The HUC boundaries are inaccurate when they attribute drainage to the wrong watershed, even though some portion of high-flow discharge does intermittently follow surface channels or overflow springs to the attributed basin.

For example, a large karst watershed, located in Barren and Edmonson counties of the Green River basin, is hydrologically mismapped where an 8-digit Cataloging Unit boundary incorrectly attributes about 85 mi² of the Green River basin to the Barren River. This error exaggerates the latter's basin by nearly 4%. Base-flow and high-flow drainage from this 85 mi² area has been traced by fluorescent dyes to large springs on the Green River rather than the Barren River. These traced groundwater basins were originally published by Quinlan and Ray (1981) and have been republished at scale of 1:100,000 (Ray and Currens, 1998).

Additionally, in Christian and Trigg counties within the Cumberland River basin, an 11-digit Hydrologic Unit boundary inaccurately attributes about 22 mi² of the Little River basin to the Sinking Fork basin. The Sinking Fork watershed does receive a portion of this basin's high-flow drainage via overflow springs and channels, but it's summer base flow drains exclusively to the largest spring on the Little River. Similar inaccuracies involving six karst drainage basins have been determined for about 40 mi² in Meade and Breckinridge counties.

To date, the actual hydrology of about 250 mi² of three different karst areas of the Mississippian Plateau, or about 15-20% of the mapped karst aquifer, varies from HUC topographic watersheds. Individually, however, the majority of a karst watershed could be incorrectly attributed. For example, about 75% of the Green River's Turnhole Spring karst watershed is included in the Barren River basin.

A basic principle of karst watersheds has been ignored since the HUC maps signify hydrologic rather than mere topographic divisions. If environmental-protection work, land and water-resource management activities, hydrologic balance calculations, flood-control structure-design calculations, or water-supply planning assessments in karst terrane were based on existing HUC maps, serious errors could result.

Although topographic divides are often used when estimating karst-basin boundaries, an important practice is the illustration of these inferred karst divides with broken lines, which more accurately reflects their imprecise nature. At a minimum, topographic divides in karst terrane should be depicted on HUC maps with *dashed or dotted lines* where the true nature of perennial stream flow and groundwater drainage is unknown. Traced groundwater-basin delineations should be utilized where available. Also, a *caveat*, alerting the user to the potential noncongruity between topographic basins and karst watersheds, should be prominently displayed in the karst regions of these maps. One must recognize, and advise the user of HUC maps, that topographic divides are unreliable when mapping valid hydrologic units in karst terrane.

Update on Dye-Tracing Efforts at Mammoth Cave National Park

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INTRODUCTION

Since the first dye-trace was performed at Mammoth Cave in 1925 – Anderson, working for Louisville Gas and Electric, conducted several traces, including Three Springs to Echo River Spring, to demonstrate that groundwater can travel through adjacent ridges which would pose engineering problems for a proposed high-dam on the Green River near Pike Spring (Brown, 1966) – dye-tracing has been used as the primary investigative tool for understanding, and thus, protecting the karst aquifer. A tremendous effort was directed by Dr. Jim Quinlan in the mid 1970's through the early 1980's, and resulted in the excellent and much used map "Groundwater Basins in the Mammoth Cave Region, Kentucky (Quinlan and Ray 1981, 1989). During the early 1990's Meiman and Ryan concentrated dye tracing efforts to the north side of the Green River where 16 groundwater basins were defined (1992). There have been many "specialized" traces over the past ten years, including a series of quantitative traces by Ryan (1992), flow-velocity traces by Murphy (1992), flood pulse tagging Hall (1994) and Ryan and Meiman (1996), and traces along Interstate 65 by Meiman and Capps (1995). It cannot be overstated that without these works we would know very little about the overall hydrogeology of the Mammoth Cave karst aquifer. It should be noted that the current work is by no means designed to refute the findings of these earlier studies, but to merely improve and expand our knowledge base.

Within the past year there has been a renewed interest in dye tracing at Mammoth Cave, as evident by 15 dye injections since late May of 1999. While at first glance it might appear that

the groundwater basin definition gained by these earlier studies have provided all the information needed to fully delineate karst groundwater basins in and around Mammoth Cave National Park, we have found it necessary to further these efforts with additional tracing.

The foremost reason is a matter of scale and resolution; as the areal distribution of traces, which define the groundwater basins, is quite lacking in detail proximal to many basin divides (Figure 1). In some cases there are several kilometers between injection sites with basin divides drawn somewhere in between, and in large part based upon groundwater potentiometric data. In areas where this condition exists in combination of potential threats to groundwater quality (primarily urban and transportation areas) additional tracing is needed to know the flow paths of individual recharge points. This situation is best represented in the Cave City area where the boundary between the Turnhole Spring groundwater basin (which drains northwestward into the park) and the Gorin Mill groundwater basin (which drains to the east through Hidden River Cave). This three-kilometer portion of boundary, through the ever-developing section of Cave City, is defined by three dye traces.

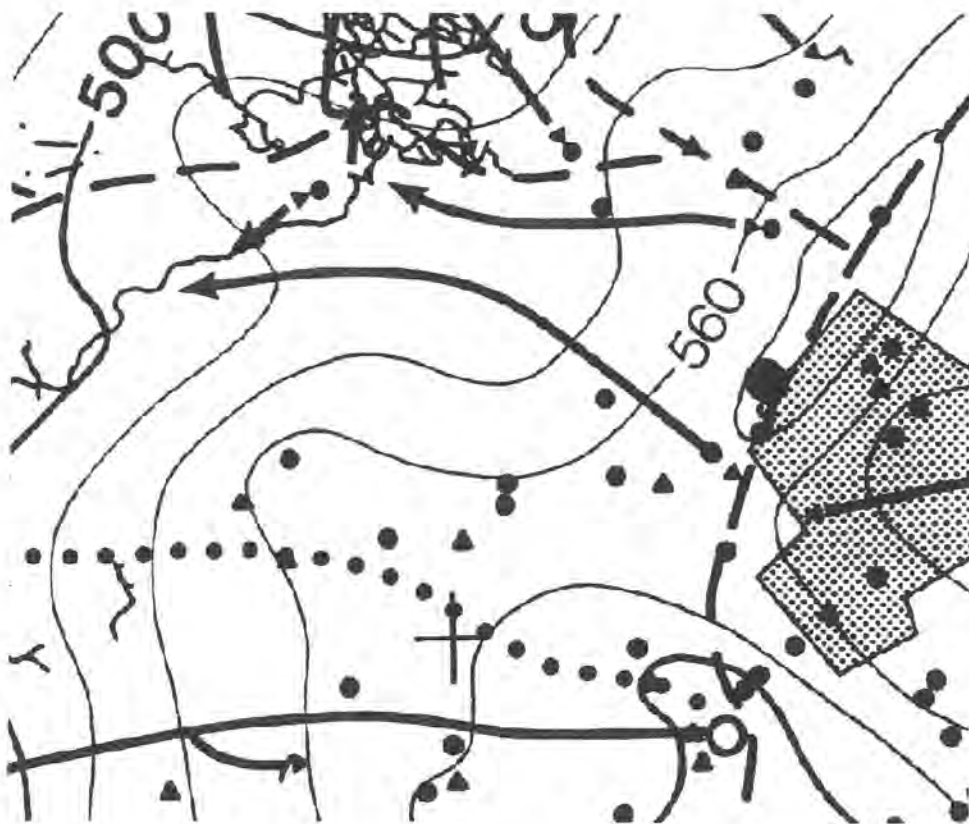


Figure 1. A portion of the 1:138,000 scale map "Groundwater Basins in the Mammoth Cave Region, Kentucky", Quinlan and Ray (1989).

A secondary reason for additional traces, is to increase our understanding of the plumbing of active conduits through the karst aquifer. For the most part past tracing efforts have focused on surface injection points and spring recovery points. We know, for example, that if a dye is introduced into a sinkpoint on the surface, and emerges at a spring, that the dye course has traversed active flow cave conduits. It would be very helpful, in respect to examining cave evolution and development, if a more detailed picture of the flow routes were described. As one could imagine this type of dye tracing is logistically demanding (requires visits to cave dye recovery locations), it can be very rewarding. This in-cave tracing will be the main focus of this paper.

NEW DATA WITHIN PREVIOUSLY DESCRIBED GROUNDWATER BASINS

Turnhole Spring Groundwater Basin

The 244 km² groundwater basin, by far the largest contributing flow into the park, has been the focus of scores of studies and water quality initiatives over the past 25 years. It is divided into the Mill Hole, Proctor, Cave City and Patoka Creek sub-basins. Each sub-basin is drained by a main trunk conduit: the Mill Hole stream, Hawkins River (Red River in Whigpistle Cave) Logsdon River, and Hawkins River, respectively. The vast majority of the sub-basins are wonderfully under-represented by accessible cave streams. We know that there is active cave passages within these areas, but, for the most part, cannot gain access — usually due to passage collapse or sumps.

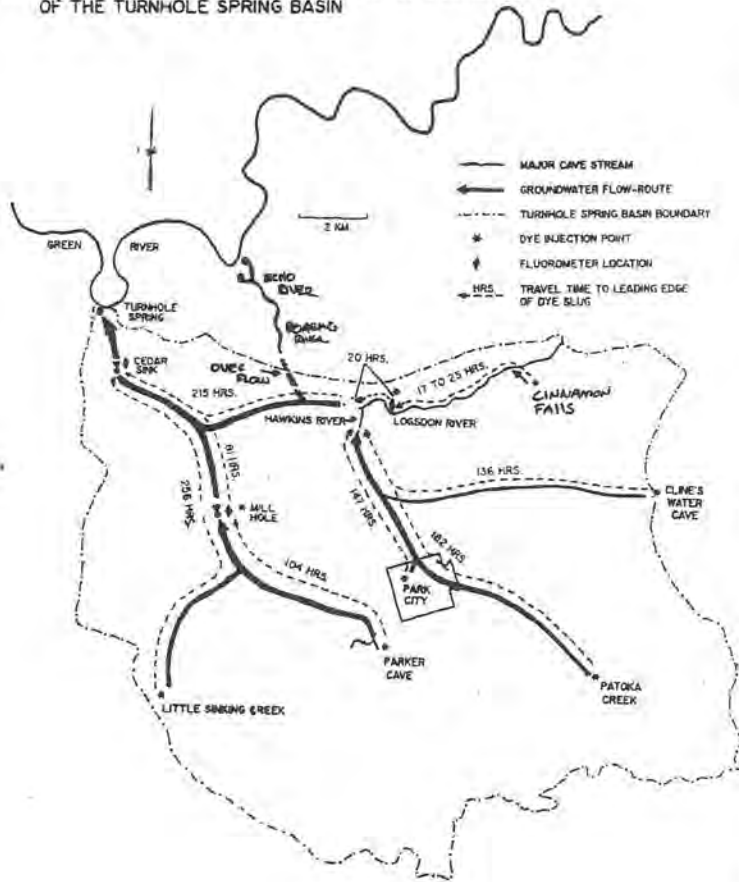
Denial River

The portion of the Cave City sub-basin adjacent to the boundary of the Pike Spring basin within Roppel Cave presents a refreshingly atypical situation, as many active flow passages are present. Near the upstream termination of Logsdon River at the S-188 Sump lies a complex tangle of small stream passages, one of which is called Denial River. This upstream portion of Logsdon River is also geological compelling as Logsdon is apparently perched atop the Corydon Chert for much of its eight kilometer traverse downstream to P. Strange Falls. There have been numerous air-filled stream passages found at elevations above and below Logsdon River in this area. Denial River seemed like a good place to start to unravel this picture. Previous traces show that lower streams in this area, the flow from the Western Kentucky Parkway for example, drains northwards to Pike Spring. On October 19, 1999 approximately 0.5 kg of power eoscin dye was injected into Denial River, which receives flow from a series of vertical shafts. Dye was recovered within two weeks at P. Strange Falls and not at Pike Spring, showing that Denial River is a tributary of Logsdon River. This was the first in a series of traces from this area of the cave and many more traces will be necessary to fully understand its complex plumbing.

Turnhole-Roaring/Echo Overflow

During the flurry of dye tracing in the late 1970's and early 1980's, Jim Quinlan and Joe Ray discovered the existence of a high level overflow route linking the main trunk of the Proctor sub-basin (Hawkins River, to which Logsdon is a tributary) to the Echo River Spring groundwater basin (Quinlan and Ray, 1981 and 1989). This overflow junction is inaccessible due to sumps in all river passages leading to it. Meiman and Ryan injected dye into Logsdon River on the recession limb of floods and demonstrated that this overflow route – taking a portion

ASE-FLOW TRAVEL TIMES THROUGH VARIOUS SEGMENTS OF THE TURNHOLE SPRING BASIN



of Hawkins River, which flows to Turnhole Spring during low flow conditions, and reassuming its original route into the head of Roaring River during overflow conditions– is active when the stage of Logsdon River near its confluence with Hawkins exceeds three meters over base flow stage (Figure 2) (Meiman and Ryan, 1993). This was important information as the Echo River groundwater basin, which is almost exclusively within park boundaries during low flow times and harbors the endangered Mammoth Cave Shrimp, receives flow from nearly 100 km² of lands beyond the park boundary when Logsdon River stage is greater than three meters. Stage excesses of three meters is quite common. A reconstruction of float level records between 1984 and 1988 shows that this horizon was exceeded 38 times; periods when the aquatic ecosystem of Roaring and Echo Rivers were recharged largely by non-park lands.

Figure 2. Hydrogeology of inter-basinal overflow, with base-flow groundwater travel velocities tossed in for good measure (Murphy, 1992).

Some discoveries are unintentional. On April 24, 2000, in support of a pesticide flood pulse-sampling effort, approximately two kg of powder fluorescein dye was injected into the Big Clifty/Girkin contact swallet at Cinnamon Falls. Under almost any other circumstances rational investigators would not use such a copious quantity of dye. However, this trace, injected

on the leading edge of a forecasted large rainfall event, was designed to place a sufficient amount of dye to "tag" a flood pulse and to detect in grab samples some five kilometers downstream in Logsdon River. Rainfall was intense during the injection, however within minutes after the dye was underground the rain event stopped. It did not rain again for weeks. We now had 2 kg of fluorescein slowly coursing through base-flow cave streams. Ouch! The flood pulse sampling operation was aborted. Two weeks later, while collecting dye receptors along the Green River, the Echo River Spring site exhibited a very strong presence of fluorescein. The highest stage in Logsdon River since the injection was approximately 0.5 meters above base level. A subsequent dye receptor recovery at the First Landing of Roaring River (upstream portion) also showed a strong positive. Dye (thus water) is leaking into Roaring/Echo Rivers from Logsdon/Hawkins Rivers during base flow. We believe that this flow route was not observed by previous investigators because, until now, no one had made the mistake of using far too much dye during base flow conditions, as "normal" quantities of dye would dilute into Roaring/Echo Rivers in concentrations below detection limits.

What does this mean? One possible explanation, relative to speleogenesis, is that we are witnessing the earliest stages of groundwater basin piracy. For many years Hawkins and Logsdon Rivers were the upstream portion of Roaring/Echo Rivers. At some point – perhaps due to a retreating nick-point in the Green River passing the Turnhole Bend – a more efficient route was established pirating flow from Hawkins River to Turnhole Bend Spring. Over time, as this piracy became the dominant flow route, the original route into Roaring/Echo was only used during high-flow periods as an overflow. It may be possible that this low-level "leak" marks the beginning of Roaring/Echo taking its flow back. Another explanation may be that the present overflow route, although a large, higher conduit, is simply wrought with many small "leaks" at lower elevations.

It is also possible for dye introduced into Logsdon River to find a secondary route before it even reaches the confluence of Hawkins River and the downstream sump and overflow area (first thoughts that the dye may enter Roaring/Echo via Mystic River, however that idea was discounted as dye receptor at the First Landing, which is far upstream of the confluence of Mystic, was positive). It remains possible, however, that the dye is taking an unknown route to the upstream segment of Roaring River. In order to put this mystery to rest, later this autumn we will introduce dye; at base-flow conditions, into Cinnamon Falls and immediately upstream of the Hawkins River sump.

Aside from a hydrogeologic curiosity, what relevance does this have to cave management and protection? The discovery of the overflow route brought about major changes to conservation efforts of park managers, as it was proven that the sewer-less community of Park City flowed directly into endangered species habitat of the main active flow trunk of Mammoth Cave. This discovery was extremely important to the realization of the regional sewer system. Until now, we thought at least Roaring/Echo River would be spared contamination events during low flow. Not anymore.

Crystal Cave

Perhaps because Cooper and Collins Springs (both Haney Limestone springs perched upon the Big Clifty Sandstone) are well within the delineated bounds of the Pike Spring groundwater basin they, as far as we can tell, have never been traced. With the assistance of Art and Peg Palmer, we placed dye receptors at six locations within Crystal Cave and introduced dye into the Big Clifty/Girkin contact swallets of Cooper and Collins Springs. Both dyes appeared at Pike Spring as suspected. Although the trace from Cooper Spring (located near the intersection of Collins and Flint Ridge Roads) was not found in the waters of Crystal, the trace from Collins Spring (located 900 m north of Cooper) was detected in a strong positive at the C-3 Waterfall Campsite. We have not given up on finding and in-cave recovery point for Cooper Spring. This fall we plan on setting a dye receptor in the western stream of Sides Cave and run the trace again.

Outward Bound

In support of a Western Kentucky University's Hoffman Environmental Research Institute study of land use delineation for the US Fish and Wildlife Service a trace was initiated from the eastern-most known stream in Roppel Cave, therefore, the eastern most stream in the Mammoth System. It seemed very possible that this stream recharged the proximal Suds Spring along the Green River. If so, this would mean that the Mammoth Cave System span seven groundwater basins and sub-basins – perhaps adding additional relevance and protection to the Suds Spring basin. Just to let the reader know that not all traces we perform produce spectacular and shocking results, the Outward Bound trace flowed to Pike Spring, nonetheless, adding new hydrogeologic information.

Three Springs

As mentioned in the introduction, the first dye trace in the Mammoth Cave area was performed at Three Springs. Quinlan and Ray traced this perched Haney Spring to Styx Spring. Meiman and Ryan found both Echo River Spring and River Styx Spring to receive flow from Three Springs. During the late fall of 1999 dye was again introduced into the Big Clifty/Girkin contact swallet of Three Springs, except this time, in addition to placing receptors at Echo and Styx Springs, we also monitored eight locations along River Styx in the cave. All receptors were positive – from the First Arch to the Dead Sea in the Cave, as well as Echo and Styx Springs. Although the Styx/Echo conduits were not experiencing a flow reversal event (water from the Green River entering Styx Spring, running through the cave and exiting at Echo River Spring), the system was not quite at base-flow levels. The flow conduit from Three Springs may enter the Echo/Styx Rivers upstream from the flow bifurcation of Echo River (see the next trace description to further examine the relationship between Echo and Styx). Additional tracing is needed, with receptors placed in Roaring and Mystic Rivers to pin-down its location.

An additional curiosity was found last autumn when Park Ecologist Rick Olson removed a visitor-constructed rock dam at Styx Spring. The removal of this dam, which increased the pool elevation of Styx Spring by several centimeters, did not register with the stage monitoring probe in the Dead Sea (which can resolve stage changes of 0.01 mm). This may indicate that there exists a free-surface segment of River Styx between its sump, as the change in stage was not propagated to the Dead Sea from Styx Spring.

Service Station

All parking lots within Mammoth Cave National Park drain into the cave system. The lot surrounding the service station near the main campground is no exception. During the fall of 1999 we injected dye into the Big Clifty/Girkin contact swallet behind the service station after placing receptors throughout the River Styx area on the cave. It should be noted that five Mammoth Cave Shrimp were observed while placing receptors in the Hades section of River Styx. The highest elevation that dye was recovered was Shaller's Brook (a shaft drain off of Gratz Avenue). From there, after dropping through Lee's Cistern, the dye appeared at Hades, River Styx, the Dead Sea, and Styx and Echo River Springs. The park will soon begin construction of oil separation filters on all major parking lots within the park.

The fact that dye which entered River Styx via the Hades lead – which is at the downstream end of Styx near the Dead Sea and well downstream of the Echo-Styx split – was also detected at Echo River is perplexing. Recall that the trace from Three Springs also appeared in Styx and Echo Springs, although that injection site was well distal and upstream of the Echo-Styx bifurcation. The service station trace was also conducted under “normal” flow conditions, that is to say, low-flow and no flow-reversal. Is it possible that a second conduit exists between River Styx and Echo River downstream of the River Styx sump? A rather simple trace will be performed (dumping dye into the Styx sump) this year.

NEW DATA WITHIN PREVIOUSLY UN-DESCRIBED GROUNDWATER BASINS

Floating Mill Hollow

Upon close inspection of the map “Groundwater Basins of the Mammoth Cave Region, Kentucky” (Quinlan and Ray, 1989) one might find a few apparently minor springs along the Green River for which their recharge area is unknown. Upon a field inspection, you may find an occasional small spring along the Green that does not appear on this or any other map. One such spring was found near the mouth of Floating Mill Hollow. Most of the time this spring does not appear to flow, as like Running Branch, Mary Parker and other small springs, base-flow is discharged into the riverbed through alluvial filled under-flow spring. Basically, the surface springs orifice, where the dye receptors were placed, acts as an overflow discharge.

In the late spring of 1999 we placed receptors in all known springs from the upstream park boundary to Echo River Spring in preparation for a trace from Candlelight River, a small shaft drain stream along the famous Flint Ridge-Mammoth Cave connection route of 1972. According to the aforementioned map, Candlelight River should drain to Pike Spring. A few CRF “old-timers” also had opinions on the spring that receives water from Candlelight – either Pike or Echo River Spring (“Everyone knows that all streams before the “Tight Tube” drains to Pike”, or “What? All that water heads to Echo”). If nothing else, dye-tracing came be a humbling enterprise: the dye appeared at neither Pike nor Echo, rather the newly discovered Floating Mill Hollow Spring (Figure 3). A new watershed was being defined.

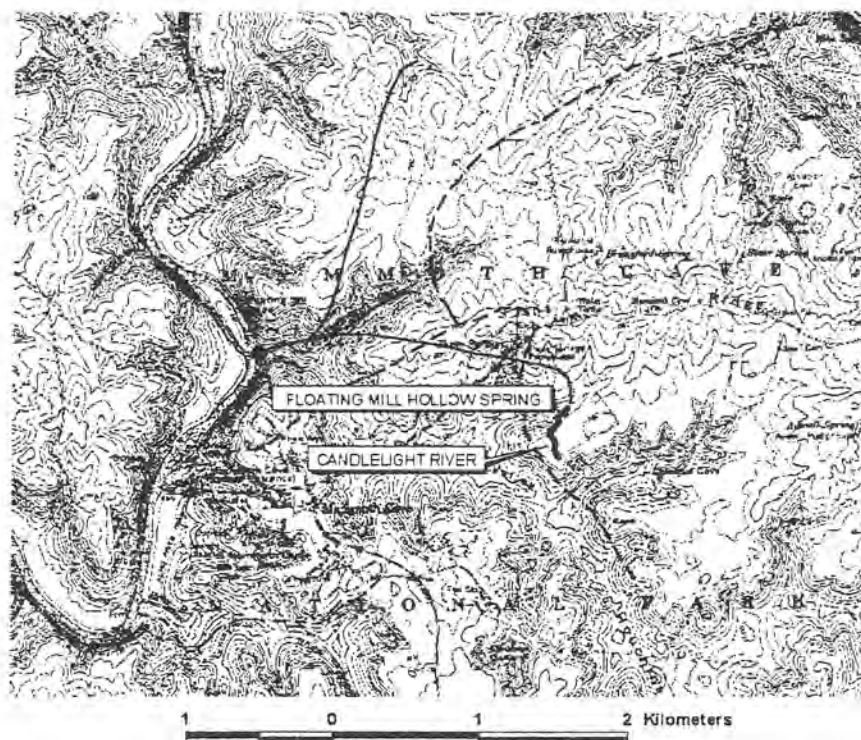


Figure 3. Dye traces to Floating Mill Hollow Spring. Dashed lines, Quinlan and Ray (1989) groundwater basin boundaries; dashed line to Styx Spring, Quinlan and Ray (1989) hypothesized flow route; solid lines, hypothesized flow routes from recent traces.

The fact that Candlelight River, which was originally placed within the Pike Spring basin, drains to Floating Mill Hollow Spring is of particular interest as in order to reach Floating Mill Hollow Spring it must either pass over, under, or around the Three Springs portion of the Echo River basin. Although we do not have direct evidence for any of these three possibilities, it will not present a deterrent from hypothesizing. It seems quite possible that the flow route from Candlelight River actually passes over the conduit draining Three Springs. As far as we know the shaft complexes beneath such large Haney springs such as Three Springs have not been discovered – if a cave explorer is interested in finding the largest vertical shafts in the Mammoth Cave System we have some ideas on where to look. The fact that they exist should

not be an issue, as even non-descript sink-points can produce large shafts (Bottomless Pit is a good example). Given that a shaft exists beneath Three Springs, it is very likely that it is very large and deep, as it receives perennial flow from Three Springs in addition to runoff from rainfall events. It is possible that such a shaft cuts deep to base-level, ignoring lithologic changes. Conversely, a small shaft drain as Candlelight River is perched upon local resistant lithologies. This perching can cause a small stream to run horizontally for several hundred meters before it falls towards base-level.

The discovery of a new groundwater basin led to two additional traces. Receptors were placed at Bögli Shafts and the river springs for a trace originating from the Big Clifty/Girkin contact swallet above the shafts. This trace was also recovered at Floating Mill Hollow Spring, however the receptors at Bögli Shafts were negative. It is very possible that individual shafts have such specific inputs that it is difficult to always make a connection.

A third trace was recovered at Floating Mill Hollow Spring from a trace initiated from the Big Clifty/Girkin contact swallet of Holton Hollow (the sinkpoint approximately 2.25 km north-northeast of the spring). Additional traces are planned for Rigdon, Taylor Coats, and an unnamed hollow, all which lie between Holton and Floating Mill Hollows.

Great Onyx

The small springs, one an underflow and one an overflow, at the mouth of Great Onyx Hollow were also blank areas on our hydrogeologic maps. During the spring of 2000 two dye traces were performed at Big Clifty/Girkin contact swallets about 800 and 400 meters south of the Green River (Figure 4). Both traces were recovered at the overflow spring (the underflow spring is used as a low-flow monitoring site). Additional traces are planned for this basin.

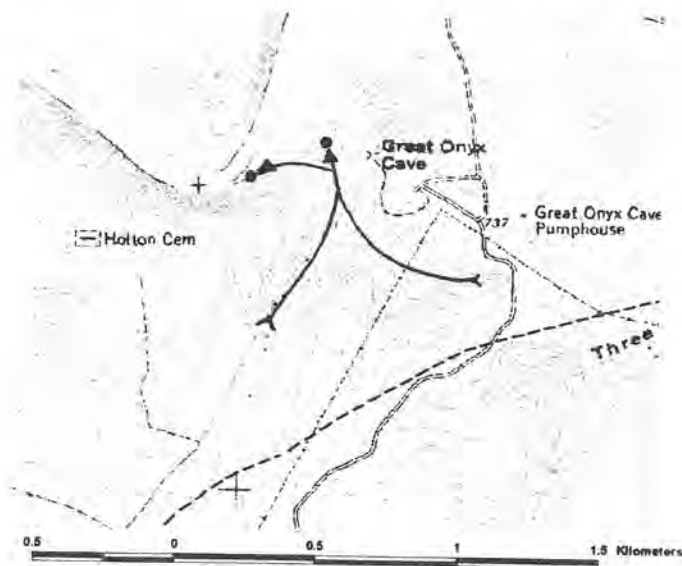


Figure 4. Dye traces within the Great Onyx Spring groundwater basin.

CONCLUSIONS

The past year has been used as a trial to gauge the success of in-cave dye tracing. As predicted, such work is strenuous and rewarding. We now know much more than a year ago, both in terms of cave hydrogeology and cave conservation and protection. Over the course of the next few years we plan many additional traces along these same lines. In addition to the future traces described above, we also plan on focusing on refining groundwater basin boundaries on the Pennyroyal Plateau, especially within developed portions of the watershed.

Another aspect of karst hydrogeology is becoming readily apparent from detailed in-cave dye tracing, especially proximal to basin boundaries: the complex three-dimensional nature of basin divides. This actually comes as no surprise as mature cave systems, such as the Mammoth Cave System, display intricate three-dimensional relationships between cave conduits, and therefore, groundwater basin boundaries are governed by flow routes. The problem is in the map display of these 3-D basin divides. At this time we have not decided on the best way to show these divides.

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References Cited

- Anderson, R.B., 1925, Investigation of a proposed dam site in the vicinity of Mammoth Cave, Kentucky, *cited in* Brown, R.F., 1966, Hydrology of the cavernous limestones of the Mammoth Cave area, Kentucky: U.S. Geological Survey Water-Supply Paper 1837, 64 p.
- Hall, C.L., 1996, Water quality variations and contaminant mass flux signatures relative to quick-flow recharge within the Turnhole Spring Groundwater Basin: M.S. Thesis, Eastern Kentucky University, 206 p.
- Meiman, J., and Ryan, M.T., 1992, Unpublished groundwater tracing data: Mammoth Cave National Park, Kentucky.
- Meiman, J., and Ryan, M.T., 1993, The Echo River-Turnhole Bend overflow route: *Cave Research Foundation Newsletter*, v. 21, no. 1, p. 1, 16-18.
- Meiman, J. and Capps, A.S., 1995, Unpublished dye tracing data: Mammoth Cave National Park.
- Murphy, J.D., 1992, Determining the hydrology of the Turnhole Spring Groundwater Basin of Mammoth Cave National Park, Kentucky using quantitative dye tracing: B.S. Thesis, University of Durham, 51 p.
- Quinlan, J.F., and Ray, J.A., 1981 and 1989, Groundwater basins in the Mammoth Cave Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky
- Ryan, M.T., 1992, Using newly-developed quantitative dye tracing techniques to determine the karst hydrogeology of the Buffalo Spring Groundwater Basin of Mammoth Cave National Park, Kentucky: M.S. Thesis, Eastern Kentucky University, 123 p.
- Ryan, M.T. and Meiman, J., 1996, An examination of short-term variations in water quality at a karst spring in Kentucky: *Ground Water*, vol. 34, no. 1, pp. 23-30.

Geographic Information Systems as a Tool for the Protection of the Mammoth Cave Karst Aquifer, Kentucky

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ABSTRACT

Threats to the health of karst ecosystems, including the Mammoth Cave Karst Aquifer, come from a variety of agricultural, urban, and transportation land use practices. For the Mammoth Cave Karst Aquifer, the US Fish and Wildlife Service has funded the Hoffman Environmental Research Institute to: 1) classify land use, 2) perform a dye-trace investigation to determine if the hydrologic network of the eastern end of the Mammoth Cave System extends into a fourth major drainage basin, 3) develop a GIS (Geographic Information System) as a data storage and retrieval tool, and 4) investigate potential protection strategies for these areas.

We conducted Anderson Level III land use classification at 1:24,000 scale for 383 km² comprising the Turnhole Bend Basin, Echo River Basin, Pike Spring Basin, Mile 205.7 Spring Basin, Suds Basin, and intermediate drainage areas. Within the Mammoth Cave Karst Aquifer, broad categories of land use include:

*17.4 km² of Urban and Built-up land
156.6 km² of Agricultural land
0.5 km² of Rangeland/Grassland
159.2 km² of Forestland
1.7 km² of Water
<0.1 km² of Wetland
1.0 km² of Barren land*

A series of dye traces was undertaken with this project. A dye trace in the northeast portion of the Mammoth Cave System, near the Kahn Entrance, emerged at Pike Spring. A dye trace near Candlelight River conducted within this study emerged at Floating Mill Hollow Spring, thus identifying a new spring basin that communicates with known passages in the Mammoth Cave System. ArcView GIS was used to catalog and analyze the results of the land use classification.

INTRODUCTION

Western Kentucky University received funding from the U.S. Fish and Wildlife Service in 1998 to investigate land use in the groundwater recharge area draining to Kentucky's Mammoth Cave karst aquifer. This area, which represents one of the most spectacularly developed of the world's karst landscape/aquifer/ecosystems, includes the world's longest known cave, the 500+ km-long Mammoth Cave System. Due to the globally significant nature of both the cave and its aquatic ecosystem, the area has been designated as a National Park, a World Heritage Site, and an International Biosphere Reserve. The park is home to at least nine federally endangered species, including the Kentucky Cave Shrimp (*Palaemonias ganteri*). In addition, the south-central Kentucky karst was recently selected by the Karst Waters Institute as one of ten of the world's karst ecosystems in most critical need of protection (Springston, 1998).

The quality of much of the water that flows through the Mammoth Cave karst aquifer has been impaired, and continues to be threatened, by agricultural, urban, and transportation land use activities within the aquifer's recharge area, much of which is outside the protective boundaries of the National Park. The intimate relationship between land use and groundwater quality in the well-developed karst areas of the Green River Basin occurs due to the rapid groundwater velocities, as high as several km per day, which can allow contaminants to travel into, and through, the aquifer in a short time with little attenuation. A toxic spill along I65 or the CSX railroad in the recharge area, for example, could potentially have rapid and devastating impacts on the habitats of numerous species. Bacteria from human and animal waste also present a particularly serious problem in water quality degradation.

PROJECT GOALS

The primary goals of this study were to complete a quantitative land use analysis of the recharge area that contributes water to the Mammoth Cave karst aquifer, along with a hydrogeologic fieldwork component by which we further defined the appropriate boundaries of the groundwater basins. This work represents a first step in developing a land use strategy designed to protect this globally significant karst ecosystem by defining a critical boundary condition on the physical structure of that ecosystem. The recharge zone is comprised of those groundwater catchments that have been shown to drain to conduits of the Mammoth Cave System, including the Turnhole Bend, Echo River, and Pike Basins. Partial development of a Geographic Information Systems (GIS) database for Turnhole Bend basin land use was completed by scientists at Mammoth Cave National Park in the mid-1990's; the current U.S. Fish and Wildlife Service (USFWS) funding allowed completion of the task for the entire Mammoth Cave aquifer as currently defined. In addition, analysis was completed for two other major adjacent basins (Suds and Mile 205.7 Spring Basins), and seven other smaller basins and interbasin areas that are likely to be included in the future as cave exploration, dye tracing, and hydrogeologic analysis continue to reveal the nature of the landscape/aquifer system and in particular, the full extent of the Mammoth Cave System. The areas for which land use was analyzed for this project include 336.4 km² of the Mammoth Cave karst aquifer and 46.4 km² in Suds, 205.7 Spring, and smaller basins, for a total of 382.8 km².

HYDROLOGY AND RECHARGE OF THE STUDY AREA

The Mammoth Cave karst aquifer is located within the broad karst region that extends through the Interior Low Plateaus of the southeastern United States, and is among the most extensively developed, well explored, and intensively studied of the world's karst landscape/aquifer systems (White *et al.*, 1970; Hess, 1974; White and White, 1989). The aquifer contains the Mammoth Cave System, which, with a currently explored length of over 500 km, is the world's longest known cave. Additionally, several hundred km of active groundwater conduits in the area have been identified by groundwater dye tracing (Quinlan and Ray, 1989; Crawford, 1985; Ray and Currens, 1998). The aquifer extends across several interrelated groundwater basins, all of which drain from large, alluviated springs along the south side of the Green River, the major base level stream for the area.

The Mammoth Cave karst aquifer is developed within a 160 m thick section of nearly horizontal, Upper Mississippian limestones of the St. Louis, Ste. Genevieve, and Girkin Formations (Pohl, 1970; White *et al.*, 1970; Palmer, 1981). The limestones are intermixed with minor chert and dolomite layers, and in the northern part of the study area, are covered by flat-lying clastic caprocks (primarily the Big Clifty Sandstone) that form the dissected Mammoth Cave Plateau. The southern parts of the study area extend onto the Pennyroyal Plateau, on which one of the world's most extensive sinkhole plains is developed. Regionally, the area lies on the flank between the Cincinnati Arch and Illinois Basin, with beds generally dipping towards the northwest at very gentle gradients of a few m per km (Deike, 1967; White *et al.*, 1970). Gentle local structures also influence the development of both landscape features and groundwater flow paths (Howard, 1963, 1964; Palmer, 1981, 1984, 1991), and Deike (1967) concluded that although two major joint sets are present, cave passage orientation, and thus groundwater flow, is controlled primarily by bedding structures. Surface elevations in the karst area range from about 127 m at local base level on the Green River, to nearly 300 m on the sandstone capped ridges of the southern Mammoth Cave Plateau.

There are three main sources of recharge to the Mammoth Cave karst aquifer, the majority of which is a large area of direct rainfall onto an extensive sinkhole plain developed within the St. Louis and Ste. Genevieve Limestones (Palmer, 1981; Richards, 1964; Haynes, 1962 and 1964a, b, and c; Klemic, 1963). Recharge derived from non-carbonate headwater areas also enters the aquifer at discrete swallets (sinking surface streams) from the argillaceous limestones and shales of the lower St. Louis along the southern margin of the sinkhole plain (the Glasgow Upland), as well as sinking streams flowing into the Girkin Limestone from the overlying clastic rocks of the of the highly dissected Mammoth Cave Plateau in the northern part of the catchment (Quinlan and Ewers, 1981). The recharge area has mean-annual precipitation of 1,264 mm, and the mean-annual temperature is 13°C (Hess, 1974). Precipitation is spread out throughout the year, although the late summer and early fall are drier than other months. Using the empirical methods of Thornthwaite (1948), Hess (1974) determined that mean-annual potential evaporation is 800 mm, varying from near zero in the winter to over 100 mm/mo during the warm season months.

AQUATIC RESOURCES

Although in many areas one would consider both surface and groundwater supplies in describing aquatic resources of a region, a feature of well developed karst systems such as this is that integrated surface drainage can be almost wholly lacking. Within much of the study area most flow is in the subsurface, where enlarged conduits in the limestone carry streams in a tributary fashion somewhat analogous to the organization of drainage systems on the surface in non-karst areas.

Within the Glasgow Upland region in the southern end of the study the headwaters of numerous small stream flow on the relatively impervious shales and argillaceous limestones of the lower part of the St. Louis Limestone. However, as these streams flow northwards they soon encounter the purer limestones of the upper St. Louis and Ste. Genevieve Formations, and sink into the subsurface as recharge to the Mammoth Cave karst aquifer. There are also small streams that flow upon the non-carbonate rocks of the Big Clifty sandstone and other clastic rocks that overlie the main karst-forming limestones in the northern part of the study area, but these too disappear into the subsurface upon reaching the limestones to become part of the groundwater supply.

The sinkhole plain areas of the surface also contain numerous small farm ponds that form in closed depressions (sinkholes) that become plugged with relatively impervious clays and silts either intentionally by farmers or by being compacted by livestock. Many of these tend to be ephemeral features over long timescales, and indeed in the sinkhole plain areas it is not uncommon to hear stories of some that have become unplugged and drained rapidly into the cave system below after years or even decades of holding water.

There are also wetland areas developed on the sandstones and possibly cherts within the study area, although these tend to be variable in extent depending on seasonal weather conditions. The few wetlands that we mapped in our land use analysis reflected those that were recognizable at the time that the infrared photos were taken March 20, 1990.

The resources that the various waters within the study area supply are primarily of importance because of the unique aquatic ecosystem that exists within the subsurface of the karst aquifer and the impact that these waters have on the aquatic health of the Green River. Except for water wells in some of the more remote areas where water supply infrastructure has not been developed, groundwater is not used for human consumption. This is largely a direct result of agricultural land use, which has made the groundwater unusable for drinking due to high levels of bacteria from animal and human waste. In some cases fecal coliform concentrations have been measured to exceed several *tens of thousands* of colonies per ml of groundwater (Quinlan and Rowe, 1978; Joe Meiman, personal communication). Increased attention in the area is also being directed towards potential threats to groundwater quality from agricultural chemicals, especially pesticides.

The aquatic ecosystem within the Mammoth Cave karst aquifer is among the most diverse known of any karst system. It is home to the endangered Kentucky Cave Shrimp (*Palaemonias ganteri*) as well as numerous other sensitive species, including two species of eyeless cavefish, *Typhlichthys subterraneus* and *Amblyopsis spelaea*. As the aquifer's waters ultimately discharge at major springs along the south side of the Green River, their quality also impacts the environment of surface river species, which include six endangered freshwater mussels in section of river along which the aquifer discharges. Two species of federally endangered bats also live within the vadose, or air-filled, part of the aquifer. The direct connection between land use and groundwater quality in the karst area poses a major threat to the health of the aquatic ecosystem.

STUDY RESULTS

Two related components were required to achieve the objectives of this study:

1. *Verification of the recharge area contributing to the Mammoth Cave aquifer.* In addition to the three major groundwater basins mentioned above, during the last decade exploration in the far eastern end of the Mammoth Cave system has suggested that the recharge area of the aquifer may extend eastward beyond the boundary of the Pike Spring Basin, although this had not been verified. It appears, on small-scale drainage basin maps of the area, to approach the three-way boundary junction of Pike, Suds Spring, and Lawler Bluehole groundwater drainage basins (Quinlan and Ray, 1984), but the mapped boundary in the region is a coarse estimate, and a direct groundwater trace from within the cave was required to verify which basin contains this section of the cave system. Using standard karst groundwater tracing techniques, we performed three fluorescent dye traces to clarify uncertain boundaries of the aquifer recharge zone.
2. *Land use classification at a scale of 1:24,000 using analysis of color infrared images, with field verification of ambiguous units.* This information was digitized and compiled into an ArcView GIS database. The information from the analysis provides a quantitative evaluation of the current land use practices impacting water quality in the Mammoth Cave aquifer.

VERIFICATION OF CONTRIBUTING RECHARGE AREA

The major question to be answered by hydrologic fieldwork for the project was whether the recharge area for the Mammoth Cave aquifer should include Suds, Mile 205.7 Spring, or Lawler Bluehole basins, in addition to the currently accepted Turnhole Bend, Pike, and Echo River basins. Since the Mammoth Cave System and its associated ecosystem has historically provided the basis for the region's political designation as a globally significant ecosystem, the Mammoth Cave aquifer is defined in this study as the recharge area of those basins that contribute flow to the 500+ km-long cave system. Recently discovered passages within Mammoth Cave, and in particular a cave stream passage named "Outward Bound", have extended to the area of the triple junction of the boundaries of Pike, 205.7 Spring, and Lawler

Blue Hole Basins. The first dye trace completed for this project was from the Outward Bound Stream, which showed that this portion of the flow system drains to Pike Spring. Thus, this part of the cave system is still within the confines of the traditionally defined Mammoth Cave karst aquifer, and the Suds, Mile 205.7 Spring, and Lawler Bluehole Basins were not shown to contribute flow to the aquifer system. However, we nonetheless completed land use analysis for Suds and Mile 205.7 Spring basins. Cave exploration in the area continues, and it seems likely that several large cave systems nearby within the two basins, including the Fisher Ridge and Vinegar Ridge Caves, may one day connect to Mammoth Cave. Thus, the definition of the recharge area of the Mammoth Cave system and aquifer depend on an anthropomorphic view of the current state of knowledge of the system, which is likely to change as time passes. For this reason we chose to complete land use analysis in the project for areas not only currently known to be included within the aquifer's recharge area, but also those areas that are likely to be contributing areas based on hydrogeologically reasonable interpretation, and which were feasible within the resources of the study.

Due to the extensive nature of the passages of Fisher Ridge Cave (150+ km), much of which is developed within the Lawler Bluehole Basin to the east of Suds, there is some chance that further exploration may show that the Mammoth Cave System extends into that Basin. However, land use analysis for this large basin was not feasible within the resources of the current project. While there is also some chance that in the future the cave system may be found to extend into the Bear Wallow Basin, even further to the east and still within the Green River Basin's area of significant cave development, none of the currently known significant cave systems are situated to suggest that connections to the Mammoth Cave System are imminent, and thus there is considerably less probability that this basin will be included as part of the Mammoth Cave karst aquifer in the foreseeable future.

In addition, beyond the original goals of the project, in June 1999 we identified by dye tracing another significant catchment that was not previously known to be included in the Mammoth Cave aquifer recharge zone. This catchment, the Floating Mill Hollow Spring Basin, lies in a triangular region of several square km bounded by Pike Basin, the Echo River Basin, and the Green River. Rhodamine WT dye traveled over 2 km from the Candlelight River area of Mammoth Cave to Floating Mill Hollow Spring. Previous estimates of the basin boundary (Quinlan and Ray, 1984) had mapped Candlelight River within the Echo River Basin. A third trace from the surface above Bögli Shafts area of Mammoth Cave also went to Floating Mill Hollow Spring, further defining the exact location of the boundary. This work is making it clear to us that this type of detailed, in-cave hydrologic work, while physically demanding and time consuming, is providing us with a new level in precision for the boundary delineation so critical for recharge zone evaluation and source water protection programs.

It should be emphasized that the criteria with which we have defined which basins are pertinent to the study are somewhat arbitrary, and have been done so in order to prioritize which ones are in most immediate need of analysis and study due the recognized global significance of those basins associated with the Mammoth Cave System. However, in ecological terms *all*

areas of the much larger karst area between the Green and Barren Rivers within the Green River Basin have both high potential for significance and high vulnerability from the same types of agricultural and other land use pressures that we are identifying the Mammoth Cave area. As resources become available similar delineation work and land use analysis would be a prudent first step in protecting these important karst areas.

LAND USE ANALYSIS

The land use analysis employed the Anderson land use classification (Anderson, *et al.* 1976). This hierarchical system is divided into three levels, with a higher level representing a greater level of detail. A one digit number represents seven broad categories of Level I land use, including agriculture, urban development, rangeland, water, wetlands, barren land, and forest-land. Level II is broken into 29 categories that are depicted by a two-digit number. Level III is most detailed, with a three or more digit number representing over 100 land-use types. The Mammoth Cave Karst Aquifer and adjacent study areas (Suds Spring Basin, Mile 205.7 Spring Basin, and several intermediate and undelineated minor basins) have 94 different Level III land use types in 7,944 land use parcels. The total area of the Mammoth Cave Karst Aquifer and adjacent study area covers 382.8 km².

Anderson Level III land use classification at 1:24,000 scale was conducted for the 382.8 km² comprising the Turnhole Bend Basin, Echo River Basin, Pike Spring Basin, Mile 205.7 Spring Basin, Suds Basin, Floating Mill Hollow Basin and intermediate drainage areas. A base map for land use parcels was constructed in an ArcView project contained on the compact disks that accompanies this report. The base map consisted of 1:12,000 digital orthophoto quarter quadrangles (DOQQ's) in the Universal Transmercator North American Datum 1927, Zone 16 coordinate system. Parcel shapes and land use codes interpreted from the color infrared images were then transposed to the base map. For some of the study area, Mammoth Cave National Park had previously classified land use for part of the study area and placed parcels and codes on mylar sheets. Since we had access to newer DOQQ's (developed from photos taken in March, 1993) compared to images used by the Mammoth Cave scientists for areas previously classified, we completely redigitized the land use parcels for the primary ArcView land use database.

Land use was identified from 1:24,000 color infrared aerial photographs taken by the Tennessee Valley Authority on March 20, 1990. The images consisted of nine-inch color positive film, which were viewed under magnification on a light table. Most polygons were drawn at 1:4,000, unless one particular land-use large area. This mainly occurred in the case of a continuous forest of the same type and thickness. Observing color patterns on the color infrared images using standard techniques and transposing the patterns into polygons in Environmental Systems Research Institute's (ESRI) ArcView GIS program created parcel polygons. For example, on infrared photography analysis, reds and greens are types of vegetation and farmland; purple trees are pines or evergreens; and reddish brown trees are cedars. These color patterns and observable features on the infrared images (cultural features and livestock,

for example) allowed classification of the levels (I, II, and III) of the Anderson scheme. Additionally, field checking was conducted to classify vague areas in more detail and verify quality. Quality control field checks of 84 randomly selected parcels found that classification for this project was above Anderson's standard 85% accuracy guideline. Using the query ability of the GIS database, an Anderson Level I land use table was generated for both the Mammoth Cave Karst Aquifer and total study area (Table 1).

Table 1: Anderson Level I land use within the Mammoth Cave Karst Aquifer and the total study area

	Mammoth Cave Karst Aquifer	Study Area and Adjacent Basins	Total
Urban/Built-Up (km ²)	17.4	1.7	19.1
Agricultural (km ²)	156.6	14.1	170.7
Rangeland/Grassland (km ²)	0.5	0.1	0.6
Forestland (km ²)	159.2	30.3	189.5
Water (km ²)	1.7	0.2	1.9
Wetland (km ²)	<0.1	<0.1	<0.1
Barren (km ²)	1.0	0.0	1.0
Total (km ²)	336.4	46.4	382.8

ECOSYSTEM PROTECTION AND FUTURE RESEARCH

With the established significance of this karst aquifer and ecosystem, there has for a number of years been a focus on water quality and ecosystem health within the Mammoth Cave karst aquifer. The major contribution of the current study, therefore, has not been to identify any particular new threats to water quality or immediate solutions to those threats. However, this work represents the first detailed quantitative evaluation of the land use practices that provide the primary threats to the system. The GIS format provides a flexible, queryable tool for the storage, analysis, and visualization of these data.

There are several strategies for remediation protection of the ecosystem supported by the results of this analysis:

- 1) The database provides a baseline with which to quantitatively evaluate and compare measured water quality changes that may result from future land use changes, in particular the implementation of various Best Management Practices (BMP's) of land management. In the study area water quality threats come from a variety of agricultural, transportation, and urban land use practices that may be amenable to BMP strategies. This detailed GIS database provides an excellent tool to record the temporal and spatial implementation of these strategies, as well as other land use changes that will take place for other reasons, driven by social and cultural influences, but nonetheless may impact ecosystem quality.
- 2) The database serves as a key component for the development of quantitative, predictive models that relate present and future land use strategies to groundwater quality and thus ecosystem health. These could allow simulation of various land use changes, with model results describing the resulting modifications in water quality at key points in the system such as springs and various cave habitats. While developing such models is a necessarily complex operation requiring significant assumptions about flow system structure, they can possibly provide useful information on trends or relative magnitudes of groundwater impacts resulting from various land use scenarios.

There are a variety of obvious and useful directions for further research related to this project and study of the ecosystem health of the Mammoth Cave karst aquifer and surrounding areas. The most immediate are to extend the two main components of the current work, including hydrogeologic study to further delineate the complex geometries of the karst groundwater basins and particularly their boundaries, and to extend the detailed land use analysis and GIS development to other areas of the south central Kentucky karst area which potentially contain both fragile and significant subsurface ecosystems.

For information about obtaining the ArcView GIS database for this project, please contact the Hoffman Environmental Research Institute at Western Kentucky University.

References

- Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976, *A Land Use and Land Cover Classification System for Use With Remote Sensor Data*. Washington, D.C.: U.S. geological Survey Circular 671, 28. P.
- Crawford, N.C., 1985, *Hydrologic Hazards in Karst Terrain*. U.S. Geological Survey Water Fact Sheet, 2.
- Deike, G.H. III, 1967, *The Development of Caverns of the Mammoth Cave Region*, Ph.D. Dissertation, The Pennsylvania State University, 235 p.
- Haynes, D. D., 1962, Geology of the Park City quadrangle, Kentucky. U.S. Geological Survey. *Geologic Quadrangle Map* GQ-183.
- Haynes, D.D., 1964a, Geology of the Glasgow North quadrangle, U.S. Geological Survey, *Geologic Quadrangle Map* GQ-339.
- Haynes, D.D., 1964b, Geology of the Horse Cave quadrangle, U.S. Geological Survey, *Geological Quadrangle Map* GQ-558.
- Haynes, D. D., 1964c, Geology of the Mammoth Cave quadrangle, Kentucky. U.S. Geological Survey. *Geologic Quadrangle Map* GQ-351.
- Hess, J.W., 1974, *Hydrochemical investigation of the central Kentucky karst aquifer system*, Ph.D. Dissertation, Geology, The Pennsylvania State University, 218 p.
- Howard, Alan D., 1963, The development of karst features. *National Speleological Society Bulletin*, vol. 25, no. 2, p. 45-65.
- Howard, Alan D., 1964, Process of limestone cave development. *International Journal of Speleology*, vol. 1, p. 47-60.
- Klemic, H., 1963, Geology of the Rhoda quadrangle, U.S. Geological Survey. *Geologic Quadrangle Map*. GQ-219.
- Palmer, A. N., 1981, *A Geologic Guide to Mammoth Cave National Park*. Zephyrus Press. Teaneck, New Jersey: 210 p.
- Palmer, A.N., 1984, Geomorphic interpretation of karst features, in *Groundwater as a Geomorphic Agent*, R.G. LaFleur, (editor) (Allen and Unwin, London), pp.173-209.
- Palmer, A. N., 1991, The origin and morphology of limestone caves. *Geological Society of America Bulletin*, vol. 103, pp. 1-21.

- Pohl, E.R., 1970, Upper Mississippian deposits of south-central Kentucky, *Kentucky Acad. Sci. Trans.*, vol.1, pp.1-15.
- Quinlan, J. F. & Ewers, R. O.,1981, Hydrogeology of the Mammoth Cave region, Kentucky. in *GSA Cincinnati '81 Field Trip Guidebook 3*, Roberts, T.G. (editor). American Geological Institute, Falls Church, Virginia, pp. 457-506.
- Quinlan, J.F., and J.A. Ray, 1989, *Groundwater Basins in the Mammoth Cave Area, Kentucky*. Friends of Karst, Occasional Publication 1 (revision of 1984).
- Quinlan, J.F., and R. Rowe, 1978, Hydrology and water quality in the central Kentucky karst: *Water Resources Institute, University of Kentucky, Research, Report 109*, 42 p.
- Ray, J.A., and J.C. Currens, 1998, *Mapped Karst Ground-Water Basins in the Beaver Dam 30 x 60 Minute Quadrangle, scale 1:100,000*. Kentucky Geological Survey, Map and Chart Series 19 (11).
- Richards, P.W., 1964, Geology of the Smiths Grove quadrangle, Kentucky, U.S. Geological Survey, *Geologic Quadrangle Map GQ-357*.
- Springston, B., 1998, Karst Waters Institute Lists top 10 endangered karst ecosystems. *American Caves*, vol. 11, p. 7.
- Thornwaite, C.W., 1948, An approach towards a rational classification of climate. *Geographic Review*, vol. 38, pp. 55-89.
- White, W.B., R.A. Watson, E.R. Pohl, and R. Brucker, 1970, The central Kentucky karst. *Geograph. Rev.* vol. 60, pp. 88-115.
- White, W. B. and E.L. White, 1989, *Karst Hydrology: Concepts from the Mammoth Cave Area*. Van Nostrand Reinhold. New York: 346 p.

Threats to Surface and Karst Groundwater of Mammoth Cave National Park from the Arthur Oil Field, Kentucky

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INTRODUCTION

In the early 1990s a small oil boom began in Edmonson County, Kentucky. Today, oil production continues and a number of wells have been drilled on properties adjacent to the southwestern edge of Mammoth Cave National Park. While steps have been taken to reduce the chance of oil spills and the potential contamination of karst aquifers of Mammoth Cave National Park, accidents can happen. Therefore, in order to be proactive, research efforts are not only lessening the possibility of an oil spill, but are also preparing contingency plans in the event that one occurs.

This potential threat was demonstrated in January 1997, when a fitting in one Arthur well ruptured and spilled 2,000 liters of crude oil, which flowed on the surface into the park. Only a quick and coordinated effort prevented the oil from sinking into and contaminating the primary karst aquifer. This spill clearly demonstrated the inherent threat posed by the area's numerous wells and petroleum facilities, while it also emphasized the need for a better understanding of the karst hydrogeology of this region of the park.

In order to prepare for potential threats in this area, scientists and students of Western Kentucky University and the National Park Service are cooperating in the development of a Geographic Information System (GIS) database. When completed, this database will depict the hydrogeology, oil well location data, karst features, access roads, and in particular, surface and subsurface flow routes adjacent to these oil facilities. The database, including a summary map for use during emergencies, will then be distributed to the various agencies, organizations, and response personnel to better plan future efforts.

GEOLOGIC SETTING OF ARTHUR AREA

Dry Branch is an ephemeral stream located just to the west of the Mammoth Cave System. While most of the Dry Branch drainage area lies within Mammoth Cave National Park, it is west of the recharge area for the Mammoth Cave karst aquifer. The "Arthur Oil Field" is primarily located in and just to the south of Dry Branch. Unlike the Mammoth Cave aquifer,

the Dry Branch aquifer is not believed to be connected to the Sinkhole Plain recharge area. Consequently, the springs within Dry Branch are small, and the karst is not well developed. Dry Branch empties into the Green River near Houchin's Ferry. Dry Branch drains approximately 644 hectares. Geologically, the surface on which Dry Branch flows is composed of 48% carbonate rocks and 52% noncarbonates. The carbonates are three distinct Mississippian limestones: the Glen Dean, the Haney, and the Girkin Limestones. The Girkin Limestone is the uppermost limestone unit comprising the main Mammoth Cave aquifer. The Girkin Limestone is only exposed within 2% of the Dry Branch basin. Separating the Girkin and Haney limestones, as well as the Haney Limestone and the Glen Dean Limestone, are fairly impermeable sandstone layers. Sandstone and shale caps much of the Glen Dean Limestone. This configuration of the bedding layers results in the hydrology resembling stair-steps. Storm events produce surface runoff on uppermost sandstones and shales, which empty into sinkholes near the upper contact with the Glen Dean Limestone. This water reappears at small springs located at the contact with the next lower sandstone layer. This runoff then drains on the surface again, only to sink into the Haney Limestone. The Haney Limestone springs are usually located at the lowest part of the limestone, near the contact with the lowest sandstone layer. Below this sandstone layer is the Girkin Limestone; however, there is no appreciable karst development known in the Girkin Limestone of Dry Branch. This is due mostly to the fact that the Girkin Limestone in this region is near the base level elevation of the Green River, thereby restricting karst development.

The stratigraphy of the Dry Branch basin lends itself to containment of potential contaminants. The Haney and Glen Dean aquifers of Dry Branch are not known to be hydrologically connected outside of the Dry Branch catchment region. Therefore, they are relatively self-contained units.

METHODS

The project consists of several parts. Dye tracing studies (Figure 1) are underway to determine the subsurface flow routes that a potential spill may take. Well sites, oil tanks and other facilities are being inventoried using a global positioning system (GPS) and aerial photography. Access roads and other features are also being inventoried and mapped, as well as basic geology and stratigraphy. This information is being used to develop a detailed ArcView GIS-based map and database of the region that park staff and response personnel can use for both developing emergency procedures and responding in the event of a spill.

CONCLUSION

This project represents an important tool for the protection of water resources for the plateau and ravine karst section of Mammoth Cave National Park, as well as the Green River below Houchins Ferry. Oil development to the south of the park boundary continues to put potential pressures to aquatic ecology and water quality in the area.

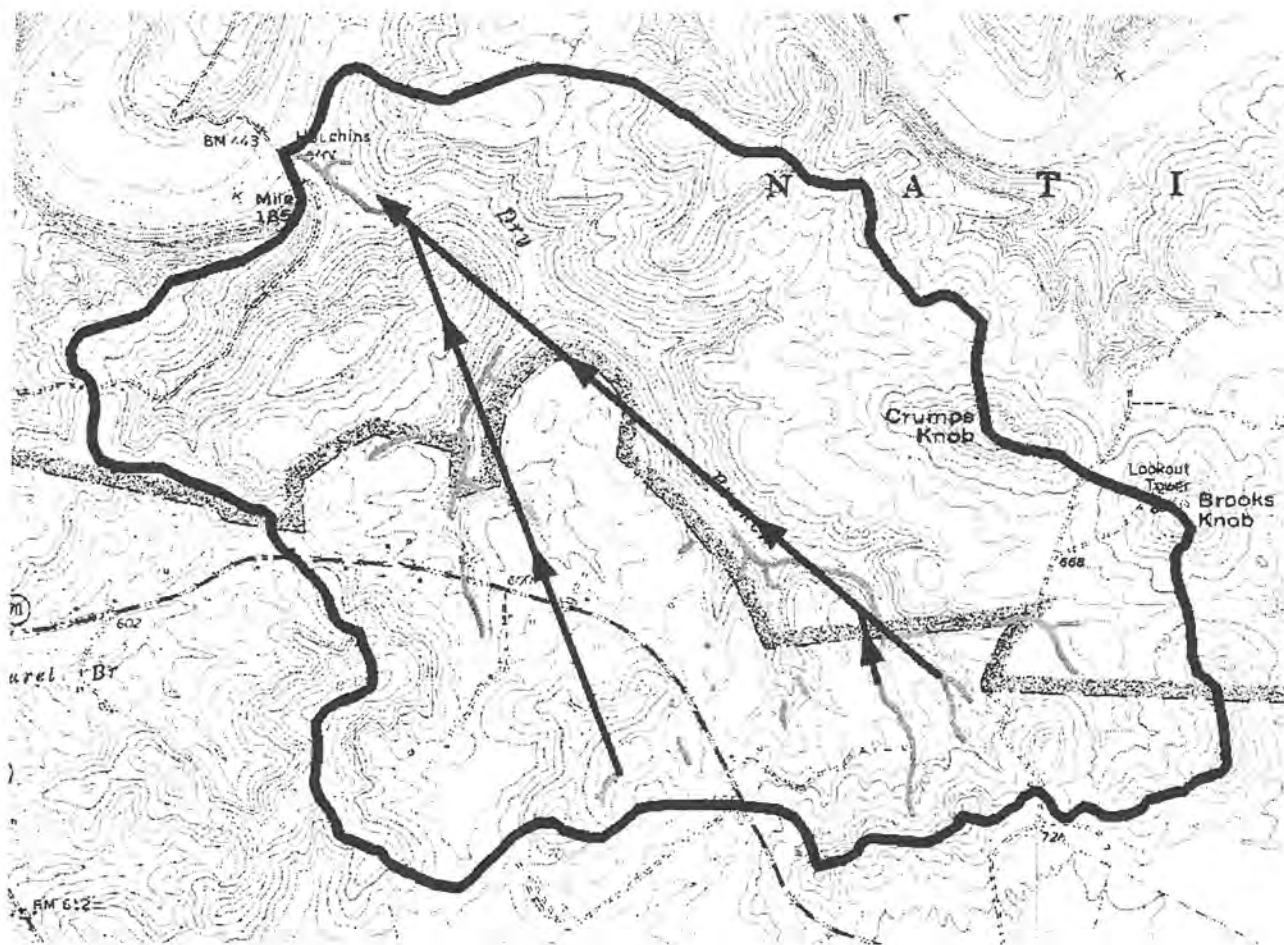


Figure 1. Drainage area and completed dye tracing for the Dry Branch catchment in the vicinity of the Arthur Oil Field. The area of potential oil contamination lies in the southern part of the catchment, to the south of Mammoth Cave National Park.

However, the best landuse strategy overall for the area requires a simultaneous need to strike a balance between the ecological, cultural, and economic needs of the area and its residents. With the construction of such a database and map, along with the preparation of emergency preparedness procedures, we will most be able to protect these resources in the case of an accidental spill from oil production activities.

There are many potential threats to cave, karst, water, and ecological resources. Each area has its own unique situation and potential problems. However, with thorough inventory, assessment, and coordinated preplanning and preparedness efforts, resource managers can responsibly maintain the ecological health of surface and karst water resources of the boundary areas of Mammoth Cave National Park.

A Historiography of Archaeological Research in the Mammoth Cave Area of Kentucky: 1824-2000

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ABSTRACT

Archaeological interest in the the Mammoth Cave area of Kentucky has been on-going since the early 19th century, primarily because of the unique preservation offered at the underground cave sites. In this paper I examine almost two hundred years of archaeological research conducted in the Mammoth Cave area. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and later by Willey and Sabloff (1993).

An examination of the history of archaeological study in the Mammoth Cave region of south-central Kentucky reflects parallel development with the growth of archaeology in North America (Schwartz 1967; Willey and Sabloff 1973), but it also demonstrates why additional intensive and systematic archaeological study should to be conducted in this very significant archaeological region. In this paper I provide an historical overview of archaeological research that has taken place in and around Mammoth Cave National Park. The paper loosely adheres to historical divisions first presented by Schwartz (1967) and expanded by Willey and Sabloff (1993).

THE SPECULATIVE PERIOD

One of the earliest archaeological records pertaining to the Central Kentucky Karst research area was written in 1824 by Constantine Samuel Rafinesque (1824). Rafinesque, a colleague of James Audubon, was deeply interested in prehistoric remains of the Ohio Valley (Stout and Lewis 1995:83-90). According to Col. Bennett Young (1910:18), Rafinesque claims to have located 148 ancient sites (settlements) and 505 monuments in a 41 county area of Kentucky, speculating as with other early nineteenth century naturalists about the origin of these "natural" curiosities. Rafinesque's entry for the Central Kentucky Karst lists "shell mounds along Green River and mummies in caves."

Following Rafinesque's initial inquiry into Kentucky's prehistory, there appears to be an absence of related literature about the antiquities of the area. This is not to say that interest in antiquities had died; it had not. According to Col. Bennet Young (1910), increased farming activity, and in general, disruption of the land due to population growth, caused an escalation

in the amount of destruction and looting of prehistoric sites. By 1870, the collecting, selling, and smuggling of antiquities in Kentucky was a major profession. Although known mostly for its large cave system, the archaeological contents of the Mammoth Cave area offered a variety of artifacts and desiccated human remains for collecting and selling. Finds, such as Fawn Hoof in 1813, Scudder's Mummy in 1814, Little Al(ice)¹ in 1875, and Lost John in 1935, helped make the Mammoth Cave area famous (Meloy 1971). During the mid-nineteenth and early twentieth centuries, many individuals explored nearby cave systems looking for mummies and Indian relics to sell (see Young 1910). Unfortunately, this dilettantic pastime stopped only in those caves that came under the protection of the National Park Service after 1940 (e.g., Salts, Mammoth, Longs, Bedquilt, and Lee caves), and even then, infrequent looting of caves within the National Park still occurred.

The earliest historic date known from inside Salts Cave is 1809 (Watson 1969:7). Dates and names upon various signature rocks in Mammoth and Salts caves indicate that the majority of historic caving dates "from the last quarter or so of the 19th century to the first quarter of the 20th century" (Watson 1969:7; see also Watson ed., 1974:21-23). The vegetal antiquities (e.g., textile bags, cordages, sandals) that could be found within the dry caves were not normally preserved in surface or "open" sites. Hence, those items were especially sought for collecting, smuggling, and looting. As an example of smuggling, in 1874 or 1875, Louis Vial and some friends explored extensively in Salts Cave using a "new side entrance known only to themselves" (Watson 1969:7). During one of those cave trips they found the "Salts Cave Mummy," nicknamed incorrectly "Little Alice" (Robbins 1971; Tankersley et al. 1994; Watson 1969:7). More recent examinations by the late Louise Robbins (1971:200-206) identified the sex and age of this individual to be those of a nine-year-old male.

During the 1890s men such as F.W. Putnam of the Peabody Museum, as well as local Kentuckians such as Colonel Bennett Young, T. F. Hazen, and W.D. Cutliff, made extensive collections and/or purchased prehistoric material from Salts and Mammoth caves. Young (1910:300, 305) states:

In 1893 Mr. Theodore F. Hazen...opened a new entrance into Salts Cave..." [and] "we obtained many interesting relics..." about the present entrance [Salts Sink], numerous spalls, flakes of flint, pestles, axes, awls, and other implements have been found...

Young goes on to describe many artifacts taken from within Salts and Mammoth Caves, such as cords of bark, hemp, cattail leaves, and grass; basketwork; half-burned cane torches; corn cobs (probably modern); an aboriginal ladder; wooden digging implements; cups, dishes, bowls and water bottles made from gourds and squash rinds; tobacco leaves and seed pods (also probably modern), as well as many chert implements. The large collection of antiquities Young acquired was sold to the Museum of the American Indian, Heye Foundation, New York (Schwartz 1958e; Watson 1974: 167). Later, John M. Nelson, who was a cave guide from 1894-1907, extensively collected antiquities both from the caves and from surrounding surface sites (Carey 1942; Schwartz 1958f:3; Watson 1969, 1974). With the exception of the John M. Nelson

collection, the other large private collections were either given or sold to the American Museum of Natural History, Smithsonian Institution, or the Peabody Museum of Archaeology and Ethnology. It was the Mammoth Cave Estates collection, donated to the American Museum of Natural History in 1913, that prompted Nels C. Nelson (no relation to John M. Nelson) to engage in the “only scientific archaeological investigations” (Schwartz 1958d) of the Mammoth Cave area up to that time and usher in the Classificatory-Historical Period of archaeological work (Schwartz 1967; Willey and Sabloff 1993).

The Speculative Period focused initially upon discovery, with only meager attempts to offer explanations of derivation of the discovered sites. Once discovered and made known, sites were vandalized and exploited for private purposes, whether pots, “arrowheads” or “mummies”—the market for trafficking in North American antiquities had begun. But it was from the seeds of site destruction that the first museum acquisitions were made that ushered in professional archaeological work of the Classificatory Period.

THE CLASSIFICATORY PERIOD, 1916-1960

Nels C. Nelson worked in Mammoth Cave National Park during May and November of 1916 as an archaeological representative of the American Museum of Natural History. Nelson’s 1917 report describes the materials found during his surface and cave reconnaissances and excavations within the Mammoth Cave area. Specifically Nelson describes and compares his surface finds from the Mammoth Cave and Eaton Valley fields to similar bifacial chipped stone materials then being found in the French Paleolithic (Nelson 1917:16-19). In total Nelson examined, through excavation and/or other study, six of nine cave sites, six of seven open surface sites, and one of four rockshelters (Nelson 1917: 11). The latter number refers to the category of site types he reported for the Mammoth Cave area. Douglas W. Schwartz (1958d:1-2) states that Nelson’s main contribution was to “scientifically document the presence in the caves of some classes of material previously only reported by amateurs.” Nelson also drew substantial conclusions from his materials, despite the lack of published reports concerning antiquities of the area and the role of plant domestication (he found large quantities of charred sunflower seeds in his Mammoth Cave Vestibule excavations) in the Central Kentucky region. Nelson concluded that the Flint-Mammoth Cave system had an economic importance to the Native Americans, e.g., the quarrying of flint (e.g., from Flint Alley in Mammoth Cave, which has since been questioned [Munson et al. 1989, Prentice 1993]); Nelson was not aware that the Native Americans also exploited the caves for minerals (e.g., mirabilite, gypsum, satin spar and selenite; see Munson et al. 1989 and Tankersley 1996).

Nelson’s archaeological excavations inside the Vestibule of Mammoth Cave is his major work in the Mammoth Cave area. Although this excavation was exploratory, it was extremely extensive and thorough. Nelson sank a series of 10 test trenches that revealed midden in two places. One was near the west wall of the entrance while the other, some 40 feet from the first, extended 50 feet back over the entire entrance area. Although Nelson’s notes are at times ambiguous, he demonstrated a strong concern for the temporal and spatial location of

artifacts excavated (personal observation in April, 1975 of Nelson's catalog record on file with the American Museum of Natural History, New York).

Nelson excavated almost all of the Vestibule entrance, but the number of artifacts found was few. Douglas W. Schwartz (1958d) explains that this was probably the result of extensive looting that had occurred earlier, throughout the nineteenth century. It also may be the result of Nelson's recovery methods (no screens were used), and/or extensive subsurface alterations resulting from cave commercialization or previous salt petre mining operations during the War of 1812 (Meloy 1968). Any of these reasons may explain the paucity of artifacts recovered from the Mammoth Cave Vestibule. Nelson did find and recognize evidence of prehistoric diet in the form of animal bone, sunflower seeds, and fresh water molluscs (Nelson 1917; Watson 1974:212). He also found prehistoric tools such as bone awls, bone flakers, antler points, tubes, stone projectile points, scrapers, ground stone implements, and items for personal adornment. Most importantly, Nelson (1917:69) concluded that two different cultures could be distinguished within his Vestibule excavations. The lower, or more "primitive" group was identified by Nelson as what archeologists would define two decades later (e.g., Ritchie 1933) as the Archaic culture (Schwartz 1960:133).

Only one other reference to Mammoth Cave area prehistory appeared in print during the first two decades of the twentieth century. This was a fleeting mention of a series of rockshelter sites near what is now the western boundary of Mammoth Cave National Park. The reference was made by C.B. Moore who visited the Indian Hill rockshelter complex in 1915 (Moore 1916). Fortunately, shallow water conditions on Green River forced Moore to terminate his plunderous Green River expedition near Indian Hill as his boat, The Gopher, was too large to continue the journey upstream.

In 1935, a newly discovered desiccated burial within Mammoth Cave, known to the cave guides as "Lost John," brought additional archaeological publicity to the area (Pond 1935, 1937). Alonzo Pond and George Neumann's analysis of Lost John (Neumann 1938), constituted the only professional archaeological inquiry in the Mammoth Cave area between N.C. Nelson's 1916 work and the formation of Mammoth Cave National Park in 1940 (although several additional references to caves and rockshelter sites in and around the present boundary of MCNP appeared in print intermittently (e.g., Fowke 1922; Funkhouser and Webb 1932). With the final acquisition of lands by the federal government on April 25, 1940, it became a federal offense to remove materials from cave interiors within Mammoth Cave National Park.

During the formation of MCNP, the Mammoth Cave National Park Association purchased from John M. Nelson, a collection of prehistoric, historic, and geological specimens that were subsequently donated to Mammoth Cave National Park on January 15, 1942 (Carey 1942:1). Henry A. Carey, then of the Archaeology Department at the University of Kentucky, was placed in charge of cataloging the Park's new acquisitions. He was assisted by a new National Park Service employee, Jesse D. Jennings (Carey 1942). Unfortunately, the majority of the 25,000 specimens in the John M. Nelson collection was without provenience. Items in the collection had been bought from the local area with no note made as to the exact collecting

location. Furthermore, Nelson kept only “mental notes” for his more unusual specimens. From the John M. Nelson collection, Henry Carey concludes: (1) the Mammoth Cave National Park area was utilized for an extensive period of time by aboriginal peoples; (2) a typological sequence could be worked out for the area using the collection, but that extreme caution should be used in drawing definitive conclusions due to the lack of controlled locational data; and (3) that scientific archaeological excavations should be started, inside the caves and at selected surface sites, immediately. Unfortunately, due to the start of World War II, the Mammoth Cave collections heralded for study by Carey were not examined again until 1957 when Douglas W. Schwartz, at the University of Kentucky examined the John M. Nelson materials and attempted to relocate some of the surface sites from which John Nelson had made his collections (Schwartz 1958f). Schwartz also brought systematization to the study of Native American sites in MCNP and visited several major museums in the East to study collections acquired from the Mammoth Cave area at the turn of the century (Schwartz 1958a-h). These activities culminated in a series of valuable descriptive reports (Schwartz 1958a-h) and other interpretive and popular accounts about the archaeology of the area (Schwartz 1960; 1965).

The Classificatory Period brought a logical, scientific inquiry to the archaeology of the Mammoth Cave area. With the first work of Nelson in 1916, to the discovery of an exsiccated individual (Lost John) in 1935, to the systematic reporting of archaeological sites above ground and below by Douglas Schwartz during the late 1950s/early 1960s, the archaeology of the Mammoth Cave area yielded ever-so-slowly, evidence of very significant information about prehistoric cultural adaptations and cultural processes. These later studies served as the foundation for investigations by Patty Jo Watson, the Cave Research Foundation, the National Park Service, and the Illinois State Museum (Watson 1969) during the next period of archaeological development.

THE EXPLANATORY/INTERDISCIPLINARY PERIOD, 1960-PRESENT

In 1942, Henry Carey emphasized the need for further surface investigations and excavations in Mammoth Cave National Park, but little was accomplished until the recent research efforts by Patty Jo Watson and her associates (Carstens 1974, 1975, 1976 1980; Carstens and Watson 1996; Marquardt 1974; Robbins 1971; Wagner 1976; Watson 1969; 1974). Whether you call it explanatory archaeology, processual archaeology, or even post-processual archaeology, the post-1960 era of interdisciplinary archaeological research in the Central Kentucky Karst began to answer many questions about the area’s prehistory and the avenues of cultural change and adaptation through time and space.

Watson’s archaeological work in Mammoth Cave National Park began in 1962 when, in conjunction with the Cave Research Foundation, the Illinois State Museum, and Mammoth Cave National Park, she initiated an archaeological reconnaissance of the large caves within the Flint Mammoth Cave system (Carstens and Watson 1996; Watson 1969:v). Watson’s initial work was carried out primarily in Salts Cave, but later research expanded into other caves (e.g., Mammoth, Lee, and Bluff), and to archaeological surface reconnaissance (Carstens 1974, 1980). Watson’s reason for studying the cultural materials from within the caves was that data

derived from those materials was highly relevant to the discovery of dietary practices during the early agricultural Late Archaic-Early Woodland period. Watson's research was expanded in April, 1969, to include, "excavation in Salts Cave Vestibule, a search for and testing of possible surface sites near Salts Sink, and recording of prehistoric remains in other caves within the Park" (Watson 1969:v). Between 1973 and 1980, Watson and her colleagues initiated comparative studies at caves outside the Park (e.g., Wyandotte Cave, Indiana, and Wolf River or Jaguar Cave, Tennessee) (Crothers 1986; P. Munson and C. Munson 1990; Robbins, Wilson, and Watson 1981; Tankersley, P. Munson, C. Munson, Shaffer, and Lieniger 1990). She also obtained a more complete radiocarbon sequence from Salts and Mammoth caves, excavated and floated a stratigraphic column from Salts Cave Vestibule; obtained pollen and parasitological analyses from human paleofecal specimens found within the cave, and took pollen core samples from nearby sinkhole ponds.

Aided in her research by scientists from many different fields of study, Watson was able to approach the archaeological problems of the Mammoth Cave National Park area in a scientifically-integrated manner, a methodological approach she had learned as a University of Chicago graduate participating in Robert Braidwood's interdisciplinary studies of agricultural origins in the Near East. This approach led to some answers, and to many new questions, particularly with respect to environmental changes and their possible effects on the prehistoric inhabitants of the study area. Watson and her colleagues (e.g., Munson et al. 1989; Tankersley 1985, 1996) documented that prehistoric people using the cave were mining the cave for minerals (e.g., mirabilite, gypsum, selenite, and satin spar) and were simply exploring the cave system. She noted similar patterns of cultural activities in portions of other caves located inside (Lee and Bluff) and outside the Park boundaries (e.g., Wyandotte Cave in Indiana, and Big Bone and Jaguar caves in Tennessee; Crothers 1986; Munson and Munson 1990; Watson 1986:109-116). Although Lee, Bluff, Wyandotte, and Jaguar caves are not comparable in size to either Salts or Mammoth Cave, the data collected by Watson and her colleagues clearly indicate that cave mining and exploration were widespread activities in this karstic region that probably began during the Late Archaic (Watson 1974:221-232; Watson 1986; Munson et al. 1989). The 50+ radiocarbon dates now available for the Mammoth Cave project clearly demonstrate the widespread prehistoric use of caves over a very important and similar time horizon (Kennedy, 1996): that of early agriculture in the Late Archaic-Early Woodland period (ca., 4,000 to 2,000 B.P.).

Watson's research between 1962 and 1980 in the Mammoth Cave region is unique for two reasons: (1) it is the first time such scientifically-integrated archaeological deep-cave research has been attempted in the eastern United States; and (2) it provides an aspect of prehistoric culture process that was extremely important (i.e., the domestication of native plants, evidence for which was not then being found in "open" surface sites in the eastern U.S.). Watson's research continues in the Mammoth Cave region.

As a part of the Watson research team between 1973 and 1975, my job was to document the culture history evident in a sample of 83 surface sites in and around MCNP, examining the

techno-economies of several of those sites diachronically, and presenting a cultural historical context within which the surface dwellers of the Central Kentucky Karst explored and exploited the large caves (Carstens 1980).

Between 1977 and 1987, MCNP witnessed only intermittent archaeological research on the Park's surface archaeology. Most of the work accomplished included small, unrelated cultural resource management surveys (e.g., Beditz 1979, 1981; Carstens 1977, 1978). Between 1981 and 1989, few archaeological projects were conducted on the surface of Mammoth Cave National Park. Exceptions are the work of Philip J. DiBlasi, who investigated the 1920s home-
stead of Floyd Collins (DiBlasi 1987a), a famous local cave explorer, and George Crothers, who documented material left in Sand Cave where Collins died in 1925 (Crothers 1981, 1983). DiBlasi (1987b, 1996), working with the Cave Research Foundation, also found, in Salts Cave, a series of prehistoric pictographs and glyphs previously undocumented. Other studies concerning the human use of the cave system, and of the people who were using the cave, focused on determining the exact nature of prehistoric mineral procurement (Tankersley et al. 1985), forensic examinations of the historic findspots of mummies (K. Tankersley et al. 1994; S. Tankersley 1993), and a new and exciting search for pathogenic microorganisms in prehistoric and historic human feces and bodily fluids (Ruppert 1994; Tankersley 1993).

The most systematic undertaking to inventory a representative sample of the Park for both historic and prehistoric cultural resources was directed by NPS archeologist Guy Prentice (1993). Although much of Prentice's prehistory is a summary of Nelson (1917), Schwartz (1958a-g), Carstens (1980), and Watson and Carstens' (1982) site inventories, Prentice adds new prehistoric and historic sites to the overall resource inventory of the Park. As a result, Prentice (1994, 1996) was able to offer a settlement synopsis of MCNP for his doctoral dissertation that includes a hypothetical seasonal round between the Big Bend shell mound area and the Mammoth Cave area.

In 1993, the Science and Resource Management Division at Mammoth Cave National Park began a long-term cultural resource inventory of all artifacts (historic and prehistoric) within the Main Cave in Mammoth Cave. This project is co-sponsored by the NPS and Earthwatch; the field work for this project has been directed by Ken Tankersley, Mary Kennedy, George Crothers, Christine Hensley, and Bob Ward (Kennedy 1993; Crothers and Ward 1995). Using an Electronic Distance Measurement (EDM) system, the Earthwatch team records the exact location of every artifact noted within the surveyed areas of the cave system. This makes it possible to prepare density plots of aboriginal activity within the cave system, and to determine prehistoric use areas within the cave despite 200 years of historic cave use and cave disturbance to the aboriginal materials in Mammoth Cave.

In 1992, Patty Jo Watson, Mary Kennedy, Kristen Gremillion, and Kristin Sobolik began a new study in Mammoth and Salts cave. This new arena emphasized the collection of human paleofecal samples for radiocarbon dating, parasitological analysis, macro- and microethnobotanical studies, and biochemical (hormonal) analysis. These studies would

allow prehistoric fecal specimens to be sexed and thereby enable a better understanding about specific individuals who explored and mined prehistoric Mammoth Cave (Watson 1992; Watson and Kennedy 1993).

In 1994, Christine Hensley and Tom Sussenbach, while working for the National Park Service in Mammoth Cave National Park, conducted excavations at the Stairway Rockshelter (Hensley 1995, 1996). The three radiocarbon samples from Hensley's excavations of Feature 1 consistently place the site's occupation in the Early Woodland period, ca., 2170 to 2570 B.P., a date range that is quite comparable to the majority of aboriginal use of Mammoth and Salts caves (Hensley 1995: 24, Table 1; Kennedy 1990, 1996). Further, Paul Gardner identified more than 5,000 seeds of domestic, semi-domestic, and wild chenopodium from the living floor of the rockshelter (Hensley 1995, 1996). Similar contractual archaeological studies continue today through the supervision of Bob Ward, cultural resource specialist at Mammoth Cave National Park and the assistance of Darlene Appelgate, archaeologist at Western Kentucky University (Appelgate, personal communication email to Carstens, July 1, 2000).

Analytically, the Explanatory/Interdisciplinary (post-1960) era of archaeological research has answered many questions about the Native Americans who explored and exploited the environment and resources above and below ground in the Central Kentucky Karst. Initial studies by Watson and her colleagues in the early 1960s through 1980s focused upon time-space and environmental reconstruction sequences, then turned to more processual issues while unraveling the prehistory of the Mammoth Cave area. That work inspired other archeologists in Tennessee and Indiana to test several of Watson's observations and conclusions about the prehistory of Mammoth Cave specifically, and prehistoric cultural processes in general, finding that prehistoric aboriginal mining and exploration was a wide-spread cultural phenomenon; it was not limited solely to Mammoth Cave National Park nor only to the Late Archaic-Early Woodland transition (e.g., Faulkner 1986). Furthermore, not only had Watson and her associates confirmed and expanded N.C. Nelson's initial observations about the importance of plant cultivation in the Mammoth Cave area, but also Watson's research teams went far beyond, examining human paleofeces for parasites and micro-organisms and determining whether prehistoric caving activities were carried out by both sexes, thereby helping to engender, and more accurately describe, Mammoth Cave prehistory.

RETROSPECT AND PROSPECT

The history of archaeology in the Mammoth Cave area closely parallels the growth and development of archaeological trends in North America. From the Speculative to the Classificatory to the Explanatory and Interdisciplinary periods, archaeological inquiry in the Central Kentucky Karst has demonstrated that the uncommon preservation characteristics of the cave environment provides unique insight into human behavior (prehistoric and historic) that may be more accessible than from open "surface" sites. Table 1 also reflects that, along with an increase in the intensity of cave archaeological investigation, a greater sophistication began once interdisciplinary research was initiated at the Park (post-1960). That work was initiated

by Patty Jo Watson and her associates and colleagues.

Early turn-of-the century interests in cave archaeology, primarily atheoretical, prompted work at surface sites in the Mammoth Cave area and led to speculation about the origins of prehistoric cultural materials, sometimes comparing them to the better-understood European record (e.g., Nelson 1917; Young 1910). Assessing significance of and attempting to order archaeological sites from within the Park area, both above ground and below, and assessing Mammoth Cave collections held outside the Park, were the foci of the Classificatory Period between 1916 and 1970, culminating in the summaries of Douglas W. Schwartz (1958a-h, 1960a,b, 1965). More recent work by Watson and her colleagues brought a theoretical and interdisciplinary framework to the

Speculative

Rafinesque (1824), Young (1910)
pre-1915

Classificatory

Carey (1942), Hanson (1960), Fowkes 1916-1970 (1922), Funkhouser and Webb (1932), Meloy (1968), Moore (1916), Nelson (1917), Neumann (1938), Pond (1935, 1938), Schwartz (1958a-h; 1960a,b, 1965, 1967), Schwartz and Hanson (1961), Schwartz and Sloan (1958, 1960a,b), Schwartz and Sloan and Hanson (1960)

Explanatory

*Beditz (1979, 1981), Carstens (1974, 1975, 1976, 1977, 1978, 1980), Carstens and 1971-Present**

Interdisciplinary

Watson (1996), Crothers (1981, 1983), Crothers and Ward (1995), DiBlasi (1987a,b, 1996), Duffield (1974), Hensley (1995, 1996), Kennedy (1990, 1993, 1996), Marquardt (1974), Molnar and Ward (1974), Munson et al. (1989), Prentice (1993, 1994, 1996), Robbins (1971, 1974, 1980), Robbins et al. (1981), Ruppert (1994), Schoenwetter (1974), K. Tankersley et al. (1994), K. Tankersley et al. (1990), K. Tankersley et al. (1985), S. Tankersley (1993), Wagner (1976), Watson (1969, 1974, 1986, 1992), Watson and Carstens (1975, 1982), Watson and Kennedy (1993)

Table 1: Archaeological research in the area of Mammoth Cave National Park, 1824-Present (*not an exhaustive list).

archaeology of the Park often reflecting various themes prominent in the "New Archaeology." Within the last decade cave art studies (DiBlasi 1996) have added a cognitive, or post-processualist research slant to the efforts begun by Watson's group. However, additional research is still needed in the Mammoth Cave area, above ground and below. Only the tip of

the proverbial iceberg at Mammoth Cave has been studied, whereas artifacts from surface sites and from within the caves continue to be damaged or stolen in spite of the security efforts of the National Park Service. New insights and new energies are needed in the 1990s to carry on the fascinating study of the aboriginal and Euro-American people who explored and exploited the Kentucky underworld.

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References

Appelgate, Darlene

2000 Fax to Kenneth C. Carstens, July 1, 2000.

Barnes, Shelley

1974 Analysis of Three Bt-5 Burials. Unpublished Manuscript. Department of Anthropology, Washington University, St. Louis.

Beditz, Lindsay C.

1979 Archaeological Reconnaissance and Testing of Alternative JCCCC Sites in Mammoth Cave National Park. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.

1981 Mammoth Cave National Park, Kentucky: Bluffline Survey of the Childress Farm/Great Onyx Job Corps Civilian Conservation Center Property. Manuscript on file, National Park Service Southeast Archaeological Center, Tallahassee.

Brown, Jeffrey

1977 The Elmore Surface Collection Site: A Paleo-Archaic Lithic Assemblage. Senior Honors Thesis, Department of Anthropology, Washington University, St. Louis.

Carey, Henry A.

1942 Report on John M. Nelson Collection. U.S. Department of the Interior, National Park Service, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.

Carstens, Kenneth C.

1974 Archaeological Surface Reconnaissance of Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis.

1975 Surface Archaeology in Mammoth Cave National Park, Kentucky. Paper Presented to the 40th Annual Meeting of the Society for American Archaeology, Dallas.

1976 Recent Investigations in the Central Kentucky Karst: A Preliminary Temporal Ordering of Several Surface Sites in the Mammoth Cave Area, Kentucky. Paper Presented to the 55th Annual Meeting of the Central States Anthropological Society, St. Louis.

1977 Three Springs Pumphouse: An Assessment of Damage. Manuscript on file, Mammoth Cave National Park, Kentucky.

1978 Mammoth Cave National Park: Archaeological Survey of Proposed Water Lines and Sewers. Manuscript on file, Southeast Archaeological Center, Tallahassee.

1980 Archaeological Investigations in the Central Kentucky Karst. Doctoral Dissertation, Department of Anthropology, Washington University, St. Louis.

Carstens, Kenneth C., and Patty Jo Watson (editors)

1996 Of Caves and Shell Mounds. University of Alabama Press, Tuscaloosa.

Cleland, Charles E.

1976 The Focal-Diffuse Model: An Evolutionary Perspective on the Prehistoric Cultural Adaptations of the Eastern United States. Midcontinental Journal of Archaeology, Vol. 1, No. 1.

Crothers, George M.

1981 Archaeological Investigations in Sand Cave, Kentucky. Eighth International Congress of Speleology, Proceedings, Vol. 1, Pp. 374-376.

1983 Archaeological Investigations in Sand Cave, Kentucky. National Speleological Society Bulletin, Vol. 45, Pp. 19-33.

1986 Final Report on the Survey and Assessment of the Prehistoric and Historic Archaeological Remains in Big Bone Cave, Van Buren County, Tennessee. University of Tennessee, Knoxville.

Crothers, George, and Robert Ward

1995 The NPS/Earthwatch Cultural Resource Survey: Discerning Patterns of Prehistoric Activity in Main Cave Despite 200 Years of Historic Use. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave.

DiBlasi, Philip J.

1987a Archaeological Monitoring of the Water Pipeline as the Floyd Collins Complex. Manuscript on file, National Park Service, Southeast Archaeological Center, Tallahassee.

1987b Drawings Found in Salts Cave. CRF Newsletter, Vol. 15, No. 4, Pp. 1-2.

1996 Prehistoric Expressions from the Central Kentucky Karst. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, University of Alabama Press, Tuscaloosa.

Duffield, Lathel

1966 The Robert Dugeon Site. National Park Service, Richmond, Virginia.

1974 Nonhuman Vertebrate Remains from Salts Cave Vestibule. Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp. 123-133, Academic Press.

Faulkner, Charles H. (editor)

1986 The Prehistoric Native American Art of Mud Glyph Cave. University of Tennessee Press, Knoxville.

Fowke, Gerald

1922 Archaeological Investigations. Part I. Cave Explorations in the Ozark Region of Central Missouri. Part II. Cave Explorations in Other States. Bureau of American Ethnology, Bulletin 76. Washington, D.C.

Funkhouser, William D., and William S. Webb

1928 Ancient Life in Kentucky. Kentucky Geological Survey, Geologic Reports, Series 6, Vol. 34.

1929 The So-Called "Ash Caves" in Lee County, Kentucky. University of Kentucky Reports in Anthropology and Archaeology, Vol. 1, No. 2.

1930 Rock Shelters in Wolfe and Powell Counties, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 1, No. 4, Lexington.

1932 Archaeological Survey in Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 2, Lexington.

1936 Rock Shelters in Menifee County, Kentucky. University of Kentucky, Reports in Anthropology and Archaeology, Vol. 3, No. 4, Lexington.

Gilmore, M.R.

1931 Vegetal Remains of the Ozark Bluff-shelter Culture. Michigan Academy of Science, Arts and Letters, Vol. 14, Ann Arbor.

Griffin, James B., editor

1952 Archaeology of Eastern United States. University of Chicago Press, Chicago.

Hagg, William

1939 Mulberry Creek Cord-Marked. Southeastern Archaeological Conference Newsletter, Vol. 1, No. 1, Lexington.

Hanson, Lee

1960 The Analysis, Distribution and Seriation of Pottery from the Green River Drainage as a Basis for an Archaeological Sequence of that Area. Unpublished Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Hensley, Christine

1995 Archaeological Investigations at the Stairway Rockshelter. Paper presented at the Fourth Annual Science Conference, Mammoth Cave National Park, Mammoth Cave, Kentucky.

1996 The Stairway Shelter (15Ed303), Mammoth Cave National Park. Paper presented at the 13th Annual Kentucky Heritage Council Archaeological Conference, March 1996, Louisville, Kentucky.

Jones, Volney

1936 The Vegetal Remains of Newt Kash Hollow Shelter. In *Rockshelters in Menifee County, Kentucky* by William S. Webb and W.D. Funkhouser. University of Kentucky Reports in Archaeology and Anthropology, Vol. 3, No. 4, Lexington.

Kennedy, Mary C.

1990 An Analysis of the Radiocarbon Dates from Salts and Mammoth Caves, Mammoth Cave National Park, Kentucky. Master's Thesis, Department of Anthropology, Washington University, St. Louis, Missouri.

1993 NPS and Earthwatch Cultural Resource Inventory of Mammoth Cave. In Cave Research Foundation Newsletter, Vol. 21, No. 4, Pg. 15.

1996 Radiocarbon Dates from Salts and Mammoth Caves. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 48-81, University of Alabama Press, Tuscaloosa.

Lewis, R. Barry

1996 The Archaeology of Kentucky. University of Kentucky Press, Lexington, in press.

Marquardt, William

1972a Recent Investigations in a Western Kentucky Shell Mound. A Research Report Read May 4, 1972 at the Annual Meeting, Society for American Archaeology, Miami Beach, Florida.

1972b Research Report on Excavations at the Carlston Annis Mound. Southeastern Archaeological Conference Newsletter, Vol. 16, No. 2.

1974 A Statistical Analysis of Constituents in Human Paleofecal Specimens from Mammoth Cave. In Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 193-209. Academic Press, New York.

Marquardt, William and Patty Jo Watson

1974 The Green River, Kentucky, Shellmound Archaeological Project. Paper Presented to the 73rd Annual Meeting of the American Anthropological Association, Mexico City.

1976 Excavation and Recovery of Biological Remains from Two Archaic Shell Middens in Western Kentucky. Paper Presented in the Symposium, "The Research Potential of Shell Middens: Methodological and Analytical Considerations," organized by Thomas Ryan. Southeastern Archaeological Conference, Tuscaloosa, Alabama. Copy of manuscript in possession of author.

- 1983 The Shell Mound Archaic of Western Kentucky. In Archaic Hunters and Gatherers in the American Midwest, edited by James L. Phillips and James A. Brown, pp. 323-39, Academic Press, New York.
- Marquardt, William, Patty Jo Watson, Mary Kennedy (editors)
1996 Archaeology of the Middle Green River, Kentucky, Kent State University Press.
- Meloy, Harold
1968 Mummies of Mammoth Cave. Shelbyville, Indiana: Micron.
- Molnar, Stephen, and Stephen Ward
1974 Dental Remains from Salts Cave Vestibule. In The Archaeology of the Mammoth Cave Area, edited by Patty Jo Watson, pp. 163-166, Academic Press.
- Moore, Clarence B.
1916 Some Aboriginal Sites on Green River, Kentucky: Certain Aboriginal Sites on Lower Ohio River. Academy of Natural Sciences of Philadelphia, Journal, 2nd Series, Vol. 16, No. 3. Philadelphia.
- Morse, Dan
1967 The Robinson Site and Shell Mound Archaic Culture in the Middle South. Doctoral Dissertation, Department of Anthropology, University of Michigan, Ann Arbor.
- Munson, Patrick J., and Cheryl Ann Munson
1990 The Prehistoric and Early Historic Archaeology of Wyandotte Cave and Other Caves in Southern Indiana. Indiana Historical Society, Prehistoric Research Series, Indianapolis.
- Munson, Patrick J., Kenneth B. Tankersley, Cheryl Ann Munson, and Patty Jo Watson
1989 Prehistoric Selenite and Satinspar Mining in the Mammoth Cave System, Kentucky. In Midcontinental Journal of Archaeology, 14(2):119-145.
- Nelson, Nels C.
1917 Contributions to the Archaeology of Mammoth Cave and Vicinity, Kentucky. Anthropological Papers, American Museum of Natural History, Vol. 22, Part I. New York.
- 1923 Kentucky: Mammoth Cave and Vicinity. Unpublished manuscript on file at the American Museum of Natural History, New York.
- Neumann, Georg K.
1938 The Human Remains from Mammoth Cave. American Antiquity, Vol. 3.
- Pollack, David (editor)
1990 The Archaeology of Kentucky: Past Accomplishments and Future Directions. Vol. 1. Kentucky Heritage Council State Historic Preservation Comprehensive Plan Report No. 1, Frankfort.

- Pond, Alonzo
1935 Report of Preliminary Survey of Important Archaeological Discovery at Mammoth Cave, Kentucky. Wisconsin Archeologist, Vol. 15.
- 1937 Lost John of Mummy Ledge. Natural History, Vol. 39.
- Prentice, Guy
1993 Mammoth Cave National Park: Overview and Assessment, Vols. I and II. Southeast Archaeological Center, National Park Service Tallahassee, Florida.
- 1994 A Settlement Pattern Analysis of Prehistoric Sites in Mammoth Cave National Park, Kentucky. Doctoral Dissertation, Department of Anthropology, University of Florida, Gainesville.
- 1996 Site Distribution Modeling for Mammoth Cave. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 12-32, University of Alabama Press, Tuscaloosa.
- Rafinesque, Samuel Constantine
1824 Ancient History, or Annals of Kentucky: Introduction to the History and Antiquities of the State of Kentucky. Frankfort.
- Ritchie, William
1933 The Lamoka Lake Site. Researches and Transactions of the New York State Archaeological Association, Lewis H. Morgan Chapter, Vol. 7, No. 4.
- Robbins, Louise
1971 A Woodland "Mummy" from Salts Cave, Kentucky. American Antiquity, Vol. 36:200-206.
- 1974 Prehistoric People of the Mammoth Cave Area. Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp. 137-162, Academic Press, New York.
- 1980 Appendix V: Report on Blue Spring Hollow Burial. In: Archaeological Investigations in the Central Kentucky Karst by Kenneth C. Carstens, Doctoral Dissertation, Department of Anthropology, Washington University, St. Louis.
- Robbins, Louise M., Ronald C. Wilson, and Patty Jo Watson
1981 Paleontology and Archaeology of Jaguar Cave, Tennessee. In, Proceedings of the VIIIth International Congress of Speleology, Volume I, B. Beck editor, pp. 377-380.
- Rolinson, Martha
1967 Temporal Perspective on the Archaic Cultures of the Middle Green River Region, Kentucky. Doctoral Dissertation, Department of Anthropology, University of Michigan, Ann Arbor.

- Ruppert, Lisa Karen
1994 Evidence for the Endoparasite *Giardia lamblia* in Human Paleofeces from Salts Cave, Mammoth Cave National Park, Kentucky. MA thesis, Department of Anthropology, Western Michigan University, Kalamazoo.
- Schoenwetter, James
1974 Pollen Analysis of Human Paleofeces from Upper Salts Cave. In Archaeology of the Mammoth Cave Area, edited by P.J. Watson, pp. 97-105, Academic Press, New York.
- Schwartz, Douglas
1958a Sandals and Textiles from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958b Archaeological Report on Materials in the John M. Nelson Collection from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958c An Archaeological Report on Physical Remains from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958d Summary and Evaluation of the 1916 American Museum Archaeological Work in Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958e Description and Analysis of Museum Materials from Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958f Archaeological Survey of Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958g Report on Two Radiocarbon Dates from Mammoth Cave, Kentucky. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
1958h The Archaeology of Mammoth Cave National Park. Manuscript, Mammoth Cave National Park Library, Mammoth Cave, Kentucky.
- 1960a Prehistoric Man in Mammoth Cave. Scientific American, Vol. 203.
1960b Archaeological Survey of the Nolin River Reservoir. Manuscript, Museum of Anthropology, University of Kentucky, Lexington.
- 1965 Prehistoric Man in Mammoth Cave. Eastern National Park and Monument Association. Interpretive Series, No. 2.

1967 Conceptions of Kentucky Prehistory: A Case Study in the History of Archaeology. Studies in Anthropology, No. 6, University of Kentucky Press, Lexington.

Schwartz, Douglas and Lee Hanson

1961 Archaeological Excavation in the Nolin Basin - 1961. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Schwartz, Douglas, and Tacoma Sloan

1958 Excavation of the Rough River Site, Grayson County 12, Kentucky. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

1960a Archaeological Survey of the Barren Reservoir. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

1960b Archaeological Survey of Twenty-Two Small Federal Projects in Kentucky. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Schwartz, Douglas W., Tacoma Sloan, and Lee Hanson

1960 Test Excavations in the Nolin Basin - 1960. Manuscript, Office of State Archaeology, University of Kentucky, Lexington.

Sides, Stan

1971 Early Cave Exploration in Flint Ridge, Kentucky: Colossal Cave and the Colossal Cavern Company. Journal of Spelean History, Vol. 4, No. 4.

Stout, Charles, and R. Barry Lewis

1995 Constantine Rafinesque and the Canton Site, a Mississippian town in Trigg County, Kentucky. Southeastern Archaeology, 14(1):83-90.

Tankersley, Kenneth

1996 Prehistoric Mining in Mammoth Cave. In Of Caves and Shell Mounds, edited by Kenneth C. Carstens and Patty Jo Watson, pp. 33-39, University of Alabama Press, Tuscaloosa.

Tankersley, Kenneth B., John Bassett and Samuel Frushour

1985 A Gourd Bowl from Salts Cave Kentucky. Tennessee Anthropologist 10:95-104.

Tankersley, Kenneth B., S.S. Frushour, F. Nagy, S.L. Tankersley

1994 The Archaeology of Mummy Valley, Salts Cave, Mammoth Cave National Park, Kentucky. North American Archaeologist, Vol. 15, Number 2, Pp. 129-145.

Tankersley, Stephen L.

1993 Detection and Recovery of Anthropogenic Introduced Pathogenic Microorganisms in Mammoth Cave, Mammoth Cave National Park, Kentucky. Unpublished MA thesis, Department of Anatomy, Wright State University, Dayton.

Wagner, Gail E.

1976 An Archeobotanical Analysis of Five Sites in the Mammoth Cave Area. Master's Thesis, Department of Anthropology, Washington University, St. Louis.

Watson, Patty Jo

1986 Prehistoric Cavers of the Eastern Woodlands. In: The Prehistoric Native American Art of Mud Glyph Cave, edited by Charles H. Faulkner, University of Tennessee Press, Knoxville.

1992 Cave Research Archaeological Project. Cave Research Foundation Annual Report, Pp. 46-47, Memphis.

Watson, Patty Jo (editor)

1974 Archaeology of the Mammoth Cave Area. Studies in Archaeology, Academic Press, New York.

Watson, Patty Jo, Richard A. Yarnell, Harold Meloy, William S. Benninghoff, Eric O. Callen, Adian Cockburn, Hugh Cutler, Paul W. Parmalee, Lionel Prescott, William B. White

1969 The Prehistory of Salts Cave, Kentucky. Illinois State Museum, Reports of Investigations, No. 16, Springfield.

Watson, Patty Jo, and Kenneth C. Carstens

1975 Archaeological Resources of Mammoth Cave National Park: A Brief Summary. Report Prepared for the National Park Service, July, Tallahassee.

1982 Archaeological Survey and Testing, Mammoth Cave National Park. An archaeological contract (#CX5000080976) between the Cave Research Foundation and the National Park Service. Southeast Archaeological Center, National Park Service, Tallahassee.

Watson, Patty Jo and Mary C. Kennedy

1993 Cave Research Foundation Archaeological Project, 1993. Cave Research Foundation Annual Report, Pp. 49-50, Memphis.

Webb, William S.

1946 Indian Knoll, Site Oh2, Ohio County, Kentucky. The University of Kentucky Reports in Anthropology and Archaeology, Vol. 4, No. 3., Lexington.

1950a The Carls[t]on Annis Mound, Site 5, Butler County, Kentucky. University of Kentucky Reports in Anthropology, Vol. 7, No. 4. Lexington.

1950b The Read Shell Midden, Site 10, Butler County, Kentucky. University of Kentucky Reports in Anthropology, Vol. 7, No. 5, Lexington.

William S., and David L. DeJarnette

1942 An Archaeological Survey of Pickwick Basin. Bulletin 129, Bureau of American Ethnology, Washington, D.C.

Webb, William, and William D. Funkhouser

1936 Rock Shelters in Menifee County. *Reports in Anthropology and Archaeology*, Vol. 3, No. 4, Pp. 105-167.

Webb, William, and William Haag

1939 The Chiggerville Site, Site 1, Ohio County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 4, No. 1, Lexington.

1940 Cypress Creek Village, Sites 11 and 12, McClean County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 4, No. 2, Lexington.

1947 Archaic Sites in McLean County, Kentucky. *University of Kentucky, Reports in Anthropology*, Vol. 7, No. 1, Lexington.

Webb, William, and Charles G. Wilder

1951 *An Archaeological Survey of Gunter'sville Basin on the Tennessee River in Northern Alabama*. University of Kentucky Press, Lexington.

Wiley, Gordon R., and Jeremy A. Sabloff

1993 *A History of American Archaeology*, 3rd Edition, W. H. Freeman & Company, San Francisco.

Winters, Howard

1968 Value Systems and Trade Cycles of the Late Archaic in the Midwest. In *New Perspectives in Archaeology*, edited by S.R. Binford and L.R. Binford, pp. 175-221, Aldine Publishing Company.

1969 *The Riverton Culture: A Second Millenium Occupation in the Central Wabash Valley*. Published Jointly by the Illinois State Museum, *Reports of Investigations*, No. 13, and the

1974 Introduction. In: *Indian Knoll* (William S. Webb, 1946) Reprinted by the University of Tennessee Press, Knoxville.
Illinois Archaeological Survey.

Young, Col. Bennett

1910 *The Prehistoric Men of Kentucky*. Filson Club Publications, No. 25. Louisville: John P. Morton.

¹Initially called Little Alice, forensic examinations by Louis Robbins (Watson, ed., 1974) clearly demonstrated that the gender of Little "Al(ice)" was male, hence the corrected named, "Little Al."

The NPS/Earthwatch Archeological Project in Mammoth Cave

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ABSTRACT

We are in the eighth year of an ongoing systematic archaeological survey of the upper trunk passage in Mammoth Cave. The survey area is three-quarters complete, and greater than 9000 historic and prehistoric items have been located and recorded. Progress of this long-term project is updated and some preliminary results discussed. For example, it is now clear from the distribution of prehistoric remains that the location of mineral salts (predominately mirabilite) was an important focal point of prehistoric activity in the cave. The distribution of mid-nineteenth century historic artifacts and wood construction debris can be used to identify the locations of several of the TB patients' residential huts built in 1841-42 for Dr. Croghan's medical experiment. The survey should be completed in 2001 or 2002 including those portions of the cave most heavily impacted by saltpetre mining. Future survey teams should help delineate features of the saltpetre operation that have been dismantled or obscured by later modifications to the cave.

Rethinking the Prehistoric Archeology of Salts Cave and Mammoth Cave

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EXTENDED ABSTRACT

The CRF Archeological Project was initiated to investigate prehistoric cultural remains in Salts Cave, Mammoth Cave, and nearby caves and rockshelters. The research was developed during the heyday of the New Archaeology (1960s-1970s) when ecological, environmental, economic foci were dominant. As Director of this CRF Project, my own interest in agricultural origins combined with that disciplinary-wide emphasis meant a heavy stress on the economic aspects of cave mineral mining and even more on the importance of plant and animal remains (subsistence and paleoenvironment). The plant remains from Salts Cave and Mammoth Cave were especially interesting with regard to the burgeoning concern about agricultural origins in Eastern North America during the 1970s and 1980s. Flotation-recovery of charred botanical material together with the well-preserved remains in thousands of human paleofecal deposits established that the caves of the Mammoth Cave System contained the most detailed and best preserved evidence yet known anywhere for an early agricultural complex (Kennedy and Watson 1998; Watson ed. 1969, 1974, 1997). We are still following that research trajectory with a recently proposed attempt (by Kristin Sobolik, University of Maine) to isolate DNA from some of the paleofecal material.

A very different theme has recently been introduced into all this, however. Over the past several years I have been convinced by slowly accumulating evidence and by persistent colleagues (George Crothers and Phil DiBlasi are chief among them) that there was much more to ancient activities in parts of the world's longest cave than I had previously conceived of. We now know about Archaic period (3000 years old or more) pictographs and petroglyphs in Salts and Fisher Ridge Caves, mud glyphs in Adair Cave, and petroglyphs in 3rd Unnamed Cave (Crothers in press; Crothers et al. in press; DiBlasi 1996; Simek et al. 1998). We do not know with any certainty what these graphic renderings on cave walls, floors, and ceilings meant to the people who created them, but there is a very large literature on what is broadly termed "rock art", some of which may be partially relevant to thinking about these cave graphics in the Midsouth and Southeast.

In MesoAmerica and North America, there is widespread belief in a layered universe. Caves are thought to be entry and exit points between the surface layer where humans and other animals live, and the layers below that surface world. Whoever enters the lower levels must be prepared to encounter not only total darkness, total lack of food (at least of food that humans ordinarily eat), and quite possibly lack of water as well. A person entering these lower levels would have had (as documented ethnographically and inferred for prehistoric people) vivid and detailed expectations about who or what was down there. In much of

ethnographically known North America, for example, one of the main inhabitants of the subterranean dark zone was the earth-serpent/water panther Longtail monster, known as Uktena in the Southeast and Meshipishew in the Northeast. This fearsome creature ordinarily attacked humans who disturbed it, but those who succeeded in eluding the Uktena, or in negotiating with it, might be able to return to the surface world with a scale dislodged from the Uktena's hide, or with some moist clay rubbed off its body. Such a person was then equipped to be a seer, healer, wisdom keeper, or shaman in league – however tenuously – with the Uktena.

A frequent motif in the prehistoric cave graphics referred to above is a lattice-work or checker-board design. In the Great Lakes region, this kind of sign apparently “represented both a spiritual bridge between cosmic layers and a level or degree of sacred society membership. ...Mishi Bizi and his cohort were particularly accessible at places where two material realms or levels of reality met, for example where rock faces met water. The pictures of Mishi Bizi were found at cliffs, or in caves, and the manitou was logically associated with blindness..” (Martin 1999: 206).

What if anything does the above discussion have to do with the fact that approximately 30% of the human bone fragments in Salts Cave Vestibule are burned, cut, or otherwise modified (Robbins 1974)? Is this pattern the result of charnel house ceremonies performed on the mortal remains of loved ones? Does it reflect ritual or other cannibalism? (Turner and Turner 1999; White 1992). Are these the remains resulting from mutilation and dismemberment of enemies? To begin answering such questions with some degree of confidence, experts must reanalyze the unusual bone assemblage from the prehistoric cultural deposits in Salts Cave with modern techniques including Scanning Electron Microscopy.

Pending that and other future work, I conclude with two final comments:

- (1) An individual scientist's theoretical orientation, early training, and past experience markedly affect that individual's research designs as well as their implementation. NEVERTHELESS, science works: what philosopher of science Thomas Kuhn called the essential tension between expectations and observations, as well as the lively exchange of data and opinions within a healthy scientific community ensure that, sooner or later, the truth will out. That is, competition among advocates of alternative hypotheses will provide a diverse array of data illuminating the subject matter far more comprehensively than does monolithic, narrowly channelled research of one person or of a single very focused research group.
- (2) After many decades of cave archaeology in parts of the Mammoth Cave System, we have learned a great deal, which is important and gratifying to those of us who work there, but equally significant is the fact that this cave system keeps delivering surprises to those who remain alert to the subtle complexities of that marvelous subterranean universe. The latest of those surprises is that clues to the cognitive worlds of ancient people who entered it seem to be subtly but undeniably preserved in the rooms and passageways of the world's longest cave.

NOTE: Carol Diaz-Granados and Jerome Jacobson kindly provided information on the water panther/Uktena monster (also see Hudson 1976), but are by no means responsible for anything I say about it here.

References Cited

- Crothers, George M.
 In Press. Early Woodland Mineral Mining and Perishable Remains in Mammoth Cave, Kentucky. In P. Drooker, ed. Fleeting Identities: Perishable Material in Archaeological Research. Southern Illinois University Center for Archaeological Investigations, Occasional Papers.
- Crothers, George M., Charles H. Faulkner, Jan F. Simek, Patty Jo Watson, and P. Willey
 In Press. Woodland Cave Archaeology in Eastern North America, In D. Anderson and R. Mainfort, eds. The Woodland Southeast. Tuscaloosa: University of Alabama Press.
- DiBlasi, Philip J.
 1996 Prehistoric Expressions from the Central Kentucky Karst. In K. Carstens and P. Watson, eds. Of Caves and Shell Mounds, pp. 40-47. Tuscaloosa, AL: University of Alabama Press.
- Hudson, Charles
 1976 The Southeastern Indians. Knoxville, TN: The University of Tennessee Press.
- Kennedy, M. C., and P.J. Watson
 1997 The Chronology of Early Agriculture and Intensive Mineral Mining in the Salts Cave and Mammoth Cave Region, Mammoth Cave National Park, Kentucky. Journal of Cave and Karst Studies, National Speleological Society Bulletin 59, 1: 5-9.
- Martin, Susan R.
 1999 Wonderful Power: the Story of Ancient Copper Working in the Lake Superior Basin. Detroit, MI: Wayne State University Press.
- Robbins, Louise M.
 1974 Prehistoric People of the Mammoth Cave Area. In P.J. Watson, ed. Archeology of the Mammoth Cave Area, pp. 137-162. New York: Academic Press.
- Simek, Jan F., Jay D. Franklin, and Sarah C. Sherwood
 1998 The Context of Early Southeastern Prehistoric Cave Art: a Report on the Archaeology of 3rd Unnamed Cave. American Antiquity 63: 663-677.
- Turner, Christy G., and Jacqueline A. Turner
 1999 Man Corn: Cannibalism and Violence in the Prehistoric American Southwest. Salt Lake City, UT: The University of Utah Press.
- Watson, P.J., editor
 1969 The Prehistory of Salts Cave, Kentucky. Illinois State Museum, Reports of Investigations No. 16. Springfield, IL: Illinois State Museum.
 1974 Archeology of the Mammoth Cave Area. New York: Academic Press.
 1997 Archeology of the Mammoth Cave Area, reprint of the 1974 edition with a new Foreword. St. Louis, MO: Cave Books.
- White, Tim D.
 1992 Prehistoric Cannibalism at Mancos 5MTUMR-2346. Princeton, NJ: Princeton University Press.

Regional Atmospheric Carbon Sink Within the South Central Kentucky Karst

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ABSTRACT

Of the $7.8 \times 10^3 \pm 1.9 \times 10^3 \text{ kg ha}^{-1}$ of total inorganic carbon (TIC) leaving the 25 km² Cave City basin of the south central Kentucky karst aquifer over one year (May 1995-96), 1% entered the aquifer as recharge, 57% was derived from carbonate mineral dissolution, and 42% was produced by biological activities. The inorganic component of the atmospheric "young" CO₂ sink was $3.4 \times 10^3 \pm 8.5 \times 10^2 \text{ kg ha}^{-1} \text{ yr}^{-1}$.

Published estimates of regional and global carbonate mineral weathering sink terms typically assume that each mole of "old" mineral carbon reacts with a mole of young carbon as H₂CO₃^{*}. Examination of the elementary reactions of the CaCO₃-H₂O-CO₂ system, however, suggests that under geologically reasonable conditions reaction with H₂O and H⁺ can lower the young/old carbon ratio.

INTRODUCTION

Limestone karst aquifer/landscape systems cover some 12% of the earth's land surface (Ford and Williams, 1989). In addition to the complex biogeochemical interactions that impact carbon transport and cycling in other geological terranes, in these areas carbon dynamics are further complicated by fluid/carbonate rock interactions (White, 1988; Ford and Williams, 1989). Numerous processes impact the evolution and transport of CO₂ within these environments. In addition to the typically low, ubiquitous atmospheric background levels, sources of carbon dioxide within carbonate karst systems include microbial respiration, oxidation of organic material, plant root respiration in the soil as well as carbonate mineral precipitation. Dissolution of limestone by H₂SO₄ can also liberate CO₂ (White, 1988). Atkinson (1977) and Wood and Petraitis (1984) found evidence of CO₂ production within the vadose zones of both carbonate and noncarbonate aquifers, presumably by oxidation of organic material washed down from the soil zone. The primary sinks include diffusive loss to the atmosphere, uptake by infiltrating recharge waters, and dissolution of carbonate minerals in CO₂-H₂O solutions.

Understanding and quantifying CO₂ landscape/atmosphere interactions is increasingly relevant with the recognition that rising atmospheric CO₂ levels have the potential to impact rates of global climate change (Keeling *et al.*, 1982 and 1995; Baes *et al.*, 1977; Houghton and Woodell, 1989; IPCC, 1990, 1992, 1994, and 1995). Weathering of carbonate rock has been recognized as a sink term for atmospheric CO₂ at the continent scale (Bernier *et al.*, 1983; Meybeck, 1987; Probst *et al.*, 1994; Amiotte Suchet and Probst, 1993, 1995; Liu *et al.*, 1998).

The broad, global estimates of large-scale carbon pool size and structure, however, are still subject to considerable uncertainty. The global "missing carbon sink", estimated at 1.2 to $1.8 \times 10^{15} \pm 1.5 \times 10^{15}$ g C yr⁻¹ (Siegenthaler and Oeschger, 1978; Broecker, *et al.*, 1979; IPCC, 1994; Joos, 1994; Hesshaimer, *et al.*, 1994), and which has remained unsolved through more than a decade of intense scrutiny, highlights this problem. The answer lies in a clearer quantitative description of cycle dynamics. Along with broad-scale "box" cycle models, detailed process/rate studies are required to develop sufficiently precise quantitative evaluation of reservoir dynamics, and to understand how pools with different sizes, residence times, and exchange rates interact.

This paper reports on results of a one year (May 17, 1995 to May 16, 1996) calibrated hydrochemical modeling program designed to study detailed inorganic carbon dynamics within the 25 km² Cave City Groundwater Basin of the humid-subtropical south central Kentucky karst aquifer. Like in other well-developed karst flow systems, fluid flow and chemical changes within the Cave City Basin can be extremely rapid, and the new, high temporal resolution methods presented here use two minute-resolution to encompass all significant features of storm-scale and seasonal variations. In this paper we report estimates of the magnitudes of mineral, atmospheric, and biological sources of the total inorganic carbon (TIC) flux from the catchment and an estimate of the inorganic component of the regional atmospheric CO₂ sink term resulting from carbonate mineral weathering. This represents a step toward quantitative evaluation of the atmosphere/landscape interaction for well-developed karst landscapes in humid-subtropical climates, which cover large areas of the southeastern U.S. as well as extensive regions of southern Asia (Köppen and Geiger, 1936).

Although not considered in this paper, field observations suggest that the transport of both dissolved and particulate organic carbon, in forms ranging from simple acids and sugars to complex humic substances (Moore, 1997; Anthony, 1988; Vaughan, 1998), also participate in aquifer carbon budgeting. Further study of organic carbon and microbial ecology within the Cave City Basin and the nearby Echo River Basin are underway (Vaughan, 1998; Elliott *et al.* 2000).

AQUIFER INORGANIC CARBON BALANCE

In our analysis we assume that there are three classes of sources for total inorganic carbon, TIC (MT⁻¹), leaving a limestone or dolomite karst groundwater basin:

- a. dissolved inorganic carbon in precipitation, in equilibrium with the atmospheric background CO_2 pressure, entering the aquifer as recharge, C_a (MT^{-1}),
- b. biological processes that produce gaseous CO_2 in the soil, vadose, and saturated zones, including microbial respiration, oxidation of organic material, and plant root respiration, C_b (MT^{-1}), and
- c. carbonate mineral dissolution, C_m (MT^{-1}).

Thus over a specified time interval t (T),

$$\int_0^t \text{TIC} dt = \int_0^t C_a dt + \int_0^t C_b dt + \int_0^t C_m dt. \quad (1)$$

Since C_a and C_b originate in the atmosphere as CO_2 gas, and leave the karst system as dissolved inorganic carbon species, we define the inorganic component of the CO_2 sink, x ($\text{MT}^{-1} \text{L}^{-2}$) due to flow and biogeochemical processes within the karst landscape/aquifer system:

$$\xi = (\int_0^t C_a dt + \int_0^t C_b dt) / tA \quad (2)$$

where t is the length of the sampling period (T), and A is drainage basin area (L^2). C_a is estimated by calculating a carbon mass flux leaving the basin, using measured river discharge and assuming TIC in equilibrium with a constant representative atmospheric CO_2 pressure, nominally set at 360 parts per million over the study period, where

$$\text{TIC} = [\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{H}_2\text{CO}_3^*] \quad (3)$$

with activities denoted by square brackets and where $(\text{H}_2\text{CO}_3^*)$ is the sum of $\text{H}_2\text{CO}_3^\circ$ and aqueous CO_2 (Stumm and Morgan, 1981). In the current study, input data with two-minute resolution of chemical and flow conditions within the river are able to encompass all significant features of storm-scale and seasonal variations, so that close estimates of the appropriate integrals can be obtained.

To obtain both C_m and C_b , we make use of the fact that during dissolution of limestone or dolomite one mole of C is released from the mineral for each mole of $\text{Ca}^{2+} + \text{Mg}^{2+}$, regardless of the elementary reaction involved (Berner *et al.*, 1983; Plummer *et al.*, 1978; Busenberg and Plummer, 1982), so that

$$\int_0^t C_m dt = \int_0^t (Ca^{2+} + Mg^{2+}) dt, \quad (4)$$

and by substituting (4) into (1) and rearranging,

$$\int_0^t C_b dt = \int_0^t TIC dt - \left(\int_0^t (Ca^{2+} + Mg^{2+}) dt + \int_0^t C_a dt \right). \quad (5)$$

Finally, having determined C_a and C_b , we can obtain a value for the inorganic carbon sink term using (2).

FIELD SITE

The geology and hydrogeology of the south central Kentucky karst has been reviewed by numerous authors including Hess and White (1988, 1989) and Palmer (1991), and Quinlan and Ray, (1983). Logsdon River is one of the major underground streams of the south central Kentucky karst. Within the Proctor Cave section of the system, near the southwestern currently explored edge of Mammoth Cave, Logsdon River converges with Hawkins River, which drains about 75 km² near Park City, Kentucky. The Logsdon River drains the 25 km² Cave City groundwater basin. Within Logsdon River, about 100 m upstream from the confluence of the two rivers, are two 15-cm diameter, 145-m deep observation wells intersecting the river. One well is equipped with a compressor-driven pump for collecting water samples from the surface, and through the other electronic probes deliver high-resolution (two-minute) data on stage, velocity, temperature, and specific conductance. The bottoms of the wells can be reached underground (for pump and probe installation and maintenance) through the Doyel Valley Entrance to Mammoth Cave, requiring a 3-km round-trip through the cave. The conduit at the Logsdon River well site is about 3 m tall and 7 m wide, and lies near the downstream end of one of the world's longest known sections of accessible underground river passage, continuously traversable for over 8 km.

FIELD AND LABORATORY METHODS

The primary objective of the research has been to collect sufficient high-resolution data on both flow and chemical characteristics of the river to quantitatively evaluate the magnitudes and rates of change of carbonate chemistry and water/rock interactions at a variety of time scales. Four probes are installed through the wells into each stream, including temperature, specific conductance, river stage, and velocity. A Campbell 21X multichannel data logger queries the probes every thirty seconds, and averages these readings every two minutes. Data are recorded at varying intervals, from each two minutes during rapidly changing flow or chemical conditions in the rivers to hourly during static conditions. Using an accurately surveyed passage cross section at the well site, stage data were used to calculate flow cross-sectional and wetted perimeter for discharge calculations.

With data resolution varying from two minutes during storms to hourly during static conditions, these values were determined for 21,473 observations between May 5, 1995 to May 4, 1996. Equipment problems led to a loss of 19.9 days (5.4% of the period) of conductance data during the year. With the large number of conductance chemographs during storms available over the rest of our study period, however, we were able to closely estimate these missing periods using a procedure analogous to unit hydrograph analysis (Chow, 1964). In addition, electrical problems created offsets of the data (29.2 days, or 8.0%) that were corrected by calibration and translation.

We also used direct velocity measurements (with two minute resolution) to estimate discharge under open channel conditions, but these were limited by measurement at a single location in the center of the flow cross-section in each stream. To account for the vertical velocity distribution the velocity at 0.6 flow depth, which has been shown to be close to the mean velocity in the vertical profile, was related to the apparent velocity at the fixed-depth point of measurement assuming a logarithmic velocity distribution (Boyer, 1964). In order to correct for longitudinal velocity variations, discharge measurements were made on eight occasions using standard wading-rod gaging techniques and a 0.3 meter longitudinal spacing (Boyer, 1964), and the average ratio between mean and maximum velocity (assumed at the center of each channel, where the velocity sonde is located) was determined. The vertically corrected apparent velocity in each stream was then multiplied by this ratio (0.57). As this represents the highest relative uncertainty in the measurements, we report the actual mass flux values $\pm 25\%$.

Hourly water chemistry measurements have been made during storms of various magnitudes by sampling from the surface through the wells. Calcium has been measured with either titration or with a Varian Spectra 10/20 atomic absorption spectrophotometer (AA) at the Ogden Environmental Water Lab at Western Kentucky University, and magnesium has been measured exclusively with atomic absorption. Samples for calcium and magnesium AA analysis were filtered (0.45 μ m) and acidified. Conductivity and pH were measured immediately after sample collection. A gel filled combination electrode using two-point calibration was used to measure pH. Bicarbonate alkalinity was been measured by acid titration either immediately after collection, or in some cases samples were stored on ice, and the titrations were done at the Ogden Laboratory within 24 hours.

ANALYSIS

With this information we have used least-squares regression analysis (Draper and Smith, 1981) to relate high-resolution specific conductivity data from within the cave rivers to calcium, magnesium, and bicarbonate concentrations, as well as pH. These relationships, along with direct temperature measurement, then allow calculation of several important components of carbonate system behavior with high temporal resolution, including inorganic carbon (TIC) fluxes through the aquifer contributed from mineral, atmospheric, and biological sources.

Activities of Ca^{2+} , Mg^{2+} , and HCO_3^- are first obtained using the extended Debye-Hückel limiting law (Stumm and Morgan, 1981). Then activities of CO_3^{2-} and H_2CO_3^* are calculated, where

$$[\text{H}_2\text{CO}_3^*] = \frac{[\text{H}^+][\text{HCO}_3^-]}{K_1} \quad (8)$$

and

$$[\text{CO}_3^{2-}] = \frac{K_2[\text{HCO}_3^-]}{[\text{H}^+]} \quad (9)$$

These are then summed using (3) to obtain *TIC* for each observation. Along with calcium and magnesium activities, this is used to solve (4), (5), and (2) for C_m , C_b , and x , respectively. C_a is obtained from discharge and atmospheric CO_2 , using appropriate equilibria. Our aqueous model assumes that the influence of ion pairing and complexation is negligible.

RESULTS

Flow and Chemistry Variations

Fifty-six storm events caused measurable changes in the flow or chemistry within the river during the study, with thirteen of the storms flooding the conduit to the ceiling. During the largest storm, on May 18, 1995, the water level reached a maximum height of 28.2 m, with a maximum rate of rise of 6.03 m/hr. The ceiling of the conduit under these conditions is about 25 m below the water table, and the conduit remained totally flooded for 114 hours. Based on observed flow characteristics, the year can be divided into a dry and wet season. After the May 1995 flood subsided, the conduit flooded only twice over the next 224 days, and one of those events was the remnants of a hurricane (Opal, study day 141, October 5), a relatively infrequent weather condition for Kentucky. In contrast, during the last 135 days of the study, beginning on Jan 2, 1996, floodwaters filled the conduit ten times, or an average of about once every two weeks.

The chemistry of the system also showed a seasonal signature, with the most highly concentrated fluids during the dry season, presumably reflecting a larger proportion of diffuse flow, in contrast to more diluted storm flow, with higher concentrations of dissolved limestone. A third-order regression curve of the 21,473 conductivity observations shows a sine-like form, apparently reflecting a higher frequency of storms during the winter which do not allow the river's waters to return to a "chemical baseflow" condition, in which river flow is completely maintained relatively concentrated diffuse flow waters. Conductivity, in contrast, continues to climb for several months between the infrequent rains of the dry summer period. This suggests that the full relaxation time for the waters to reach a "chemical baseflow" condition in the river is on the order of months, rather than days in the case of river stage.

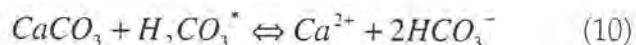
The minimum conductivities reached as a result of storms nearly all fell within a close range, suggesting a minimum bounding value of about 190 mS that, for sufficiently large rainfalls, is independent of season, rainfall amount, and antecedent moisture conditions. The one exception is the large May 1995 flood, where the conductivity reached a low of 167 mS.

Inorganic Carbon Flux

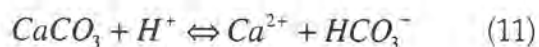
Of the $7.8 \times 10^3 \pm 1.9 \times 10^3$ kg ha⁻¹ of total inorganic carbon that left the Cave City basin during the year, 1% entered the aquifer as recharge, 57% was derived from carbonate mineral dissolution, and 42% was produced by biological activities. The inorganic component of the atmospheric "young" CO₂ sink was $3.4 \times 10^3 \pm 8.5 \times 10^2$ kg ha⁻¹ yr⁻¹, which includes that which came in as recharge plus the biologically produced inorganic carbon, which originally came from the atmosphere through plant and microbial processes.

DISCUSSION

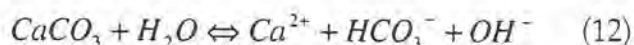
Regional and global carbon models that consider carbonate mineral weathering have generally assumed that for all of the riverine dissolved inorganic carbon leaving the continents, mostly as HCO₃⁻, the source has been one mole of mineral carbon reacting with one mole of atmospheric carbon as H₂CO₃^{*} (e.g. Berner *et al.*, 1983; Meybeck, 1987; Berner and Lasaga, 1989; Probst *et al.*, 1994; Amiotte Suchet and Probst, 1993, 1995; Liu *et al.*, 1998), through the reaction



Inspection of the elementary reactions of the CaCO₃-H₂O-CO₂ system, however (Plummer *et al.*, 1978, 1979), shows that in addition to the reaction of with H₂CO₃^{*}, calcite (and similarly, dolomite (Busenberg and Plummer, 1982)) simultaneously reacts with protons and water in the reactions



and



The roughly 57:43 ratio of "old" mineral C to "young" atmospheric C produced within the Cave City Basin can be explained by noting that to the extent that calcite dissolution occurs due to the elementary reactions (11) and (12), each mole of C produced comes from the "old" mineral source *without* an atmospheric contribution. This appears to be geologically reasonable, as the CO₂ pressures reported for a wide variety of geochemical environments within the south-central Kentucky karst [e.g. Miotke, 1974, 1975; Hess, 1974; Hess and White, 1988; Palmer,

1995, Anthony, 1998; Vaughan, 1998) range from atmospheric ($\sim 10^{-3.5}$ atm) to about $10^{-1.5}$ atm. Waters in equilibrium with the range of CO_2 pressures reported for the overall flow system may reach a pH of about 4.5 for the highest soil CO_2 levels, but within the aquifer, due to rapid buffering upon contact with calcite, they are generally above 6.5. Under these conditions the reaction with carbonic acid can be expected to dominate, with a smaller contribution from reaction (12), limited by the solubility of calcite in pure water, and perhaps reaction (11) where acidic soil solutions first meet the soil-bedrock interface.

Although the difference between the 50:50 ratio assumed in most carbonate mineral weathering sink term estimates and the 57:43 ratio shown by our data will not lead to a dramatic correction of this term with global carbon cycle estimates, it does point out the need for detailed process studies such as this to compliment the large scale global estimates. More importantly, these results show that the details of atmospheric CO_2 /carbonate mineral interactions have some dependence on the kinetics of the dissolution and precipitation reactions. Thus the overall balance between the continental CO_2 sink (from weathering of carbonate minerals) and the oceanic CO_2 source (from an equal amount of precipitation) assumed to exist (Berner and Lasaga, 1989), may not be in balance to the extent that the kinetics of the reactions vary.

Within global carbon cycle, while the general budget models and concepts can be straightforward, the geochemical details are in some ways complex. Additional, detailed work to describe these processes quantitatively at a variety of scales is required to ensure that our understanding of model dynamics is sufficiently precise to answer the hugely important questions posed by the carbon cycle and the potential for anthropomorphic influence on the rates global climate change.

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References

- Amiotte Suchet, P. and J.L. Probst, A global model for present day atmospheric/soil CO₂ consumption by chemical erosion of continental rocks (GEM-CO₂), *Tellus*, 47B, 273-280, 1995.
- Amiotte Suchet, P. and J.L. Probst, Modeling of atmospheric CO₂ consumption by chemical weathering of rocks: Application to the Garonne, Congo, and Amazon Basins. *Chem. Geol.*, 107, 205-210, 1993.
- Anthony, D.M., 1988, *Seasonal effects on the geochemical evolution of the Logsdon River, Mammoth Cave, Kentucky*. Unpublished MS. Thesis, Department of Geography and Geology, Western Kentucky University, 140 p.
- Atkinson, T.C., Carbon dioxide in the atmosphere of the unsaturated zone: An important control of groundwater hardness in limestones, *J. Hydrol.*, 35, 111-125.
- Baes, C.F. Jr., H.E. Goeller, J.S. Olson, and R.M. Rotty, *The Global Carbon Dioxide Problem*, 72 pp., Oak Ridge Natl. Lab. Report NTIS ORNL-5194, Oak Ridge, Tennessee, 1976.
- Berner, R.A. and A.C. Lasaga, Modeling the geochemical carbon cycle, *Scientific Am.*, 260, 74-81, 1989.
- Berner, R.A., Lasaga, A.C. and R.M. Garrels, The carbonate-silicate geochemical cycle and its effect on atmospheric CO₂, *Am. J. Sci.*, 283, 641-683, 1983.
- Broecker, W. S. *et al.*, Fate of fossil fuel carbon dioxide and the global carbon budget, *Science*, 206, 409-418, 1979.
- Busenberg, E. and L.N. Plummer, The kinetics of dissolution of dolomite in CO₂-H₂O systems at 1.5 to 65°C and 0 to 1 atm PCO₂, *Am. J. Sci.*, 282, 45-78, 1982.
- Draper, N. and H. Smith, *Applied Regression Analysis (3rd Edition)*, 706 pp., John Wiley & Sons, Inc., New York, 1981.
- Ford, D. C. and P. Williams, *Karst Geomorphology and Hydrology*, 601 pp., Unwin Hyman Ltd., Winchester, Massachusetts, 1989.
- Hess, J. and W. White, 1988, Storm response of the karstic carbonate aquifer of south-central Kentucky. *Journ. Hydrol.* 99, 235-252.
- Hess, J. and W. White, 1989, Chemical hydrology: in *Karst Hydrology: Concepts from the Mammoth Cave Area*, W.B and E.L White, eds., New York: Van Nostrand Reinhold, 346p.

- Hesshaimer V., M. Heimann and I. Levin, 1994: Radiocarbon evidence for a smaller oceanic carbon dioxide sink than previously believed, *Nature*, 370, 201-203, 1994
- Houghton, R.A. and G.M. Woodell, Global climate change, *Scientific Am.*, 260 (4), 36-44, 1989.
- IPCC (Intergovernmental Panel on Climate Change). *Climate Change: The IPCC Scientific Assessment*. J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.). Cambridge University Press, Cambridge, U.K., 1990.
- IPCC (Intergovernmental Panel on Climate Change), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, 200 pp. , Cambridge Univ. Press, Cambridge, 1992.
- IPCC (Intergovernmental Panel on Climate Change), *Radiative Forcing of Climate Change: The 1994 Report of the Scientific Assessment Working Group of the IPCC*, Meteorological Office Marketing Communications Graphics Studio, Bracknell, United Kingdom, 1994a.
- IPCC (Intergovernmental Panel on Climate Change), *Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, edited by J. T. Houghton, L. G. Meria Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haites, N. Harris and K. Maskell, Cambridge University Press, Cambridge, Great Britain, 1994b.
- IPCC (Intergovernmental Panel on Climate Change), *IPCC Second Assessment - Climate Change 1995*, 64 pp. , IPCC, WMO, Geneva, Switzerland, 1995.
- Joos F., Imbalance in the budget, *Nature*, 370, 181-182, 1994.
- Keeling, C.D., R.B. Bacastow, and T.P. Whorf, Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii in *Carbon Dioxide Review: 1982.*, Edited by W.C. Clark, Oxford University Press, New York, 1982.
- Keeling, C.D., T.P. Whorf, M. Wahlen, and J. van der Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature*, 375, 666-670, 1995
- Köppen, W. and R. Geiger, *Handbuch der Klimatologie*, 44 pp., Gebrüder Borntraeger, Berlin, 1936.
- Liu, Z., Y. Daoxioan, S. He, and J. Zhao, Contribution of carbonate rock weathering to the atmospheric CO₂ sink, *International Geological Correlation Program, Project 379: Karst Processes and the Carbon Cycle Newsletter 1998*, 27-34, 1998.
- Meybeck, M., Global chemical weathering of surficial rocks estimated from river dissolved load, *Amer. J. Sci.*, 287, 401-428, 1987.
- Miotke, F. -D., 1975, *Der Karst im zentralen Kentucky bei Mammoth Cave*, Jahrbuch der Geographischen Gesellschaft zu Hannover für 1973, 360p.

- Miotke, F. -D., 1974, Carbon dioxide and the soil atmosphere. *Karst u. Höhlenkunde, Abh. Ser. A*, No. 9, 1-49.
- Moore, T.R., Dissolved organic carbon: Sources, sinks, and fluxes and role in the soil carbon cycle, in *Soil Processes and the Carbon Cycle*, edited by R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart, pp. 281-292, CRC Press, New York, 1997.
- Palmer, A., *A Geological Guide to Mammoth Cave National Park*, 196 pp., Zephyrus Press, Teaneck, New Jersey, 196 p., 1981.
- Plummer, L.N., T.M.L. Wigley, and D.L. Parkhurst, The kinetics of calcite dissolution in CO_2 -water systems at 5 to 60°C and 0.0 to 1.0 atm CO_2 . *Am. J. Sci.*, 278, 179-216, 1978.
- Pohl E.R. and W.B. White, Sulfate minerals: Their origin in the central kentucky karst, *Am. Mineral.*, 50, 1461-1465, 1965.
- Probst, J.L., J. Mortatti, and Y. Tardy, Carbon river fluxes and global weathering CO_2 consumption in the Congo and Amazon River basins, *Appl. Geochem.*, 3, 1-13, 1994.
- Siegenthaler, U. and H. Oeschger, Predicting future atmospheric carbon dioxide levels, *Science*, 199, 388-395, 1978.
- Stumm, W. and J. Morgan, *Aquatic Chemistry An Introduction Emphasizing Chemical Equilibria in Natural Waters*, 780 pp., John Wiley and Sons, New York, 1981.
- Vaughan, K., 1998, *A quantitative analysis of interstitial fluid chemistry and limestone dissolution rates within the clastic sediment of a karst aquifer conduit, Mammoth Cave, Kentucky*. M.S. Thesis, Western Kentucky University, 128 p.
- White, W.B., *Geomorphology and Hydrology of Karst Terrains*, 464 pp., Oxford University Press, New York, 1988.
- Wood and Petraitis, Origin and distribution of carbon dioxide in the unsaturated zone of the southern High Plains, *Water Resour. Res.*, 20, 1193-1208, 1984.

Acidic Bog Drainage and Limestone Dissolution, Mammoth Cave National Park

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ABSTRACT

Stagnant ponds or bogs produce abundant amounts of humic material and organic acids. Organic acids are also produced on forest floors and by simpler organisms such as bacteria or lichens, thus accumulating in the upper horizon of the soil. The potential impact of these species on karst landscape development has received relatively little study. Organic acids have been found to promote mineral dissolution via two mechanisms, acidification and metal complex formation. In most natural settings, carbonic acid will be the predominant proton donor. The ability to form multifunctional complexes with cations, in addition to their acidic properties alone, allows these compounds to be effective at mineral dissolution. Two small catchments in similar geologic settings within Mammoth Cave National Park are being examined to study the phenomenon. One of these drainage areas contains a large bog with abundant organic matter and a pH of that has been measured below 4. The control stream does not contain bog vegetation and typically has more circumneutral pH levels. An approach combining geochemical modeling with limestone tablet weight loss methods is underway to determine the effect of these organic acids on limestone dissolution, and thus potentially on landscape development. Preliminary results indicate significant differences in the geochemistry of the two streams. Conductivity measurements in the bog stream (often <20 microSiemens) are as low as any surface or groundwaters that we know of recorded in the Mammoth Cave area.

Carbonate Chemistry Variations in Showerbath Spring, Mammoth Cave, Kentucky

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ABSTRACT

Vertical shafts (often referred to as pits, domes, and domepits) are a common feature of the south central Kentucky karst. These features are created by water flowing vertically downward within the vadose zone. While they may be concentrated at caprock margins and especially where ephemeral caprock streams cross onto the carbonate sequence, they may occur at any location within the aquifer. They vary in size, up to 25 m in diameter and 60 m deep, and in plan view may have cylindrical or elongated shapes. Vertical shafts are important because they:

- 1) often represent the headwaters for subsurface streams,*
- 2) form pathways for the rapid transport of pollution to the aquifer, and*
- 3) are often closely related to the surface drainage topography.*

Previous studies conducted on the genesis of horizontal river cave passageways in the Mammoth Cave area suggest that growth of the major base level conduits may be dominated by infrequent storm events. This project represents a pilot evaluation of temporal variations in water chemistry within Showerbath Spring, a perennially flowing vertical shaft in the Frozen Niagara section of Mammoth Cave. Weekly analyses of pH, temperature, bicarbonate, and calcium concentrations allow quantification of dissolution rates and CO₂ pressures. This in turn allows comparison of the temporal variation of these parameters with those of active, base level horizontal passages within the cave and their impacts on conduit development. During the year-long study the vertical shaft waters of Showerbath Spring were undersaturated at all times, and had a much smaller range of dissolution rates (~0.7-1.3 mm/yr) than those measured in Hawkins and Logsdon Rivers. Carbon dioxide pressures were generally low, in some cases less than atmospheric background levels.